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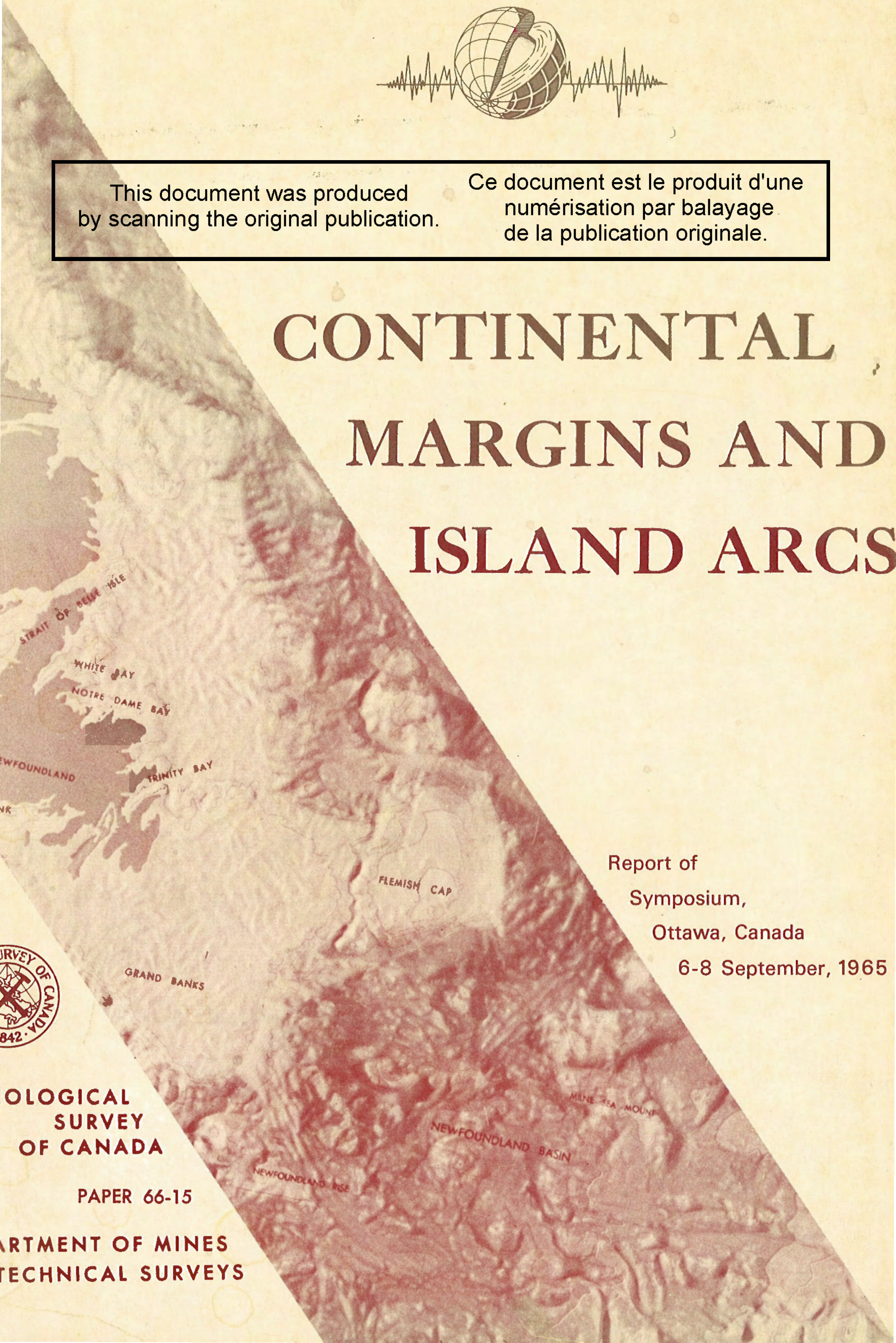
CONTINENTAL MARGINS AND ISLAND ARCS



Report of
Symposium,
Ottawa, Canada
6-8 September, 1965

OLOGICAL SURVEY OF CANADA

PAPER 66-15

ARTMENT OF MINES
TECHNICAL SURVEYS

The Upper Mantle Project is an international programme of research on the solid earth sponsored by the International Council of Scientific Unions; the programme is coordinated by the International Upper Mantle Committee, an IUGG committee set up jointly by the International Union of Geodesy and Geophysics and the International Union of Geological Sciences, with rules providing for the active participation of all interested ICSU Unions and Committees.

COVER PICTURE: Continental margin off Newfoundland from relief model, U.S. Navy Chart NPIC 910/60-U.

GEOLOGICAL SURVEY

OF CANADA

PAPER 66-15

CONTINENTAL MARGINS AND ISLAND ARCS

Report of a symposium held in Ottawa 6-8 September, 1965, under the sponsorship of the International Upper Mantle Committee with financial assistance from UNESCO

Edited by W. H. Poole

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

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CONTENTS

Page

Page

CONTINENTAL MARGINS AND ISLAND ARCS

INTRODUCTION

At its first major meeting, held in Moscow in May 1964, the International Upper Mantle Committee (IUMC) decided to convene special symposia on three of the main programs sponsored by the Committee. The invitation of the Canadian Upper Mantle Committee to hold these symposia in Ottawa prior to the IUMC business meeting in September 1965, was accepted. The Geological Survey of Canada has published the proceedings of the symposia on Drilling for Scientific Purposes[1] and The World Rift System[2]. The present volume contains the papers from the remaining symposium.

The Symposium on Continental Margins and Island Arcs was concerned with the junction of the earth's two first-order structures – continents and oceans. The obvious structural differences of each are reflected in crustal and mantle differences extending to depths of several hundred kilometres. At continental margins, the continental crust thins to oceanic crust. Some margins are marked by vulcanism, trenches, and deep-focus earthquakes, while others are quiescent and in places associated with filled trough-like structures. The origin and evolution of continental margins, and their relation to mountain building and the growth of continents and oceans, are problems of prime importance.

In this volume, the forty-two papers are grouped by major ocean basins. Most of the papers deal with the margins and arcs in the Northern Hemisphere; for example, only two were devoted to the South Atlantic and Indian Ocean. The sequence in the volume departs considerably from the original program appearing in Appendix I.

The Session on the Atlantic and Mediterranean continental margins summarizes some studies of the margins of Eastern North America, Argentina, Western Europe, and the Mediterranean. Keen and Blanchard investigated the crustal structure off Eastern Canada near the northeastern end of the exposed Appalachian System, mainly by seismic refraction. The Scotian Shelf has a normal 35-kilometre crust underlain by mantle with a velocity of 8 km/sec. However, along the axis of the Appalachian System, the crust is 50 kilometres thick. Here, the lower part of the crust has intermediate velocities, and the mantle has a high velocity of 8.5 km/sec. Hood describes magnetic surveys off Eastern Canada; he reasons that the Flemish Cap lying east of the Grand Banks may be composed of Mesozoic or younger basalt. The extensive studies of the shelf off the east coast of United States, carried out over more than a decade by various methods, are described by Drake. He postulates that the two filled troughs underlying the shelf, slope,

[1]Geol. Surv. Can. Paper 66-13, 1966, 264 p.
[2]Geol. Surv. Can. Paper 66-14, 1966, 471 p.

and rise are analogous to a miogeosyncline and eugeosyncline prior to deformation. Of equally great interest is his hypothesis, arising from the relations of an apparent strike-slip fault to the shelf structures and onshore geology, that the basement structures under the shelf and rise must have been in existence at the end of Devonian. Geddes and Watkins concentrate on the linear magnetic anomaly, the Atlantic Shelf anomaly, which extends from Newfoundland to Florida over Drake's postulated "eugeosyncline". They favour a similar hypothesis - a buried, quiescent island arc. Ewing, Ewing, and Leyden describe the history of the Blake Plateau, while Ludwig, Ewing, and Ewing discuss the filled basins found on the shelf off Argentina, some of which are transverse basins and continuous with those onshore.

Demenitskaya and Dibner present a geomorphological and structural map of the Norway-Greenland basin, an area they appropriately call "Scandic". All features are classified and their origins explained. Structures extend into Scandic from the Atlantic. Of great importance are the metamorphic rocks of presumed Caledonian age, which have been dredged from the mid-ocean rift-zone. The crust of Scandic is predominantly of transitional type; upper mantle velocities of 7.5 and 8.1 km/sec have been determined. Hersey and Whittard describe the structure of the Cretaceous and Cenozoic sediments in the Western Approaches of the English Channel. The morphology and sedimentation of a submarine canyon off the Atlantic margin of France and of a region off the Mediterranean margin are described by Nesteroff. The final paper, by Berkhemer and Hersey on the Mediterranean, arrives at a postulated sequence of events in orogenesis, each stage of which is represented by different parts of the Mediterranean. The sequence includes crustal thinning and formation of a basin, sedimentary infilling of the basin, deformation, and irregular, oscillatory vertical movements of the deformed basin.

In the second session, on Caribbean island arcs, Mattson describes the geology of Puerto Rico, where most of the rocks are Cretaceous and younger. He speculates that the granitic intrusions, occurring as they do in a region of oceanic and transitional crust, were derived by successive refusions of a liquid which originated by partial fusion of the mantle. The tectonics of the West Indies are discussed by Hurley. Hersey and Bunce each present accounts of the Caribbean, Puerto Rico Trench, and outer ridge. Miss Bunce believes that the trench was probably formed in Eocene or later time. Talwani describes the gravity anomaly belts in the Caribbean. And, finally, Hamilton presents an interesting hypothesis on the origin of the Scotia and Caribbean island arcs, and their tectonic and "drifting" relations to the North American, South American, and Antarctic continents.

All but one of the papers in the third session on the Pacific and Indian Ocean island arcs are concerned with Pacific arcs. Burk begins the session with a comprehensive summary of the varied and complex geology of the Alaska Peninsula, the Aleutian island arc, bordering shelf, trench, and, to a lesser extent, the Bering Sea basin. He concludes that the island arc formed in early Tertiary across both oceanic and continental crust, while the trench formed in Tertiary or later time. Shor draws a comparison between the Aleutian Trench and filled trenches along the Pacific coast of North America, and considers that they represent a sequence of evolution. The linear magnetic anomalies in the Pacific Basin south of the Alaska Peninsula are described by Peter, while Hayes compares the topography, gravity, and magnetic anomalies along the exceedingly long and continuous Peru-Chile trench.

The western margin of the Pacific is discussed in several papers. Weizman describes the structure of the Kurile-Kamchatka arc and its relation to vulcanism and tectonics. Ludwig and others describe the Japan Trench, and Vacquier and Taylor speculate on their magnetic and heat flow data off the coast of Sumatra. An interesting historical account of the gravity surveys in the Solomon Islands is presented by Grover. Sykes examines the significance of more accurately located earthquakes in the Tonga-Fiji region. Deformation of the outer shelf off New South Wales, Australia, is discussed by Phipps; the deformation conforms to the limits of the onshore Permian-Triassic basins and probably occurred since the beginning of the rise of sea-level as a result of melting of ice of Wisconsin age. Woollard describes attempts at solving the complex relations of crustal structure, vulcanism, and growth of the Hawaiian Island chain. In conclusion, Hess comments on the Pacific Ocean basin, the ocean rises, and their ages of formation and pattern of growth.

Three papers deal with the Arctic region. Roots briefly summarizes the salient points of the continental margin off the Canadian Arctic Islands. Demenitskaya and Karasik report that the Nansen-Amundsen Basin of the Arctic Ocean is a typical ocean basin; and Hunkins presents a description of the margin off northern Alaska.

The final session on Petrology and Geophysics of Continental Margins and Island Arcs deals with certain problems of general interest, rather than specific areas. Kuno and Sugimura each correlate the variation in composition of basaltic magmas found in island arcs with the depth in the upper mantle where the magmas are generated along the zone of earthquake foci dipping beneath the arcs. Hamilton, on the other hand, arguing from high-pressure laboratory studies, explains the variation in magma types by melting of the mantle above and below the gabbro-eclogite transformation boundary. Ringwood contributes some interesting ideas on the problem in the discussion following these papers, based on his laboratory studies. Worzel presents his comparisons of many of the world's trenches and arcs; he concludes that the trenches formed by extensional forces resulting in graben faults or a fault-flexure combination. The size and shape of arcs and mountain ranges and their relation to polygonal cratonic blocks are examined by Brock. Wilson explains his views on the growth of oceans by upwelling along mid-ocean ridges and the growth of continents along island arcs, all caused by a shallow convecting layer in the mantle. Lee, Uyeda, and Taylor describe the results of statistical analyses of heat flow along continental margins and island arcs; and Nagata reviews the problem of conductivity anomalies along continental margins and refers them to a difference in electrical conductivity of the upper mantle under the ocean and under the continent. The gravity characteristics of many trenches and rifts are examined by Bowin. He concludes that if they formed by tensional forces, then 40 to 100 kilometres of separation is required before dense substratum begins to rise beneath a trough or rift. From an analysis of the Sa phase of earthquake-generated energy, Brune concludes that the Sa phase has high velocities under shield areas of the world. And, finally, Zietz and King describe the crustal structure and trends found along a transcontinental aeromagnetic survey study across the United States.

The closing session records the recommendations and discussions of the participating scientists for future investigations of continental margins and island arcs. From these recommendations, the International Upper Mantle Committee drafted and approved the recommendations appearing in the next section of this volume.

The discussion which followed the presentation of each paper is recorded as fully as possible. Every effort was made to retain the essence of the questions and answers, for often they contain important ideas and counter arguments. We apologize if in our zeal to attain brevity and a standard form we have misquoted a participant.

The support of a number of people and organizations contributed to the success of the meetings. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) provided financial assistance to participants. The International Union of Geological Sciences (IUGS) helped defray the cost of preparation of manuscripts. The Department of Mines and Technical Surveys and the National Research Council acted as hosts; J.M. Harrison provided the overall direction and coordination, and C.H. Smith handled the local arrangements.

The authors without doubt deserve commendation for their participation and for the ideas and stimuli they provided toward the problems discussed. B.C. Heezen arranged the program and enlisted the speakers. The sessions were chaired by J.B. Hersey, B.D. Loncarevic, V.A. Magnitsky, T. Nagata, A.E. Ringwood, S.K. Runcorn, and J. Tuzo Wilson. The reporters at the sessions were T.N. Irvine, A. Larochelle, W.H. Poole, and E.F. Roots. The displays and meeting hall were cared for by

A.S. MacLaren, and Mrs. Betty Thomas was the mainstay in the office. Miss F.C. Aitkens assisted in assembling the manuscripts, and Mrs. M. Shanks and Mrs. B. Richard with great forbearance and care moved them through the typing process.

Ottawa
August, 1966

W.H. Poole

RESOLUTIONS AND RECOMMENDATIONS ON CONTINENTAL MARGINS AND ISLAND ARCS

The following resolutions and recommendations were formally adopted by the Upper Mantle Committee meeting in Ottawa, September 9-11, 1965. They were based on the proposals and discussions of the General Session on Resolutions and Recommendations which appear near the end of this volume. The Committee also appointed a Commission on Continental Margins and Island Arcs composed of I.P. Kosminskaya (chairman); C.L. Drake, B.D. Loncarevic, and T. Rikitake.

1. The margins of the continents constitute important discontinuities in the crust. Geophysical studies are required to delimit the related boundaries in the upper mantle. Therefore, a Commission has been formed to provide liaison between the Working Groups of the UMC concerned, to coordinate proposals, and promote research on the structure and history of continental margins and island arcs.

2. The margins are potentially favourable localities for studies of major aspects of the tectonic history of the earth. Extensive observations and experiments are required to answer questions regarding the fundamental geophysical and geochemical processes governing the formation and evolution of continental margins and island arcs.

3. Studies should not be confined to the present distribution of structures but should also include palaeogeographic reconstructions of ancient structures. Moreover, the margins and island arcs should be considered in the broadest sense.

4. Small ocean basins, such as the Mediterranean Sea and Bering Sea, and basins of intermediate size such as the Tasman Sea, should be studied to establish whether they are significantly different from large ocean basins and to establish their relation to the development of island arcs and continental margins.

5. The study of continental margins requires detailed comparisons of different types in different localities. One type of promising comparison is the investigation of structures of opposed continental shelves in such regions as between Australia and Antarctica and in the northern North Atlantic, using as a guide the various hypotheses of development of continents and ocean basins.

6. All types of geophysical and geochemical techniques should be employed in investigations of continental margins and island arcs. As an example, the interpretation of magnetic observations raises a number of

questions: Does the succession of magnetic anomalies in ocean basins provide a key to the history of the ocean floor? Does this succession, analyzed statistically, change at continental margins? Are linear magnetic anomalies, parallel with the margins, characteristic of all continental margins? A related question is, can anomalies in electromagnetic induction trace changes in temperature and chemical composition at depth across the margins through their effect on electrical conductivity?

7. Detailed studies of the geology and petrology of continental margins and island arcs are also required.

8. The direct, observational methods of investigation — geophysical, geochemical, and geological – should be accompanied by and interpreted in the light of extensive theoretical and laboratory investigations of the constitution and dynamics of the mantle.

PROCEEDINGS OF THE SYMPOSIUM

A. OPENING REMARKS

Prof. V.V. Beloussov

Ladies and gentlemen, among the most important problems selected by the Upper Mantle Committee as central problems to be studied is the problem of continental margins and island arcs. The importance of this large problem is quite obvious. All of us are aware that the greatest puzzle we face is the mystery of the origin of continents and oceans, and their development. In this area of earth science you will meet several different hypotheses. Some of us believe in the gradual accretion of continental masses and the gradual transformation of oceanic crust and mantle into continental crust. Some others prefer to think that there is a gradual collapse of the continent and a transformation of continental crust and mantle into oceanic crust. May I call these two views 'optimistic' and 'pessimistic'. The boldest of us move the continents or inflate the globe. The disagreement which exists clearly indicates the shortage of positive data. Obviously such data may and should be obtained first of all by studying the critical zones where these two great structural elements of the earth meet and where the transition between them may be observed. We do hope that, if the detailed geophysical data on the deep structure of the crust and the upper mantle in these zones is combined with historical data provided by geology, we will have more opportunity to choose the more reliable of these different hypotheses which now confront us.

With such great expectations, let us plunge into high waves of new facts and ideas which will certainly come to us during the forthcoming discussions. Thank you.

B. SESSION ON ATLANTIC AND MEDITERRANEAN CONTINENTAL MARGINS

THE CONTINENTAL MARGIN OF EASTERN CANADA

M.J. Keen and J.E. Blanchard[1]
Institute of Oceanography
Dalhousie University

Abstract

The geology of Eastern Canada suggests that the continental margin may be different off the northeast coast of Newfoundland from what is probably a typical Atlantic continental margin off Nova Scotia.

Seismic refraction profiles giving depths to the Moho have been obtained on the continental slope, on the edge of the shelf, on the coast of Nova Scotia, across the roots of the Appalachian system in the Gulf of St. Lawrence, and on the west and northeast coasts of Newfoundland.

There is a normal crust 35 kilometres thick with a very thin or no intermediate layer at the continental margin off Nova Scotia. An analysis of sea gravity data combined with the seismic information indicates that there is a density difference between continental and oceanic upper mantle material, although upper mantle seismic velocities of about 8 km/sec were obtained under the continental and oceanic crust.

The crust and upper mantle northeast of Newfoundland are both profoundly different from those off Nova Scotia. Deep seismic refraction studies enable one to trace the roots of the Appalachian system from the Gulf of St. Lawrence across Newfoundland. An intermediate crustal layer is present, the crust is about 50 kilometres thick, and a seismic velocity at 8.5 km/sec was obtained from the upper mantle.

Further work is to be carried out off Newfoundland. If the Appalachian structure stops abruptly at the continental margin, a most interesting experiment would be to look for a similar feature off Ireland and thus possibly add to our knowledge of continental drift.

---

[1] Speaker

INTRODUCTION

This paper is a review of a number of seismic experiments undertaken by Dalhousie University during the past four years, as well as a number of sea gravity meter profiles by the Bedford Institute of Oceanography which have contributed to our understanding of the continental structure of Eastern Canada. Most of the results have been published or are in press.

GEOLOGY

Figure 1 is a geological map of Eastern Canada. There is a large bulge in the continental shelf forming the Grand Banks of Newfoundland and a change in the character of the continental shelf northeast of Newfoundland.

Figure 2 is a generalized tectonic map of the Canadian Appalachian region (Neale et al., 1961). Most of the region is underlain by rocks of Palaeozoic age, although metamorphosed Precambrian rocks are exposed in northwestern and southeastern Newfoundland, in Cape Breton Island, and in the Saint John area of New Brunswick. Some of the older rocks are considered to be remnants of the Grenville basement on which the Appalachian geosyncline developed.

During Palaeozoic time, the region underwent two major tectonic events, the Taconic and Acadian orogenies (Neale et al., 1961). The former occurred in late Ordovician time, and is usually marked by an unconformity between Middle Ordovician rocks and Silurian rocks. The Taconic orogenic belt in the Canadian Appalachians trends northeasterly through New Brunswick and central Newfoundland. The zone of deformation is bounded on the northwest by the south shore of the St. Lawrence River and the west coast of Newfoundland; and on the southeast by the north shore of the Bay of Fundy in New Brunswick and a line between Fortune and Bonavista Bays in southeastern Newfoundland. During this time, the ultrabasic rocks were emplaced in Gaspé and Newfoundland.

Widespread deformation associated with the Acadian orogeny affected most of the Taconic belt and in addition many areas of rocks which previously were undeformed. Large areas of the Maritimes and Newfoundland were intruded by granite during the orogeny. Isotopic age determinations of many of the intrusions indicate a Devonian age.

Subsequent deformation has been attributed to a fragmentation of the pre-Carboniferous basement into large uplifted and downwarped blocks just prior to and during Carboniferous time. It is in this environment that the thick Carboniferous sediments were deposited.

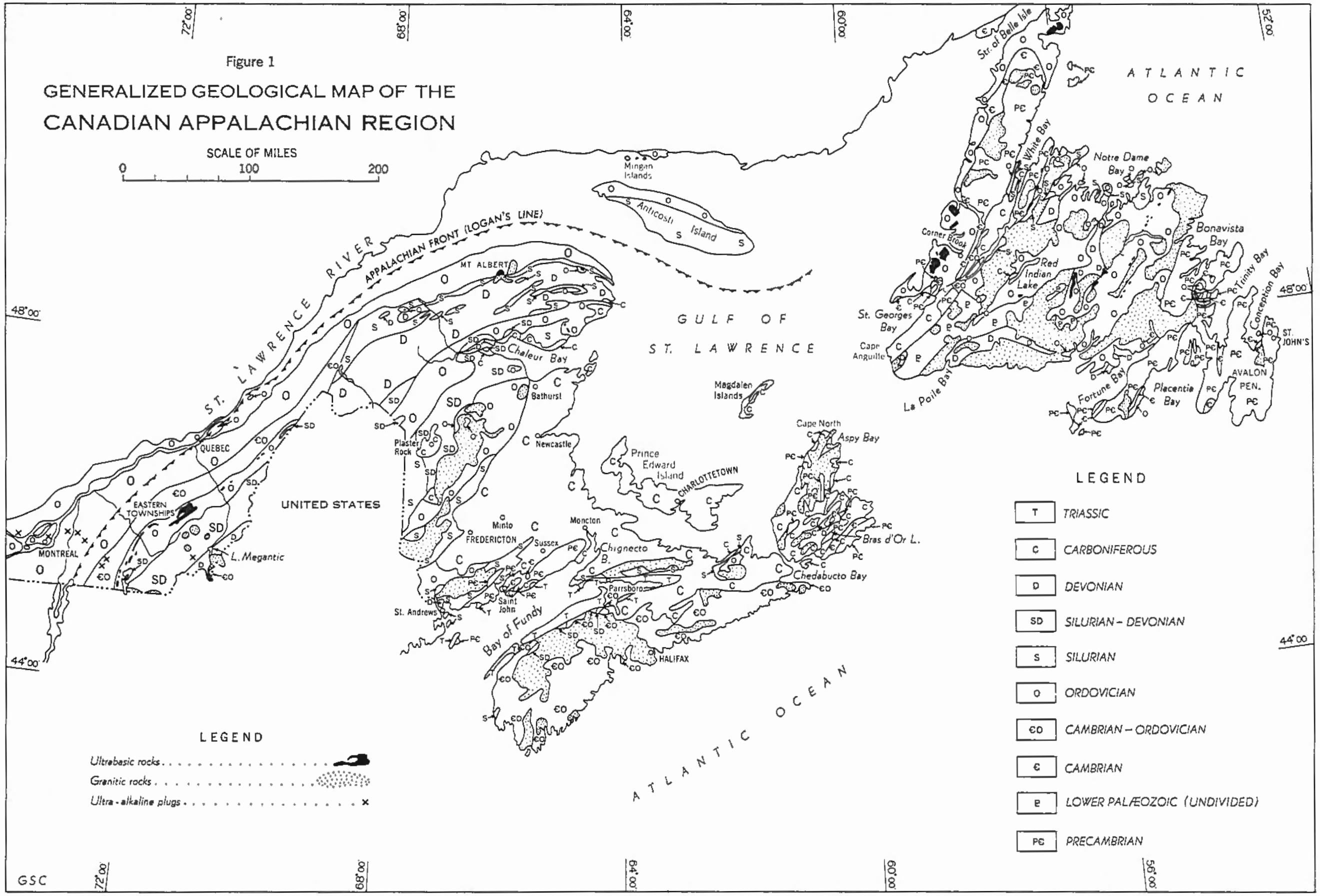

Figure 1. Generalized geological map of the Canadian Appalachian region. (From Neale et al., 1961)

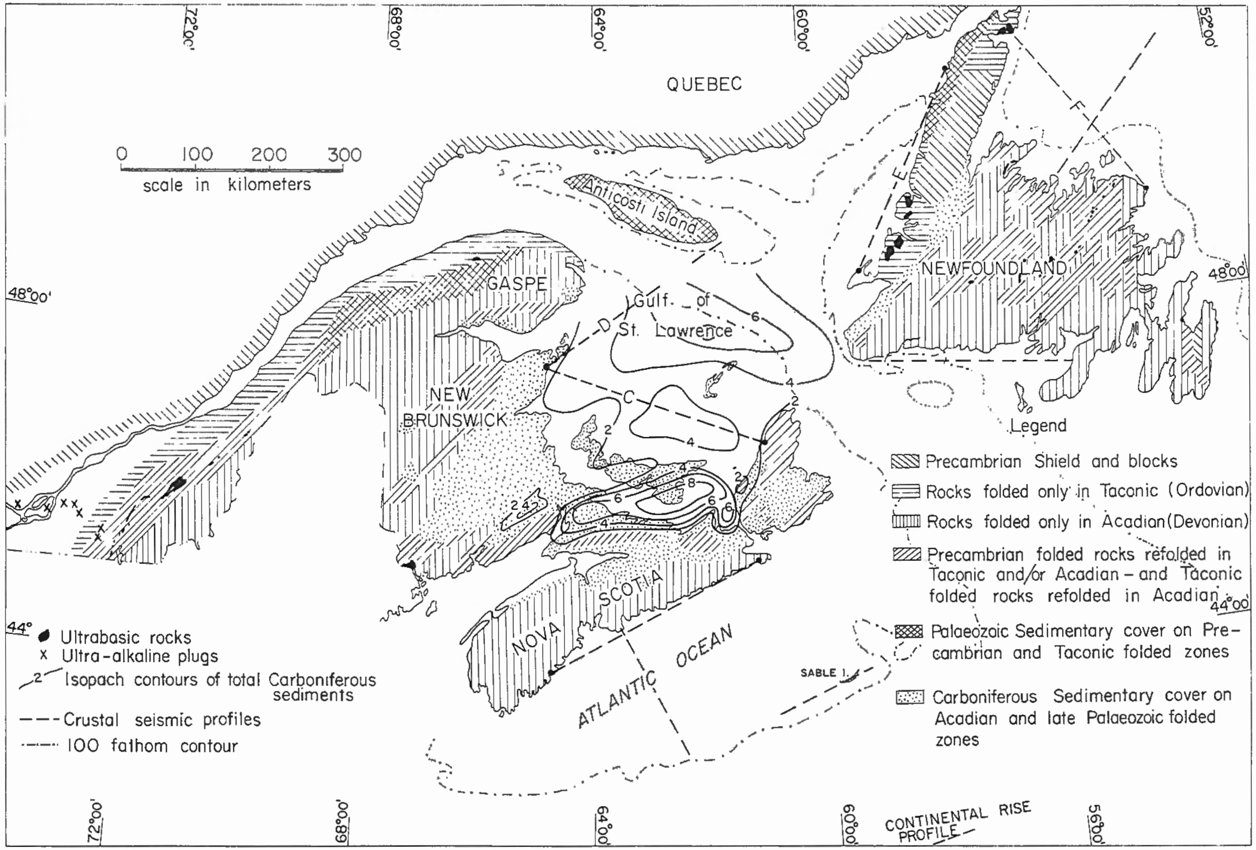

Figure 2. Generalized tectonic map of Canadian Appalachian region showing the location of seismic profiles. (After Neale et al., 1961) Isopach contours in part from Howie and Cumming, 1963, modified by Ewing et al., in press.

There are also troughs of thick sediments on the shelf areas. Seismic data suggest that between 4 and 5 kilometres of consolidated and semiconsolidated sediment underlie Sable Island (Berger et al., 1965). The ages of these sediments are as yet unknown (Drake et al., 1959).

SEISMIC PROFILES

The seismic profiles are located on Figure 2. They occur on the edge of the shelf (Sable Island) (Berger et al., 1965 and in press), across the shelf, along the coast of Nova Scotia (Barret et al., 1964), in the Gulf of St. Lawrence, and around the coasts of Newfoundland (Ewing et al., in press). These profiles were obtained by firing explosives in the sea and recording on land (Barret et al., 1964). In all cases, upper mantle velocities were obtained as first arrivals. A profile southeast of Sable Island, also shown in Figure 2, is located on the continental slope; recording there was by means of sonobuoys (Keen and Loncarevic, in press). There are also two sea gravity meter profiles across the shelf in this area (Keen and Loncarevic, in press), as well as Lamont's "Halifax" section (Drake et al., 1959).

SCOTIAN SHELF

The seismic profile on the edge of the shelf used Sable Island as a recording station. While the signal-to-noise ratio on the island was not good, nevertheless an unreversed seismic profile with upper mantle velocities was obtained and the results agree with the seismic profile extending southeast from Halifax. By integrating these seismic data and the gravity data, several models were constructed (Keen and Loncarevic, in press). The most acceptable one is shown in Figure 3. The continental margin section here is much simpler than that obtained for the Pacific. In fact it is strange that the Pacific-type structures in the Atlantic seem to be confined to the Caribbean and the Scotian Arc (which is not part of the Scotian Shelf!). An important feature of the interpretation is the necessity in this model to have different densities for oceanic mantle material and continental mantle material. The best fit was obtained by using a density of 3.22 gm/cc for the oceanic mantle and a density of 3.42 gm/cc for the continental mantle. This model has the density discontinuity extending to a depth of 100 kilometres. This depth was chosen because of Dorman's surface wave results (Dorman et al., 1960).

CONTINENTAL SHELF TO GULF OF ST. LAWRENCE

The seismic crustal structure from the continental rise to the Gulf of St. Lawrence is shown in Figure 4. At Cole Harbour, Nova Scotia,

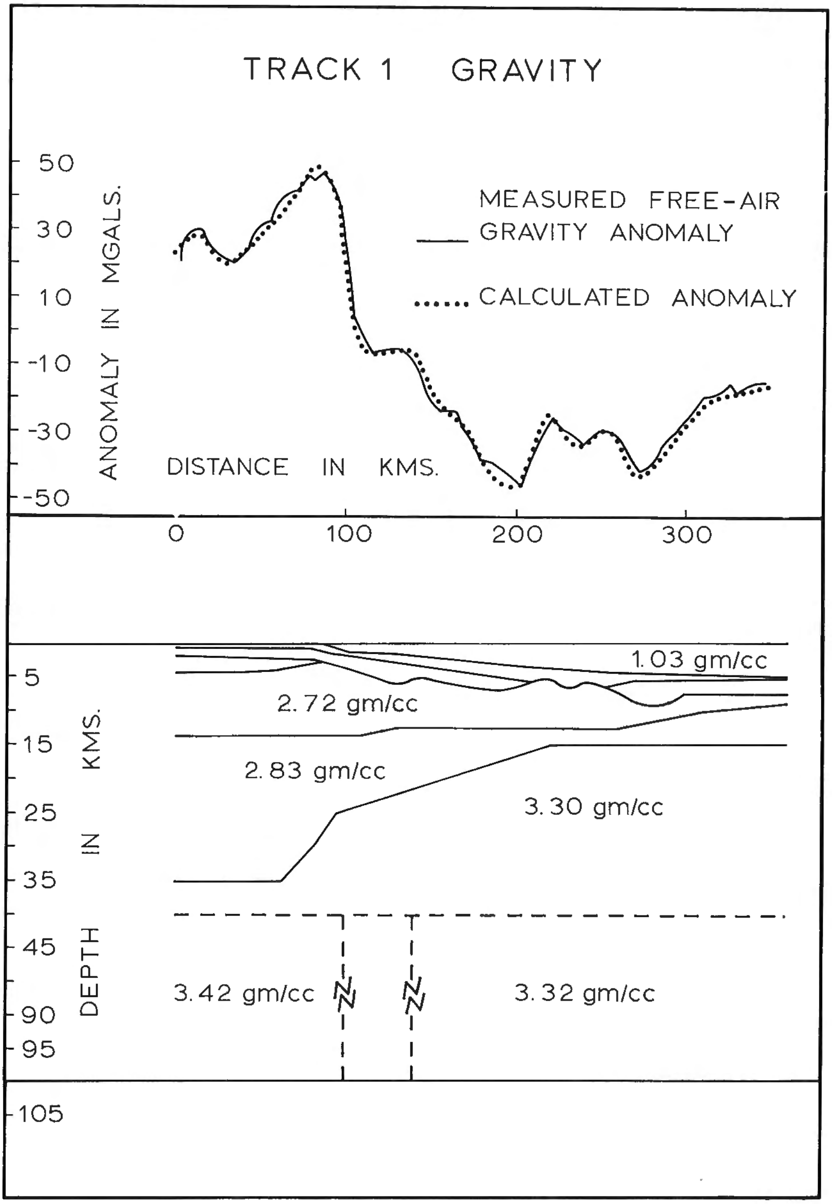

Figure 3. Gravity profile across the continental shelf, south of Halifax, Nova Scotia. (After Keen and Loncarevic, in press)

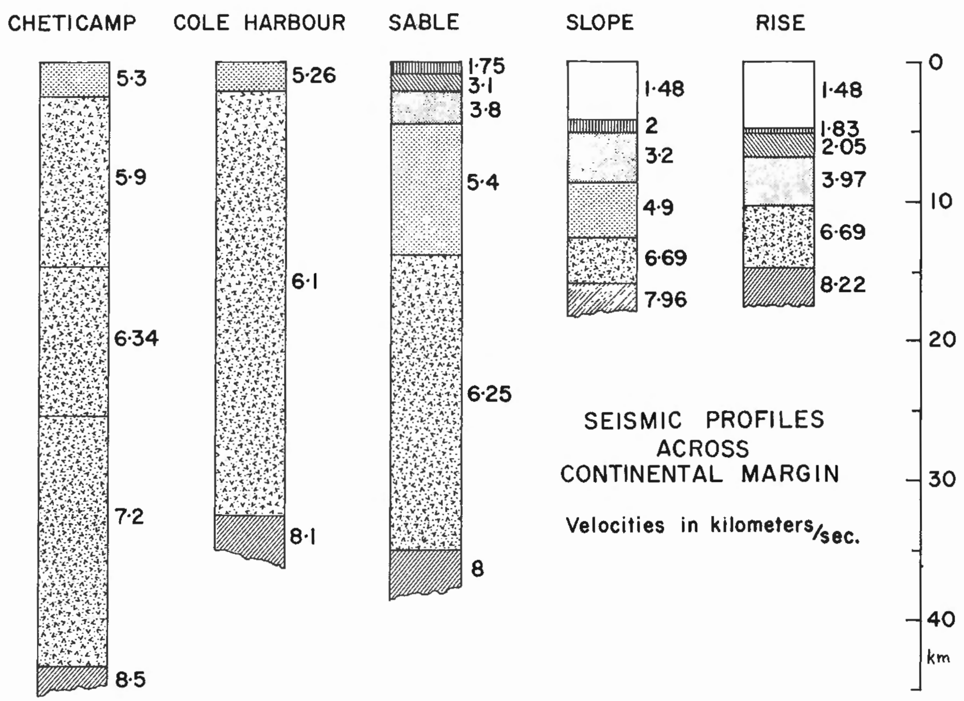

Figure 4. Seismic profiles across the continental margin of Eastern Canada. (After Ewing et al., in press)

no sedimentary layer and no intermediate layer were found. And, no first or second arrivals could be constructed in terms of an intermediate layer. However, a program of reflection studies (Berger et al., 1964) suggests that the velocity contrast at the Moho is more like 7:8 than 6:8, indicative possibly of a thin intermediate layer. Under Cheticamp in the Gulf of St. Lawrence, the crustal structure is profoundly different. The crust is thicker, there is an intermediate layer, and the upper mantle is characterized by a high velocity of 8.5 km/sec. This is not an isolated high velocity; it seems to be characteristic of the Taconic orogenic belt with its ultrabasic intrusions. A similar high-velocity mantle was found on the northeast coast of Newfoundland. Additional work in this region confirmed the high velocity.

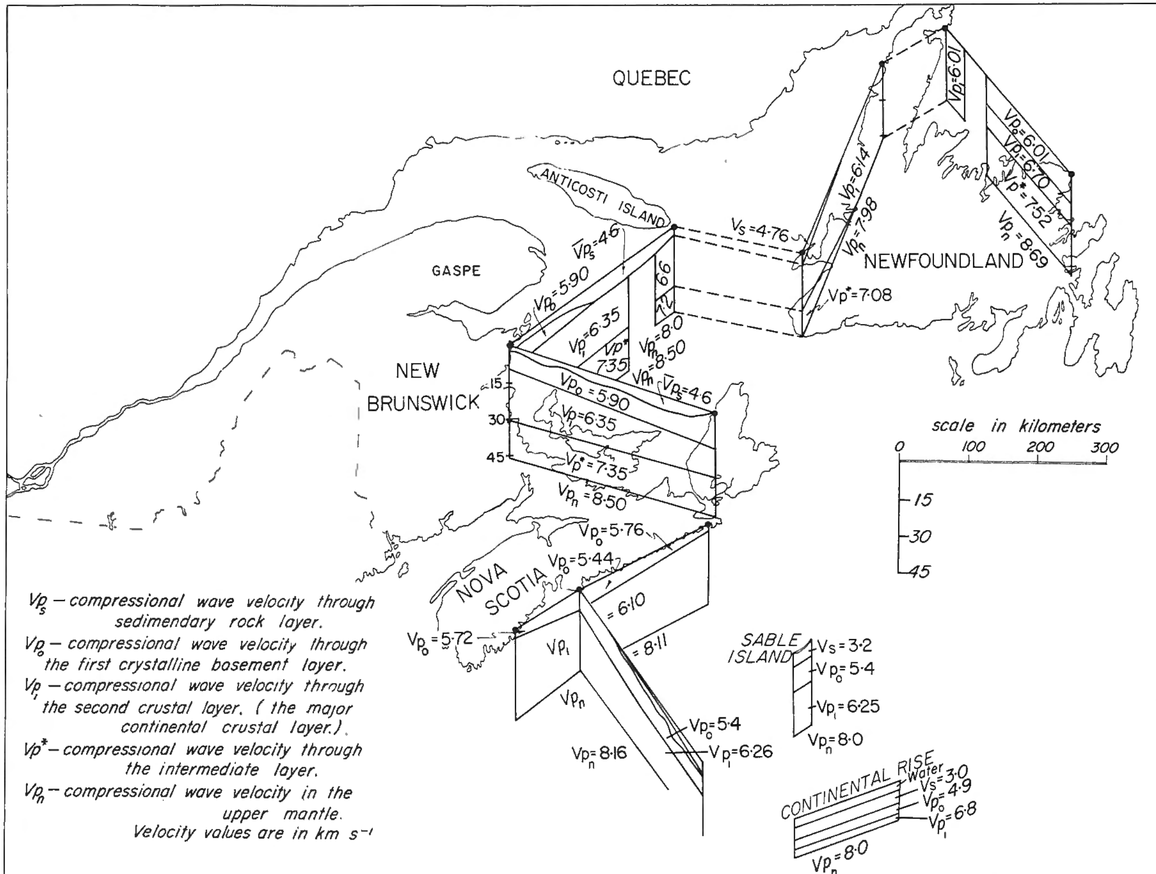

Figure 5. Crustal structure and Mohorovicic discontinuity in Eastern Canada based on seismic evidence. (After Ewing et al., in press; with additions)

CANADIAN APPALACHIAN REGION

Figure 5 shows the various profiles that have obtained upper mantle velocities and the interpretation of the results. The continental margin northeast of Newfoundland is clearly an area for further study. If the high-velocity mantle material extends northeasterly to the continental margin and then stops, one might look for its extension off Ireland. If it continues under the ocean, it should be traced to its limits. Regardless of what happens to it, this is a most interesting feature which may provide us with more information regarding continental drift.

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DISCUSSION

Dr. B.D. Loncarevic (Canada)

The continental margin of Eastern Canada is one of special interest because of its unusual shape. In the area of the Grand Banks, the continental margin takes a very sharp corner. This unusual feature is deserving of special study.

Prof. V.A. Magnitsky (USSR)

During investigations in the Pacific Ocean east of the Kuril island arc, a discontinuity 6 or 8 kilometres below the Moho was detected which gives a velocity of longitudinal waves of 8.6 km/sec. Perhaps in various parts of the earth, there exists such a discontinuity close to but slightly beneath the Moho with a high velocity of longitudinal waves.

Prof. Blanchard

With regard to Professor Magnitsky's comments, when we found this density contrast between the oceanic mantle and the continental mantle, we looked for arrivals in our seismic profiles which might give us a higher velocity near the continental margin but were unable to find them.

Dr. M. Talwani (USA)

With regard to Professor Magnitsky's remark, is it not difficult to measure a layer only 6 kilometres thick with a velocity of 8.2 km/sec above a layer with a velocity of 8.6 km/sec?

Prof. Magnitsky

I don't know exactly the technique of this work. Dr. Fedynsky who carried it out told me. I know only the result, and I cannot explain how it was obtained.

MAGNETIC SURVEYS OF THE CONTINENTAL SHELVES OF EASTERN CANADA

Peter Hood
Geological Survey of Canada

Abstract

Sea and airborne magnetometer results are presented for parts of the Scotia Shelf, the Grand Banks of Newfoundland, and the Flemish Cap. A circular magnetic low, surrounded by a halo of magnetic highs, is observed south of Halifax on one of the Scotia Shelf aeromagnetic maps, and is probably produced by a Devonian granite such as occurs on the mainland of Nova Scotia. The eastern limit of the Cambro-Ordovician Meguma Group and Devonian granites is inferred from the total intensity map obtained from the CSS KAPUSKASING 1961 sea magnetometer survey of the eastern Scotia Shelf.

A zone of relatively flat magnetic contours extends east and south from Chedabucto Bay in an area where a negative free-air gravity anomaly ("Orpheus" anomaly) has been reported; a substantial thickness of underlying sediments is indicated. A line of isolated magnetic anomalies parallels the edge of the continental shelf along the southwestern part of the Grand Banks. One anomaly appears to have been produced by a rock formation having a magnetization vector aligned in a direction quite different from the present earth's field. Depth determinations in this area indicate that the cover over the magnetic basement is between 14,000 and 19,000 feet thick.

A series of sharp shallow-source anomalies was recorded over the Flemish Cap; this feature appears to have a negatively polarized core whose longer horizontal dimension is oriented in a north-northwesterly direction. It is suggested that the Flemish Cap may be composed of basaltic material Mesozoic or later in age.

INTRODUCTION

Since 1958 the Geological Survey of Canada has been carrying out magnetic surveys over the continental shelves of Eastern Canada. The objective of these surveys is to aid the geological study of the shelves, and particularly to outline for further study areas of thick sediments which might be oil-bearing.

Two types of magnetic survey have been carried out. Aeromagnetic surveys using fluxgate magnetometers were begun in 1958, and in 1959 shipborne surveys using proton-precession magnetometers were commenced in cooperation with the Canadian Hydrographic Service (Bower, 1961, 1962). Late in 1963 the shipborne magnetometers were transferred to the Bedford Institute of Oceanography at Dartmouth, Nova Scotia, and that organization is presently carrying on the sea magnetometer work.

This paper describes some hitherto unpublished sea magnetometer results from the eastern Scotia Shelf and the Grand Banks of Newfoundland, together with results obtained during magnetic airborne detector (MAD) surveys carried out in cooperation with the National Aeronautical Establishment and the Royal Canadian Air Force.

Figure 1 shows the present magnetic coverage of the continental shelves adjacent to the Maritime Provinces of Eastern Canada and indicates the two types of survey. The aeromagnetic coverage over the land area is not shown.

AEROMAGNETIC SURVEYS OF CENTRAL SCOTIA SHELF

Figure 2 shows the proof copy of one of the Scotia Shelf aeromagnetic maps, a new format by the Geological Survey of Canada for aeromagnetic surveys of water-covered areas. On the published map, the aeromagnetic contours are printed in red using a 10-gamma contour interval, and all other lines are printed in a light grey. The survey flight lines are the straight, solid lines running north-northwest across the map. The aircraft flew along the "purple" lines of the Decca Navigation Chain 7. The "green" Decca lines, used to position the aircraft along the "purple" Decca lines, are shown as dashed lines. The bathymetry has also been printed on the map using a contour interval of 25 feet, and the track of the ship, which obtained the echo-sounder profiles, is shown by the dashes on the bathymetric contours themselves. Hence the control for both the aeromagnetic and the bathymetric data is clearly indicated on the map. It is thus possible, in carrying out subsequent geophysical or geological investigations, to position survey ships with respect to a given geological feature deduced from the magnetic data by using the Decca coordinates appearing on the aeromagnetic map. Also, in preparing a smaller scale compilation map, the aeromagnetic contours may be readily separated by photographic means from the rest of the data because they are a different colour.

Figure 3 shows one of the maps from the 1962 Scotia Shelf aeromagnetic survey. The area is located immediately south of Halifax and the contour interval is 20 gammas. The magnetic grain parallels the coastline. There is little doubt that the underlying rocks are slates and quartzitic

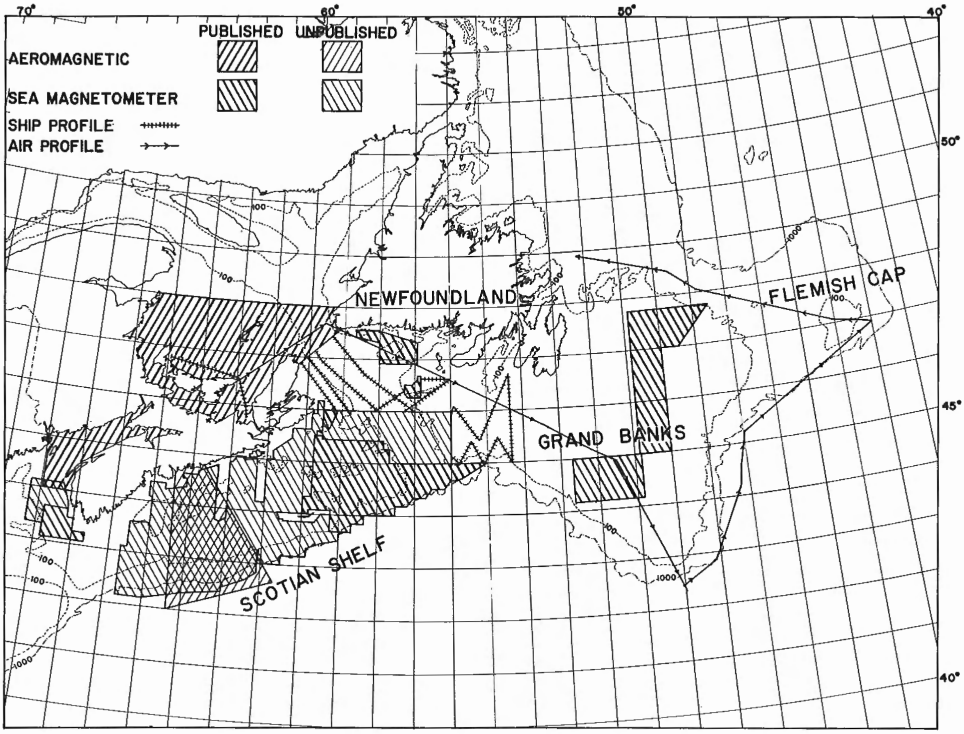

Figure 1. Magnetic coverage (1965) of the continental shelves adjacent to the Maritime Provinces of Eastern Canada by the Department of Mines and Technical Surveys.

greywackes of the Meguma Group which outcrop on the mainland. A noticeable offset in the magnetic contours runs northerly through the middle of the area and is very probably caused by a transverse fault on the continental shelf. The two interesting circular magnetic lows, which occur in the south half of the area, have been labelled A and B. The larger feature B is reproduced in greater detail at the top of Figure 4, while the bottom of the figure is part of an aeromagnetic map compiled from survey lines flown at 1,000 feet elevation over a Devonian granite body which intrudes the Meguma Group south of Chedabucto Bay (Stevenson, 1964). It is obvious that the granite has a very low intensity of magnetization and thus contains an extremely low percentage of magnetite. The anomalies at the edge of the granite appear to have been produced by the intrusion and form a magnetic aureole around the

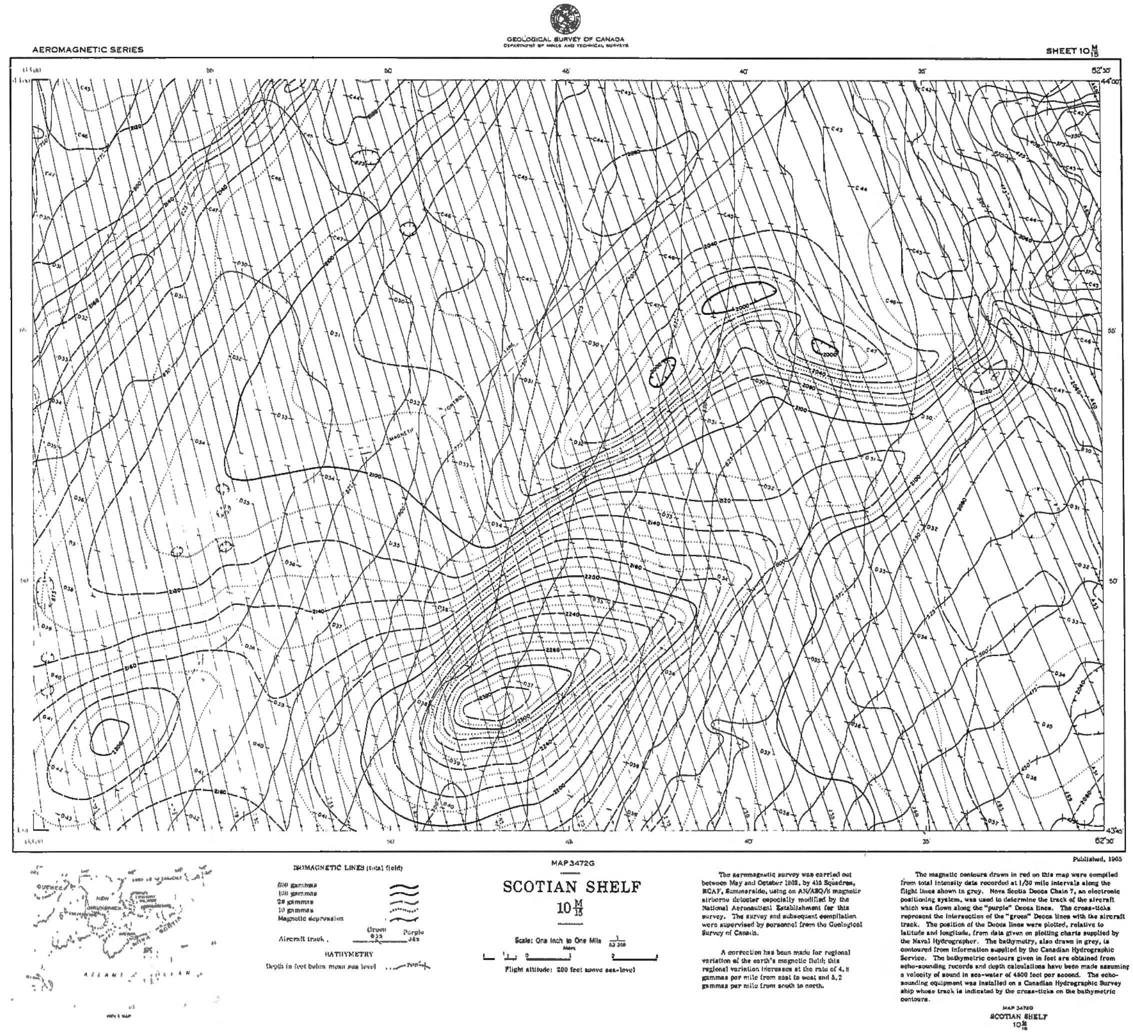

Figure 2. Aeromagnetic map 3472G of part of the central Scotia Shelf.

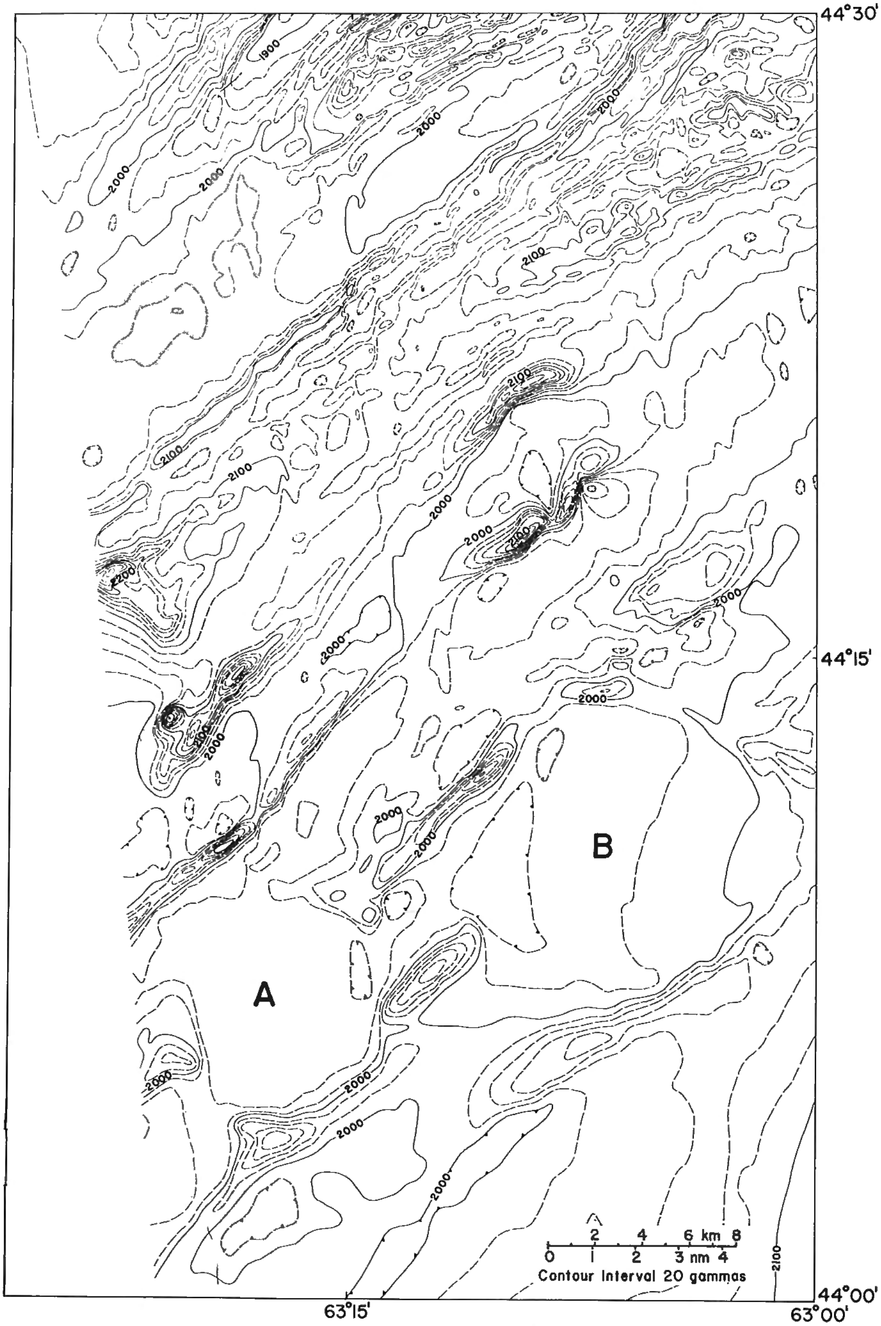

Figure 3. Aeromagnetic map of part of the central Scotia Shelf south of Halifax.

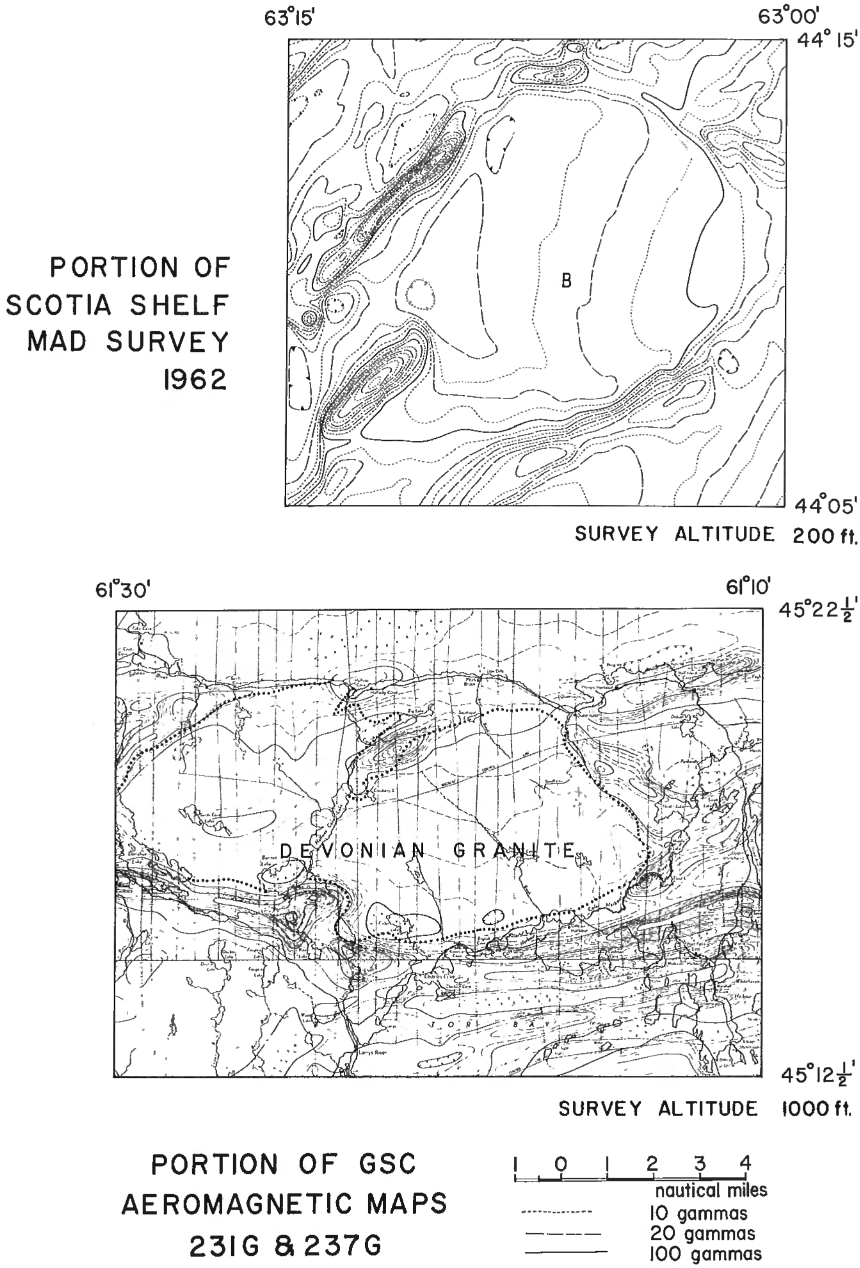

Figure 4. Comparison of circular aeromagnetic features on the Scotia Shelf with similar patterns from an aeromagnetic map on the mainland of Nova Scotia (Chedabucto Bay area).

Devonian granite. The most obvious explanation for this phenomenon is that the natural remanent magnetization of the country rock has been considerably increased by its being heated at the time of the intrusion of the granite through the Curie point of the constituent magnetic minerals, and then acquiring an augmented intensity of magnetization by subsequent cooling in the earth's magnetic field. In addition, contact metamorphism of the country rock may have produced some magnetite. There are a number of examples of this phenomenon elsewhere in Nova Scotia and it seems to be a diagnostic feature of granites that where they intrude formations already possessing significant magnetic properties, i.e. contain about one-half per cent or more magnetite, then the anomalies at the margins of the intrusion will usually be enhanced by an increased intensity of remanent magnetization.

It seems highly probable that the circular lows found on the Scotia Shelf aeromagnetic map (Fig. 3) are also granite intrusions. If this inference is correct, the features could also be expected to have concomitant negative gravity anomalies associated with them because of the low density of granite.

SEA MAGNETOMETER SURVEYS

Eastern Scotia Shelf

The eastern Scotia Shelf, which includes Sable Island, was surveyed in 1961 by sea magnetometer on board the CSS KAPUSKASING. These results as well as the aeromagnetic data obtained over the mainland are shown in Figure 5. A considerable regional magnetic gradient extends northwesterly across the map, and causes some distortion of the anomalies. For instance, there is a magnetic high southeast of Sable Island, but due to the regional gradient this appears merely as a nose in the magnetic contours.

In general near the Nova Scotia coast-line, the magnetic anomalies consist of short-wavelength, high-amplitude anomalies whereas those near the edge of the continental shelf are of longer wavelength and of lower amplitude. This characteristic reflects the increased depth to the magnetic basement near the edge of the shelf and indicates that the overlying sediments thicken away from the coast. The eastern limit of the Cambro-Ordovician Meguma Group and granites, which outcrop on the Nova Scotia mainland may be inferred because the Meguma produces a characteristic magnetic pattern.

Of particular interest is a zone of relatively flat magnetic contours extending eastward from Chedabucto Bay in an area where Loncarevic (1965) reported a negative free-air gravity anomaly (his

"Orpheus" anomaly). The geophysical results indicate that either thick sediments or a non-magnetic crystalline rock underlie the bay. Because granite, which has a very low intensity of magnetization and gives rise to a negative gravity anomaly (Bott, 1953; Garland, 1953), outcrops in the area, this is the more probable alternative. However, the preceding discussion concerning Figure 4 would indicate that the formations underlying Chedabucto Bay

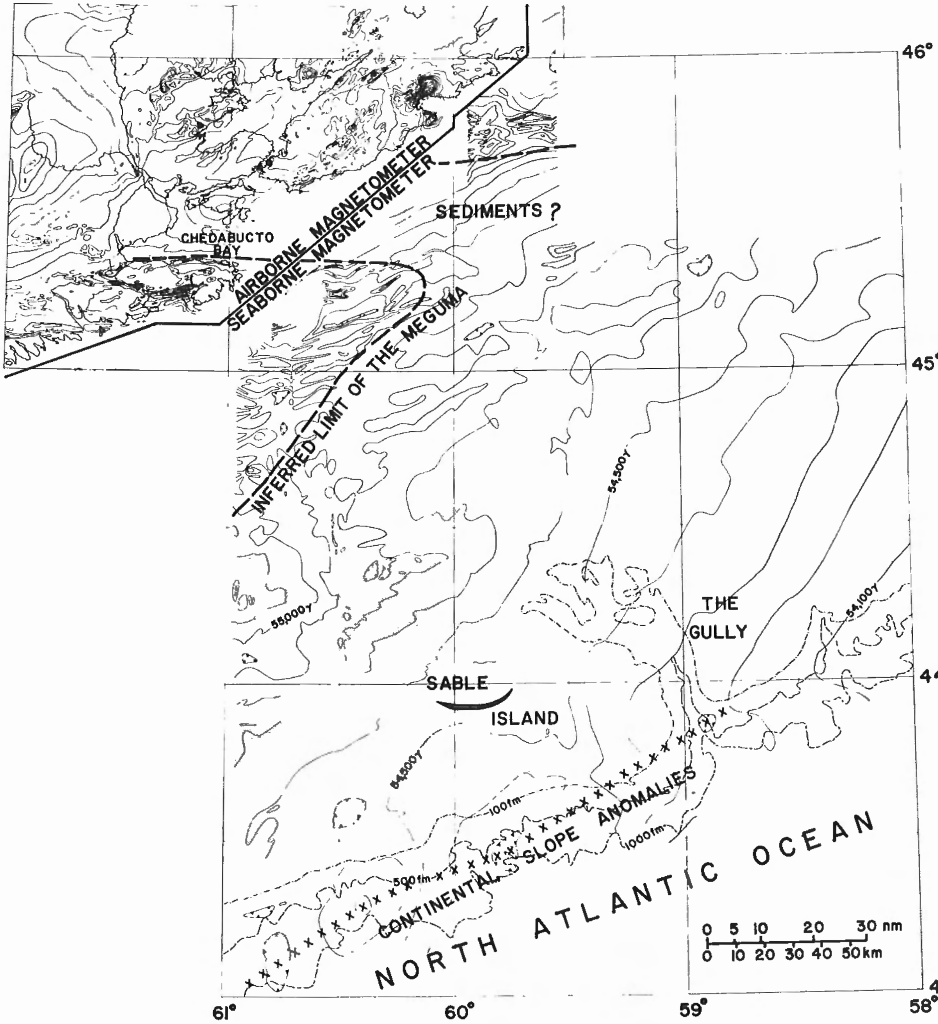

Figure 5. Sea magnetometer results of the CSS KAPUSKASING 1961 survey of eastern Scotia Shelf, together with aeromagnetic results on the adjacent mainland. The contour interval is 100 gammas.

are, in fact, sedimentary because there is no noticeable magnetic aureole around the margins of the bay. Moreover granite contacts in the area are rarely linear over distances greater than a few miles. The formations underlying Chedabucto Bay are most probably Carboniferous sedimentary rocks which are bounded on the south by a fault contact with the Meguma Group. Pockets of Triassic sedimentary rock outcrop at the western end of Chedabucto Bay (Stevenson, 1964), so that it is also possible that the bay is underlain in part by formations of Triassic age. The validity of this interpretation could be tested by measuring the longitudinal wave velocity of the formations underlying Chedabucto Bay by the seismic refraction technique. Thus Devonian granite could be expected to give a seismic velocity in excess of 16,000 feet/second (4.9 km/sec) whereas the Triassic or Carboniferous sediments would have velocities lower than 14,000 feet/second (4.3 km/sec). However, a drill-hole is the only infallible way of testing this interpretation. A line of magnetic highs and lows is located along the edge of the continental shelf immediately south of the 100-fathom contour. They are presumably part of the well known continental slope anomaly and are indicated on Figure 5 by the line of crosses. The position of these anomalies does not coincide very well with the basement high found by Officer and Ewing (1954) from seismic refraction profiling across the Scotia Shelf. From their paper the basement high appears to be located a few miles northwest of the 100-fathom contour, although they do not give the probable accuracy of positioning of the profiles. Berger et al. (1965) suggested that the basement ridge lies south of Sable Island.

Grand Banks of Newfoundland

The sea magnetometer map from the CSS BAFFIN 1963 survey of an area of the Grand Banks of Newfoundland (Fig. 6) contrasts strikingly with the maps from the Scotia Shelf (Figs. 2, 3, and 5). Several anomalies with amplitudes exceeding 1,000 gammas occur on the Grand Banks map. They are fairly circular in their horizontal dimensions. The four prominent anomalies on the map (Fig. 6) as a group appear to strike roughly parallel with the edge of the continental shelf about 50 nautical miles to the southwest. The central anomaly, a complex of several smaller anomalies, seems to have been produced by a rock formation having a magnetization vector aligned in a direction quite different from the present earth's field. In fact, a number of the individual smaller anomalies within the central anomaly apparently are produced by horizontal dipoles, thus indicating that the causative bodies have considerable remanent magnetism. Perhaps the anomalies, which appear to be produced by basic intrusive bodies trace out a line of weakness in the earth's crust. The old suggestion that a right-lateral wrench fault runs along the southwest edge of the Grand Banks through Cabot Strait and into the Gulf of St. Lawrence has recently been renewed by Drake and Woodward (1963); this postulated fault may be related

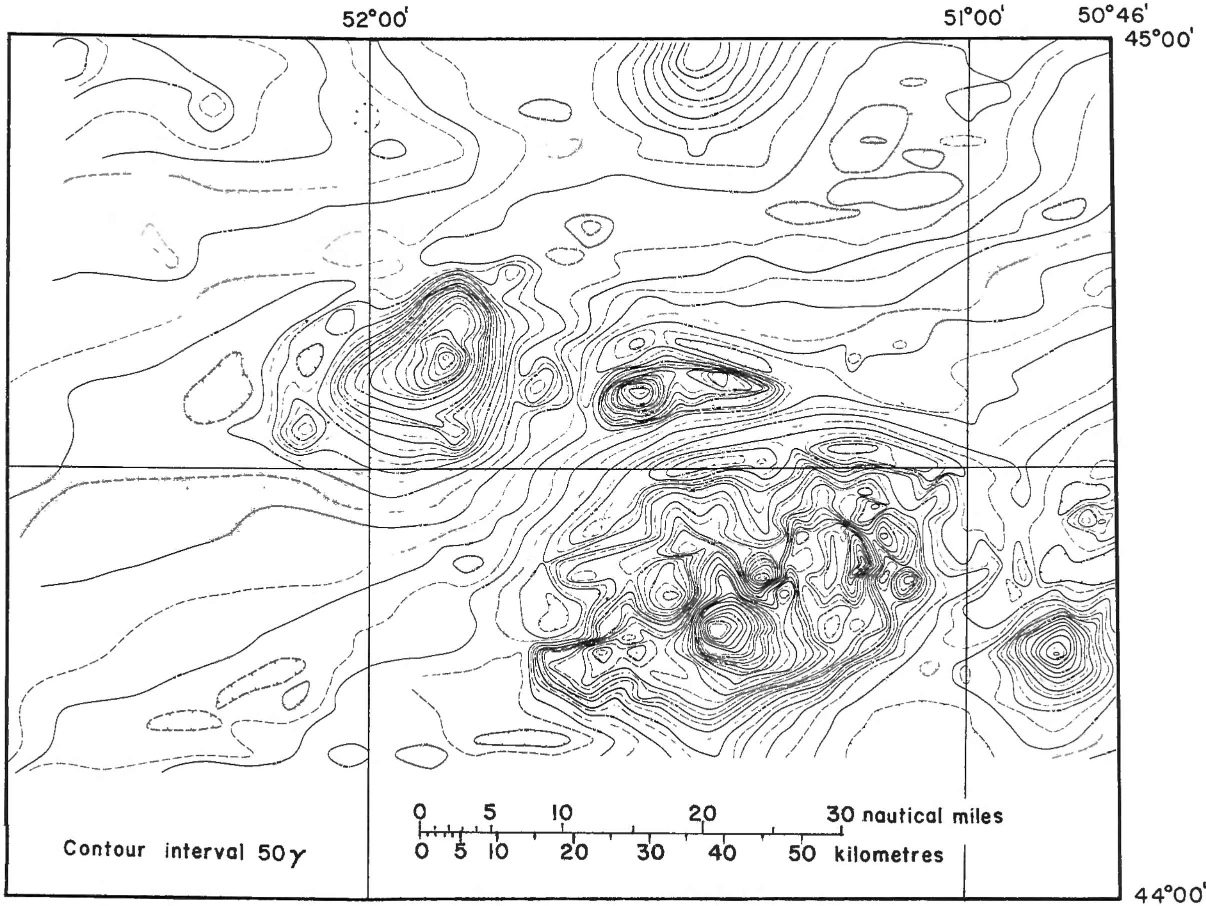

Figure 6. Sea magnetometer results of the CSS BAFFIN 1963 survey of a part of the Grand Banks of Newfoundland.

to the line of weakness. Depth determinations using various published methods were carried out on the anomalies. The top of the anomaly which occurs in the southeast corner of Figure 6 appears to be about 14,000 feet below the surface, and the top of the western anomaly is about 19,000 feet below the surface. These values are quite consistent with the 6 kilometre layer located by seismic refraction surveys carried out by Lamont Geological Observatory (Press and Beckman, 1954; Bentley and Worzel, 1956; Ewing and Ewing, 1959).

AEROMAGNETIC PROFILES OVER THE FLEMISH CAP

Figure 7 shows the track and resultant aeromagnetic profiles of an Argus aircraft which flew over the Flemish Cap at a survey altitude of 200 feet (Hood and Godby, 1965). A digital fluxgate magnetometer built at the National Aeronautical Establishment (Godby, 1963) recorded the total intensity of the earth's magnetic field. A series of shallow-source anomalies was recorded on both traverses across the Flemish Cap. The feature appears to have a negatively-polarized band (between parallel dashed lines on Figure 7), whose longer dimension is oriented in a north-northwest direction. It is possible to correlate between individual anomalies on the profiles even though the two tracks diverge at an angle of 45 degrees, and moreover the south profile merely skirted the southern edge of the Cap while the north profile passed directly over it. The depth determinations carried out on the anomalies indicate that the causative bodies reach the ocean floor, or perhaps are buried a hundred feet or so beneath the bottom. The anomalies west of the central anomalous zone of the Cap are caused by rock well below the bottom. Thus the geological contact along the west side of the rock forming the central part of the Cap dips steeply west.

The Flemish Cap must be underlain by basic intrusives which are dyke-like in form. There is thus a distinct possibility that the Cap, which is separated from the main continental shelf by a distinct trough (Fig. 7), is part of the oceanic crust, and would therefore be expected to consist of basaltic material Mesozoic or younger in age, as are other volcanic rocks in the North Atlantic (see for example Wilson, 1965). We intend to carry out additional aeromagnetic surveys over the Cap in order to investigate further the origin of this intriguing physiographic feature.

ACKNOWLEDGMENTS

Acknowledgment is made to E.A. Godby, R.C. Baker, and H.C. Lyster of the National Aeronautical Establishment and to Margaret E. Bower of the Geological Survey of Canada for their cooperation in the

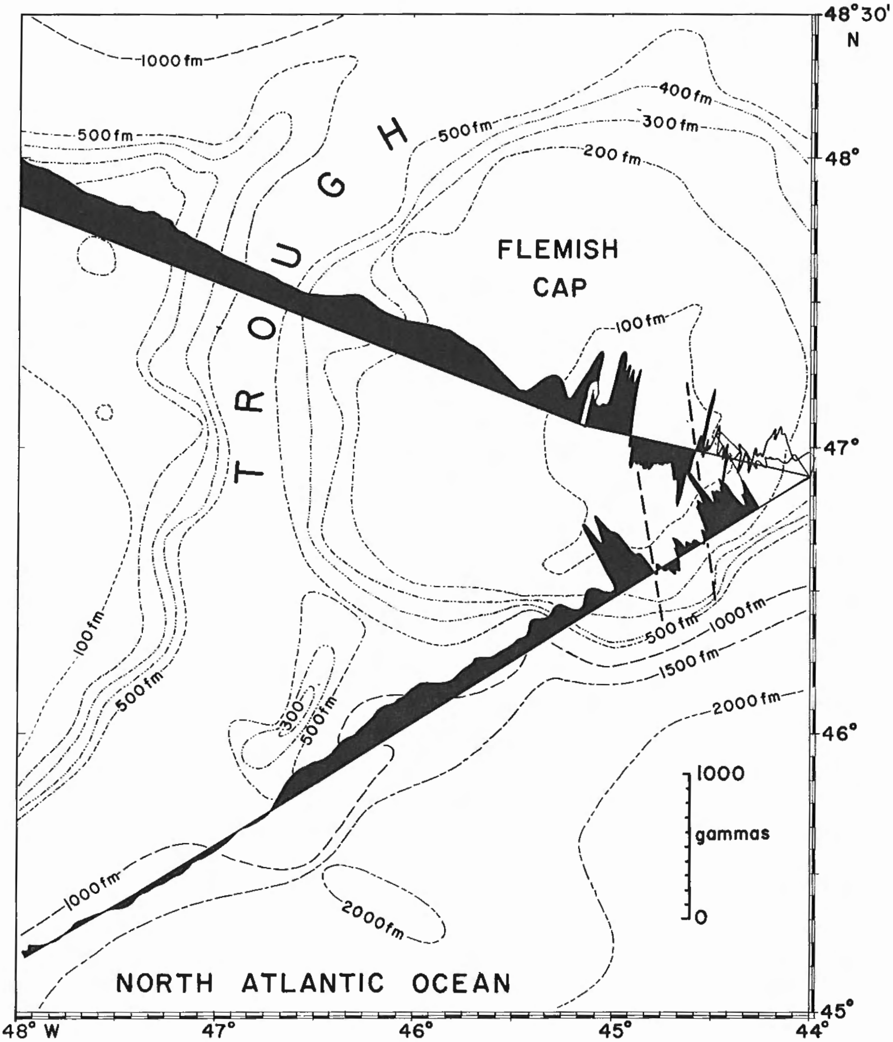

Figure 7. Aeromagnetic profiles over the Flemish Cap.

execution and subsequent compilation of the aeromagnetic surveys described in this paper. This article is Canadian Contribution No. 90 to the International Upper Mantle Project.

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RECENT INVESTIGATIONS ON THE CONTINENTAL MARGIN OF EASTERN UNITED STATES[1]

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Lamont Geological Observatory

Abstract

Geophysical measurements on the continental margins between Cape Hatteras, North Carolina, and Halifax, Nova Scotia, have revealed the presence of two sediment-filled troughs, one on the continental shelf, the other under the continental slope and rise. These are separated by a basement ridge near the edge of the shelf. These results, combined with geological information at sea and ashore, suggest that a parallel may be drawn between this offshore structural feature and the Appalachian system prior to its deformation.

The area south of Cape Hatteras presents more problems due to the presence of high-velocity carbonate rocks in the sedimentary section. Seismic refraction results, interpreted with the aid of reflection data and the bore-holes made during the recent JOIDES drilling project on the Blake Plateau off Florida, indicate that the basic structure is similar to that to the north, but that the upper part of the sedimentary column differs due to erosion or non-deposition.

A clue to the age of the basic structures may be found in an apparent strike-slip fault with approximately 90 miles displacement found at lat. 40°N. Investigations ashore suggest that movement along this fault may have occurred at the end of Devonian time, indicating that the basement structures under the shelf and rise were in existence at that time.

INTRODUCTION

The continental margin of the Eastern United States has been extensively examined over the past twenty or thirty years by investigators from Columbia University, the Woods Hole Oceanographic Institution, and other organizations. The investigations include both geological and geophysical work and, before discussing the more recent measurements, it is appropriate to review the earlier findings.

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[1]Lamont Geological Observatory Contribution No. 984.

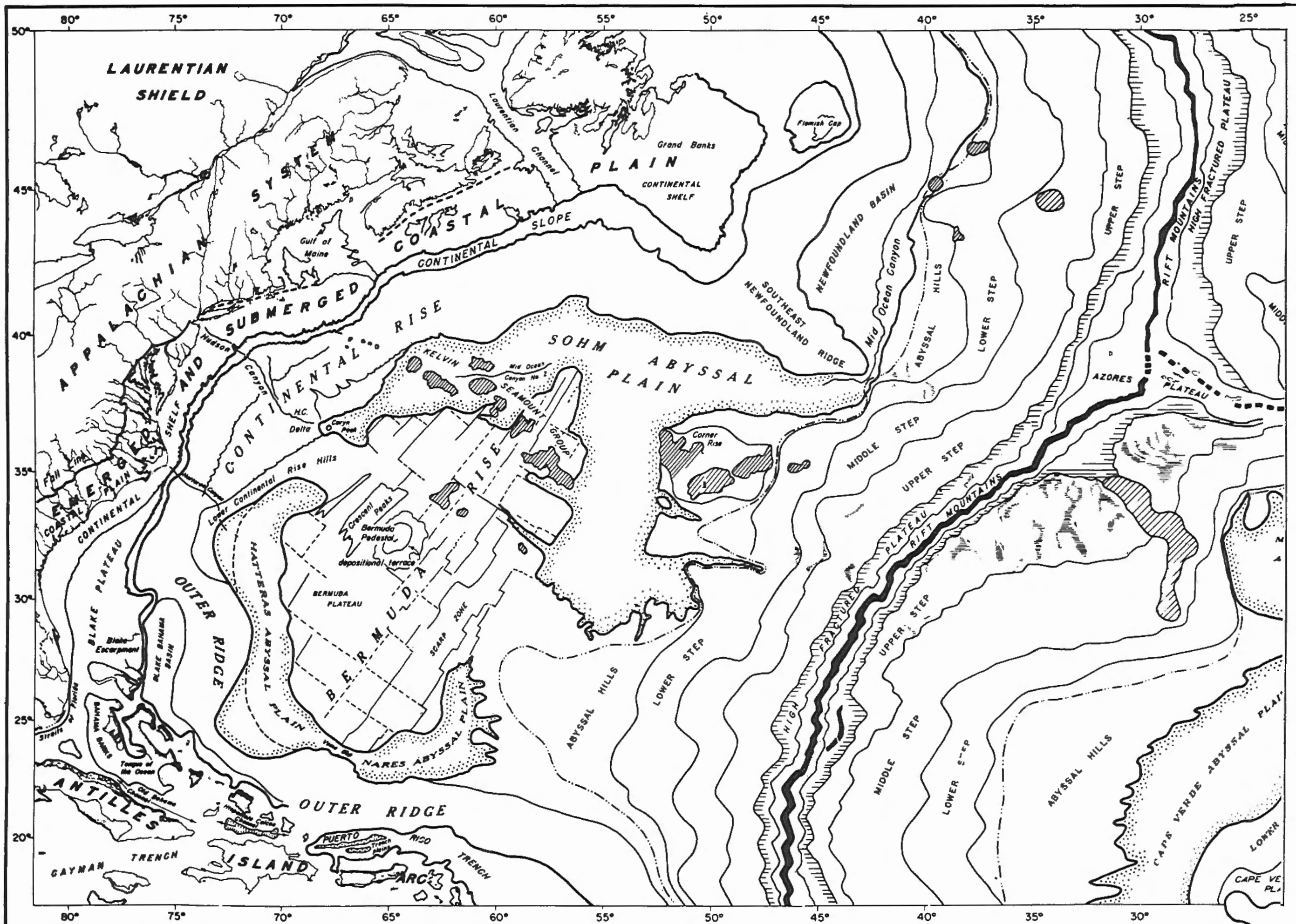

Figure 1. Physiography of the continental margin of eastern North America. (After Heezen et al., 1959)

The physiography of the area has been defined by Heezen et al. (1959) and is given in Figure 1. The area which will be discussed lies between Halifax, Nova Scotia, and the Bahama Islands. Two areas should be noted in particular: the Blake Plateau and the adjacent narrow shelf off the southeastern United States, to be discussed later in light of recently interpreted data, and the region near lat. 40°N, where the edge of the continental shelf swings into line with the New England-Kelvin seamount chain, which extends some hundreds of miles to the east. This latter area will also be discussed in terms of structure and age of the marginal features.

CAPE HATTERAS TO HALIFAX

In the area between Cape Hatteras and Halifax, a great many refraction profiles have been made by investigators from Columbia University and these have been supplemented by data from the Woods Hole Oceanographic Institution. The results of these measurements have been published in many papers and are summarized together with previously unpublished data in Drake et al. (1959).

Sections across the shelf, slope, and rise differed only in detail in this length of continental margin. An isopach map of total sediment thickness (Fig. 2) demonstrates the presence of two parallel sedimentary troughs: one under the continental shelf, the other beneath the slope and rise, and separated by a ridge in the basement near the edge of the continental shelf. The elevation of the top of the ridge decreases towards Cape Hatteras. There is a suggestion that in the Hatteras area the basement ridge separating the two troughs may not be very high. The area near lat. 40°N gave some difficulty in contouring at the time this illustration was made for reasons which will be made clear later.

Many interesting comparisons can be made between the present sedimentary system on the continental margin and the older Appalachian geosyncline. The dimensions are fortuitously similar to those of a reconstructed section across the latter by Kay (1951) at the end of the Ordovician. The sedimentary trough under the shelf bears strong resemblance to the Appalachian miogeosyncline in character, sediment type, and faunal abundance, while the trough under the slope and rise can be compared, not unfavourably, to the Appalachian eugeosyncline, with the exception that there is little evidence for volcanic rocks in the deep-water trough at the present time. This is not a critical exception since there is evidence that the major vulcanism in the Appalachian system is associated with the orogenic activity with little vulcanism during the early stages of its development.

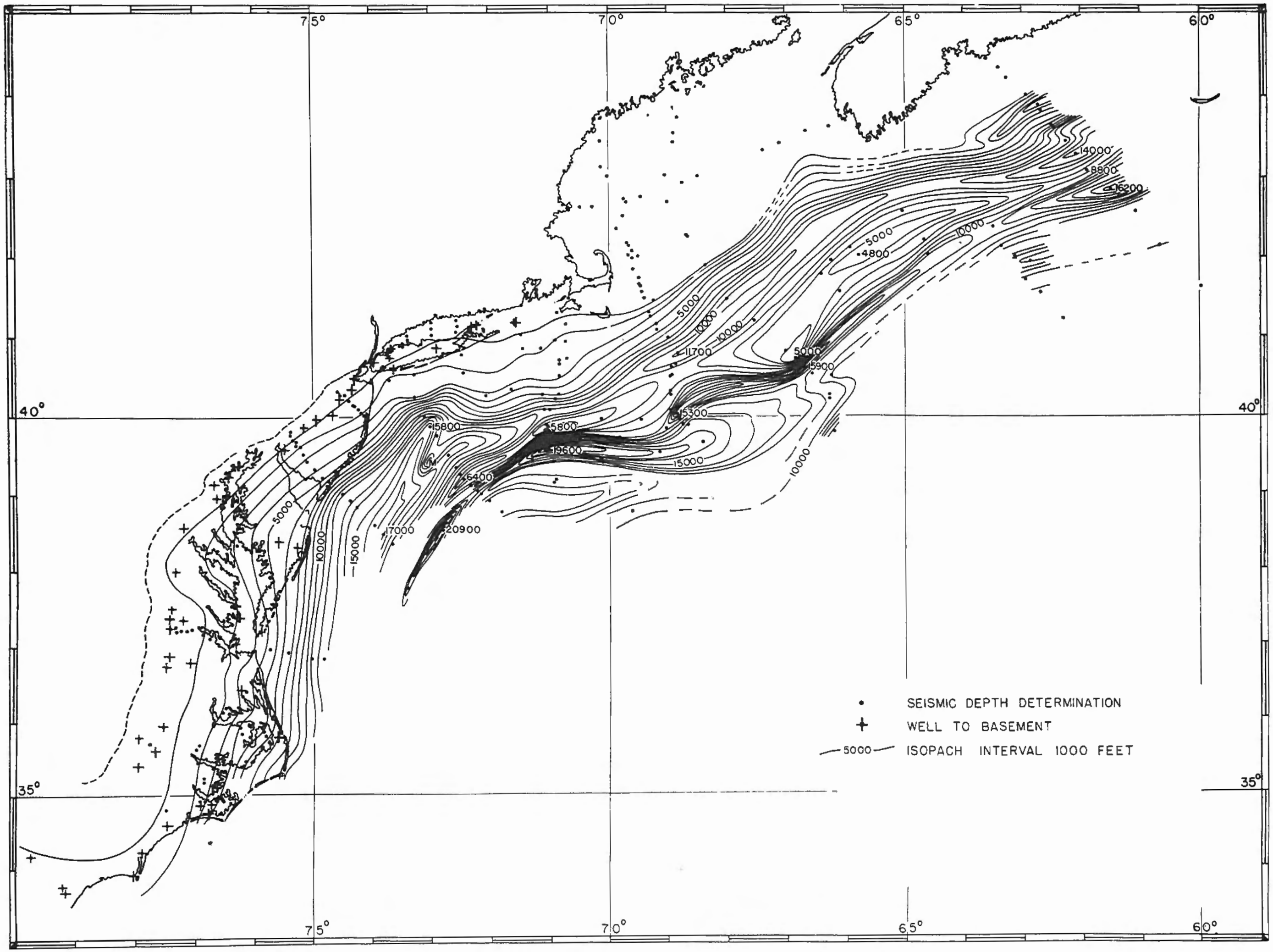

Figure 2. Isopach map of total sediment thickness, Cape Hatteras to Halifax. (After Drake et al., 1959)

It was also found during these investigations that the compressional velocity in the basement rocks decreases seawards in a systematic manner, suggesting that the Appalachians comprise a two-sided system with a metamorphic axis as suggested by King (1950). This model was borne out by borings in Florida which revealed the presence of unmetamorphosed Ordovician, Silurian, and possibly Devonian sedimentary rocks as well as volcanic rocks lying east of the crystallines of the Piedmont Province, but was compromised to some extent by indications of crystalline rock in the central Florida Peninsula. A point not emphasized at the time was that a two-layered basement was found in several areas, notably in the Gulf of Maine. Here the higher velocities (greater than 6 km/sec) appear to correlate with the Precambrian crystalline rocks and the lower velocities (between 5 and 6 km/sec) with the Palaeozoics of New England and Nova Scotia. This is of some importance because such a double basement has been found elsewhere on the shelf and because bands of higher velocity rocks parallel the shelf and may indicate the presence of and structure in the older crystalline rocks.

FLORIDA TO CAPE HATTERAS

The area south of Cape Hatteras is more difficult to study by the seismic refraction method because the clastic sediments are here replaced by carbonates and evaporites in which the compressional velocities are as high as or higher than the basement velocities which are observed north of Cape Hatteras. As a result, it is difficult to decide whether a high velocity line represents basement or part of the sedimentary column. However, through the extensive seismic profiler work done by Lamont in this area (Ewing et al., in press) the lines run by Bunce and Knott of Woods Hole, plus the recent holes drilled by the JOIDES group (1965), it is possible to sort out the data and establish the basic structure.

Prior to the availability of the above data, it was suggested on the basis of discontinuity of layers of similar velocity that there might be a fault at the edge of the Florida shelf separating it from the Blake Plateau. Matching seismic layers of similar velocity under varying topography is a practice fraught with uncertainty and, in this case, leads to error, since the reflection data, together with piston cores at critical points, and the results from the borings, indicate that the physiography of the shelf edge is due to sedimentary rather than tectonic processes.

The first attempt at determining the structure across the Florida shelf and Blake Plateau is shown in Figure 3. Here a seismic section extending eastward from Jacksonville, Florida, is compared to an earlier section off Cape May, New Jersey. The postulated fault is indicated at the shelf break. As noted earlier, the basement (pre-Jurassic) rocks

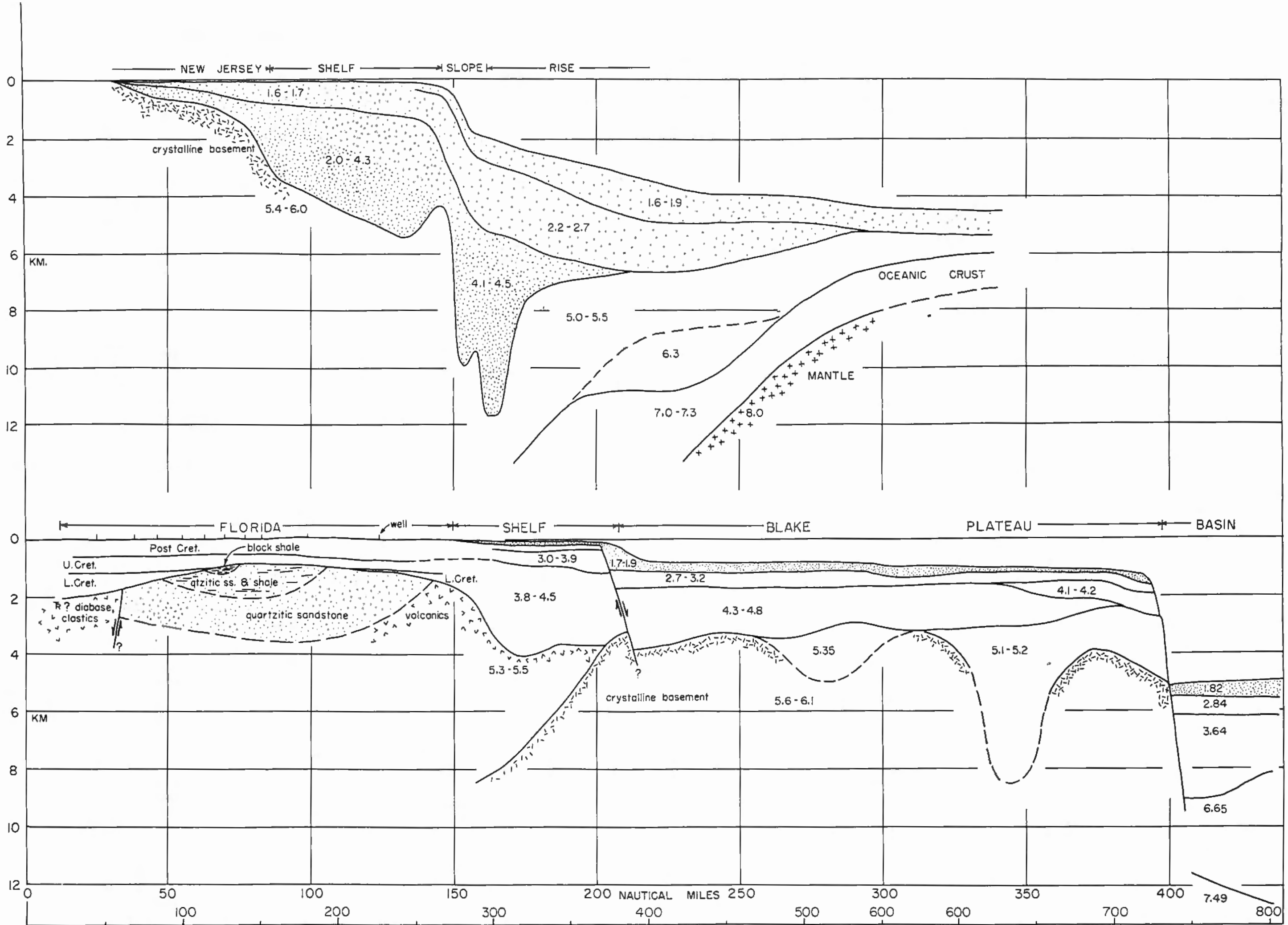

Figure 3. Cape May and Jacksonville structure sections from seismic refraction data.

under Florida consist of unmetamorphosed Palaeozoic sedimentary rocks, volcanics, and in one area, crystalline rocks, and that the velocities which might be expected in these rocks are not unlike those for well indurated carbonates or evaporites. A possible way of separating the two is to determine whether there is a systematic relationship between velocity and depth of burial in the sediments (Sheridan et al., in press). Such a relationship was indeed found, although with considerable scatter of the data points, and a new structure section was constructed on the assumption that if a questionable seismic layer had a velocity-depth relationship that fell within the scatter of the data points, it was probably in the sedimentary column rather than part of the pre-Jurassic basement. On this basis and with the aid of the reflection profiler and the bore-hole data, a new section was constructed (Fig. 4).

The structure under Florida has not been changed because it is based on bore-hole data. At the edge of the shelf the postulated fault has been removed since the drilling indicated that the topography was due to either erosion or non-deposition on the Blake Plateau. Under the plateau is a thick sedimentary section the age of which cannot at present be completely determined. Samples recovered from the steep outer face of the Blake Plateau are sedimentary rock as old as Cretaceous, but a considerable thickness of sediment lies below those sampled. In light of the occurrence of unmetamorphosed Palaeozoic sediments and volcanics in the pre-Jurassic of Florida, it is not unreasonable to suspect that the deeper part of the sedimentary fill under the Blake Plateau is Palaeozoic.

On the basis of well-velocity information, the velocity-depth relationships, experience to the north of this area, and geophysical measurements, it has been concluded that the layers with velocities in the order of 5.5 km/sec and less, which were included with the basement in the earlier interpretation (Fig. 3), should really be placed in the sedimentary column. This results in a trough-like feature under the Blake Plateau which is bounded on its outer flank by a ridge of high-velocity rock presumed to be crystalline. The existence of this ridge is supported by a magnetic anomaly which extends from Cape Hatteras to the Bahamas, making it unlikely that the ridge consists of carbonate rocks. If we accept an analogy with the Gulf of Maine and a few other scattered areas of the shelf where the high velocity subbasement appears to represent Precambrian crystalline rocks, we have the implication that Precambrian rocks extend to the eastern limits of the continent in this area – an implication important to concepts of continental accretion.

An interesting question is whether erosion or non-deposition is the more important factor in removing the sedimentary material from the Blake Plateau and making the area so physiographically different from the shelf to the north. One approach to this problem is through the velocity-depth relationships. Figure 5 illustrates the average velocity-depth curve

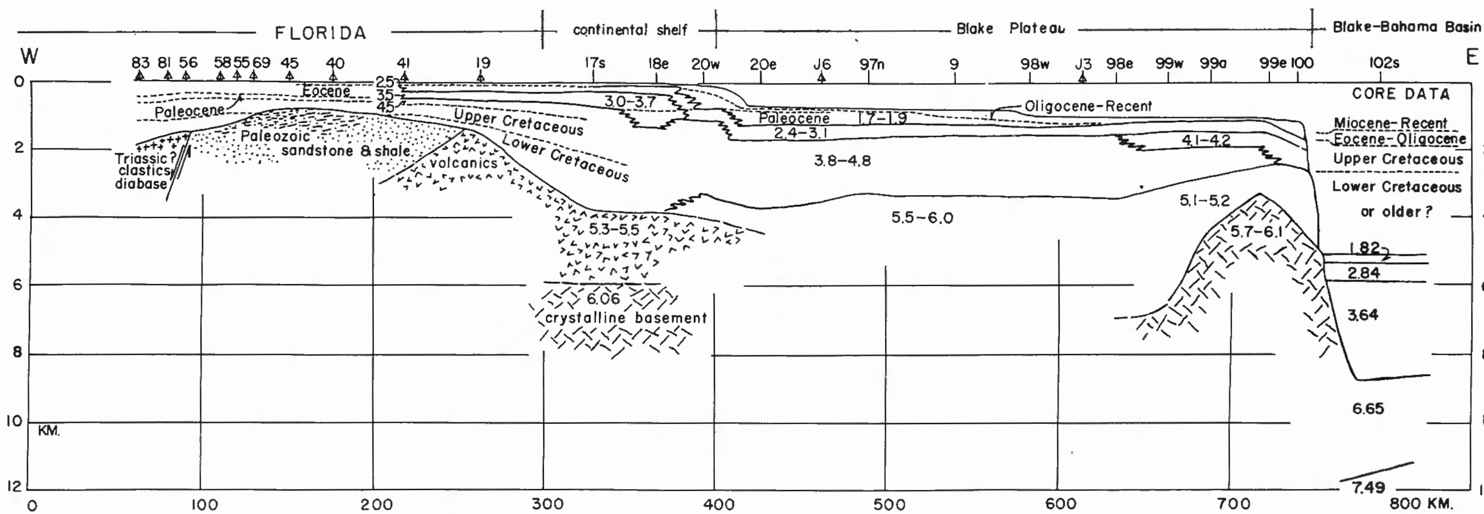

Figure 4. New seismic structure section off Jacksonville, Florida. (After Sheridan et al., in press)

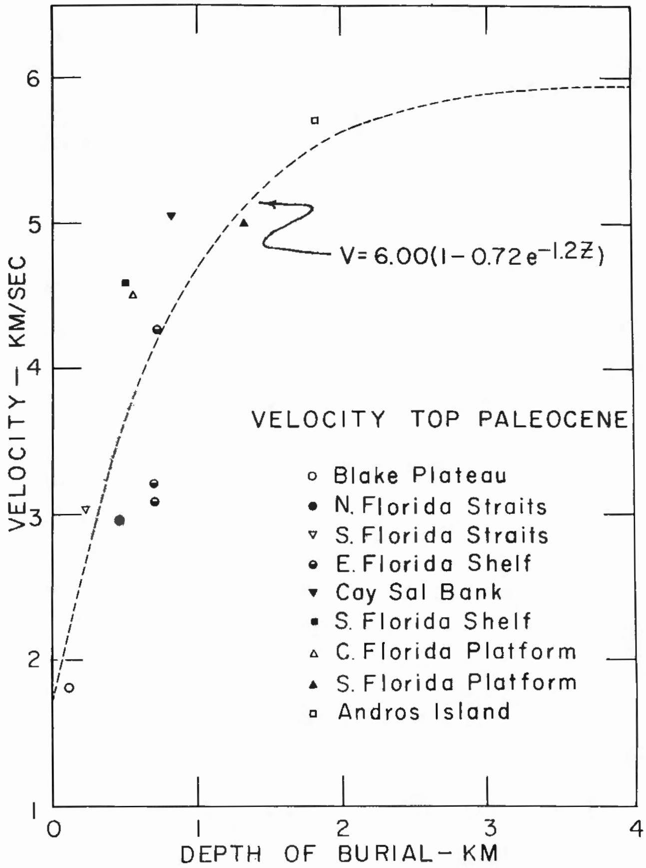

Figure 5. Velocity-depth data for Paleocene of Florida area. (After Sheridan et al., in press)

found for the sediments in the Florida-Blake Plateau area, and plotted with this are data from the Paleocene only. Note that the velocity for Paleocene rocks from the Blake Plateau is very low and falls very close to the curve. It therefore seems unlikely that they had once been compacted or lithified during deep burial, and hence it may be surmised that they have not been so and that the younger sediments supplied to the area have been removed almost as rapidly as they were deposited. This would in turn suggest that the Blake-Bahama outer ridge, which appears to be constructed in large part from these sediments (Ewing et al., in press) has been in the process of construction at least since Paleocene time. It further implies that the strong, smooth reflector which is found within the sedimentary column of the deep Atlantic Ocean basins and which extends beneath the sediments of the outer ridge without deformation must be at least pre-Paleocene in age.

Taking the results from all the seismic refraction investigations, we find that the configuration of the basement is as shown in Figure 6. It is similar to that under the shelf to the north, except that in the south the physiography has been altered by sedimentary processes and the sediments consist largely of carbonates and evaporites. There is some evidence that the basement ridge becomes deeper toward Cape Hatteras and that the inner trough, like the one to the north, may have only a low sill in the Hatteras area. This is of some significance since the Blake-Bahama outer ridge (Fig. 1) is composed of a great thickness of undisturbed sediment. Deposition of material from the Blake area (Ewing et al., in press) may have begun when the sediment filled this trough to the top of the suggested low sill and then overflowed eastwards. A similar process may have taken place to the north.

AGE OF BASEMENT STRUCTURE

We might now ask when the basement structure came into existence. A few clues are found in the area near lat. 40°N. The difficulty in contouring the seismic layers was mentioned earlier, and when magnetic surveys (Drake et al., 1963) showed that the linear anomalies paralleling the coast were offset, the area was examined afresh.

It was found that the offset in the magnetic anomalies was reflected in the surface topography (Fig. 1), and also that the offset in the edge of the shelf was in line with the New England-Kelvin group of seamounts and with a peculiar circular magnetic anomaly under the New Jersey shelf which resembled those found over the seamounts. Re-examination of the refraction results demonstrated that the contours became understandable if one assumed that a right-lateral wrench fault with approximately 90 miles displacement occurred along this line (Fig. 7). It was further noted that the trace of this proposed fault to the west placed it in the region where

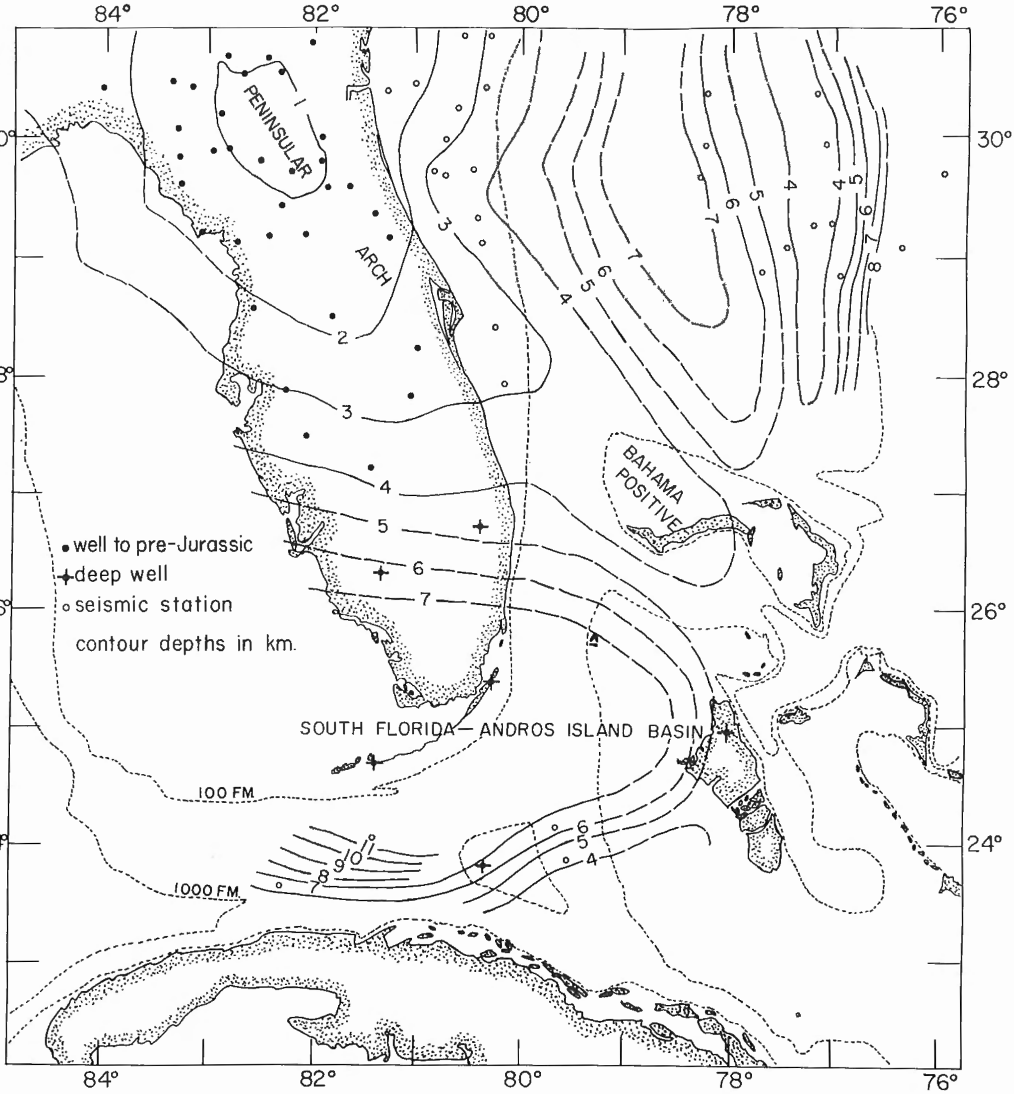

Figure 6. Structure contours of basement east of Florida. (After Sheridan et al., in press)

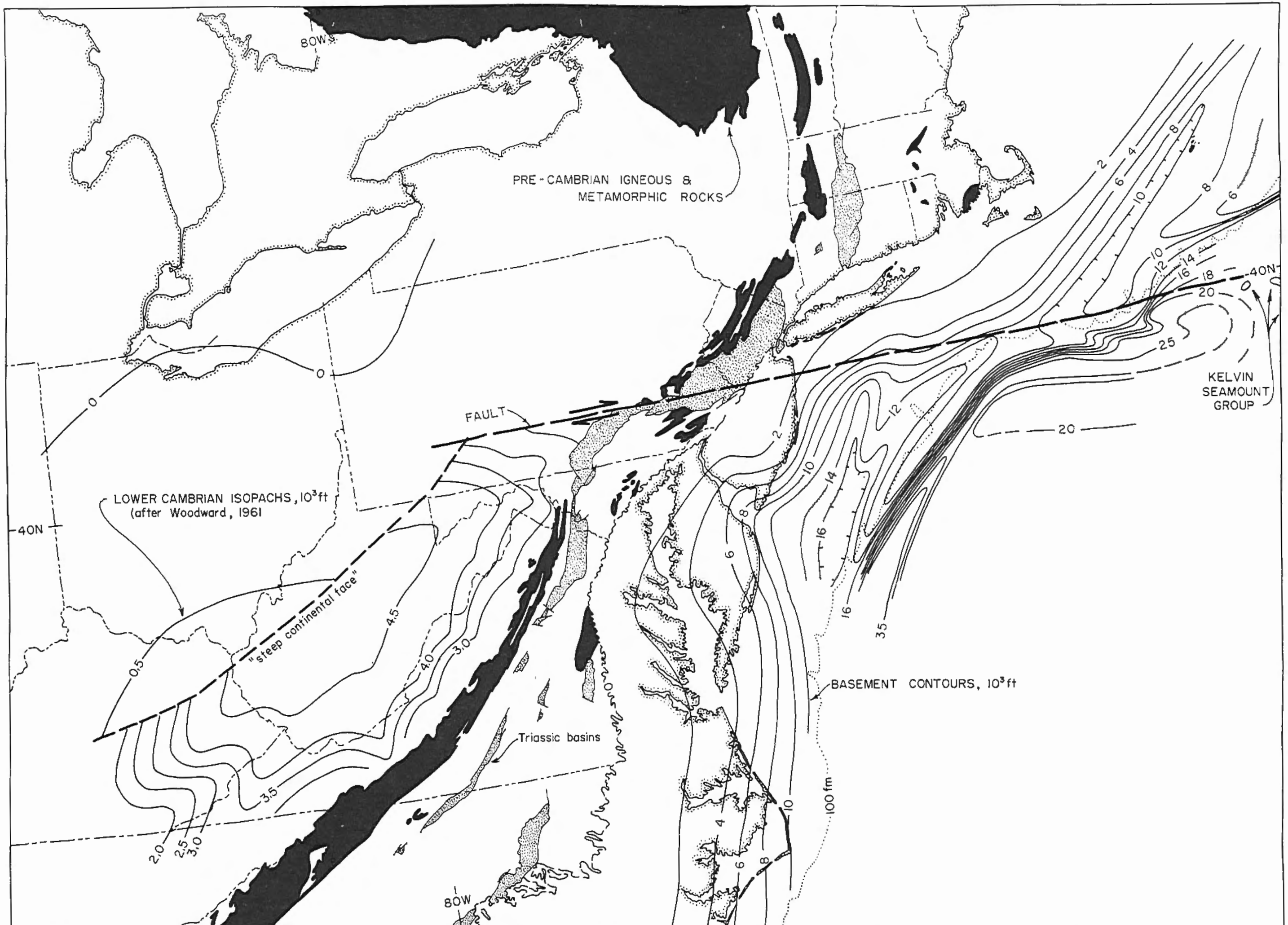

Figure 7. Proposed wrench fault at lat. 40°N. (After Drake et al., 1963)

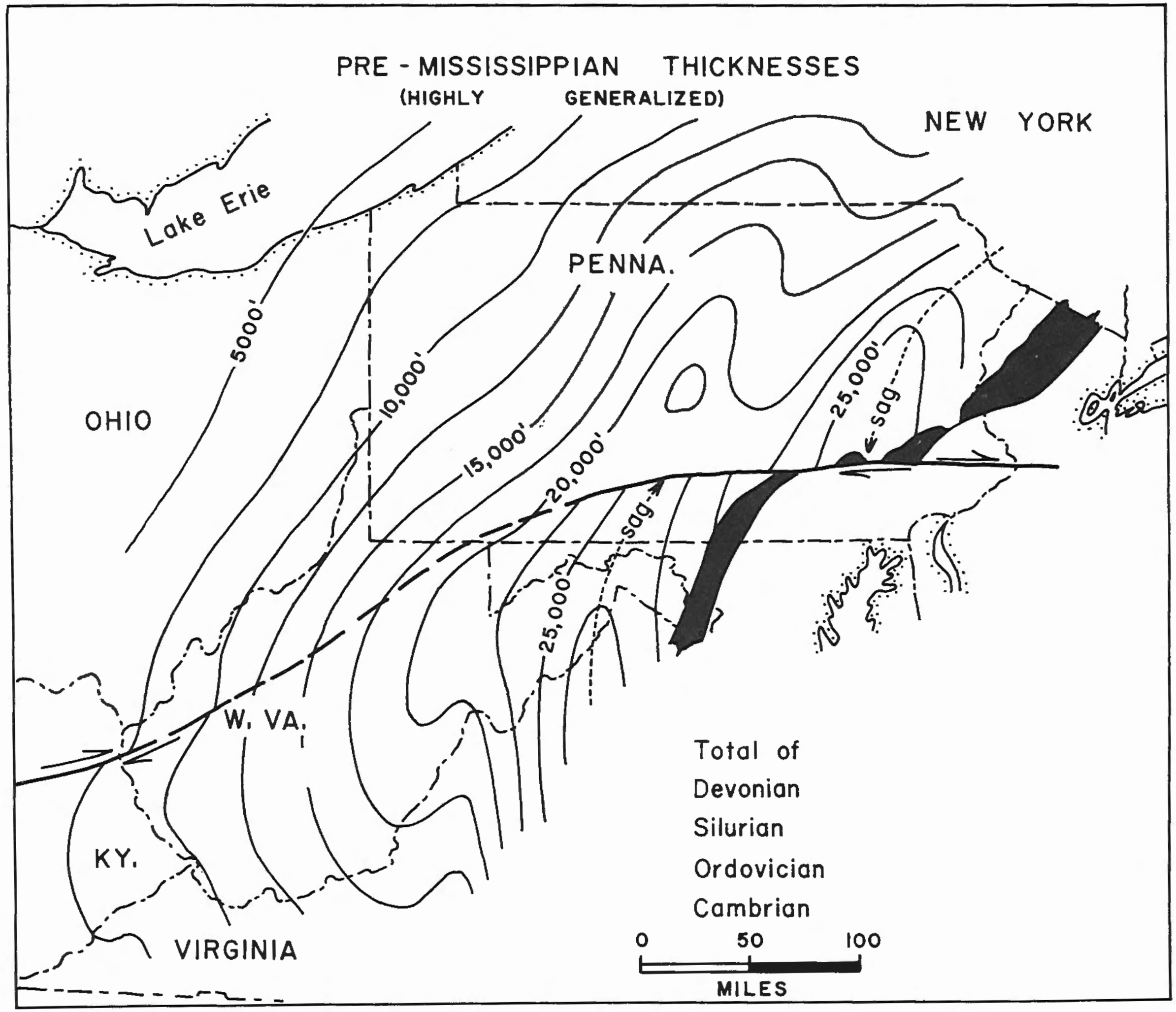

Figure 8. Pre-Mississippian isopachs in Pennsylvania and adjacent states. (After Drake and Woodward, 1963)

Appalachian folds and the Triassic basins show a marked change in trend. In collaboration with Professor Herbert Woodward of Rutgers University (Drake and Woodward, 1963), evidence from isopachs of pre-Mississippian sedimentary thicknesses (Fig. 8) suggested a time of movement along this proposed fault of near the end of the Devonian.

The proposed fault extends seaward and follows the line of seamounts, but there is no evidence that movement in the ocean basin dates back to Devonian. Repeated dredging on the seamounts has recovered Eocene and Miocene sediments but, to date, nothing older. Nevertheless, at least the shelf, slope, and part of the rise show evidence of displacement and must have been in existence prior to movement along the fault. If movement did continue farther out to sea, then an ocean basin must have existed in late Palaeozoic and the fits proposed by "continental drifters" must be re-examined.

SUMMARY

In summary, the structure north and south of Cape Hatteras is very similar. The sedimentary troughs under the shelf and the Blake Plateau appear to have leaked sediments in the Cape Hatteras area. Sediments from these areas may have contributed to the construction of the Blake-Bahama outer ridge. The deep structure of the continental margin in this area is at least as old as middle Palaeozoic.

ACKNOWLEDGMENTS

The seismic data used in this paper were collected over a period of some years with the support of the Office of Naval Research, particularly contract Nonr 266(48), and the National Science Foundation. Some of these data were taken in cooperative programs with the Hydrographic Office of the Argentine Navy, the Woods Hole Oceanographic Institution, and the California Research Corporation. Magnetic data were kindly provided by the U.S. Navy Oceanographic Office, the U.S. Geological Survey, and the U.S. Coast and Geodetic Survey. The bore-hole data from the Blake Plateau came from the JOIDES group, which conducted the project.

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DISCUSSION

Dr. G.G. Shor (USA)

What would you consider to be the age of formation of the basin south of lat. 40°N?

Dr. Drake

If you draw the analogy to the Appalachians and say that the sediments within the entire basin are shallow-water sediments, then you are implying that it was filling as it was produced; and this would imply that the lower part of the section in that area is post-Devonian or would certainly have to be post-Ordovician.

ATLANTIC SHELF MAGNETIC ANOMALY

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U.S. Naval Oceanographic Office

and

Joel S. Watkins
U.S. Geological Survey

Abstract

The Atlantic Shelf magnetic anomaly is a linear anomaly that extends from Newfoundland to Florida, and closely parallels the edge of the continental shelf. The anomaly becomes quite complex south of Charleston, South Carolina, where it splits into several linear anomalies. At least one of these branches has no associated topographic feature.

An intrusive-extrusive igneous rock complex probably causes the magnetic anomaly. Geophysical data imply that the basement ridge is a buried island arc. Southeast of the Bahama Islands, a linear anomaly can be traced for 200 miles and is clearly associated with the outer ridge north of the Puerto Rico Trench. The shelf anomaly and the outer ridge anomaly appear to be related.

INTRODUCTION

The Atlantic Shelf magnetic anomaly is a linear anomaly that extends from Newfoundland to Florida, and closely parallels the edge of the continental shelf. The anomaly is apparently continuous except near latitude 40°N where it is disrupted by an inferred transcurrent fault (Drake et al., 1963). It ranges in amplitude from 150 gammas to over 600 gammas and in width from about 30 to 80 kilometres.

SHELF ANOMALY OFF UNITED STATES

Figure 1 is a magnetic map, compiled by Watkins and Geddes (1965), of an area of the continental shelf between Cape Henry, Virginia, and Cape May, New Jersey. It consists of data from two separate airborne surveys: one flown by the U.S. Geological Survey and the other by the U.S. Naval Oceanographic Office. The magnetics of the area between the airborne surveys were compiled from a seamagnetic survey conducted by the U.S.

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[1]Speaker

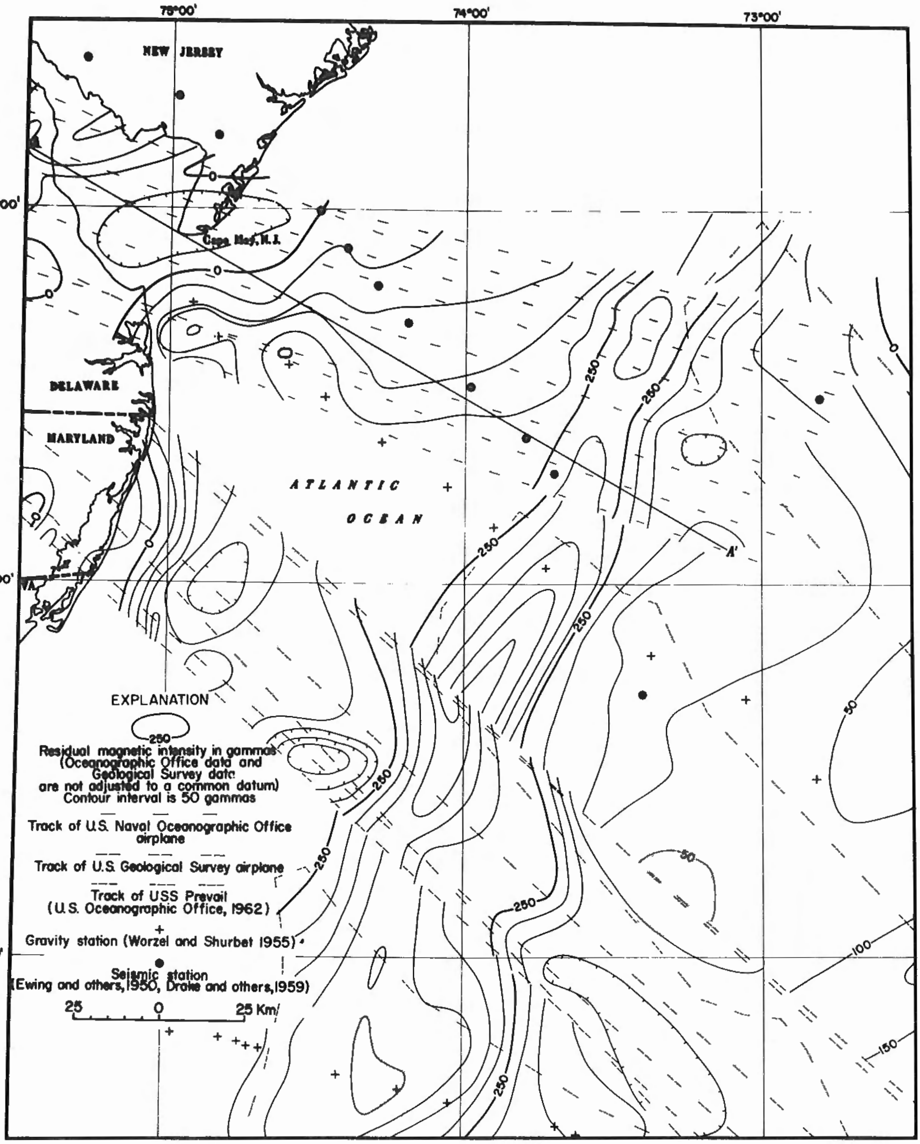

Figure 1. Residual magnetic intensity map of the continental shelf between Cape Henry, Virginia, and Cape May, New Jersey. (After Watkins and Geddes, 1965)

Naval Oceanographic Office (1962). Regional gradients have been removed from all the data. Each survey was contoured separately and no attempt was made to fit the data into a coherent contour map. Differences in intensity between the surveys are undoubtedly caused by differences in the height of the magnetometers above the disturbing body. The amplitude of the anomaly in this region is about 350 gammas above the earth's normal field.

Figure 2 is a total intensity map of an area east of Charleston, South Carolina. The map was compiled from an airborne survey and the regional gradient has not been removed. The Atlantic Shelf anomaly is shown in the northwest corner of the map. Although the linear anomaly that trends northeasterly through the area is low in amplitude, it has two interesting features. First, there is no topographic feature associated with the anomaly; and second, it is clearly a branch of the main shelf anomaly. The anomalies split (not shown on the map) at the point where the edge of the continental shelf swings abruptly to the west.

South of Jacksonville, Florida, the shelf anomaly becomes quite diffuse and data are not sufficient to determine whether the anomaly terminates, continues through the Bahamas, or turns inland into Florida.

A total magnetic intensity map (Fig. 3) of a part of the Puerto Rico Trench area (Geddes and Dennis, 1964) was compiled from an aeromagnetic and a seamagnetic survey. Regional gradients have not been removed. The east-trending band of extremely high anomalies at latitude 18°N lies over Puerto Rico and the Virgin Islands. The axis of the Puerto Rico Trench trends east at approximately latitude 19°30'N. The large anomaly in the northwest corner of the map is associated with the outer ridge north of the Puerto Rico Trench. Burton (1965) has shown that the anomaly is linear and can be traced for at least 200 miles northwesterly. Southeastward, the anomaly becomes less intense, but a faint anomaly appears to extend through the Puerto Rico Trench to the Virgin Islands. Perhaps the outer ridge anomaly is in some way related to the Atlantic Shelf anomaly.

Figure 4 shows the location of two aeromagnetic profiles that nearly coincide with refraction seismic and gravity surveys. The interpreted crustal sections are shown in Figure 5.

SOURCE OF SHELF ANOMALY

The source of the Atlantic Shelf anomaly is undoubtedly quite complex. It must be caused by a combination of intrusive-extrusive igneous rocks. The Newport, Rhode Island, and Fire Island magnetic profiles suggest that the anomaly is caused by a narrow source with vertical sides. The Cape May, New Jersey, profile suggests that the source of the anomaly

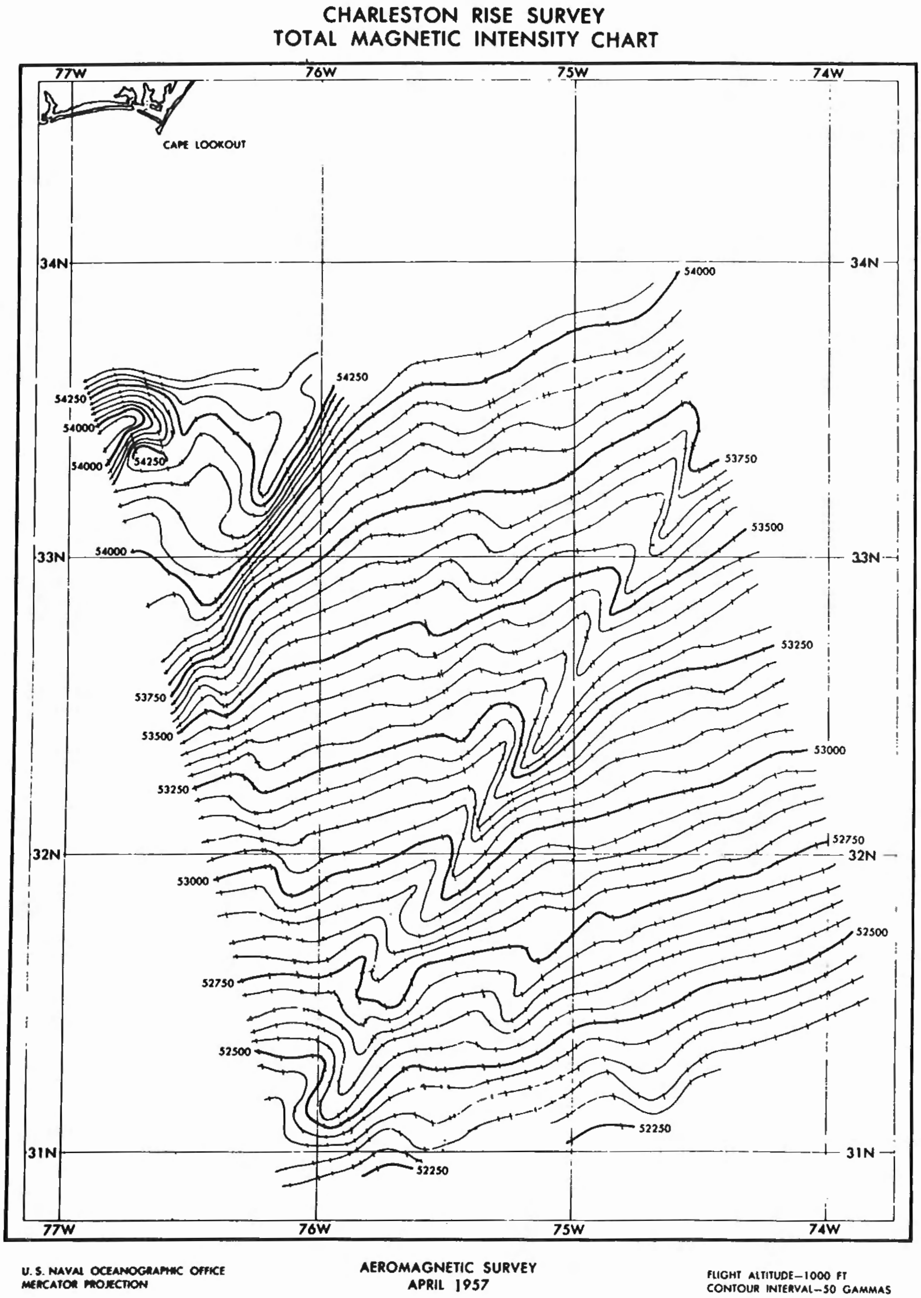

Figure 2. Total magnetic intensity map of the continental shelf east of Charleston, South Carolina.

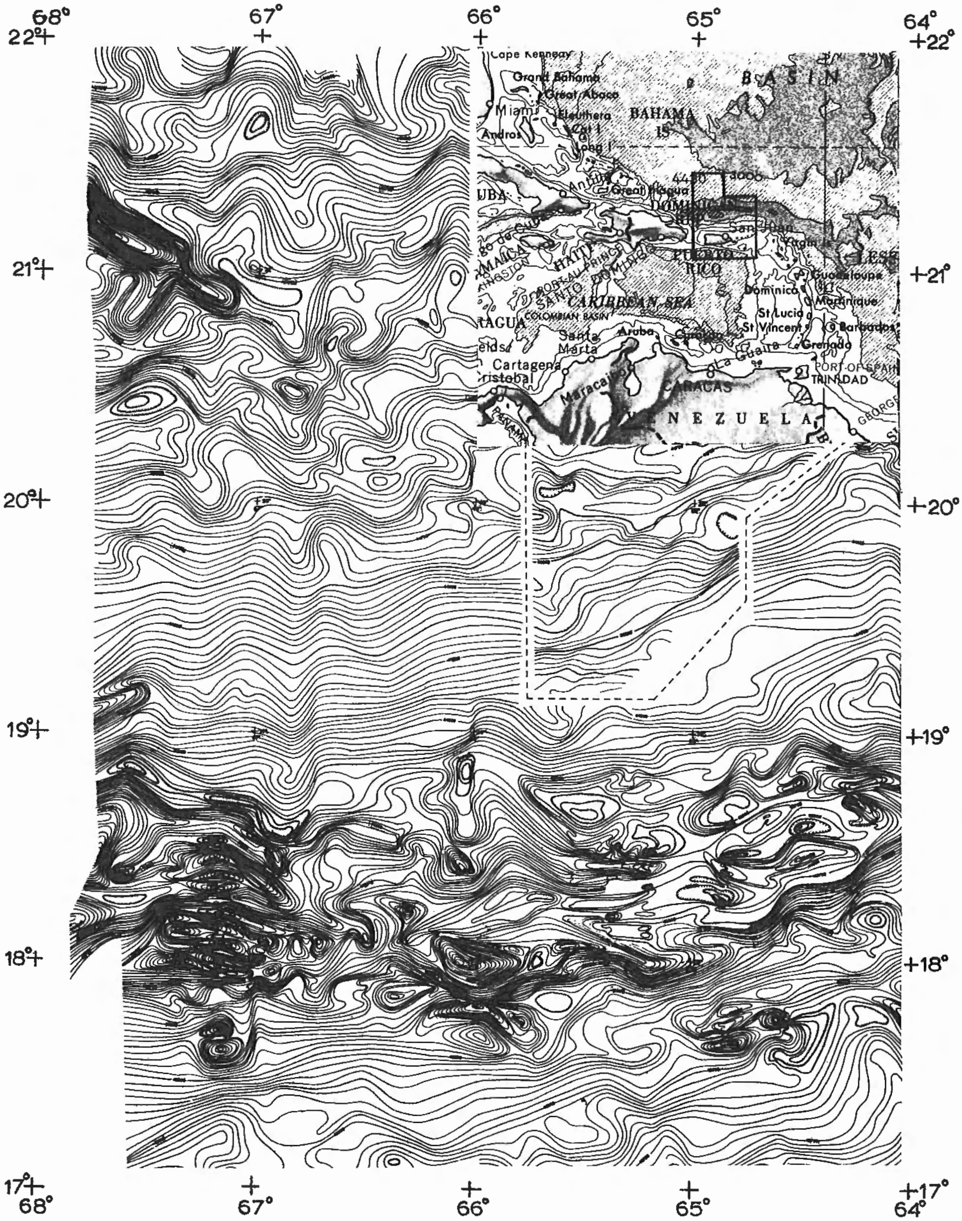

Figure 3. Total magnetic intensity map of Puerto Rico Trench area. (After Geddes and Dennis, 1964)

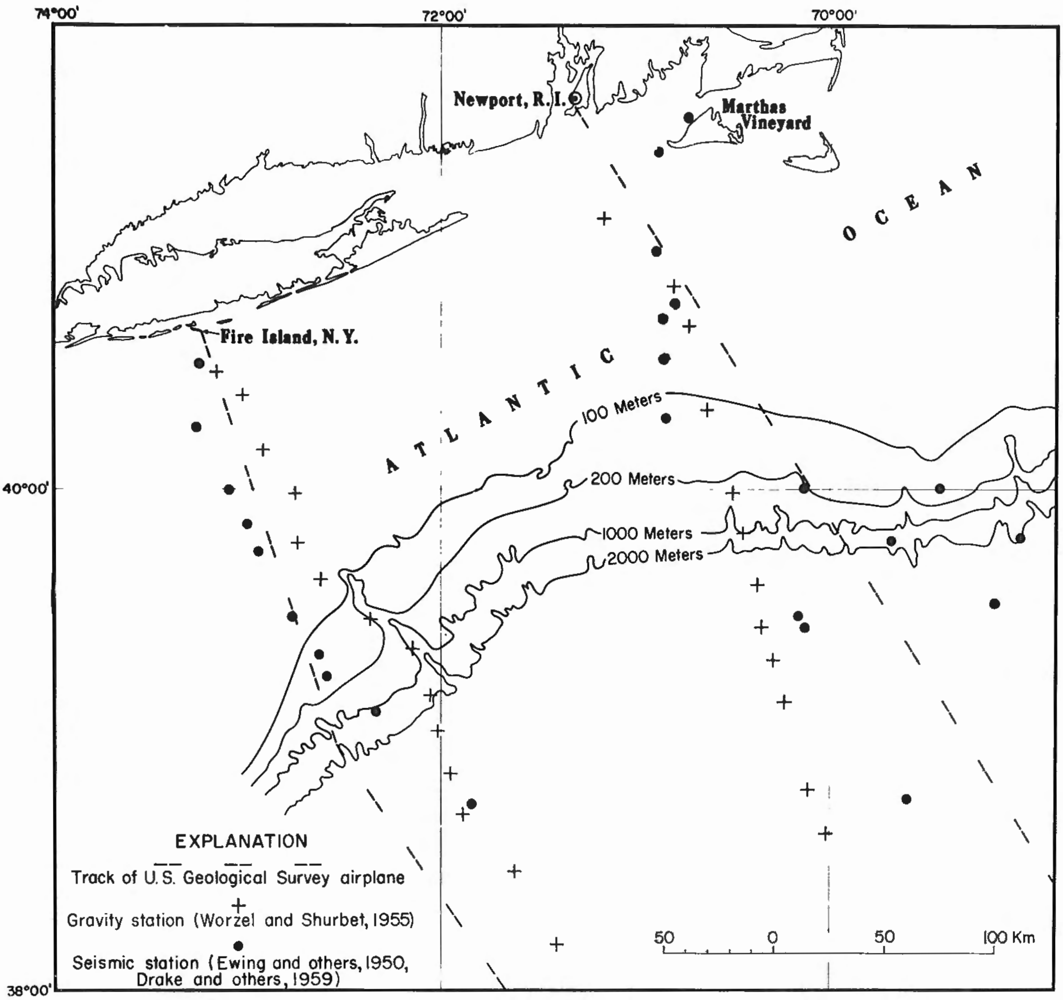

Figure 4. Location of two profiles with aeromagnetic, gravity, and refraction seismic surveys, southeast of Long Island, New York.

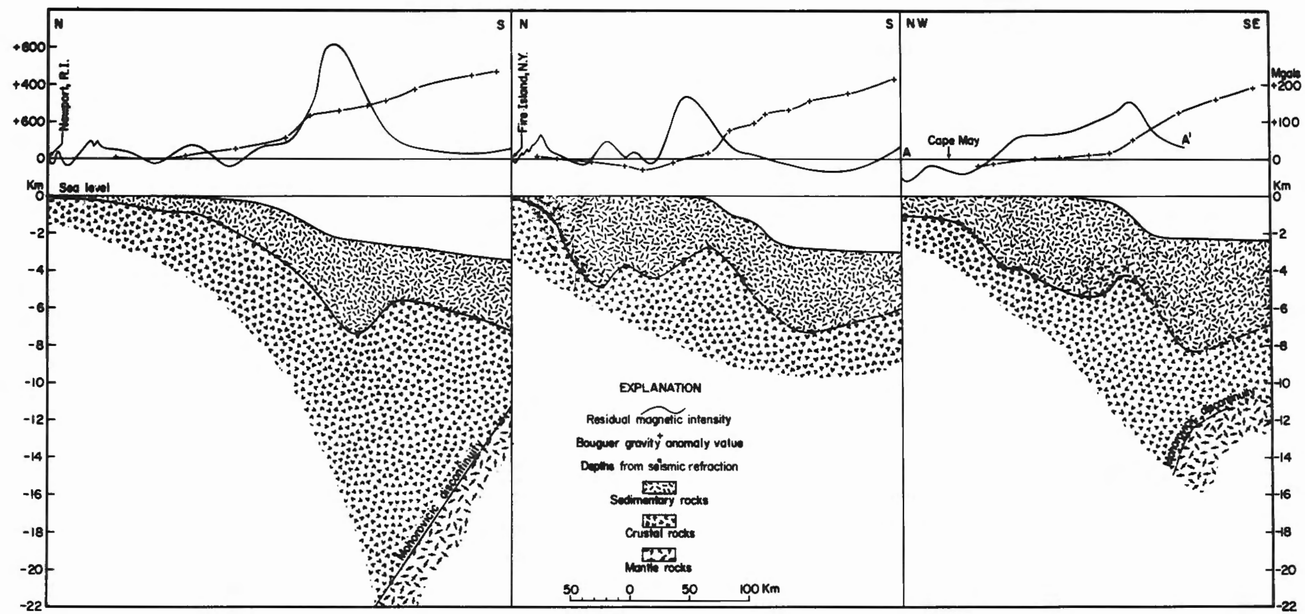

Figure 5. Crustal sections interpreted from refraction seismic surveys and aeromagnetic and gravity profiles, off the Atlantic Coast of the United States. Location of northern two sections are shown on Figure 4.

is quite broad, such as is typical of lava flows. King et al. (1961) have shown that the anomaly cannot be accounted for from the topography of the basement. Drake et al. (1963) believed that the source of the anomaly lies within the basement.

We have suggested (Watkins and Geddes, 1965) that the basement ridge is a buried, quiescent island arc and that the magnetic anomalies associated with the ridge are caused by volcanic rocks of an earlier, more active tectonic phase.

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DISCUSSION

Dr. D.C. Krause (USA)

I think this is a very interesting paper. The edge of the continent off the west coast of the United States is very prominent, and you can pick out the margin of the continent from the magnetic map just as easily as you can from the bathymetric map. Vick suggested many years ago that the margin of the continents might be marked by very broad anomalies - much broader than what you've shown, and broader than that which usually results by removing the regional gradient. Have you seen anything like this?

Mr. Geddes

I have examined isolated profiles from many sections around the world. There are two problems in determining whether the anomaly is actually associated with the continental margin. First of all, the profile must be at right angles to the continental margin, because otherwise you are faced with the problems of visualizing what it would look like if it were at right angles to the continental margin. And secondly, you are faced with a difficult decision when you have two bands of anomalies, perhaps neither one of which fits exactly a preconceived idea of where the edge of the continent is. There are many cases where the anomaly is linear, and exactly parallels the edge of the margin.

Dr. J.B. Hersey (USA)

Have you compared the location of your branching anomalies off Charleston, South Carolina, with seismic data published by Woods Hole several years ago?

Mr. Geddes

No, I did not make a comparison because I missed that report.

Prof. S.K. Runcorn (UK)

Do you know how the trace of the shelf anomaly compares with the edge of the continent as defined in Bullard's paper on the origin of North America? Perhaps this anomaly represents the initial break along which North America and Europe separated, because, assuming that this has occurred, presumably one would expect to get an upwelling of basaltic material along the break and this kind of anomaly would result.

Mr. Geddes

I have not made a direct comparison but this anomaly follows almost exactly the 100-fathom contour down the east coast of the United States.

Prof. Runcorn

Yes, almost exactly where continental drifters suppose that the break between North America and Europe began.

Mr. Geddes

I might add that I've looked at the African side and I find no indication of a linear anomaly around the Atlantic continental shelf off Africa.

Dr. M. Talwani (USA)

There is one along the southwest African shelf, though.

Mr. Geddes

Oh yes! I was thinking in terms of some major feature that you could follow all the way along the African Atlantic Shelf. There is, of course, a highly magnetic zone along the continental shelf off South Africa. It does not have the same kind of linear anomaly which we find along the east coast of the United States, judging from the data that I have been able to examine.

SEISMIC PROFILER SURVEY OF THE BLAKE PLATEAU[1]

J.I. Ewing, Maurice Ewing, and Robert Leyden[2]
Lamont Geological Observatory

Summary

Continuous seismic reflection profiles on the Blake Plateau have been correlated with sediment cores, seismic refraction data, and well logs on Florida in order to study the structural relationship between the Florida Peninsula, the continental shelf, and the plateau. Results indicate that the entire Blake-Bahama-Florida area was receiving shallow-water carbonate sediments behind a barrier reef until late Mesozoic. Death of the reef along the Blake Plateau margin, coupled with continued subsidence of the entire area, resulted in the present submerged plateau. Florida and the Bahama Banks continued to be built up throughout the Tertiary and have maintained an elevation close to sea-level.

Four strong reflectors were observed in the plateau sediments; the deepest apparently represents an interface within the Upper Cretaceous and correlates with the top of a 4.5 km/sec refracting layer. The overlying beds are probably composed of bank-derived calcarenites and calcilutites; the reflectors correspond to major changes in sediment types or rates of deposition. The Tertiary sediments on the plateau essentially form a wedge, about 1,200 metres thick on the west side and 200 to 300 metres thick near the escarpment on the east.

The southward extension of the Cape Fear Arch onto the plateau apparently diverts and restricts the flow of the Gulf Stream, with the result that much of the surface of the plateau is being eroded. In places, beds of Eocene and Paleocene age have been uncovered. The material eroded from the plateau by the stream, as well as that carried in suspension from the continent, has been swept off the plateau and has formed the Blake-Bahama outer ridge.

DISCUSSION

Dr. A.S. Laughton (UK)

At what depth has erosion taken place, and how does the current velocity compare with those measured along the Gulf Stream?

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[1]Complete paper has been submitted to the American Association of Petroleum Geologists for publication.

[2]Speaker

Mr. Leyden

We believe that erosion took place when sea-level was lower. The present Gulf Stream keeps these erosion channels clear, but they were not necessarily cut by the present Gulf Stream.

Dr. Laughton

At what depth?

Mr. Leyden

A depth of 500 metres.

Dr. B.C. Heezen (USA)

The question of whether this erosion occurred in the past or is occurring today is very interesting. Recently we had the opportunity of examining this area in search of such evidence. We have obtained definite bottom current evidence on three expeditions of the Duke University ship EASTWARD. Along the western edge of the Blake Plateau, bottom photographs show blocky rocks and well developed, asymmetrical ripple marks on a sand bottom. In depths over 1,000 metres on the plateau, the bottom is smooth and has slight lineations, but we know from cores that it consists of a manganese crust about a centimetre thick overlying Miocene or Pliocene sediments. In the northern part of the plateau, blocks of rock are lacking, but asymmetrical ripples are present, indicating velocities of the order of 1 knot.

The most interesting feature is the outer ridge. What is its origin? A couple of years ago, Ewing, Ewing, and Worzel reported that the basement passed straight beneath the ridge. The ridge, therefore, consists purely of sediments which may in part have come from the Blake Plateau. The questions are: is the ridge ancient or modern; is sedimentation still building it up; what is the sediment source; along what route is it transported? We took sea-bottom photographs with a camera on which we mounted a compass. On the ridge, we found bottom lineations - very smooth groove-like markings or streamers a few inches to a foot across and from one foot to eight feet long streaming out behind burrows and scattered debris. All paralleled the contours and on the east side of the ridge indicated a southerly flow. We took about 300 photographs at some 40 stations in this region. Apparently, sediment is being carried north at the base of the Gulf Stream to a point just south of Cape Hatteras where bottom transport takes an abrupt hairpin curve and turns south along the outer ridge (Fig. 1). But most of the sediment moving along the ridge is not carbonate sediment. Carbonate sediment was found only along the crest of the ridge; on the east side we found silty lutite apparently derived from far to the north. So here two streams of sediment transport join, the carbonate sediment coming off the Blake Plateau and a large amount of silty lutite coming from the north, possibly some of it from as far away as Greenland. Similar

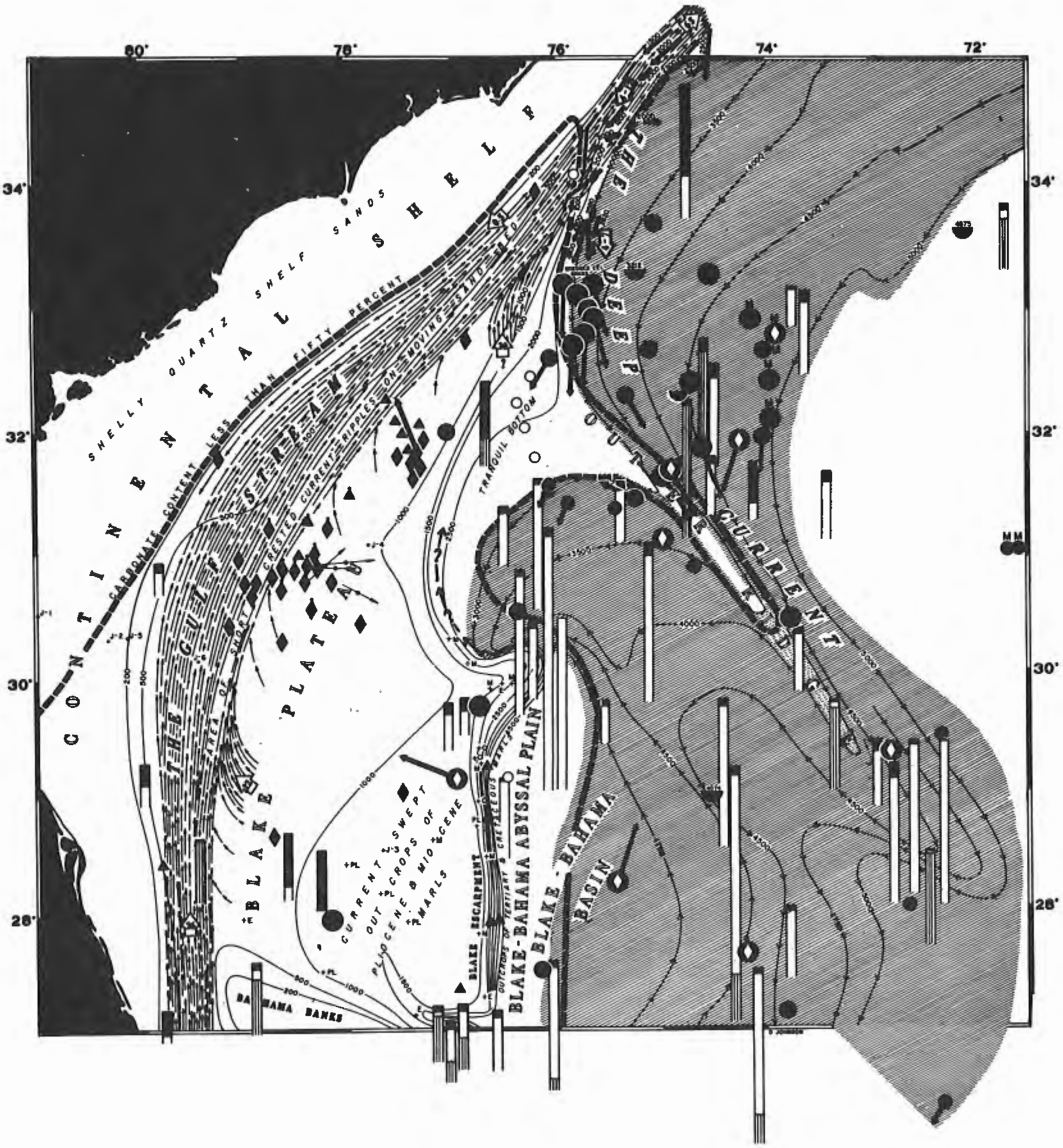
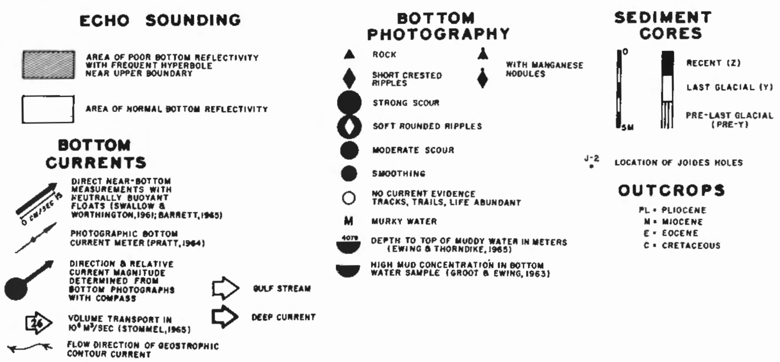


Figure 1. Bottom currents and sediments on the Blake Plateau and Blake-Bahama Outer Ridge (Heezen, Hollister, and Ruddiman, in press). Short-crested ripples, manganese nodules, and Tertiary outcrops are found beneath the Gulf Stream which acts as a barrier to seaward transport of terrigenous sediment. The outer ridge is formed by rapid lutite deposition from the southerly flowing, sediment-laden Western Boundary Undercurrent flowing parallel with the contours. Water-rich sediments that result from rapid deposition exhibit poor reflectivity.



bottom lineations have been observed on the continental rise off Greenland, Labrador, the Grand Banks, Nova Scotia, and New York. But only in the Blake Plateau area did we have a compass on the camera. The sediment is apparently transported parallel with the contours by the geostrophic contour-following currents which shape sediment wedges that form the continental rise and outer ridge.

ARGENTINE CONTINENTAL MARGIN

W.J. Ludwig[1], J.I. Ewing, and Maurice Ewing
Lamont Geological Observatory

Summary

Seismic refraction measurements on the Argentine continental shelf have defined the seaward limits of several large sediment-filled transverse depressions: the Rio Salado, Bahia Blanca (Rio Colorado-Negro), San Jorge-Chubut, and the Magellan (Santa Cruz-Austral) basins. The Rio Salado and Bahia Blanca depressions in the Buenos Aires province extend out to the edge of the continental shelf with no indication of closure at the seaward end.

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[1] Speaker

MORPHOLOGICAL STRUCTURE AND THE EARTH'S CRUST OF THE NORTH ATLANTIC REGION[1]

R.M. Demenitskaya and V.D. Dibner
Institute of Geology of the Arctic, Leningrad

Abstract

The report deals mainly with the Norway-Greenland Basin. The basin has the same general structure as the Atlantic but differs by having a more complex, transitional-type crustal structure and some peculiarities of the bedrock petrology.

1. Morphological structure

The abyssal area of the Norway-Greenland Basin, named "Scandic", is bordered and crossed by huge neotectonic scarps which we call "morphodisjunctions".

The Norway and East Greenland continental shelves consist of folded rocks, dominantly of Caledonian age, and an overlying cover of sediments and plateau basalt. Both areas are crossed by the Britain-Norway and the East Greenland morphodisjunctions. The writers distinguish a special type of shelf which originated partly by faulting, and call it an "avantshelf" (the Norway and the West Iceland avantshelves, etc.).

Iceland is situated on the junction of the Baffin-Britain Sill and the rift zone of the mid-oceanic ridge, and is of special importance in the earth's crustal history.

The rift zone is an important structural element of Scandic. It is continuous with the mid-Atlantic rift and is marked by modern volcanic activity, a rift fracture system, epicentres of shallow-focus earthquakes, etc.

Petrological investigations (M. Polyakov) of rocks dredged by the Institute PINRO expeditions (Litvin and others) showed outcrops of the metamorphic Caledonian (?) complex in two places in the rift zone. This complex appears to form the basement of the Mon Ridge and that of other mid-oceanic volcanoria.

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[1]By title.

2. Structure of the earth's crust

The crustal structure of the Norway-Greenland Basin may be reconstructed by Demenitskaya's or Woollard's method of "averaged curves", using the still sparse seismic data available (J. Ewing, M. Ewing, Båth, Tryggvason, and others). In this region the crust is predominantly of the transitional type but is represented by both transitional and oceanic types. Of great interest under the Scandic area is the oceanic crust which is bounded on the west by the Greenland-Jan Mayen morphodisjunction 1,500 kilometres long. Another feature of this region is the absence of a clear discontinuity between the "normal" (8.1 km/sec) and the "anomalous" (7.5 km/sec) mantle. It is unlikely that the lack of a discontinuity is characteristic only of the rift zone of the mid-oceanic ridge. The results of the Soviet seismic studies, as well as the data of foreign investigators analyzed by Demenitskaya, Zalesova, and Gorodnitskaya (in press), have shown that the 7.5 km/sec seismic layer usually occurs under areas of the world having quite different tectonic history. The authors suggest that a northwest-trending world-wide lineament extends from the Mid-Indian Ridge to Baffin Bay. All these data are based on the map of geoidal topography (Kaula), on magnetic field contours (Bauer), and on modern seamagnetic and seismic results.

INTRODUCTION

This report deals mainly with the Norway-Greenland Basin.[1] Having the same general structure as the Atlantic, this basin differs from it by having lesser depths, greater crustal thicknesses, a more complex transitional structure of the earth's crust, and some peculiarities of the bedrock petrology. This water area, which is traditionally considered by the oceanologists as the Atlantic part of the Arctic Ocean, is thus a key to our knowledge of the geology and crustal structure of the Atlantic Ocean.

MORPHOLOGICAL STRUCTURE

1. Main morphodisjunctions and morphostructural areas

We use the term "morphodisjunctions" to describe the rectilinear topographical scarps which are unusually long and high, and are caused by both deep-seated faults and relatively young (Neogene-Quaternary) faults. The main morphodisjunctions form continental slopes and slopes of the great block-uplitts of the ocean floor. These slopes are the most prominent parts of the still more extensive and locally activated faults which extend into the shelves and adjacent continental areas.

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[1] Bathymetric data on this area were taken from Litvin (1964).

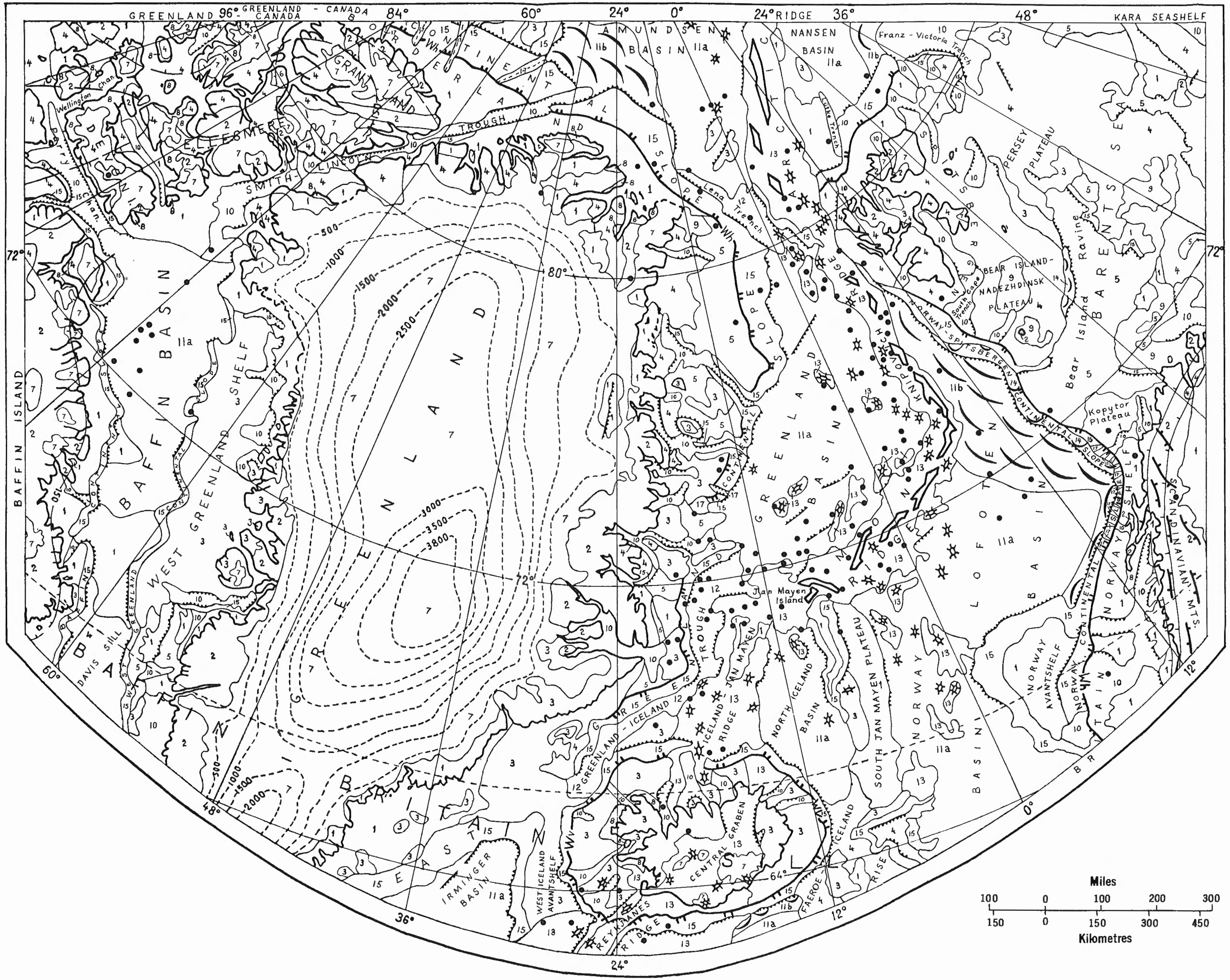

Figure I. Geomorphological diagram of the North Atlantic Regions

LEGEND

RELIEF TYPES OF CONTINENTAL ORIGIN

I EROSIONAL RELIEF

1 Basement peneplains

2 Fold-block mountains with trends of individual ranges

II STRUCTURAL RELIEF

3 Volcanic plateaus

4 Plateaus on strata of solid sedimentary rocks

III SUBAERIAL DEPOSITIONAL RELIEF

5 Glacial, washed and lacustrine alluvial plains

6 Alluvial and delta plains

7 Modern ice-sheets and ice caps (isopachous lines of ice thickness in meters)

IV DENUDATION AND/OR DEPOSITIONAL RELIEF ASSOCIATED WITH EXOGENOUS PROCESSES WITHIN SHELF ZONE

8 Raised marine erosional surfaces and beaches

9 Submerged erosional and depositional plains

10 Plains of pelagic sedimentation in shelf troughs

RELIEF TYPES OF OCEANIC ORIGIN

V RELIEF FORMED BY SEDIMENTATION BELOW WAVE-BASE

11 Abyssal plains of pelagic (a) and turbidite (b) sedimentation in oceanic basins

12 Plains of pelagic sedimentation in oceanic troughs

VI RELIEF ASSOCIATED WITH VULCANISM AND DISJUNCTIVE NEOTECTONICS

13 Mid-oceanic volcanoria

14 Landslide (gravitational) topography at foot of continental and other slopes

15 Continental slopes and other regional neotectonic scarps (morpho-disjunctions)

16 Tectonic scarps of smaller order

ADDITIONAL SYMBOLS

17 Submarine canyons

18 Thalwegs of submarine valleys and canyons

19 Modern scarps

20 Unstable line of shallow coasts

21 Volcanic cones and cone clusters

22 Epicentres of shallow-focus earthquakes with a magnitude exceeding 4 3/4

23 Rift fissures

24 Limit of maximum distribution of main (Wh) and old (Wv) stages of Würm glaciation

25 Isobases of post-Pleistocene glacial isostatic uplift

Compiled by V. D. Dibner and T. P. Vlasova.

Geomorphological map of Arctic Ocean area generalized from compilation by Dibner, Gakkel, Litvin et al., in press.

To accompany paper "Morphological Structure and the Earth's Crust of the North Atlantic Region" by R. M. Demenitskaya and V. D. Dibner in Geological Survey of Canada Paper 66-15

Within the Norway-Greenland Basin, we distinguish the Greenland-Jan Mayen and East Greenland meridional morphodisjunctions as well as the Britain-Norway and Baffin-Britain "diagonal" morphodisjunctions (Fig. 1). These form the boundaries of the abyssal parts of Scandic Basin and divide it into two parts, each differing in morphology and crustal structure.

2. Norway and East Greenland shelves

The geology, neotectonics, and geomorphology of any shelf generally reflect the continental structure. But those shelves (and avantshelves) which occupy relatively extensive areas of sea floor, together with the adjoining continental lowlands, form special morphostructural zones. The folded basement of various ages, even relatively young, have subsided under the sedimentary cover. These zones are also characterized by a general thinning of the crust.

Judging from the bedrock material collected by Bøggild (1909), O. Holtedal (1940), Belov and Lapina (1962), Avilov (1962), and by V. Litvin, V. Dibner, V. Rvachev and others, the same geological structures are typical of the Norway and East Greenland shelves and adjoining continental areas. The characteristic feature of these areas, as well as the greater Arctic shelf off Eurasia, is a relatively extensive development of post-folding formations, namely, the Palaeogene plateau basalts, resting on the metamorphosed formations which underlie the East Greenland shelf.

These post-folding formations also include the epi-Caledonian Mesozoic-Cenozoic deposits which rest on the folded Caledonian basement of the Norway shelf (O. Holtedahl, 1940; H. Holtedahl, 1955, 1959). Another peculiarity of the geology of the Norway shelf is that the widest parts of the shelf and the adjoining avantshelves are located on the axis of the cross-uplift of the coastal folded structure where, in the North Trøndelag area, some outcrops of the Riphean structural stage of the Caledonides occur.

We conclude that the Norway and East Greenland Caledonides extended onto the adjoining shelves, and are "cut" by the continental slopes. This phenomenon was established long ago in some Atlantic areas where the shelf is narrow or non-existent.

3. Iceland and its island shelves

Iceland is part of the half-submerged "bridge" formed by the Baffin-Britain Sill (see below) and is also located on the axial zone of the mid-oceanic ridge of the Atlantic and Arctic Oceans. Iceland is of special importance to the understanding of the crustal history and to the establishment of the morphostructure of the modern ocean floor in the North Atlantic and adjacent water areas of the Arctic Ocean.

Iceland can be divided naturally into three morphostructural parts (Thorarinsson, 1937, 1960). The first two are the plateau and the adjoining shelves of east and west Iceland; both are composed of plateau basalts of the Britain-Arctic province (Einarsson, 1960). Between them is the "Central Graben", the third morphostructural part, which is filled with Pliocene-Pleistocene palagonite formation and Holocene volcanics, to an average thickness of about 2,100 metres (Kjartansson, 1960; Båth, 1960; Tryggvason, 1962). This is the zone of active volcanoes. It extends onto the ocean floor immediately southwest and especially north of Iceland in the form of a rift zone of the mid-oceanic ridge (Sonder, 1939; Muratov, 1963; Litvin, 1964; Atlasov et al., 1964a, 1964b).

According to Thorarinsson (1960), the Icelandic Central Graben is the area of greatest concentration of active volcanoes in the world. Up to now, flood-basalt vulcanism is dominant. Every episode of vulcanism is accompanied by the appearance of new fractures, named eldja, which pass along strike into the linear explosion canals represented by rows of volcanic cones or craters of the maar type. The canals contain cinder and lava, and are several dozens of kilometres long.

On the northern and southwestern continuation of the Central Graben, the Iceland shelf is weakly developed because of recent and present-day volcanic activity in the mid-oceanic ridge zone.

4. Avantshelves

We use the term "avantshelf" for a special type of shelf which has the form of a deeply subsided plain, in water depths of up to 700-1,000 metres and more, with a thin irregular mantle of bottom sediments. The plain lies in front of an ordinary shelf in the form of a huge apron. American scientists call such forms in the western Atlantic by a less suitable term (which is nongenetic), a marginal "edge plateau" (Heezen et al., 1959).

The typical avantshelf in the Norway-Greenland Basin is the Norway avantshelf. It is situated at a depth of 1,200-1,400 metres and is the faulted northeastern continuation of the middle part of the Norway shelf. The fault occurs along the continental slope. In this area, the shelf is widest and deepest, and occurs on a cross-uplift of the Norwegian Caledonides. South of the Norway-Greenland Basin, the Ireland avantshelf is a morphostructural equivalent of the Norway avantshelf.

5. Baffin-Britain Sill

The Norway-Greenland Basin is limited on the southwest by a chain of uplifts forming a natural boundary with the Atlantic Ocean. The sill can be traced westward through the uplifted area of Greenland's bedrock, the West Greenland shelf, and the Davis Sill, the last of which separates the Baffin Basin (depth of more than 2,000 metres) from the Labrador Basin (depth of 2,000-3,500 metres and more). The plateau-like character of the top surface of the Baffin-Britain Sill and the relatively weak dissection of the adjoining shelf areas suggests that the shelf areas are underwater extensions of the Palaeogene plateau basalt cover. Preliminary data on the coarse material from the sea bottom sediments indicate that under the basalts and sedimentary mantle in the area of Faeroe Islands and their adjacent sea floor (Faeroe-Iceland and Y. Thomson Sills, South Jan Mayen Plateau, Rokoll Shoals, etc.), there are remnant blocks of the Eria platform, the Precambrian basement which outcrops in the Hebrides and northwest Scotland.

A poorly developed sill separates the Norway and Lofoten Basins. It lies subparallel with the Baffin-Britain Sill, and is marked by plateau-like underwater uplifts traced from the Norway avantshelf to Jan Mayen Island.

6. Abyssal zone of the Norway-Greenland Basin: Scandic

The main structural element of the abyssal zone of the Norway-Greenland Basin is the system of underwater ridges, or "volcanoria", named the Icelandic, Mon, and Knipovich Ridges. They are the natural continuation of the Mid-Atlantic Ridge northward from Iceland and form a zone of underwater volcanoes, rift fractures, epicentres of shallow-focus earthquakes, etc. (Gakkel, 1960; Heezen and Ewing, 1961; Demenitskaya et al., 1962, 1964; Atlasov et al., 1964b).

According to Litvin (1962, 1964), the Icelandic and Mon Ridges consist of many underwater mountains with cone-like, crater-like, and flat-topped crests separated by narrow winding depressions and troughs. These data, considered with the huge above-water volcano, Berenberg (2,250 metres above sea-level) on Jan Mayen Island at the junction of the two ridges, prove the volcanic origin of the relief of both ridges. This conclusion has been confirmed by the bedrock material collected from the submarine ridges by Litvin, Avilov, Dibner, and other scientists and originally investigated by L. Anykeyeva. Among other components of the material, there predominates palagonite basalt and andesite, dolerite, the unusual tuffite named "tephra", and other volcanic rocks typical of the Pliocene-Pleistocene palagonite formation of the Icelandic Central Graben. Heezen and Ewing (1961) identified the graben with the "rift valley" of the Mid-Atlantic Ridge, but these structures have very different sizes. The rift valleys or, better, the rift fractures, have now also been found in the Norway-Greenland volcanoria by Litvin (1964) and Dibner et al. (1965), where they form a linear system of en echelon elongate canyons with a relief of 1,500 metres, a width of 30-40 metres, and a length of up to several hundred kilometres.

The equivalent of these canyons in the Central Graben may be the above-mentioned eldja, which are thus embryonic rift fractures. The Central Graben itself is a result of further morphostructural development of the earlier formed volcanorium in which the volcanic rocks were erupted.

The geomorphological and seismic data also confirm the volcanic origin of the relief of the Knipovich Ridge (or volcanorium) (Dibner et al., 1965) as established by Gakkel (1959) and Litvin (1962) from data of the "Ob" and PINRO expeditions.

It should be noted that within the Norway-Greenland volcanoria there occur some extremely old structural elements. In the northern part of the Icelandic Ridge (lat. 70°N) and in the Louise Boyd oceanic bank (Mon Ridge), Litvin dredged phyllitic and quartz-mica slates and even granitic gneisses which are conditionally correlated with the Riphean rocks of the Norway-Greenland system of Caledonides. These ancient rocks seem to be of agglomeratic origin, being connected with some volcanic necks and are filled with material carried up from the metamorphic basement. The old siliceous formations of the volcanorium basement may have caused, by contamination of normal basalt, the more acid nature of the effusive rocks which compose the volcanorium near Jan Mayen Island, since Berenberg volcano is composed mainly of trachybasalt (Nickolls, 1955; Carstens, 1961).

The volcanic "superstructure" resting on the Caledonian-folded basement may probably be found on West Spitsbergen, where the volcanic embryos, related to the upper stage of the mid-oceanic ridge, are represented by two late Holocene volcanic cones in the Bøkfiord area (Orvin, 1940; Krasilschikov, 1964).

The morphostructure of the mid-oceanic ridge of the Norway-Greenland Basin, at least near Jan Mayen Island, is sharply disturbed by a regional thrust fault; faults of this kind are very typical of the Mid-Atlantic Ridge. On such a fault, the southern end of the Mon volcanorium has been shifted 150 kilometres eastward in relation to the northern end of the Icelandic volcanorium.

The ridge-system of the Icelandic, Mon, and Knipovich volcanoria, plus the South Jan Mayen Plateau and the Norway-Jan Mayen Sill, divide Scandic into several ocean deeps (Litvin, 1964). They are the Greenland deep (depths up to 3,800 metres and more), the Norway deep (up to 3,600 metres), and the Lofoten deep (2,400-3,200 metres). The deepest parts are located east of the Greenland-Jan Mayen morphodisjunction (Fig. 1). West of the morphodisjunction are located the southwestern and most shallow part of the Greenland deep, and the North Iceland deep (1,500-2,200 metres).

In all the deeps, except the Lofoten deep, some submarine volcanoes have been found with a relief of 500-2,000 metres (Litvin, 1962, 1964). In the Norway deep, they actually form a half-buried volcanorium which extends northeast from Iceland and resembles the transverse branches of the Mid-Atlantic Ridge. This volcanorium[1] is thought to be the continuation of the Reykjanes Ridge. The Reykjanes Ridge and PINRO volcanorium are structurally related by a northeast-trending zone of deep fractures which dissect Iceland.

The general morphostructural position of the Norway-Greenland deeps suggests that these depressions have been formed on an ancient cratogene massif located between branches of Caledonian fold-belts. The bottoms of the modern ocean deeps are underlain by a crust 7 to 10 kilometres thick and even thinner east of the Greenland-Jan Mayen morphodisjunction, and consist of an irregular cover of bottom sediments underlain by Recent lavas equivalent to the palagonite formation.

The oceanic "basalt" layer underlies the Recent lavas, and the Palaeogene-Miocene plateau basalts are probably relics of the cratogene cover.

STRUCTURE OF THE EARTH'S CRUST

Preliminary information about the crustal structure of the Atlantic Ocean was based on the observation of seismic waves from earthquakes. Results of analysis of Rayleigh and Love wave dispersion through oceanic regions have shown that the Atlantic Basin has the same general crustal structure as some other oceans. Special seismic investigations of the earth's crust of the North Atlantic have been carried out mainly along the European and American coasts, while the regions of the Central and North Atlantic remain less explored.

Because of its importance, the problem of the crustal structure of the North Atlantic attracts the attention of such geophysicists as M. Ewing, J. Ewing, Tryggvason, Båth, Rutten, Bodvarsson, and others, who

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[1]We propose the name "PINRO volcanorium" in honour of the Institute PINRO (Murmansk), the collaborators of which successfully investigated the bathymetry of the region.

have been conducting seismic investigations of that region for many years. Great advances have been made by the Soviet investigators, Demenitskaya and Korjakin, who used gravity and bathymetric data to describe its regional characteristics.

A standard crustal section for the Norway Sea and the North-east Atlantic has been obtained from seismic refraction studies in these regions. The section consists of an upper layer (0.5-1.0 kilometres thick) with a seismic velocity of 4.5-5.5 km/sec, and a lower, oceanic layer (4.0-6.0 kilometres thick) with a velocity of 6.5 km/sec. The oceanic layer is underlain by the upper mantle with a velocity of 8.0 km/sec. The crust appears to be typical of the oceanic type.

The results obtained by Ewing and Ewing (1959) for the Norway-Greenland Basin are similar to those for the Mid-Atlantic Ridge. This fact, considered with the continuity of the seismically active belt, suggests that the Mid-Atlantic Ridge continues across Scandic into the Arctic Basin. However, it is not surprising that the crustal section for this region is quite different from that found in regions of deeper water. Ewing and Ewing point out that the area has relatively constant water depth and yet is characterized by wide ranges in travel-times for the deep layers, probably indicating inhomogeneous structures. Beneath the sediments with normal velocities of 1.7 to 2.0 km/sec, a 3.6 km/sec layer has been observed which reasonably corresponds to the 3.7 km/sec palagonite formation of Iceland. The underlying layer has quite variable velocity and thickness: the velocity changes from 4.96 to 5.37 km/sec and the thickness from 2.5 to 3.0 kilometres. This layer, in turn, is underlain by a layer at a relatively constant depth (7 ± 0.7 kilometres below sea-level) with a velocity ranging from 6.07 to 8.04 km/sec.

The crustal structure of the North Atlantic as a whole can be obtained only by using Demenitskaya's or Woollard's method of "averaged curves". Although all the available seismic data have been used, a regional pattern can be determined only by integrating the bathymetric and gravity data. In 1964, such a calculation was made by Canadian scientists for various regions of Canada. Using gravity data, they calculated by Tsuboi's computational method the increase of relief of the M surface at a point where the depth to the Moho discontinuity had been estimated by seismic methods.

The map thus constructed (Fig. 2) shows the principal features of crustal thickness.

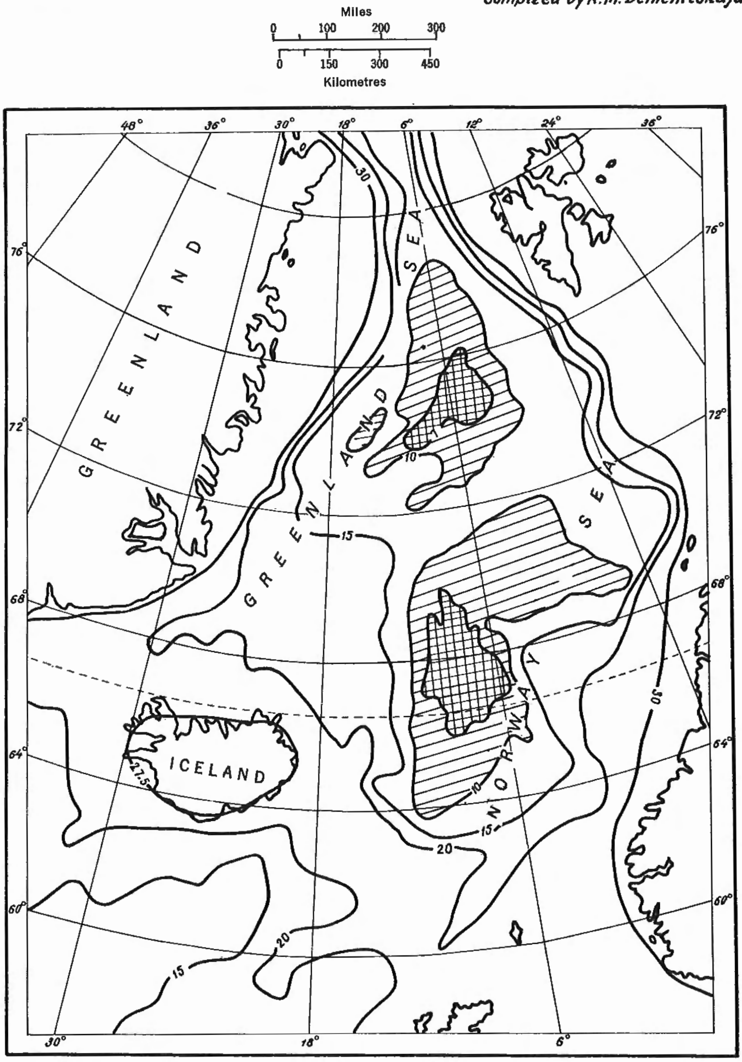
Within the depression in the earth's surface occupied by the northern Atlantic water areas, the crust represented by both transitional and oceanic type is thought to be predominantly transitional. The bordering continents are areas of continental crust.

СХЕМАТИЧЕСКАЯ КАРТА
ТОЛЩИНЫ ЗЕМНОЙ КОРЫ
СЕВЕРНЫХ РАЙОНОВ АТЛАНТИЧЕСКОГО ОКЕАНА

Составила Р. М. Деменицкая

SKETCH-MAP
of the CRUSTAL THICKNESS
of the NORTHERN ATLANTIC REGIONS

Compiled by R. M. Dementskaja



—20— *Изолинии равных мощностей земной коры.*
Contours of equal crustal thickness

Область развития типично океанической земной коры, толщина 7-10
Areas of development of typical oceanic crustal thickness, 7 - 10 km

Область развития типично океанической земной коры, толщина менее 7 км.
Areas of development of typical oceanic crustal thickness, less than 7 km

Figure 2. Sketch-map of the crustal thickness of the northern Atlantic regions.

The characteristic features of Scandic are a relatively slight variation of crustal thickness and an absence of clear trends of distinct structures, while the Central and South Atlantic are characterized by variations of crustal thickness and the presence of distinct structures. Scandic seems to have the most interesting oceanic crust. Noteworthy are the relative simplicity of the outlines of these regions, bordered on the west by the Greenland-Jan Mayen morphodisjunction and on the east by the rather complex morphodisjunctions controlled by the configuration of the Norway avant-shelf. It must also be noted that the western edge of this zone, near the Mon volcanorium, extends, with but a short interruption, for about 1,500 kilometres.

Seismic studies indicate the absence of a recognizable discontinuity between a "normal" mantle with a velocity of 8.1 km/sec and an "anomalous" mantle with a velocity of 7.5 km/sec, a characteristic that is another peculiarity of the crustal structure of this region. As would be expected from Cook's hypothesis (1962) of "the mantle-crust mix", the areas with a thin, typical oceanic crust must be underlain by a "normal" mantle, and, hence, it may be supposed that the areas with an "anomalous" mantle are localized in the region of the mid-oceanic ridge. But, Demenitskaya, Zalesova, and Gorodnitskaya (in press) did not find such a correlation. McConnell and McTaggart-Cowan's (1963) and Soviet seismic data together suggest doubt as to whether the 7.5 km/sec layer usually corresponds to structures of rift origin. This seismic layer occurs not only under the rift systems but also under other, tectonically different parts of the world, as shown on the map of its distribution, based on extensive seismic observations. Therefore, Cook's model of the earth's crust for mid-oceanic ridges and their rift analogues on land seems to require more study.

The discussion about the crustal structure of the North Atlantic may be concluded with the interesting observation that there exists a geotectonic linear feature trending southeast, as shown on a map of geoidal heights compiled by Kaula (1961) using recent satellite data. In his recent work, Van Bemmelen (1965) postulated a boundary between different phases of the Atlantic mega-undation about along this line. This trend may also be seen on Bauer's (1899) magnetic contour map. Located along this linear feature (Fig. 3) are the axes of Baffin Basin and Davis Strait, the east-trending offset of the Mid-Atlantic Ridge at latitude 50°N, a series of subparallel faults, the northwest trend of the continental slope bounding Bay of Biscay, the deepest parts of the Mediterranean Sea, the Red Sea, and the Mid-Indian Ridge. On the northwest end of the feature in the deep part of Davis Strait, a magnetic anomaly characteristic of a rift has been found by American geophysicists (Heirtzler and Le Pichon, 1965). The anomaly is believed to be associated with the Mid-Labrador Ridge. In 1964, Soviet seismic investigations confirmed the existence of the Laptev Sea in the

ПРЕДПОЛАГАЕМОЕ ПОЛОЖЕНИЕ СРЕДИЗЕМНОМОРСКО-ГРЕНЛАНДСКОЙ ВЕТВИ МИРОВОЙ РИФТОВОЙ СИСТЕМЫ

Составила Р.М.Деменицкая

SUPPOSED LOCATION of the MEDITERRANEAN-GREENLAND BRANCH of the WORLD RIFT SYSTEM

Compiled by R. M. Demenitskaja

1965г.

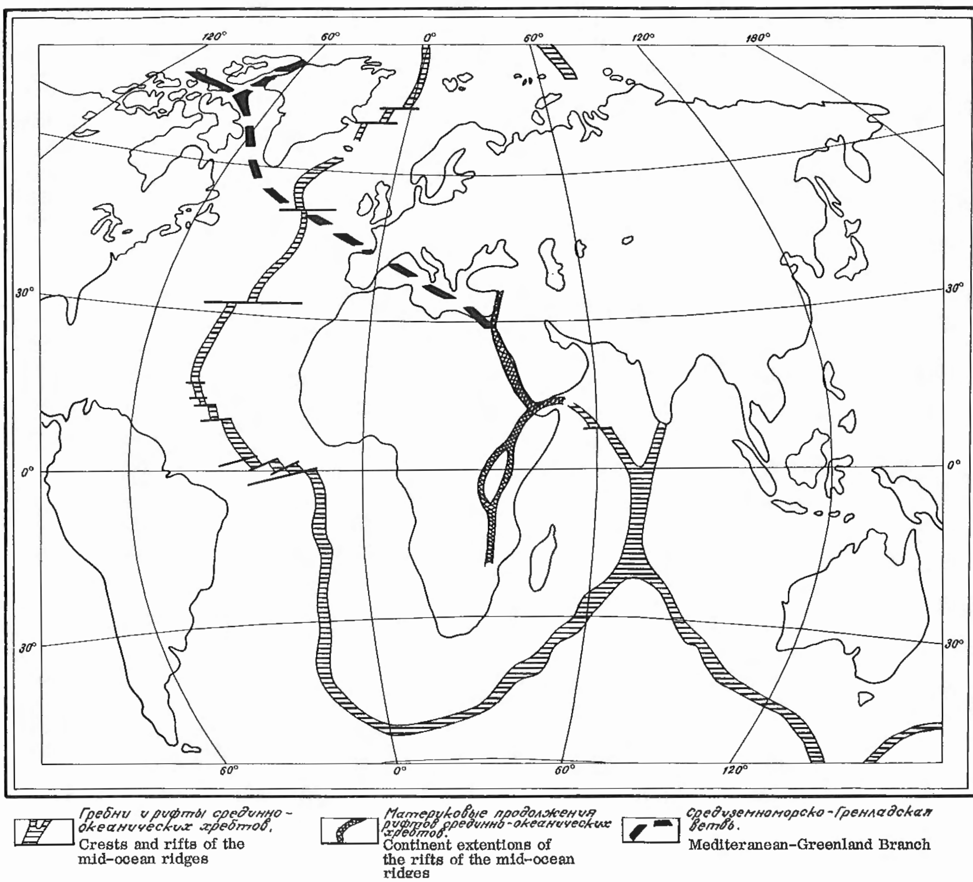


Figure 3. Supposed location of the Mediterranean-Greenland branch of the world rift system.

southern part of the Nansen-Amundsen Basin. In this latter area, the Mid-Arctic Ridge is no longer reflected in bottom topography but can still be detected by magnetic surveys.

The above-mentioned facts suggest that another world-wide lineament marks the creation of a mid-oceanic rift system. It represents the northwestern continuation of the western mid-Indian branch. Activity in the northwest part is indicated to some degree by earthquakes beneath Baffin Bay.

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THE GEOLOGY OF THE WESTERN APPROACHES OF THE ENGLISH CHANNEL V. THE CONTINENTAL MARGIN AND SHELF UNDER THE SOUTH CELTIC SEA[1,3]

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Abstract

Upper Cretaceous and Tertiary deposits, mainly of shallow-water origin, form a broad, complex synclinal structure which trends east-northeast, closes eastwards, and occupies most of the central part of the Western Approaches of the English Channel west of longitude 3°W. Important anticlines and synclines occur throughout this structural sedimentary trough as well as many minor flexures shown in seismic reflection profiles.

Stratigraphic evidence indicates that, from Eocene to Plio-Pleistocene times, a gulf or channel extended eastwards towards the English Channel at least as far as longitude 5°W. Seismic refraction and magnetometer results by the Cambridge group also indicate a complex trough which was traced to the shelf-break and which corresponds reasonably well with the trough deduced stratigraphically.

West of a line trending approximately northwest from a point at lat. 48°30'N, long. 6°W, cored samples of solid rock have not been collected owing to the increased thickness of superficial deposits. Seismic reflection profiles in this region show that the stratified rocks are gently flexed almost as far as the shelf-break, but the ages of the rocks involved in this folding for the most part remain unknown.

Five crossings of the edge of the shelf all provide the same basic pattern, viz., strata gently inclined towards the continental slope by which they are sharply truncated. On four crossings of the extensions of the

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[1]Parts I and II in Phil. Trans. B245, 267-290 (1962) and B248, 315-351 (1965); parts III and IV in Colston Papers. 17, 239-264 (1965) and 17, 287-301 (1965).

[2]Speaker. Professor Whittard died in March, 1966.

[3]Woods Hole Oceanographic Institution Contribution No. 1828.

north and south limbs of the main syncline in the English Channel, the most prominent and deepest reflector lies about 1,200 to 1,600 feet below sea-level; on the fifth, near the axis of the syncline, a similar reflector is found at about 4,000 feet.

On the continental slope at approximately longitude 10°W and at a depth of about 250 fathoms, an upper series of more steeply inclined strata wedges out against a lower series, as if the upper series has prograded seawards over a surface formed by the lower series. A reasonable inference, founded on dredged samples, is that the lower series comprises Miocene and older chalks, and the upper series Plio-Pleistocene deposits. It is possible that homologous structures between longitudes 10°W and 6°40'W have the same significance, thus outlining the pre-Plio-Pleistocene surface. Near the intersection of the synclinal axis with the continental slope, this surface lies 4,000 feet below sea-level.

It is suggested that, subsequent to the formation of the continental margin, faulting has progressively fashioned and remodelled the slope up to near-Recent times and, furthermore, that the continental slope is receding faster than it is built out by modern sedimentation.

INTRODUCTION

The modern era for the study of the structure of the sea-bed and underlying rocks of the Western Approaches of the English Channel started about 15 years ago, prior to which pioneer investigations had been carried out using gravity (Vening Meinesz, 1934; 1941) and seismic (Bullard and Gaskell, 1941) techniques, several of which had been devised in the 1930's. Further gravity surveys were made from a submarine in 1964 by Browne and Cooper (1950), but it was not until the 1950's that seismic work gained impetus (Hill and King, 1953; Hill and Laughton, 1954; Day et al., 1956). In recent years, magnetic measurements at sea have contributed another approach to geophysical studies (Allan, 1961). These reconnaissance surveys were made mainly by the Cambridge group. Latterly, this same group has concentrated on some specific problems, such as: 1) a magnetometer survey of the Western Approaches as far as the shelf-break where, however, most of the magnetic anomalies are presumably due to the characteristics of the basement suite of rocks rather than to any special properties of the overlying sediments (Hill and Vine, 1965); and 2) a seismic survey along lines subparallel with and close to the shelf-break which was completed using R.S.S. DISCOVERY II and R.V. CHAIN (Bunce et al., 1964).

The geology of the sea-bed west of longitude 3°W has been illustrated in two maps (Whittard, 1962; Curry et al., 1962) and a third which extends the mapped area farther westwards accompanies the present paper

(Fig. 1). Detailed stratigraphic accounts have been supplied by the Bristol group of some of the stratigraphic subdivisions of the continental shelf (Curry, Hersey et al., 1965; Curry, Murray, and Whittard, 1965; Smith et al., 1965) and of a few samples of Tertiary chalks from the upper parts of the continental slope (Curry et al., 1962).

Traverses by sparker and(or) boomer have greatly aided the elucidation of the geology of the Western Approaches and the bedded rocks were "sampled" using these methods south of Looe in Cornwall (Curry, Hersey et al., 1965); in 1964 Hersey recorded on R.V. CHAIN four traverses across the western part of the continental shelf and five (one in 1960) across the upper reaches of the continental slope. The present contribution deals mainly with these latter investigations.

APPARATUS AND METHODS

The seismic reflection data were obtained by means of a continuous seismic profiler basically similar to those described by Hersey (1963) and Curry, Hersey et al. (1965). The sound source in this work was a sparker which derived its energy from a storage capacitor consisting of four 500-microfarad condensers. These capacitors are especially designed for use at high potential and are charged to 5,000 to 8,000 volts for each actuation of the sparker. (Different maximum charges in this range were employed in different parts of the work but they have no effect on the travel-time measurements.) During the early hours of the recordings over the Western Approaches, the full bank of 2,000 microfarads was used, but a single 500-microfarad unit was utilized during the majority of the work because a much shorter sound pulse was generated and higher resolution resulted. In shallow water with several bottom-surface multiple echoes, the less energetic pulse seemed to penetrate just as successfully as the loudest that could be generated.

The receiver consisted of an array of five hydrophones (the Eel of Alpine Geophysical Associates) towed in a single line astern at a distance of 200 feet. The sparker electrode was towed 20 to 40 feet astern so that the separation of source and receiver was about 180 feet. This separation of source and receiver must be taken into account for dimensional measurements of reflecting layers in water as shallow as the Western Approaches. Curry, Hersey et al. (1965, pp. 323-4) have discussed the sort of computation which must be made where the source-receiver separation is not negligible compared with the depth of the water.

The output of the Eel was fed through a flat amplifier to one channel of a four-channel Crown model 800 magnetic tape-recorder. Another output of the amplifier was filtered through two different band-pass filters in the region 30 to 300 cycles per second for recording on two Precision Graphic Recorders (PGR) (Knott and Witzell, 1960). Typical settings of these filters were 37.5-75 cycles per second. Examples of the recordings so made are reproduced in Figures 2-10. They were produced by replaying the magnetic tapes to a PGR, also through a band-pass filter. These latter recordings clarified features that were obscure in the original PGR records, but the tape recordings are intended for experimentation with methods of signal processing. For both purposes the original time-base is recorded on another channel of the tape-recorder. A third channel is used for voice announcements and the fourth for timing indices.

STRATIGRAPHY OF THE MAPPED AREA

Approximately 15,000 square miles of the Western Approaches west of longitude 3°W have been sampled with corers and dredges.

The Mesozoic and Tertiary strata which occupy most of the floor of the Western Approaches west of longitude 3°W (Fig. 1), are flanked to the north by Newer Palaeozoic slates in which have been emplaced Variscan granitic masses, such as those of the Scilly Isles and Haig Fras (Smith et al., 1965), and to the south by the highly disturbed Variscan metamorphic and sedimentary rocks, and associated plutonic types, of Brittany. One small granitic mass with affinities with Brittany, about 20 miles north of Roscoff, is covered to the north by Cretaceous and to the south by Tertiary rocks, and in the vicinity of the Eddystone Lighthouse, Phillips (1964) has recently described inliers of schists and gneisses which protrude through the cover of New Red Sandstone.

The New Red Sandstone shows its broadest outcrop of breccias, sandstones, arkoses, and shales south of the coast between Falmouth and Start Point, and wedges out westwards against the Palaeozoic rocks which extend southwestwards as a broad ridge from the Cornubian Peninsula. The continuation of this Palaeozoic region is terminated on the sea-bed by the unconformably overlying Upper Cretaceous beds which lap round it; on the northwestern side the New Red Sandstone reappears and presumably continues northeastwards, although this region has not yet been cored, to connect with similar strata in the Bristol Channel.

Jurassic rocks appear in two inliers. The western occurrence has been described elsewhere and consists of Lower Liassic shales with limestones (Curry, Hersey et al., 1965, pp. 328-330). The second, eastern inlier forms an irregularly-shaped outcrop and, although the analysis is not completed, additional Liassic rocks occur there but are associated with black shales probably of Rhaetic age and of a similar facies to that found on the mainland.

The Upper Cretaceous and Tertiary deposits form a broad, complex, synclinal structure which trends east-northeast, closes eastwards, and occupies most of the central part of the English Channel and Western Approaches. An examination of the map (Fig. 1) shows that important anticlines and synclines are distributed throughout this structural trough, in addition to the many minor flexures that have been detected in the sparker traverses.

The Upper Cretaceous shows the familiar facies of the English Chalk, including in some places near its base an Orbitolina-rich glauconitic, calcareous sandstone probably of Albian age. However, the Upper Cretaceous includes Maestrichtian rocks which are younger than any chalk known from the English mainland and resting upon them, with apparent conformity, are additional chalks with Danian microfaunas. Danian has been identified in two areas, viz., on the northern side of the Palaeogene of the structural trough approximately between longitudes 4° and 5°W, and on the northern side of the Palaeogene adjacent to the Variscan rocks of Brittany at approximately longitude 3 1/2°-4°W. There are other examples of chalky rock which await study and doubtless other locations of Danian sediments will be found.

The top of the Cretaceous-Danian sequence is a pronounced unconformity, and the overlying Eocene and possibly Lower Oligocene rocks are mainly coarse-grained limestones deposited in warm, shallow seas. According to Mr. D. Curry, the facies of these coarse-grained beds may be matched in beds of similar age which occur in the northern part of the Aquitaine Basin of southwest France.

The central region of the main syncline is occupied by the Globigerina Silts, correlated with the Miocene and predominantly of Aquitanian and Vindobonian ages (Curry, Murray, and Whittard, 1965, pp. 240-250). Dr. Murray has also recognized a foraminiferal assemblage which suggest that the youngest strata, represented by grey clay, are Plio-Pleistocene (Curry, Murray, and Whittard, 1965, p. 253).

SEISMIC REFLECTION TRAVERSES A-C, D-F, AND G-I

Traverse A-C

An account of the A-C traverse made in 1960 has been published (Curry, Hersey et al., 1965). This was the first time that low

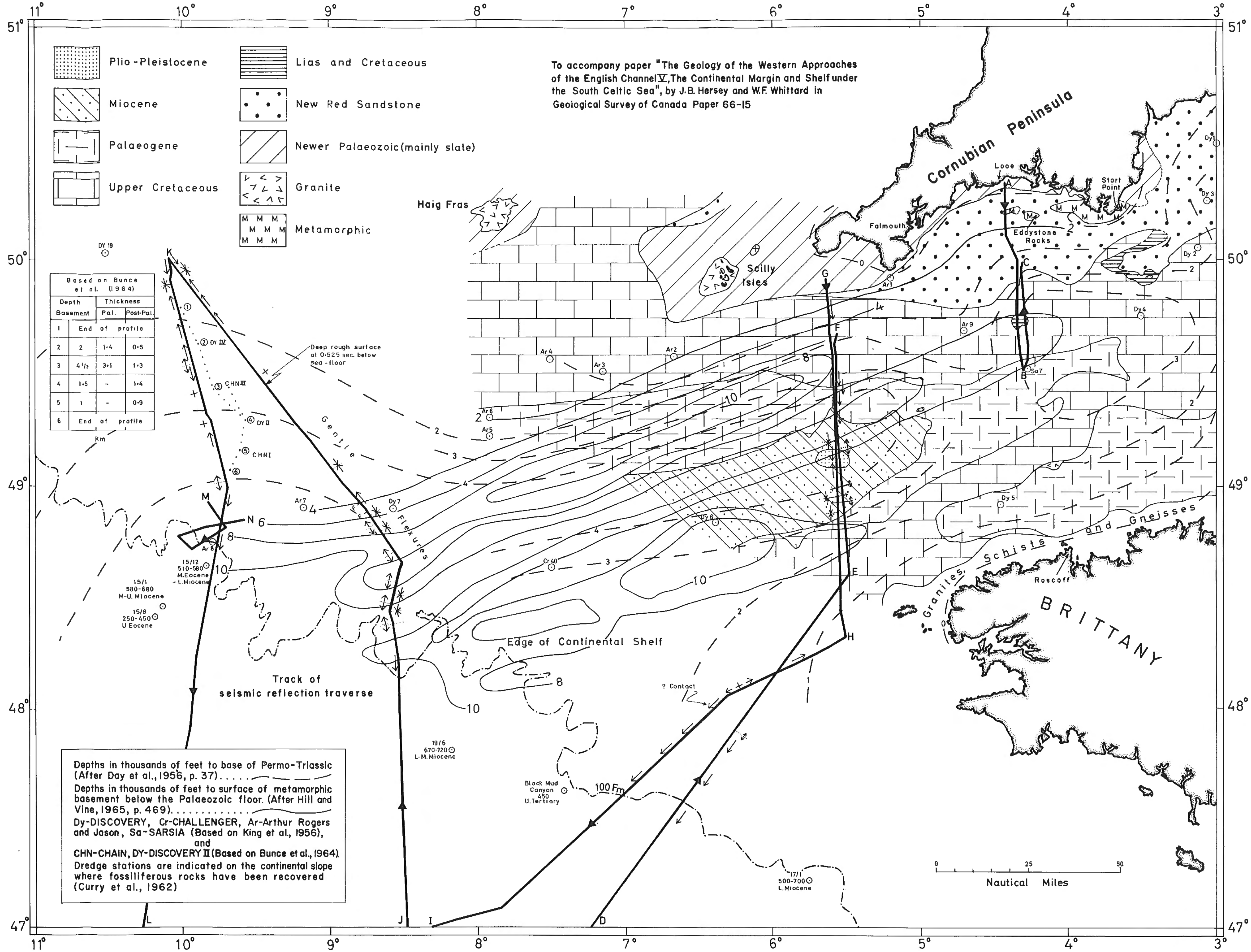

Figure 1. Western Approaches to the English Channel, showing the five sparker-boomer traverses A-C, D-F, G-I, J-L, and M-N. Details determined from the records are added to traverses, D-I and J-L

frequency techniques had been applied to the rocks of the Western Approaches and, fortuitously, nearly optimum conditions were met south of Looe, Cornwall, for this type of investigation. The sediment generally forms no more than a thin veneer, a few inches thick, or, in some places, the sea-bed there may have been swept clean of superficial sediment. Furthermore, the wide variety of rock that was sampled by seismic reflection mehtods included many good reflectors. Apart from delineating the geological arrangement to a depth of about 400 feet (energy-source of 1,000 joules) below the sea-bed, the records proved invaluable in checking and correcting the geological lines laid down on the map as constructed from cored samples.

West of a line trending approximately northwestwards from a point lat. 48 1/2 °N, long. 6 °W, superficial sediment is much thicker than to the east, and cored samples of rock are generally unobtainable with the Stetson-Hill corer. The purposes of the 1964 traverses were: 1) to try to carry the geological lines westwards beyond the confines of the geological map (Fig. 1) and under the blanket of recent sediments; 2) to correct the boundaries of the Globigerina Silts; 3) to determine whether the broad synclinal form of the central part of the Western Approaches was as simple as coring methods suggested it might be; 4) to seek igneous masses; and 5) to ascertain the geological structure at the shelf-break.

Traverses D-F and G-I

In making computations of thicknesses and dips from the records, it is first necessary to make an estimate of the speed of sound through the beds explored; the various estimates used in this paper are quoted at the relevant points. When the distance between the source and the receiver is of the same order of magnitude as the depth of water, the apparent depth of the reflector as calculated from a simple consideration of travel times will be greater than the true depth and relatively tedious computations are necessary to correct for this factor.

The present records have not been corrected according to this method because, firstly, computer time has not been available and, secondly, the maximum error which is likely to arise is about 10 per cent while the probable error in the cases studied is not likely to be over 3 per cent. As all the calculations are based on an estimate of the speed of sound in the floor, which may be in error by a factor of up to 20 per cent, the additional error due to failure to correct for the finite distance between source and receiver is here not considered to be significant. In more refined studies it will no doubt be necessary to ascertain the speed of sound through the floor by direct experiment and to correct any calculations based on this speed by means of the formulae set out in Curry, Hersey et al. (1965, pp. 323-324).

The courses which the ship followed were sufficiently close that the northern arms of traverses D-F and G-I are conveniently treated together.

Traverses E-F and G-H were chosen approximately along longitude 5 1/2 °W in order, first, to try to delimit the boundary of the Globigerina Silts and thus to correct where possible the published map (Curry, Murray, and Whittard, 1965, p. 241); and, secondly, to determine the internal structural pattern of the Globigerina Silts, because the evidence provided from 33 cores suggests that the structure in detail is more complex than that of a simple syncline. The locations of the cores were such as to allow the delineation on a map of straightforward stratigraphical successions if they existed. Successions could not be recognized, and there were good reasons to believe that there was repetition, probably by minor folding.

When the traverse A-C, south of Looe, was run in 1960 with a 1,000-joule sparker source, the seismic reflection profile over the New Red Sandstone was not clear because these rocks apparently contain few reflectors; nevertheless, some structures were detected (Curry, Hersey et al., 1965, Fig. 6 and 9a, Pl. XXVI). At the northern ends of traverses D-F and G-I, eastward runs over the New Red Sandstone, to and from the vicinity of the Eddystone Lighthouse (which are not included on our map), were made with the 100,000-joule sparker, but the records are extremely confused and reflecting surfaces are too few to determine the geological structure. Similar inconclusive and confused profiles were also obtained southwards from position G, where coring has established Newer Palaeozoic slates, succeeded to the south by a thin sequence of New Red Sandstone and then by Upper Cretaceous; not even the stratigraphic contacts were identified on this traverse. In fact, the first indications of southerly dips were recognized at latitude 49°45' on G-H (Fig. 2) in the Cretaceous, but convincing and definitive reflectors do not appear until the Cretaceous/Palaeogene unconformable contact is reached at latitude 49°42', south of which the structure in the central syncline of the Western Approaches is amply illustrated in both the profiles.

Both on the northern and southern flanks of the central syncline the positions of the unconformable contacts between Cretaceous/Palaeogene and Palaeogene/Miocene, as determined by corings, required only slight alteration, and in all cases the error lay within the limits laid down by contiguous core-stations. A few years ago, a small sample, less than a cubic inch, of grey clay recovered from a core-barrel was obtained towards the middle of the central syncline for which Dr. Murray has claimed a Plio-Pleistocene age for the foraminiferids (Curry, Murray, and Whittard, 1965, p. 253). Luckily, both seismic reflection profiles passed near the position where the sample was obtained, and there is clear evidence, particularly in traverse G-H (Fig. 3), of a shallow synclinal form in these Plio-Pleistocene

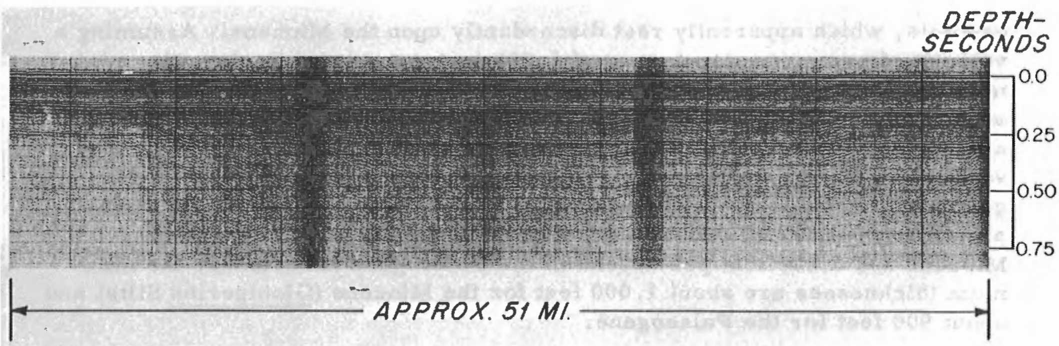

Figure 2. Seismic reflection profile between lat. 49°34'N, long. 5°35'W (left) and lat 48°43'N, long. 5°22.5'W (right) on traverse G-H.

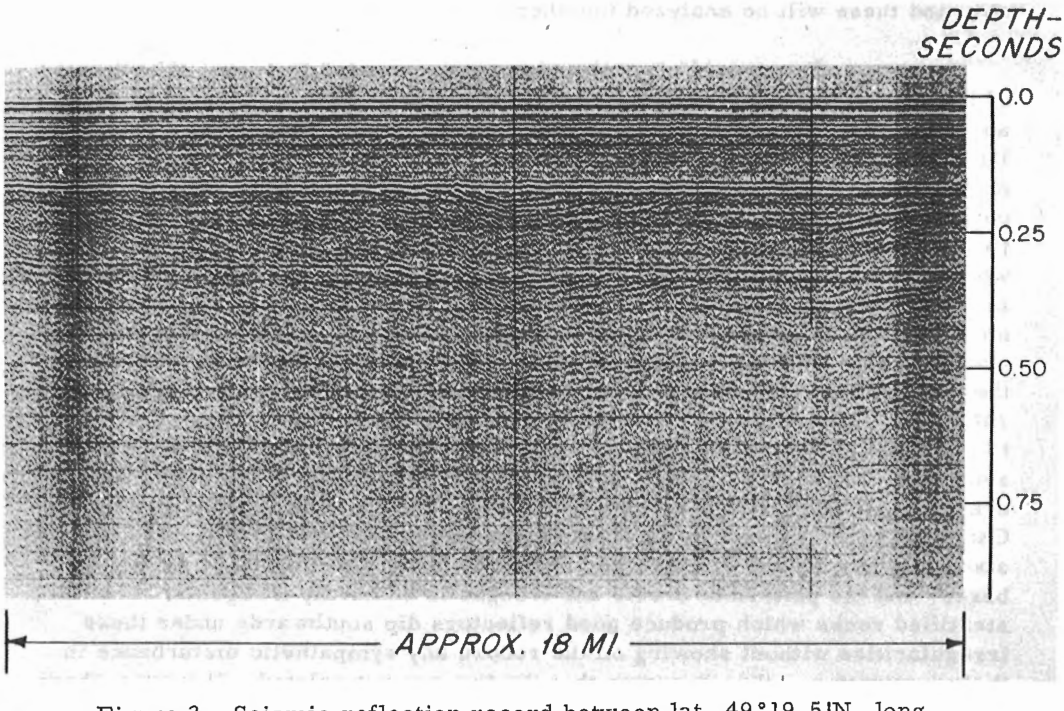

Figure 3. Seismic reflection record between lat. 49°19.5'N, long. 5°34'W (left) and lat. 49°01'N, long. 5°33.5'W (right) on traverse G-H.

deposits, which apparently rest discordantly upon the Miocene. Assuming a velocity of a compressional wave of 6,000 feet per second in clay, the minimum thickness of the Plio-Pleistocene is about 240 feet. The Miocene to the south of the outlier of Plio-Pleistocene (Fig. 1) shows two minor anticlines alternating with synclines which can be identified in both profiles, and the vertical distance between crest and trough is about 150 feet; to the north, a gentle monocline is developed (see Fig. 1). Allowing a velocity for compressional waves of 7,000 feet per second in the silts and clays of the Miocene and 8,000 feet per second in the Palaeogene limestones, the minimum thicknesses are about 1,000 feet for the Miocene (Globigerina Silts) and about 900 feet for the Palaeogene.

South of the central syncline, the records of both seismic profiles are disappointing and lack information of a geological kind; readable dips reappear on H-I at latitude 48°13' and on D-E at latitude 47°55' where, on the latter profile, southerly dips are associated with a feeble anticline and continue southerly to the shelf-break. The structure underlying the shelf-break has been recorded in seismic reflection profiles in five crossings by ship and these will be analyzed together.

Traverse H-I produced some unexpected features. Northeast of latitude 48°03', an exceedingly gentle structural arch, calculated to be about 500 feet high, occurs over a distance of 20 nautical miles (Fig. 4). At latitude 48°03', a pronounced hump on the sea-bed is 125 feet high and 6 miles across, and has all the appearance on the echo-sounder record of being composed of resistant rock; this may be another granitic region, possibly partly obscured by Cretaceous or Tertiary rocks, situated about 60 miles west of the coast near Brest. In this region is seismic station Sa 12 (Day et al., 1956, Fig. 15) where the results were interpreted as indicating the absence of New Red Sandstone (layer B). South of this location, the seismic profiles show a series of good reflectors (Fig. 5) which are inclined towards the shelf-break. Adjacent to the "granitic" hump mentioned above, the reflectors appear to show a sedimentary contact; these beds might also belong to the same stratigraphic division as those to the north of the hump. Farther south additional irregularities in the sea-bed, both steeper and narrower, are probably not sand waves of the kind that have been described from La Chapelle Bank 18 miles to the west (Cartwright and Stride, 1958); the crests stand between 50 and 80 feet high, they are about 3,000 feet wide at their bases, and the pattern of crests and troughs is decidedly irregular. The stratified rocks which produce good reflectors dip southwards under these irregularities without showing on the record any sympathetic disturbance in their inclination – thus it seems that the two are not related. However, these strata which are good seismic reflectors are clearly overlain discordantly by more shallow-dipping rocks which, when projected northeastwards to intersect the sea-bed, terminate at, and include, the northeasternmost irregularities; it is with this series that the irregularities appear to be directly

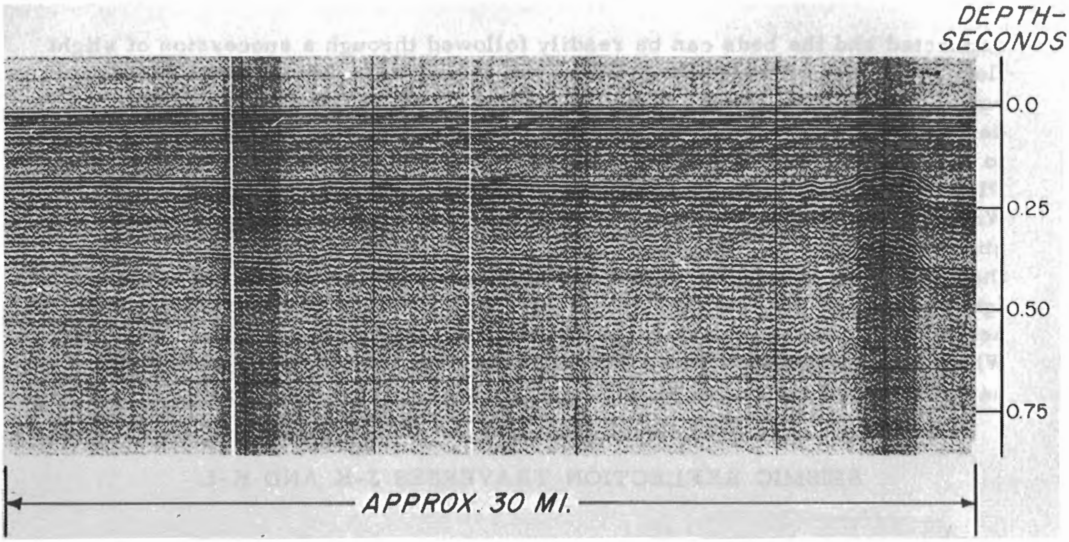

Figure 4. Seismic reflection profile between lat. 48°14.5'N, long. 5°45.5'W (left) and lat. 48°01'N, long. 6°23'W (right) on traverse H-I.

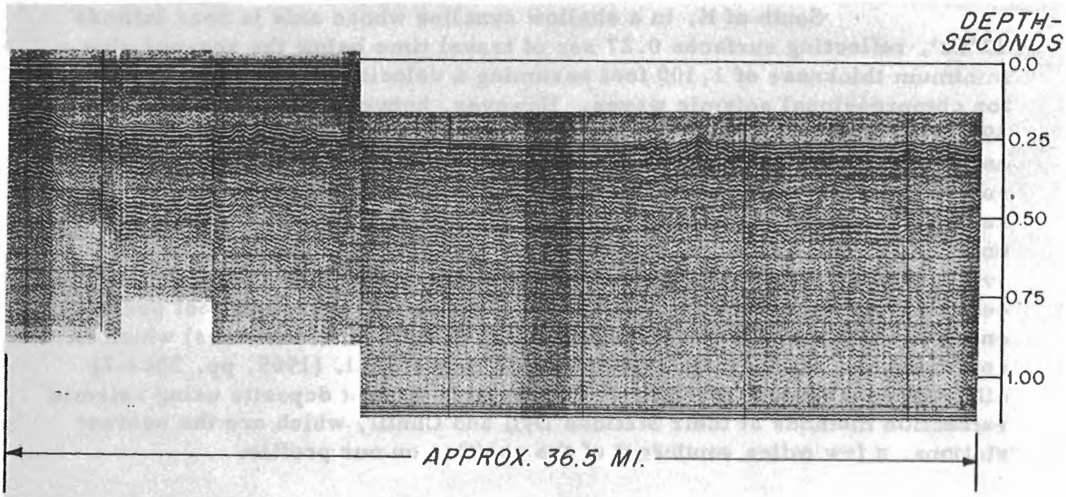

Figure 5. Seismic reflection profile between lat. 48°03.5'N, long. 6°18.5'W (left) and lat. 47°39'N, long. 6°56.5'W (right) on traverse H-I.

connected and the beds can be readily followed through a succession of slight flexures as far as the shelf-break. The enigma to solve is what are these rocks which produce the sea-bed irregularities with the characteristics described? The most ready answer, having regard to their position relative to the shelf-break, is that they could reasonably be expected to be Plio-Pleistocene, but our very scanty knowledge of rocks of this age in the Western Approaches suggests that they do not include rocks sufficiently durable and resistant to erosion such as could form the features on the sea-bed that have been recorded. Alternatively, they might be the loci of other igneous masses, but as they do not persist in depth to penetrate the bedded sequence of underlying stratified rocks this is an opinion difficult to uphold. When the opportunity arises, this part of the sea-bed must be extensively sampled by corers and dredges.

SEISMIC REFLECTION TRAVERSES J-K AND K-L

Traverse K-J

That part of traverse K-J north of the point where it turns south, trends about 30 degrees to the general direction of the shelf-break. No direct evidence of the stratigraphic age of any of the rocks which occur in this region is available.

South of K, in a shallow syncline whose axis is near latitude 49°50', reflecting surfaces 0.27 sec of travel time below the sea-bed give a minimum thickness of 1,100 feet assuming a velocity of 8,000 feet per second for compressional seismic waves. However, between latitudes 49°37' and 49°24' there are two humps on the sea-bed (Fig. 6), respectively about 150 and 120 feet high and 9 and 6 miles across, associated with a strong discordance between an upper northerly inclined series and a lower nearly horizontal series; the humps are not due to anticlinal flexures because the reflectors underlying them are uniformly dipping. Significantly, however, there is evidence of a "rough" surface (which does not correspond with multiple echoes) at 0.525 sec below the sea-bed. Again, allowing 8,000 feet per second, this rough surface is about 2,200 feet deep (0.67 kilometres) which is approximately one-half the thickness that Bunce et al. (1965, pp. 3861-2) allocated to what they assumed to be Permian-Recent deposits using seismic refraction methods at their Stations DyII and ChnIII, which are the nearest stations, a few miles southwest of the position on our profile.

At about latitude 49°14', the northern limb of a very gentle syncline can be identified, with an axis at about latitude 49°05' (Fig. 7); this structure can readily be followed southwards by means of a closely-set group of five or six reflectors which cross two well-defined faults, with a down-faulted block between them, and which then pass into a series of anticlines

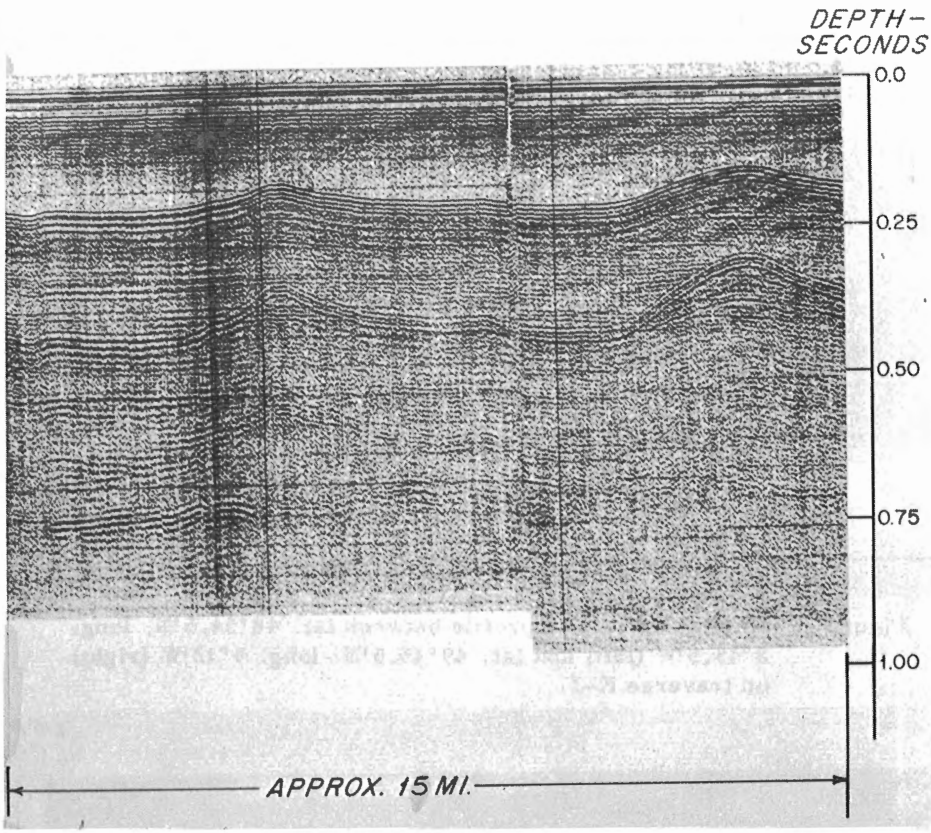

Figure 6. Seismic reflection profile between lat. 49°22'N, long. 9°20'W (left) and lat. 49°36'N, long. 9°36'W (right) on traverse K-J.

and synclines (Fig. 8). Above these good reflectors there again appear to be more disturbed, ruckled beds which suggest another stratigraphic series distinct from that which underlies them. The upper series could reasonably represent the Globigerina Silts because it occurs along the continuation of the mapped outcrop of these Miocene rocks to the east, and the lower series carrying the good reflectors may be Palaeogene; similarly, the discordance mentioned above, which is present between latitudes 49°37' and 49°24', may mask the unconformity between the Miocene and Palaeogene. These suggestions regarding the ages of the strata involved can, however, only be surmise. (There are three more humps of varying shapes on the sea-bed which attain heights of about 100, 75, and 75 feet widths along the traverse >1, <1, and 3 1/2 miles, respectively.)

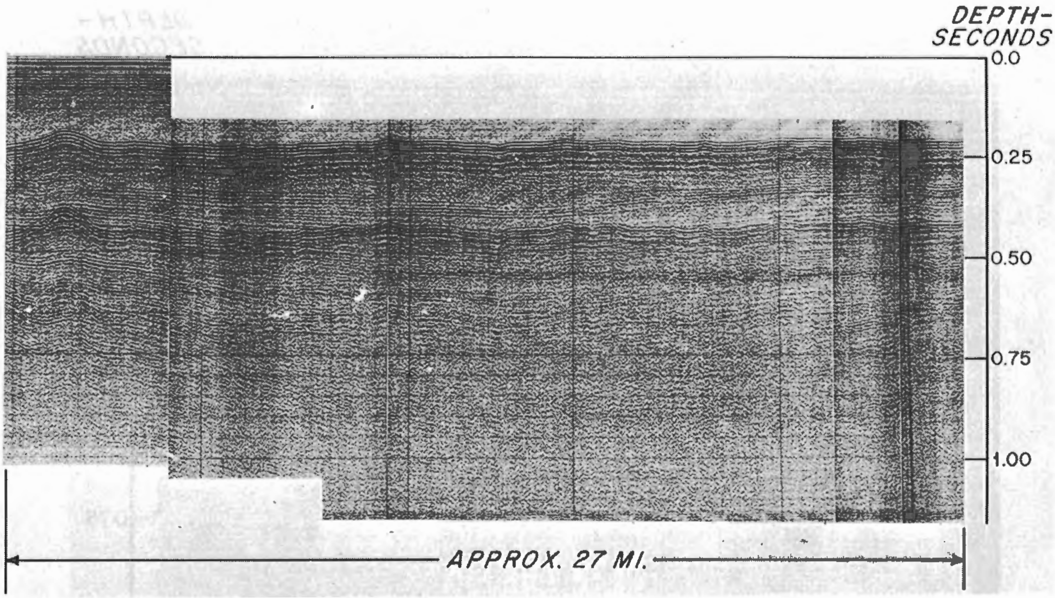

Figure 7. Seismic reflection profile between lat. 48°54.5'N, long. 8°45.5'W (left) and lat. 49°15.5'N, long. 9°12'W (right) on traverse K-J.

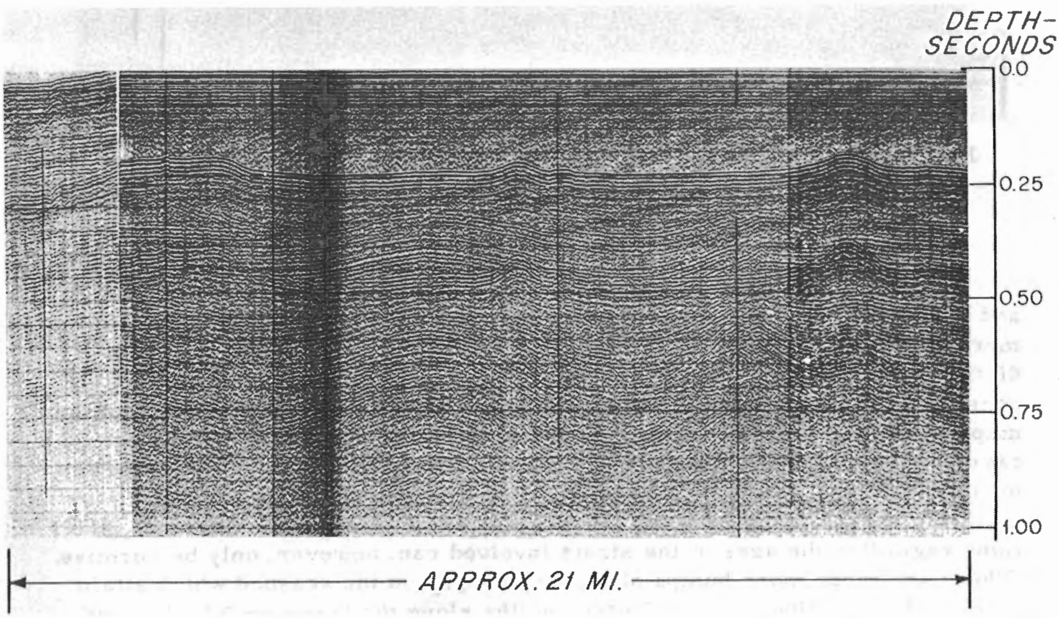

Figure 8. Seismic reflection profile between lat. 48°42'N, long. 8°33'W (left) and lat. 48°58.5'N, long. 8°51'W (right) on traverse K-J.

Traverse K-L

Traverse K-L detected additional structural flexures, but there is insufficient evidence, and traverses K-L and K-J are too far apart, to allow the folds to be cross-connected, except for the syncline immediately south of point K.

South of K a shallow southerly dip leads to the axis of a syncline at latitude 49°45'; here there are relatively deep reflectors overprinted upon, and extending below, the series of second echoes, and the reflectors are at least 0.42 sec below the sea-bed which, again assuming 8,000 feet per second, indicates a sedimentary depth of about 1,700 feet. Farther south, the syncline is replaced by an anticlinal form of which it is difficult to resolve the structure; at latitude 49°33', on the northern side of this anticline, a discordance between reflectors shows a wedging out northwards of a lower minor synclinal structure against truncating and simply dipping beds of the anticlinal limb, but we offer no solution of the stratigraphy of this part of the traverse. Northerly dips prevail until an anticlinal axis is reached at latitude 49°02', and then southerly dips are apparent southwards to where they are truncated by the continental slope.

STRUCTURE UNDERLYING THE SHELF-BREAK

Seismic reflection profiles were obtained from R.V. CHAIN in five crossings of the shelf-break, one in 1960 and the remainder in 1964.

In the early 1940's, the first refraction seismic results (Bullard and Gaskell, 1941) suggested that the continental shelf was built outwards like foreset deposits, and the continental slope, down to a depth of about 15,000 feet, "must represent merely the edge of a pile of sediments growing seaward"; and the increased velocity detected in the lower components of the sedimentary accumulation was explained as a result of consolidation. Shepard (1940, p. 432) critized this explanation for no other reason than that samples of Cretaceous rock had been dredged from a depth "of a few hundred fathoms near the shelf edge".

Hill and Laughton (1954, Fig. 12) composed a vertical section along their stations Dy4-Dy16, redrew Bullard's section, and divided the sedimentary material into unconsolidated, semiconsolidated (which they were inclined to correlate with New Red Sandstone), and consolidated; the latter rested on basement rock, the surface of which becomes progressively deeper southwestwards beneath the continental shelf to beyond the shelf-break. On Hill and Laughton's profile, the vertical thickness of unconsolidated material directly under the shelf-break is about 1.2 kilometres (666 fathoms), a figure which does not agree with depths at which chalky sedimentary rock has been dredged from the continental slope (Curry et al., 1962; Black, 1962). Although navigational errors in the location of the dredged samples, which Curry et al. (1962) described, can be expected, the specimens all originated from depths greater than 100 but less than 700 fathoms. Furthermore, samples dredged from canyons between longitudes 10° and 11°W show that at least in some parts unconsolidated sediment cannot be present except as a thin veneer a few feet thick. Whatever the seismic velocities indicate, it seems unacceptable nowadays to argue for an appreciable thickness of unconsolidated sediments, a term which geologically connotes sediment which has suffered virtually no diagenetic changes. In addition, seismic reflection profiles clearly show the existence of good reflectors which suggest strata of varying densities, velocities, degree of cementation and diagenetic change, and grain-sizes.

The five profiles across the shelf-break all show the same basic pattern, viz., strata very gently inclined toward the shelf-break and abruptly cut off by the continental slope (Figs. 9-12); there is an apparent downward bend of the reflecting surfaces adjacent to the continental slope in four out of five traverses, but this is largely the effect on the echo travel times of the increasing depth of water there. Probably the dip of the beds changes little right to the slope where they terminate.

Figure 12 is an interpretation of the travel-time profiles of the reflection records. Examples of the records are shown in Figures 9-11. The outcropping reflectors are evident in all except profile D-E where reflectors clearly terminate but are buried beneath younger material, probably prograded.

In the K-L record (Fig. 9), at a position on the continental slope corresponding with a depth below sea-level of 250 fathoms, there is an obvious discordance in reflecting surfaces; an upper series of more steeply inclined strata wedges out against a lower series as if the upper series had prograded seawards over a surface formed by the lower series. In the vicinity of this seismic profile, Miocene chalky rocks have been dredged from the slope from depths which are not less than 250 fathoms. A reasonable inference is that the lower series represents the Miocene, and perhaps older, chalks, and the upper series the Plio-Pleistocene, which elsewhere is known to lie unconformably upon the Miocene.

In the M-N record (Fig. 10), the continental slope descends by steps at depths below sea-level of 130, 200, and 260 fathoms. The structure in the continental shelf out to the 130-fathoms step is not easy to disentangle but there are several southward-dipping reflecting surfaces. Vertically below the 130-fathom step and down to the 260-fathom step, the reflections are much more clearly recorded; a discordance between an upper and a lower series, similar to that described for K-L, occurs at a depth of 225 fathoms on the continental slope, which is in reasonably good agreement with

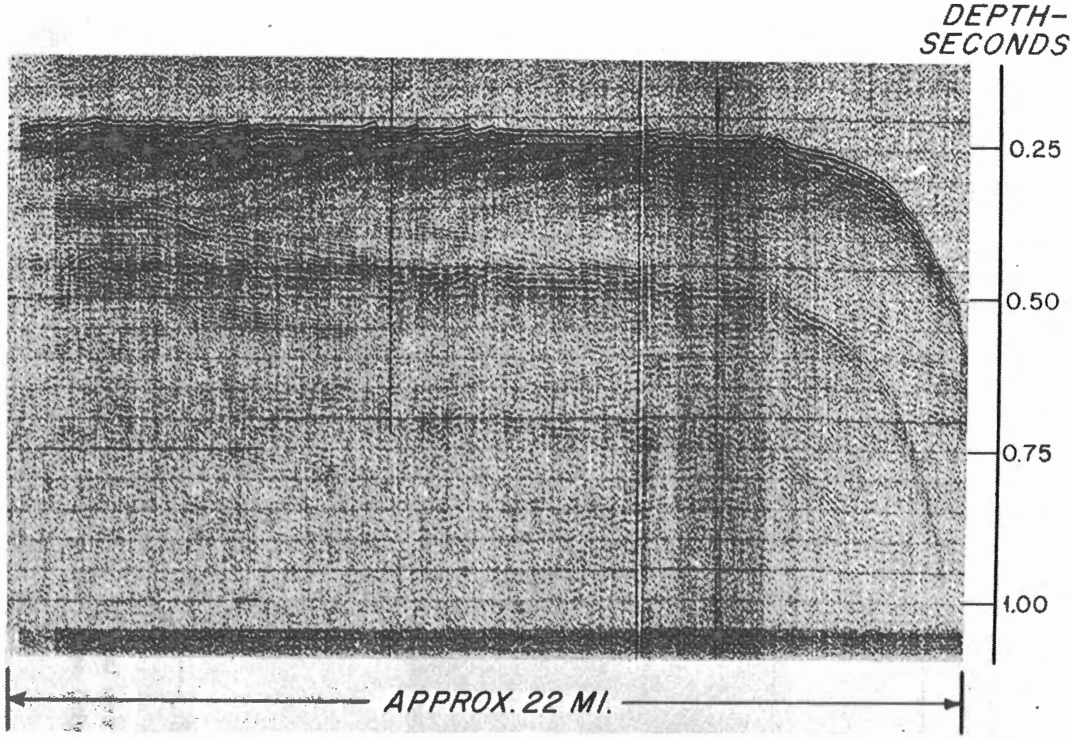

Figure 9. Seismic reflection profile between lat. 49°00.5'N, long. 9°41'W (left) and lat. 48°39'N, long. 9°47'W (right) on traverse K-L.

250 fathoms for the nearby K-L crossing 4 miles away. In four of the five profiles, there is a strong reflection which terminates at or near the continental slope at 200-260 fathoms (0.5-0.65 sec). There is no prominent, continuous reflector at greater depths. If on profile K-L this strong reflection is the Miocene/Plio-Pleistocene contact, then, plausibly, this reflector may represent the same contact along the portion of the slope from profiles K-L to D-E.

On the exceptional traverse, K-J, the prominent reflector crops out on the slope at 4,000 feet and there are shallow layers clearly discordant with it (Fig. 11). The discordance here lies about 2,400 feet below the similar structures of the other traverses noted above; it also lies near the axis of the syncline of Hill and Vine (1965). The results of Hill and Vine (see Figure 1) suggest comparable relief in the metamorphic basement,

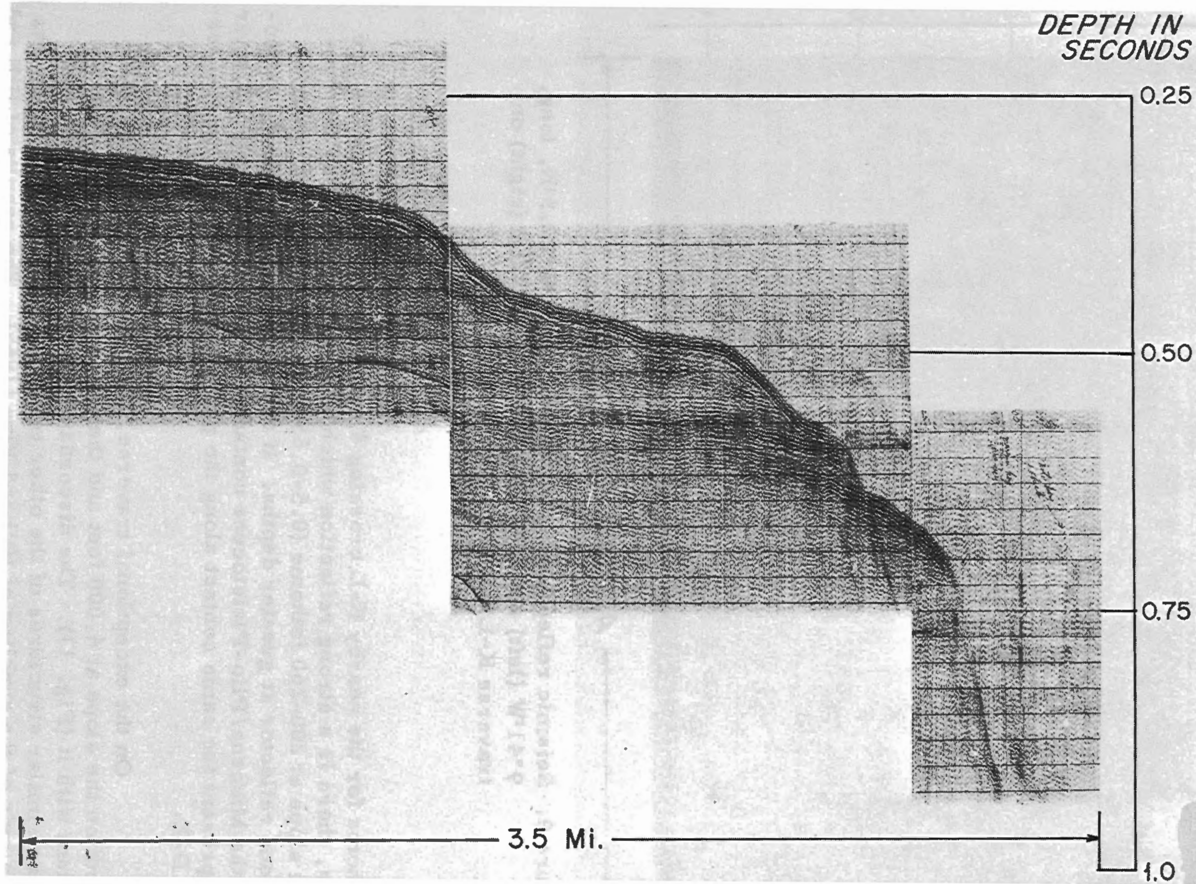

Figure 10. Seismic reflection profile between lat. 48°44.5'N, long. 9°51.1'W (left) and lat. 48°43'N, long. 9°57'W (right) on traverse M-N.

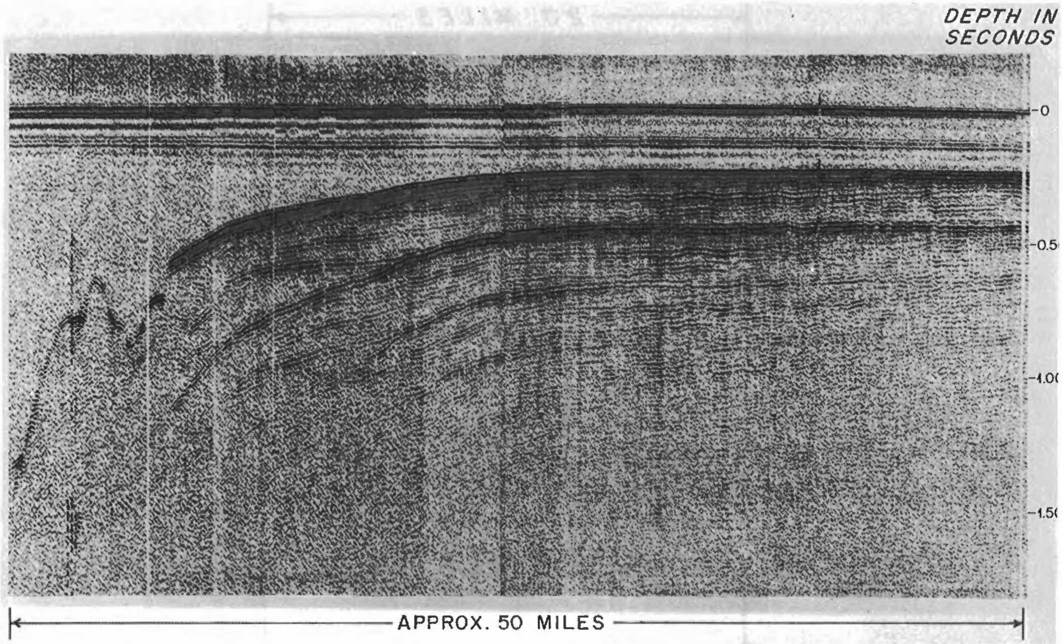

Figure 11. Seismic reflection profile between lat. 47°25'N, long. 6°47.5'W (left) and lat. 47°57.5'N, long. 6°12'W (right) on traverse D-E.

but the control is obviously not suitable for more than a surmise. It would seem, however, that the possible continuity of the discordance should be both easy to trace by seismic profiling along the shelf-break and easy to identify by coring at carefully selected locations.

To summarize:

1) In the K-L and M-N crossings a sedimentary break has been identified between presumed Plio-Pleistocene and Miocene rocks which, though not clearly evident in the remaining crossings, may be represented by the deepest prominent reflector.

2) There is no exception to the southerly or southwesterly inclination of the stratification in the upper parts of the continental slope.

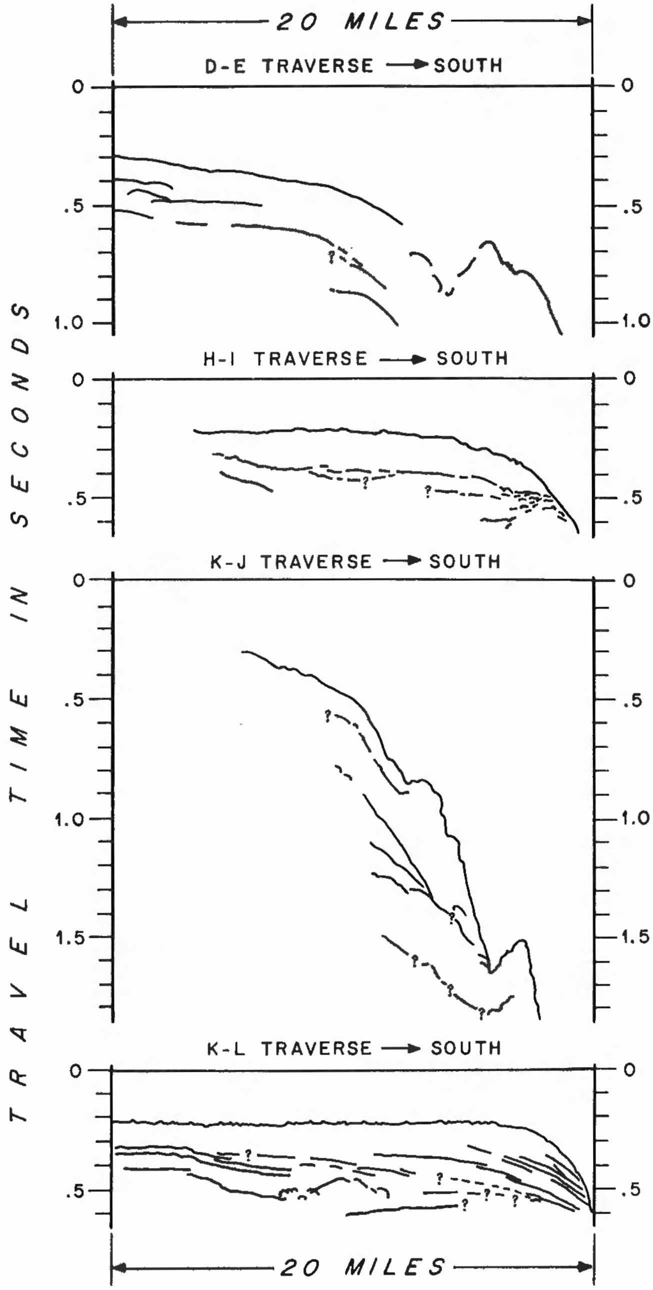

Figure 12. Seismic reflections across the shelf-break on traverses D-E (see Figure 11), H-I, K-J, and K-L (see Figure 9).

3) The dimensions of the main syncline may be shown in the outcrop of the deepest prominent reflector at the shelf-break. This reflector may well be the same stratigraphic break on K-J, H-I, and D-E as was identified on K-L and M-N.

4) The stratification is abruptly cut across by the continental margin, and the latter has all the appearance of having been fashioned tectonically, certainly in its later geological history.

5) Except for the supposed Plio-Pleistocene beds, evidence of prograded sedimentation is not a conspicuous feature of the seismic records made near the shelf-break.

ORIGIN OF THE CONTINENTAL MARGIN

Hess (1965, p. 321) has observed with regard to continental drift that the "jig-saw puzzle fits back together so well in detail that the proposition that the pieces were once together appears to be as incontrovertible as any geological proposition ever can be. Supplementary evidence from the comparison of the geology where it is well known on both sides, and from palaeomagnetism, strengthen the case but need not be appealed to for proof which is sufficient without them". If Hess's premise is accepted, when did the continental drift commence which first formed the continental margin of the Celtic Sea?

Refraction seismic work (Bunce et al., 1964) has shown that along north-northwest-trending profiles the surface of the basement rocks is markedly irregular with valleys up to 3 kilometres deep and flanks steeply inclined at slopes of 1 in 7; profiles aligned northeasterly show that the surface is inclined southwestwards and at a depth of 5 kilometres is approximately in line with the foot of the continental slope (Bullard and Gaskell, 1941; Hill and Laughton, 1954). The oldest rocks which have been sampled on this continental slope are of Middle Eocene age (Curry et al., 1962) at a depth not greater than 580 fathoms and, if the foot of the slope is taken at 2,800 fathoms, then stratigraphically there is room for an additional 13,000 feet of sedimentary rocks of one kind or another below the Eocene rocks sampled.

Approached from the strictly stratigraphical point of view and having regard to the facies differences between the Palaeogene and Miocene (<u>Globigerina</u> Silts) of the shelf on the one hand, and the entirely different Tertiary chalks of the slope on the other, it was argued in 1962 (Curry et al., 1962, p. 289) and again in 1965 (Curry, Murray, and Whittard, 1965, p. 252) that a major gulf extended into the English Channel during Tertiary times and reached at least to the longitude of Falmouth-Ushant. At its northeastern end this gulf was the site of the deposition of the Globigerina Silts, which are thought to have accumulated in depths of the order of 100 fathoms, and of Plio-Pleistocene sediments possibly representative of slightly deeper water conditions; at the southwestern end foraminiferal and coccolithophorid calcareous muds were laid down in open seas and in "deep water which continued at least from Middle Eocene to Middle or possibly Upper Miocene times" (Curry et al., 1962).

The results obtained from refraction seismic profiles were coordinated in 1956 (Day et al., 1956, Figs. 13-15); evidence of a similar gulf was adduced and there is marked agreement between the two entirely independent methods. In their Figure 15, Day et al. calculated a thickness of sedimentary rocks of 5,400 feet which increases southwestwards to 8,100 feet at the 100-fathom line. They attributed to these sedimentary rocks an age-range of "Permian and younger sediments", an opinion founded on experimental data on the velocity of compressional seismic waves in different kinds of rock-samples and on velocities determined at sea.

We have no direct knowledge of the rocks which comprise the slope below, say, 700 fathoms, and three times that thickness of sedimentary rocks can be accommodated below that level. The oldest known sedimentary rocks are Eocene; Funnell (1964, p. 427) has reported a large flint (?Cretaceous) at about 920 fathoms, but this might not have been in situ. Accordingly, it seems probable that Mesozoic rocks crop out on the slope but the suggestion that Permian strata of a terrestrial origin, such as are found in southwest England, may occur at these depths is unacceptable. At this stage in the work on the continental slope of the south Celtic Sea, there is an enormous gap in our stratigraphic data, and the probable geological date at which continental drift commenced, if it did, cannot be assessed with any certainty.

Once the slope came into existence in pre-Tertiary times it received sediment several thousands of feet thick; subsequently, diagenetic changes converted the unconsolidated material into rock, and in the Tertiary a remarkably constant group of chalks was formed. The few chalky samples collected from the slope southwest of traverse M-N (Curry et al., 1962) presented a problem because there was no agreement between the depths at which the samples were obtained and the increasing stratigraphic age; on the available data this disagreement was best explained by faulting. The five crossings of the shelf-break which have been described herein all support a faulted origin for the recent surface of the upper part of the slope, because stratification is obviously sharply truncated by the slope; the relationships are therefore not those found in a normal sedimentary accumulation because the outer parts of the sedimented material have been removed. But if faulting is conceded as a later stage in the sequence of events which has progressively modelled the slope, then such faulting operated as late as Miocene times, and even into near-Recent times if the Plio-Pleistocene occurs at the shelf-break as has been claimed particularly in traverses K-L and M-N.

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DISCUSSION

Dr. A.S. Laughton (UK)

May I just note something about the steepness of the continental slope in this general region? Off the Western Approaches, the continental slope is highly dissected with canyons, some of which are very nearly overlapping. The slopes in the bottom of these canyons are extremely steep, very much steeper than is indicated by the mean slope of the continental slope. It seems highly possible, therefore, that the places where erosion and subsequent slumping have occurred is right at the base of the "V" of these steep-sided submarine canyons. We do not at present have any means of telling quite how steep these are.

Prof. Whittard

Yes, that may be quite true, but it is a question of the composition of the canyon walls. I think still that, even with a slope of 30 or 40 degrees, chalks and the like should be stable. Can you remember what the slope angles are at the bottom? Are they 60 degrees or more?

Dr. Laughton

I don't know; one can't get the information on this from surface echo soundings. But it seems quite conceivable that these slopes may be almost vertical in places, as in the canyons off California which Dr. Shepard examined. This doesn't seem out of the bounds of possibility.

Prof. Whittard

There is still the question of whether these would necessarily slump, isn't there? Clays laid down on such steep slopes would slump. But I still think that pure chalks are much more resistant to slumping than one might have thought at one time. The highly calcified material is very resistant under normal circumstances.

Dr. C.A. Burk (USA)

What is the general slope angle of the continental slope?

Prof. Whittard

I don't think I can answer that. Can you, Dr. Laughton?

Dr. Laughton

I think the mean slope angle of the shelf edge is something of the order of 1 in 15.

Dr. Burk

Well then, presumably there is no slumping at all down the postulated fault.

Prof. Whittard

If it is 1 in 15, then this is how I would interpret it. This is not the slope of the fault; it is the overall slope produced by the fault complex.

Dr. H.P. Laubscher (Switzerland)

What about facies changes? A slight stratification of the chalk might make the whole sequence highly unstable. You may have some marls interbedded with harder strata; and you must anticipate facies changes as you go towards the continental slope.

Prof. Whittard

That is very true, but we have no evidence at all of heterogeneity in these chalks. The chalks from the Middle Eocene to Miocene have a remarkably consistent appearance. Now, it may be that draping has been selective, but I have no evidence of this. The uniformity of the calcareous facies of these Tertiary deposits is a striking feature.

Dr. J.L. Worzel (USA)

When these materials were laid down in the trough, they were very much like the materials laid down on the Blake Plateau. Would not a deep-seated current, such as has been described for the Blake Plateau, have carried them away in this outer region?

Prof. Whittard

There is no sign of any terrigenous material in these calcareous deposits, as far as we know.

Dr. Worzel

There is not in the Blake Plateau either, or very little.

Prof. Whittard

The only fauna we have collected, so far at least, are pelagic and benthonic foraminifera and coccoliths. The specific details of the assemblages all suggest a deep-water origin, and have the appearance of oozes, rather than of anything else.

DEUX EXEMPLES DE BORDURE CONTINENTALE FRANÇAISE: LE GOUF DE CAP BRETON ET LE CAP CARTAYA

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Laboratoire de Géologie Dynamique, Sorbonne

Résumé

Dans le golfe de Gascogne, le canyon sous-marin du "Gouf de Cap Breton" entaille le plateau continental de la ligne du rivage jusqu'à la plaine abyssale. Un certain nombre de carottages ont montré que toutes les parties de ce canyon (tête, flancs, dépôts de thalweg, et cône de déjection profond) sont formés de turbidites ou de fluxoturbidites, dont les premières ont été prélevées dans 30 mètres d'eau. Enfin la tête du canyon est entaillée dans des turbidites plus anciennes, mais non consolidées.

En opposition à cet exemple, la région du Cap Cartaya, en Méditerranée, se prolonge vers le large par une plate-forme rocheuse en gneiss, située par 60 mètres de fond. Cette plate-forme est limitée par un rebord très franc, tandis qu'une pente assez forte la raccorde directement aux fonds de 2,000 mètres. Le rebord et la partie supérieure de la pente sont rocheux. Une pellicule sédimentaire ne dépassant pas quelques dizaines de centimètres les recouvre.

La nature géologique du plateau continental constitue une donnée extrèmement importante pour notre connaissance des marges continentales. Ce n'est toutefois que sur la bordure du plateau et sur la pente continentale qui lui fait suite, que nous pouvons espérer rencontrer systématiquement des affleurements de roches consolidées. Mais les navires océanographiques conventionnels, à l'exclusion des plates-formes de forages, rencontrent souvent de grandes difficultés à effectuer un tel échantillonnage à cause de la couverture de sédiments modernes qui masque souvent les roches consolidées. Je voudrais présenter deux exemples-types de marges continentales françaises qui illustrent les cas extrêmes que nous avons rencontrés.

L'incision profonde du Gouf de Cap Breton dans le plateau continental du Golfe de Gascogne semble, au premier abord, exposer des parois particulièrement propices à un échantillonnage. En particulier, l'étroite gorge située en aval du canyon, gorge dont le thalweg présente une dénivellation de plus de 1,000 mètres par rapport à la surface du plateau, pourrait recouper des horizons assez anciens du plateau continental.

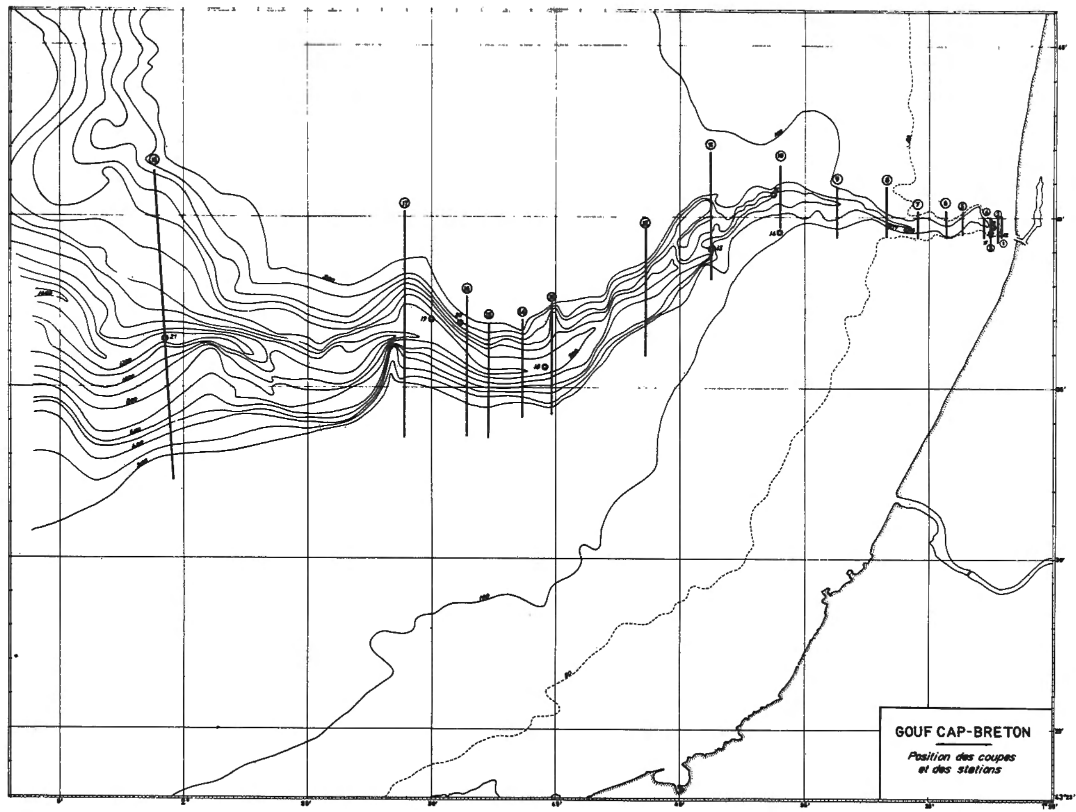

Figure 1. Le canyon du "Gouf de Cap Breton" découpé dans le plateau continental du Golfe de Gascogne. Equidistance des isobathes: 100 mètres. Position des coupes et des stations.

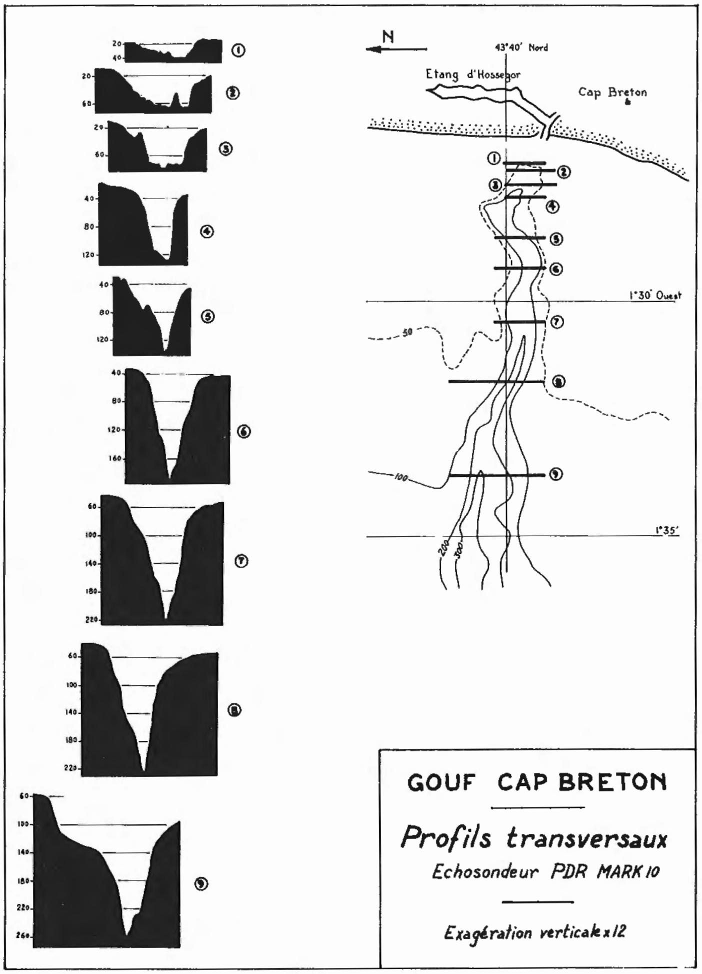

Figure 2. Profils transversaux du Gouf de Cap Breton. Les carottages ont été effectués de façon à obtenir des échantillons du fond du canyon et des pentes à diverses hauteurs au dessus du fond.

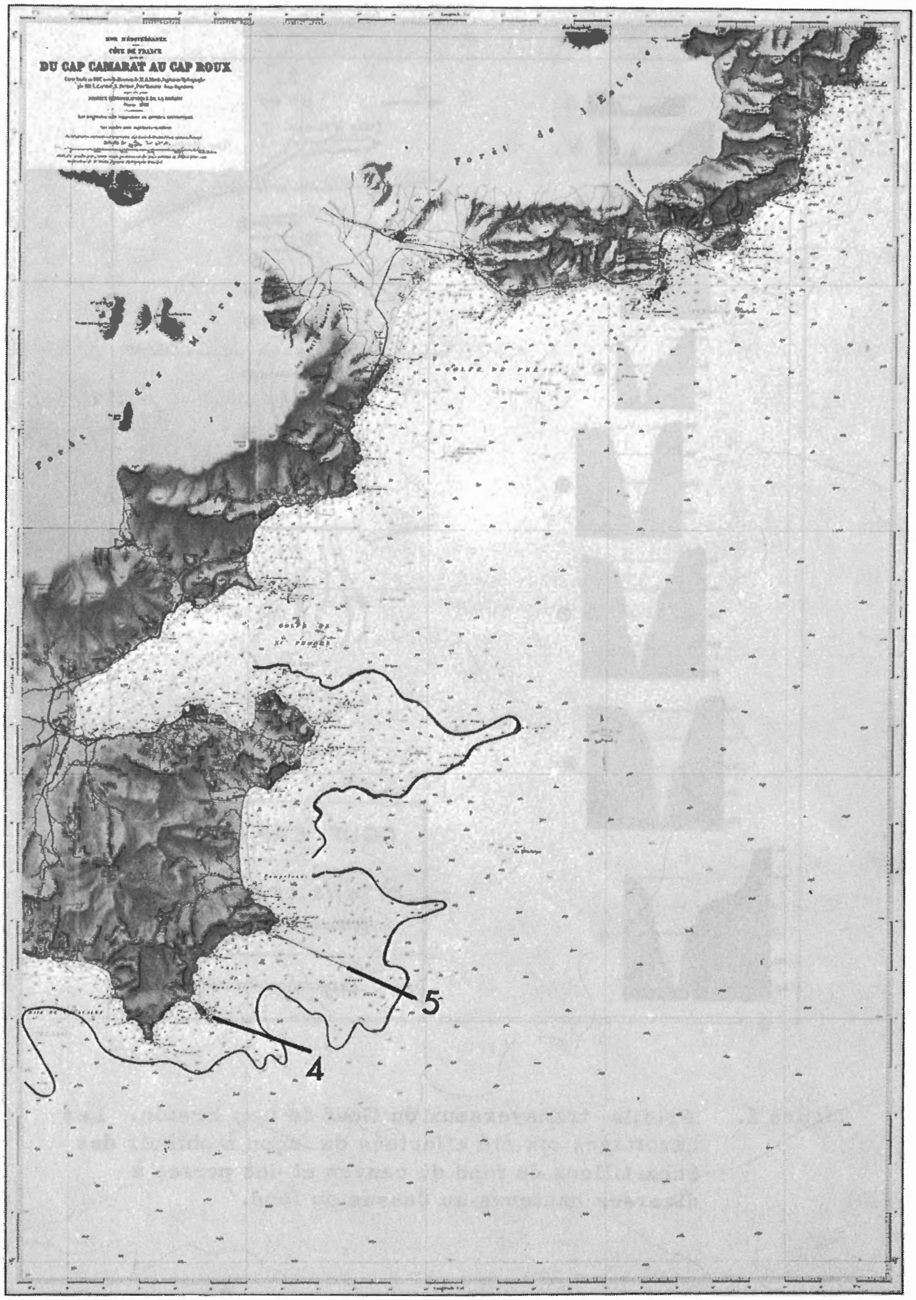

Figure 3. Disposition du plateau rocheux au large des caps Cartaya, Camarat et St-Tropez. Le trait fort montre le rebord du plateau par 60 mètres de fond. Les numéros indiquent les positions des coupes des figures 4 et 5 (d'après la carte du Service Hydrographique N° 5337).

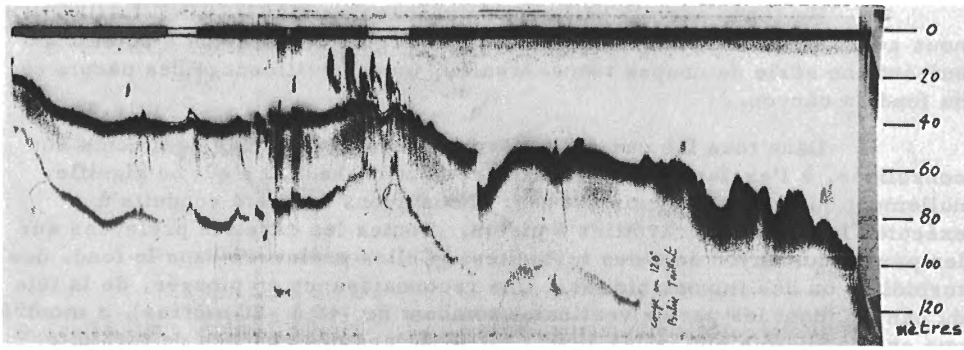

Figure 4. Le plateau rocheux au large du Cap Cartaya. Seule la partie la plus littorale porte une couverture sédimentaire que percent de nombreux pointements rocheux.

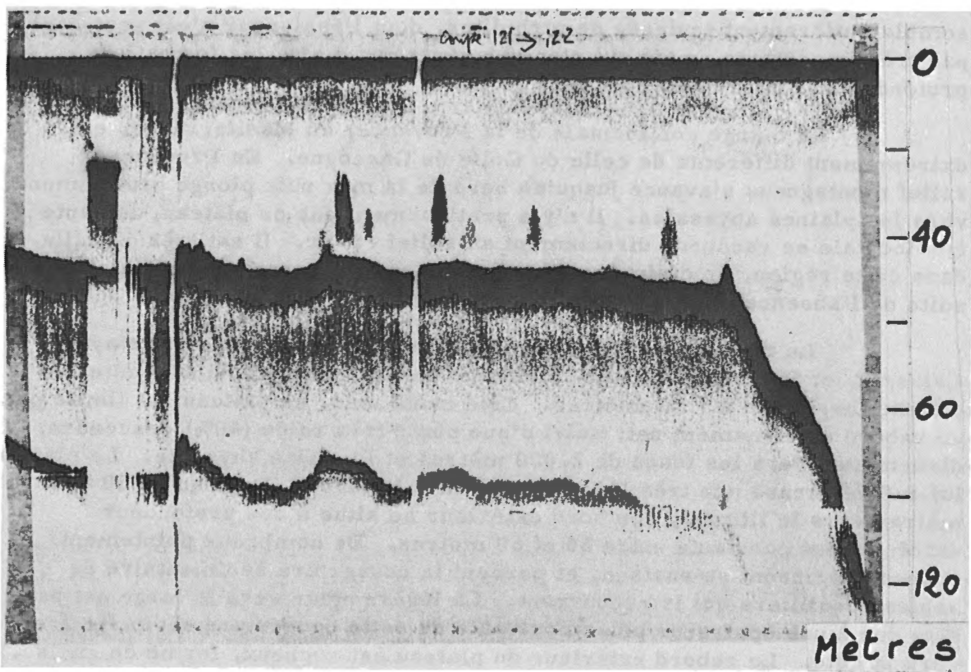

Figure 5. Coupes du plateau rocheux entre Camarat et Cartaya. On note la pente très rapide vers le large et le rebord parfois marqué d'un ressaut rocheux.

En 1964, avec le bâtiment de recherches CATHERINE LAURENCE, nous avons reconnu systématiquement cette région en essayant d'obtenir, suivant une série de coupes transversales, un échantillonnage des parois et du fond du canyon.

Dans tous les cas nous n'avons rencontré que des sédiments non consolidés, à l'exclusion de tout affleurement rocheux, ce qui ne signifie nullement que ceux-ci n'existent pas. Nous avons donc été conduits à exécuter le travail au carottier à piston. Toutes les carottes prélevées sur les parois du canyon sont des turbidites. Celles prélevées dans le fond, des turbidites ou des fluxoturbidites. Une reconnaissance en plongée, de la tête du canyon (dont les parois verticales tombent de -40 à -80 mètres), a montré que ces parois étaient, elles aussi, taillées dans des couches de turbidites non consolidées. Par contre, lorsqu'on s'écarte du canyon sous-marin pour arriver sur le plateau continental, on y prélève des carottes entièrement constituées de vase ne présentant aucun caractère de turbidite. Il s'agit donc de vase déposée, particule par particule. Cette disposition montre que le parcours des courants de turbidité reste limité, dans cette région, à la vallée sous-marine.

Ainsi la saignée du Gouf de Cap Breton dans le plateau continental semble entièrement tapissée de turbidites, dont l'épaisseur n'est peut-être pas très importante, mais qui n'en masquent pas moins les formations profondes du plateau continental.

La marge continentale de la Provence, en Méditerranée, est extrêmement différente de celle du Golfe de Gascogne. En Provence le relief montagneux s'avance jusqu'au bord de la mer puis plonge brutalement vers les plaines abyssales. Il n'y a pratiquement pas de plateau, la pente continentale se raccorde directement au relief côtier. Il est très difficile, dans cette région, de délimiter avec précision la "marge continentale" par suite de l'absence d'une rupture de pente bien individualisée.

Le tableau est toutefois différent au large des caps Cartaya, Camarat, et St-Tropez. Dans cette zone on observe, accolé à la côte, un plateau large de 6 à 7 kilomètres. Côté haute mer, ce plateau est limité par un rebord extrêmement net, suivi d'une pente très raide (40%) descendant directement vers les fonds de 2,000 mètres et la plaine abyssale. Le plateau lui-même accuse une très légère pente vers le large. Profond de 30 à 40 mètres vers le littoral, son bord extérieur se situe à une profondeur extrêmement constante entre 50 et 60 mètres. De nombreux pointements rocheux hérissent sa surface, et percent la couverture sédimentaire de sables coquilliers qui le recouvrent. La légère pente vers le large est peut-être due à une épaisseur plus importante de cette couverture sédimentaire vers la côte. Le rebord extérieur du plateau est rocheux, formé de gneiss. La pente qui suit le rebord est rocheuse elle aussi. Par endroits un plaquage de sables coquilliers vaseux et de vase ne dépassant pas quelques dizaines de centimètres la recouvre. Ces plaquages demeurent sporadiques et de très faible épaisseur jusqu'aux profondeurs de 250 mètres au moins.

Des canyons sous-marins entaillent ce plateau, mais les bords de ces encoches se trouvent, comme le reste du plateau, à une profondeur constante de 40 à 60 mètres.

Ainsi la bordure continentale de la région Cartaya-Camarat se présente sous la forme d'un plateau rocheux immergé par 60 mètres d'eau. Hérissé de pointements rocheux et limité par un rebord et une pente extérieure rocheux, ce plateau est extrèmement différent d'une bordure de plateau continental classique. On pourrait penser qu'il s'agit d'une ancienne surface d'érosion subaérienne, limitée vers le large par des fractures.

DISCUSSION

Someone asked what is the origin of this platform?

Dr. Nesteroff

It is my opinion that this platform is just a continuation of the land. It appears to be similar to the two or three subaerial erosional plateaus that we have in this area. These plateaus have been studied by geomorphologists and are Miocene and Pliocene in age. The Cape Cartaya submerged platform seems to belong to the same type.

Dr. B.C. Heezen (USA)

Do you think that this current, travelling all the way down the slope, would suggest a very recent origin of this slope, perhaps corresponding to the subsidence of the Mediterranean Basin?

Dr. Nesteroff

What do you call "very recent"?

Dr. Heezen

Well, you would expect some sediment on the slope unless there are currents removing it. So the absence of flat sediments on the outcrops of granite on the slope would indicate an age, let's say, of at least late Tertiary or Pleistocene?

Dr. Nesteroff

Yes, I suppose so. At least late Tertiary or Miocene. But one of the questions is, of course, why there is no sediment being deposited nowadays on this slope. I do not know why.

SOME FEATURES OF THE ALPINE-MEDITERRANEAN OROGENESIS

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Abstract

Central Europe is bounded to the south by the Alpine mountain chain which, at its western end, curves toward the Mediterranean Sea. The earth's crust in Central Europe has an average thickness of 30 kilometres, and shows at most places a clear subdivision into two layers with P-wave velocities of 5.8-6.1 km/sec and 6.4-6.7 km/sec and a rather pronounced variation in the depth of the interface. Toward the Alps, the M-discontinuity dips down and reaches its maximum depth below the Central Alps of approximately 60 kilometres. On the southern border of the Alps, towards the Po Plain, an extended body ("Ivrea Body") with a velocity of 7.4 km/sec has been found at a depth of less than 10 kilometres. It seems to flatten out to the east. The Alpine chain ends at the Mediterranean Sea. Sediments in the Alpes Maritimes, on the islands of Corsica and Sardinia and in northern and western Italy, indicate the former existence of a mountain range between them, which possibly has been depressed 3 kilometres below sea-level in the Tyrrhenian Sea.

Today, the Tyrrhenian Sea is underlain at shallow depth by rock with a velocity of about 7.2-7.4 km/sec and is partly filled by undisturbed layers of recent sediment. This area is volcanically and seismically active (intermediate-depth earthquakes) and has evidence of rapid subsidence in modern times. Other evidence in the Mediterranean suggests that the Tyrrhenian Sea is a recently formed depression underlain by a crust which is thin compared with that of surrounding land-areas, and hence profoundly transformed from its state when it served as a source of clastic sediments for basins in Italy, Corsica, and Sardinia.

In the Ligurian Sea between Corsica and France, seismic refraction profiles over an abyssal plain immediately south of the Alpes Maritimes show the crust to be thin (M-discontinuity, 12-13 kilometres deep) and similar to that of the ocean basins, except that the low-velocity layers are thicker than those under the deep oceans. Less complete data suggest that velocities in the range 7.2-7.7 km/sec are to be found at shallow depth beneath the Balearic Basin to the south.

The irregular relief of a 3.8 km/sec layer beneath the abyssal plain in the Ligurian Sea and the Balearic Basin is similar to the relief of the sea-floor in a large area of the eastern Mediterranean south and west of Crete. The eastern Mediterranean also contains sediment-filled basins and other structures which suggest different stages in a hypothetical sequence of development. The first stage is crustal thinning, like that under the Ligurian Sea, accompanied by the formation of a depression similar to that of the Tyrrhenian Sea. The depression is then filled by sediment as in the Balearic Basin. The next stage is deformation of the basinal sediments accompanied by vertical movements. These movements appear to have been irregular and, over long periods, oscillatory. Possibly the thin crust beneath the Ligurian Sea and close to the marine basinal deposits of the Appennines of northern Italy is an expression of this oscillation. Another possible example is in Greece and the Ionian Sea. Similar tectonic activity may be characteristic of the entire Alpine-Himalayan belt.

INTRODUCTION

In terms of this symposium, the Alpine orogen in its broader sense is probably the most remarkable structure in Europe. Although the area under consideration has been the subject of geological studies for generations, we are still far from understanding its complete history. The main reason is the extreme complexity of structures in the Mediterranean region where the continents of Europe and Africa have been linked together in different ways during their geological history. The original Mediterranean, or Paleotethys, probably exhibited the characteristics of a true ocean. The present Mediterranean and its surroundings, however, cannot be called typical of any other ocean.

CENTRAL EUROPE AND ALPS

If we try to describe the deeper structure of this area (Fig. 1), it is safe to start where our information is the most complete. This is the stable mass of Central Europe north of the Alpine chain. A considerable amount of refraction seismic work has been carried out particularly in Germany as well as in France and Czechoslovakia. Subsurface contour maps of the main interfaces were presented at the 1963 meeting of International Union of Geodesy and Geophysics and published since then by the German Research Group of Explosion Seismology (1964). The crust in Central Europe is about 27-30 kilometres thick. A layer with a P-wave velocity of 5.8-6.1 km/sec can be clearly distinguished from an intermediate layer with a velocity of 6.4-6.7 km/sec. The remarkable variations in depth of this Conrad interface can be related partly to some Variscian tectonic zones striking southwesterly. Toward the Alps the M-discontinuity dips down and

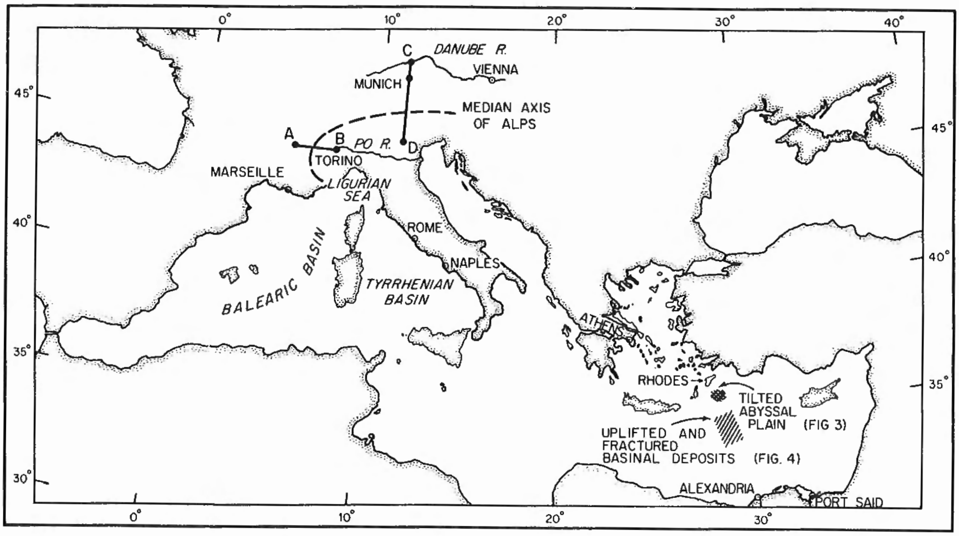

Figure 1. The Alps and Mediterrranean Sea, showing locations of sections of Figures 2a and 2b, and of reflection profiles of Figures 3 and 4.

reaches its maximum depth below the Central Alps of about 60 kilometres. The section AB (Fig. 2a) is drawn across the Western Alps where they curve toward the Mediterranean Sea (Groupe d'Études des Explosions Alpines, 1963). There, the most intense crustal shortening took place by overthrusting and later periods of folding. A shortening from an original width of about 600 kilometres to a present-day 150 kilometres is probable (Cadisch, 1953). Although the crust shows still some evidence of having an intermediate layer, it cannot be traced continuously. Near the western border of the Po Plain, an extensive body with a velocity of 7.2-7.4 km/sec was found which dips steeply toward the central axis of the Alps. According to seismic evidence, the upper boundary of this so-called "Ivrea Body" is about 10 kilometres below the surface. Yet, at some places, peridotitic rocks are exposed at the surface together with highly metamorphosed and recrystallized rocks, all of uncertain age but much older than the main uplift of the Alps. Interpretation of the pronounced positive Bouguer anomaly requires a great vertical dimension of the Ivrea Body. On the other hand, good evidence suggests that the M-discontinuity exists below the Ivrea Body. Beneath the Po Plain, the presence of the body is obscured by thick sediments. On the section CD across the Eastern Alps (Fig. 2b), this high-velocity zone may exist at greater depth, an interpretation partly based on the gravity studies of Talwani and Mueller (in preparation). Refraction and reflection seismic work in the Alps has been carried out by various institutions in France, Germany, Italy, and Great Britain (Groupe d'Études des Explosions Alpines, 1963) and is still in progress.

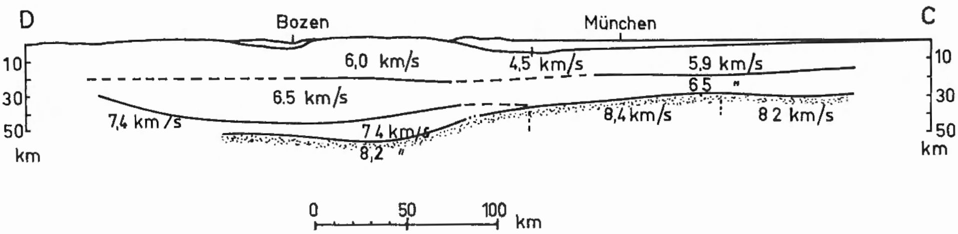

Figure 2a. Crustal section across the Eastern Alps. (After C. Prodehl, 1965)

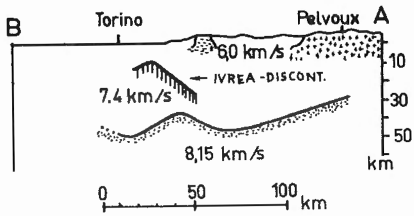

Figure 2b. Crustal section across the Western Alps. (After Groupe d'Études des Explosions Alpines, 1963)

The Alpine chain ends where the Alpes Maritimes reach the Mediterranean Sea. Studies of the Cretaceous and Oligocene sediments in the Alpes Maritimes, on the islands of Corsica and Sardinia, and in northern and western Italy, indicate that a former mountain range existed between them in the present area of the Ligurian and Tyrrhenian Seas. The range was depressed up to 3 kilometres below sea-level beginning in Oligocene (Kuenen, 1959).

MEDITERRANEAN

From 1958 to 1964, a series of cruises was made in the Mediterranean by CHAIN and ATLANTIS of the Woods Hole Oceanographic Institution, and the U.S. Coast Guard Cutter YAMACRAW. Programs of refraction and reflection seismic profiles, gravity and magnetic measurements, and geological observations and collections were carried out. The seismic refraction program was carried out cooperatively with scientists on VEMA of the Lamont Geological Observatory of Columbia University and

WINNERETTA-SINGER of the Oceanographic Institute of Monaco. The work is far from complete, but neveretheless has advanced to the state where some speculation about models of tectonic development of the Mediterranean region can be made. The model presented below was first discussed at the Colston Symposium (Hersey, 1965a) and will only be summarized here. It is based mainly on a comparison between several structures in the Mediterranean, and on a speculation about their possible relationship to structures in the mountains of northern Italy and of Greece. In addition, Pfannenstiel (1960) has published an account of Mediterranean bathymetry, and Emery et al. (in press) and Giermann (1964) have presented analyses of the morphology of the eastern basin while Menard et al. (1965) and others have presented a parallel analysis of the western basin. Other research in several countries bordering the Mediterranean is in progress and will contribute greatly to our understanding of its geological history.

The Tyrrhenian Basin (Fig. 1) is one of active vulcanism and intermediate-focus earthquake activity. It is also a region where from historical accounts we know that the coast-lines are sinking. One seismic refraction profile located over an abyssal plain near the central and deepest part of the Tyrrhenian Sea shows 7.2 km/sec material at shallow depth. Beneath this plain are about 1,000 metres of horizontally layered sediments which appear to be accumulating at about 1 metre per year (Ryan et al., 1965). Thus this basin appears to be young and still forming. The presence of the 7.2 km/sec material attests possibly to considerable crustal alteration. This velocity does not identify pure mantle material because it is intermediate between the $8.0\pm$km/sec velocity of the upper mantle and the 6.7 km/sec of the lower crust, but it suggests interaction or mixing of crustal and mantle material, and either thinning or other profound alteration of the crust.

In the Balearic Basin of the western Mediterranean (Fig. 1), there is other seismic evidence for crustal thinning. One continuous abyssal plain stretches in a sigmoidal pattern from the northeastern part of the Ligurian Sea southward and westward nearly to Gibraltar. Especially in the northern part, very close to the Alpes Maritimes, an almost oceanic-type crust occurs. Its sequence of velocities with depth is similar to those beneath typical ocean basins. At a depth of 12.0 kilometres a velocity of 7.9-8.0 km/sec is found. This section in the northern Balearic Basin differs from the standard ocean section by having a water depth of only about 2,400 metres, thus allowing a thickness of layer 2 (4.0-5.5 km/sec) and of unconsolidated sediments considerably greater than in the deep ocean. Farther south in the Balearic Basin, a few scattered seismic refraction profiles indicate a possible trend to slightly lower velocities, of the order of 7.4-7.5 km/sec.

In summary, there is good evidence of a thin crust in the western Mediterranean close to the Alps and over much of the remainder of the northern Balearic Basin, and that a thin crust is possibly in process of formation in the Tyrrhenian Basin.

In the eastern Mediterranean, there is a basin southeast of the island of Rhodes (Fig. 1) containing an abyssal plain which slopes ever so slightly northward (Fig. 3). The seismic reflection record across the basin suggests that an old sedimentary basin has been warped, uplifted, tilted, and fractured, and, within it, a new basin has formed permitting a considerable accumulation of horizontally stratified sediments forming a modern abyssal plain. The slight northward tilt of this plain suggests that during recent tectonic activity the whole basin has been tilted northward. Figure 4 shows another complexly fractured zone immediately south of this basin. Hersey (1965a) suggested that this fractured zone was originally a basin, a suggestion based on the sediments which are thick at the centre and thin both to the north and south.

TECTONIC DEVELOPMENT

The areas sketched above can be arranged in an order that illustrates a model of tectonic development which appears to be consistent with other features of the Mediterranean-Alpine belt. The first stage is a thinning and destruction of the continental crust, and formation of a basin, as represented by the Tyrrhenian Basin. In the second stage, sediment is deposited in the basin and includes structures such as sediment ponds, delta deposits, and slumps, as exemplified by the Balearic Basin. During this stage the basin may or may not be subjected to external stress. The Balearic Basin seems to have been relatively little disturbed during the deposition of about a kilometre-thick layer of sediments. However, the basin southeast of Rhodes (Fig. 3), if it developed first as a sediment pond, has been distorted and tilted, and a smaller pond has been formed (and subsequently tilted) in a basin within the northern part. In a still later stage, the hypothetical basin may lose its basinal character almost entirely, as suggested in Figure 4. The final stages of such a development may include further deformation and uplift as represented by some, if not all, of the mountains of the Alpine belt.

This outline has shown that different parts of the Mediterranean may now be at these different stages of development. The Appennines in the northern Italian Peninsula were formed from basinal deposits which had their source in mountains in an area now covered by the Ligurian Sea (Merla, 1964). A similar relation appears to obtain between rocks of Greece and their source-area under the Ionian Sea (Hess, personal communication). Thus in these regions and in the Mediterranean, uplift and subsidence of the

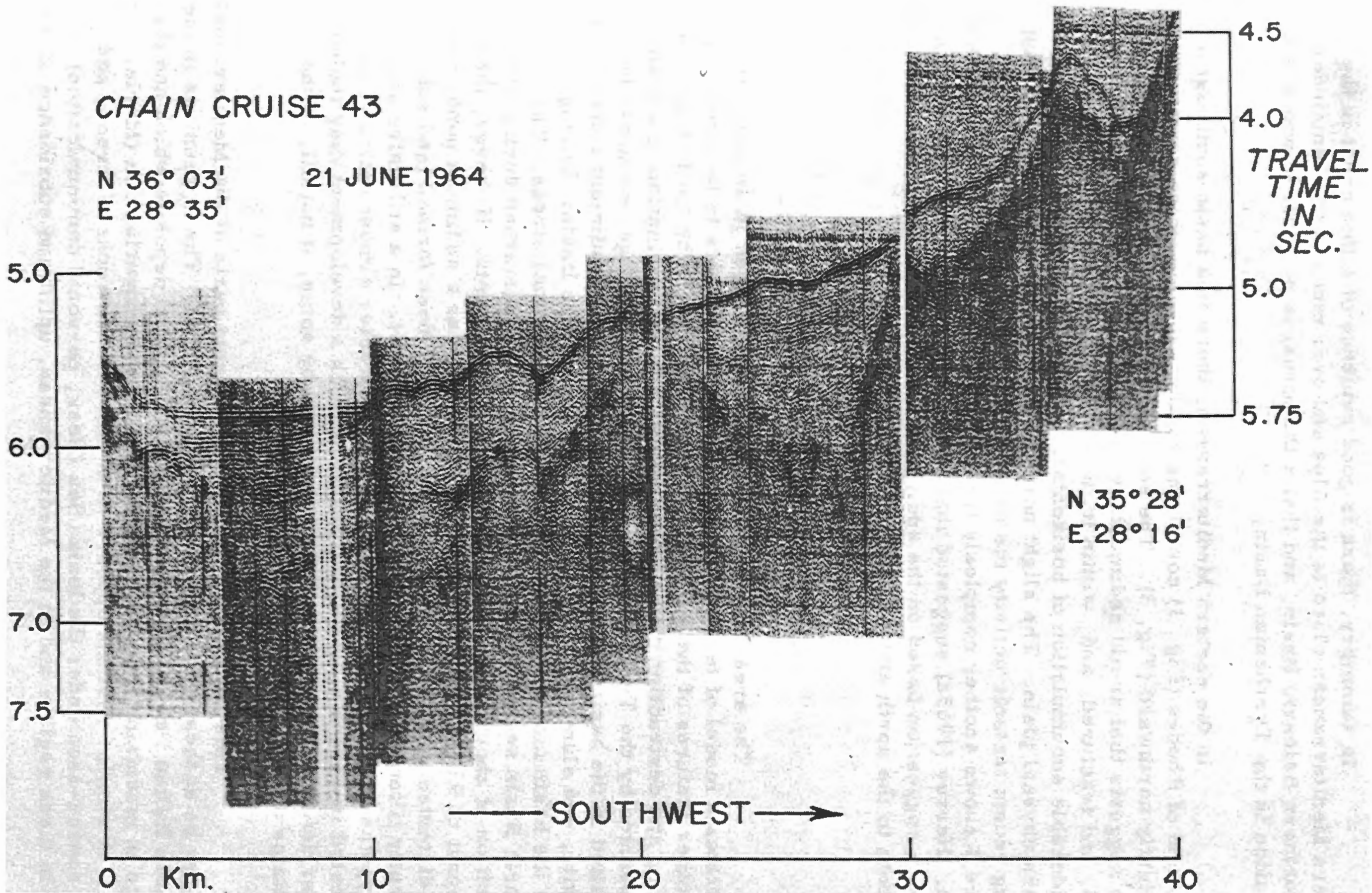

Figure 3. Reflection profile across a basin in the eastern Mediterranean 50 miles east-southeast of Rhodes.

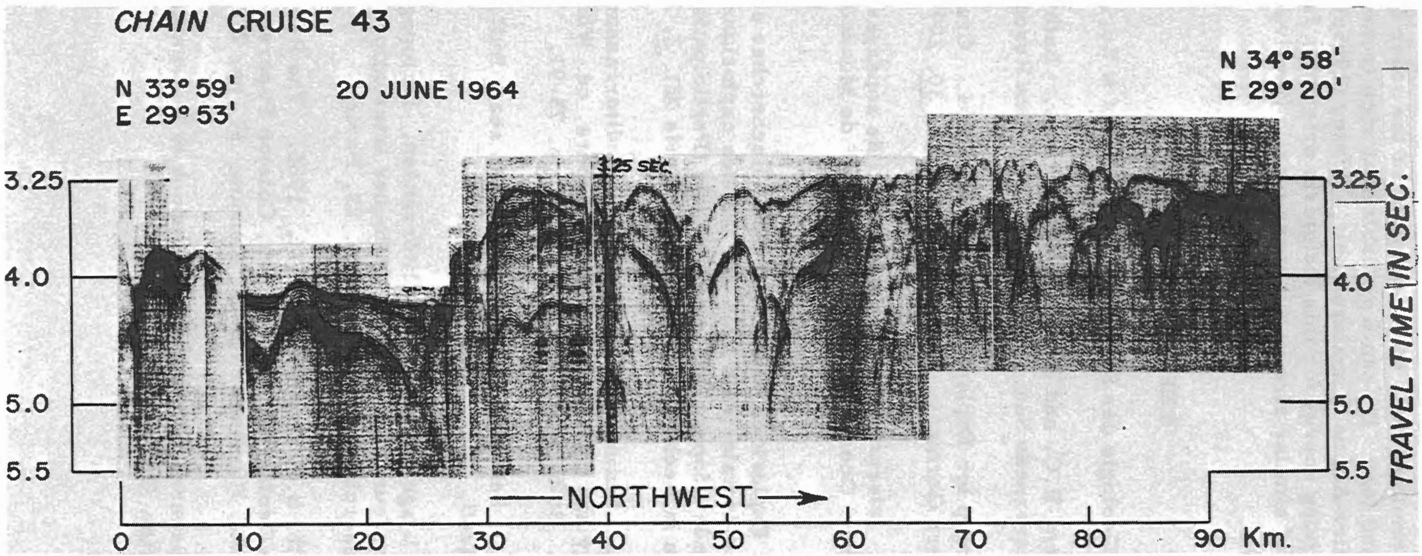

Figure 4. Reflection profile across an area in the central part of the eastern Mediterranean.

crust has occurred simultaneously on local scales of the order of a few hundred miles wide and less. It seems probable that such tectonic activity characterizes the entire Alpine-Himalayan belt. Hersey (1965a) has suggested that the driving energy for this tectonism originates from changes taking place in units of similar size in the upper mantle (involving regional units of similar size).

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C. SESSION ON CARIBBEAN ISLAND ARCS

GEOLOGICAL CHARACTERISTICS OF PUERTO RICO

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Abstract

Puerto Rico consists of a volcanic belt formed from Albian to Eocene and deformed at least twice during this period. It is flanked by Oligocene and younger limestones and clastic rocks. Gneiss, basaltic amphibolite, and serpentinite form a basement in southwestern part of the island and are Albian or pre-Albian. The volcanic rocks, both marine and non-marine, are interbedded with volcanic-derived greywacke and mudstone, and some limestone. The volcanic rocks belong mainly to the calc-alkaline suite, but an alkali basalt suite and possibly other rock suites exist on the island. Detrital quartz occurs only rarely in the clastic rocks and no evidence of a quartzo-feldspathic, continental-type basement is apparent. Total stratigraphic thickness in any one tectonic unit on the island is 6 to 8 kilometres; the composite thickness for the entire island is about 15 kilometres.

Plutons of granodiorite and quartz monzonite have intruded the Cretaceous volcanic rocks and provide a source of detrital quartz for younger clastic rocks. The volcanic and plutonic magmas were possibly derived by successive refusions of an original magmatic rock, which probably separated from the mantle by partial fusion. Such a postulated origin requires high thermal gradients. Episodes of refusion probably occurred in Albian, Santonian, and Maestrichtian.

Intense, closely spaced faulting has deformed the strata and raised the island above sea-level. Two broad zones of west-trending, left-lateral transcurrent faults cross the island; both are deflected near a batholith in the centre of the island. Rocks of the island apparently were deformed by pre-Oligocene compressional forces perhaps related to the broad transcurrent fault zones. Since Eocene, vertical movements have been dominant. There exists very little evidence of compressional deformation since that time.

INTRODUCTION

This paper presents a general summary of the significant geological characteristics of Puerto Rico. It is based upon geological work carried out since 1950 mainly by the writer and his colleagues of the U.S. Geological Survey, the Commonwealth of Puerto Rico, and Princeton University, and by geologists of Rice University.

LITHOLOGIC AND STRATIGRAPHIC CHARACTERISTICS

The oldest rocks yet found in Puerto Rico are serpentinite, gneiss, and amphibolite which outcrop in the southwestern corner of the island (Figs. 1 and 2; Mattson, 1960). The relations between these rocks are still not clear. They are unconformably overlain by an undated sequence of bedded, radiolarian-bearing cherts, and both they and the cherts are unconformably overlain by Campanian (upper Cretaceous) limestones and volcanic rocks. Hornblende in the gneiss was dated by the potassium-argon method as 110 million years (S.R. Hart, personal communication, 1963).

The central part of the island consists of a belt of Albian (latest Lower Cretaceous) to Eocene volcanic and volcani-clastic rocks, flanked by Oligocene and younger non-volcanic detrital and carbonate deposits (Fig. 3). Volcanic rocks make up almost the entire pre-Oligocene sequence, with only a small amount of detrital and organically derived limestone. The environment was generally marine in which submarine volcanoes occasionally built their cones above sea-level and provided shallow platforms for the growth of reefoid limestones. The younger volcanic rocks have more evidence of subaerial activity than the older volcanic rocks, but non-marine volcanic deposits as old as Albian are known.

The volcanic rocks consist of lava, breccia, and tuff in varying proportions. Mixed rocks are common, and almost all pyroclastic rocks show some evidence of transportation by water. Thick sequences of tuffaceous sandstones and mudstones occur at several stratigraphic levels within the volcanic rocks in the central part of the island.

There is a great stratigraphic thickness of rocks in central Puerto Rico. A minimum composite thickness for the entire island, 50 by 160 kilometres, is about 15,000 metres. Because of the extreme lenticularity of the volcanic units, this figure is not accurate. If only measurements within each of the various tectonically defined areas are considered, in an attempt to eliminate some of the influence of lenticularity, calculated thicknesses in individual areas range from 6,000 to 8,000 metres.

Sedimentary features have not yet been studied in great detail. Slump structures and current features are fairly common, and gravitationally transported large blocks have been mapped in the early Tertiary rocks (Glover and Mattson, 1960). Detrital quartz is common only in post-Cretaceous sedimentary rocks (Mattson and Glover, 1960).

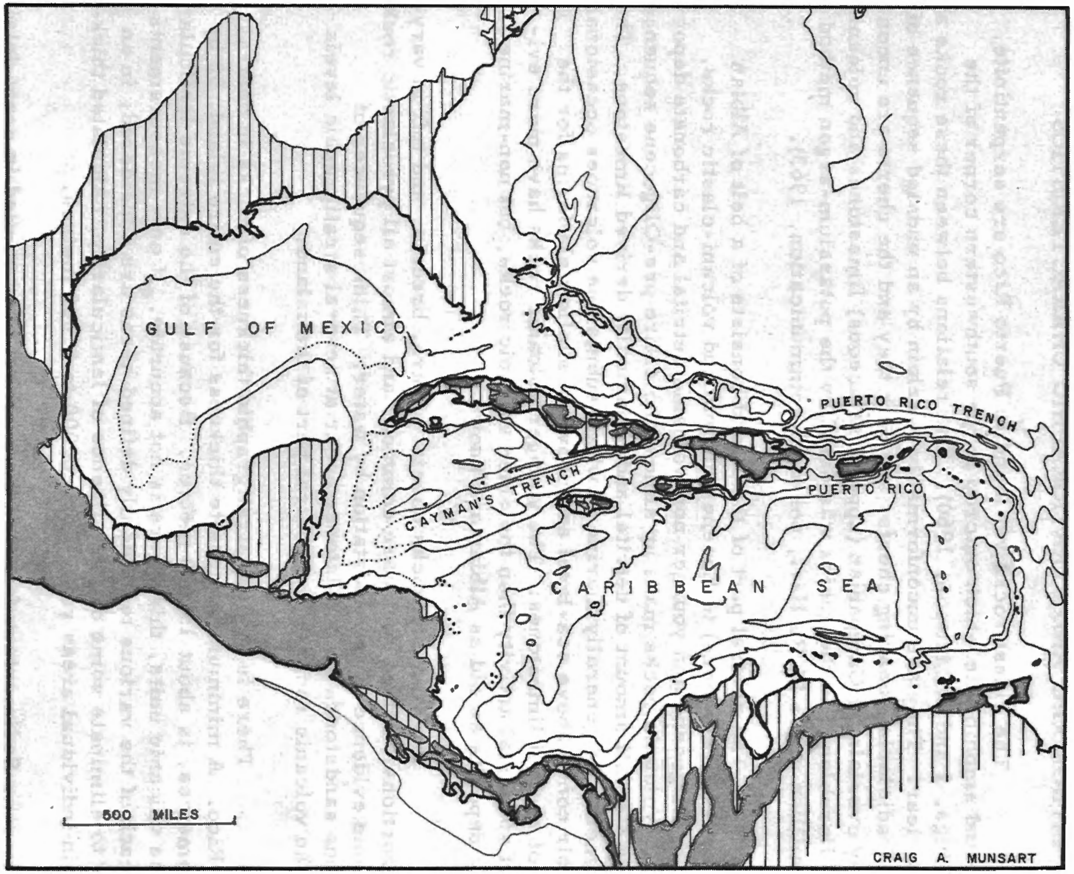

Figure 1. Puerto Rico and nearby areas. Shaded portions are exposures of pre-Tertiary rocks; lined areas are Tertiary rocks. Diagram adapted from Eardley (1962).

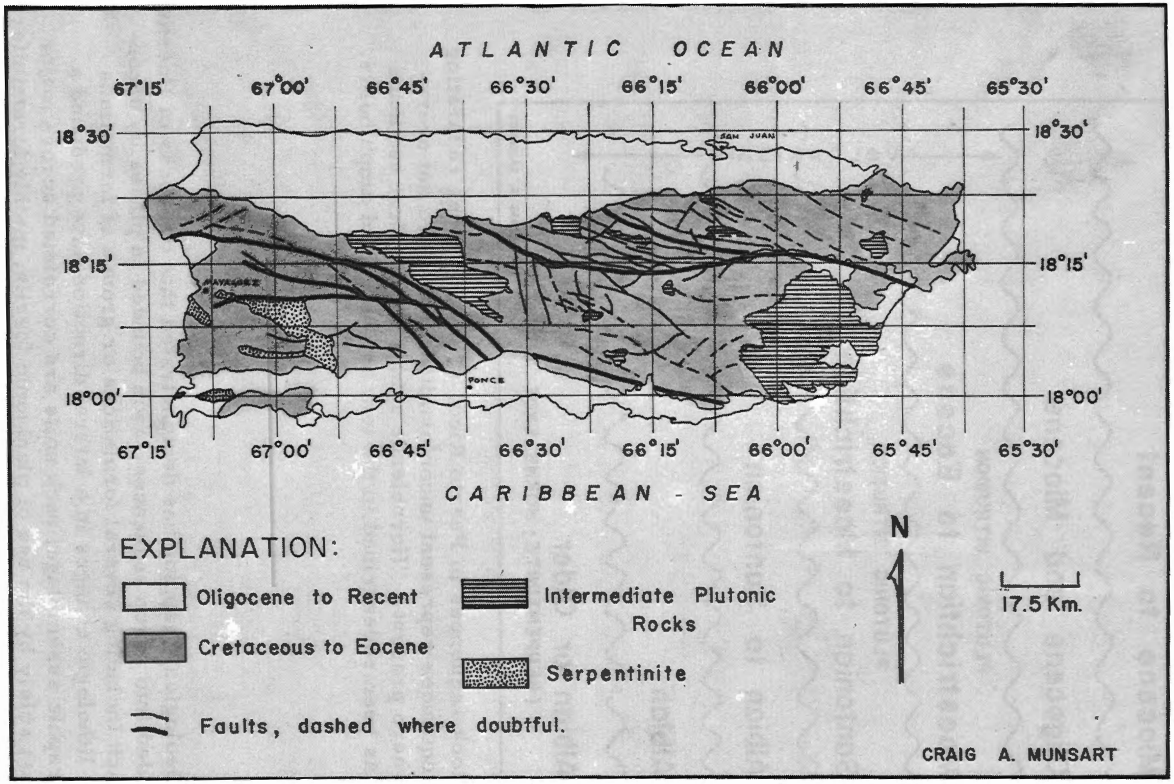

Figure 2. Geological sketch-map of Puerto Rico, modified from Briggs and Akers (1965). The major fault zones are shown as heavy lines. The southernmost serpentinite areas include other rocks (see text).

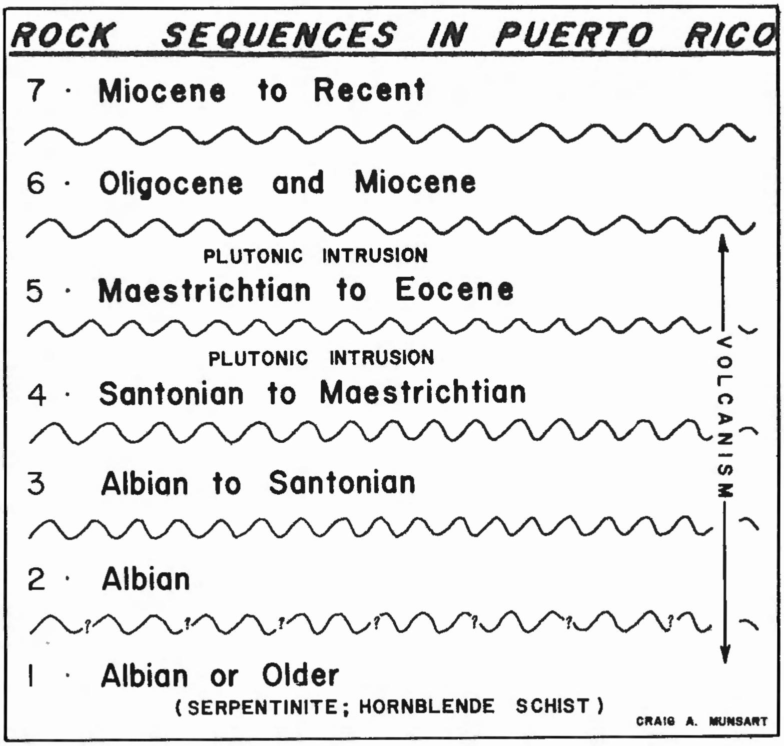

Figure 3. Rock sequences in Puerto Rico. The wavy lines separating sequences represent unconformities which are not everywhere present. "Hornblende schist" in the first sequence has been redescribed in the text as gneiss and amphibolite.

Geological mapping has demonstrated that the rocks of Puerto Rico can be divided into seven sequences, each bounded in places by unconformities and each including several formations or groups of formations (Fig. 3). Rapid lithologic changes in a lateral direction have produced a complex stratigraphic assemblage; rock units are correlated across major fault zones almost solely by the use of planktonic fossils, mainly foraminifera (Pessagno, 1960, 1961, 1962; Mattson, 1960, and in press).

GEOCHEMICAL CHARACTERISTICS

The oldest sequence (Fig. 3) belongs to the ophiolite suite. A single chemical analysis of amphibolite (Mattson, 1960) suggests it was derived from olivine basalt. The serpentinite is a normal serpentinized alpine peridotite (Burk, 1964). The oldest, relatively unmetamorphosed volcanic rocks (sequence No. 2 in Figure 3) have not yet been studied in detail, although both T.W. Donnelly and L. Glover (personal communications, 1963-1965) suggested that this level contains spilitic and keratophyric rocks. More than twenty chemical analyses of a suite of basalt and andesite from sequence No. 3 suggest alkaline basalt affinities (Mattson and Nelson, in preparation). These and other analyses from younger Puerto Rican sequences are illustrated in Figures 4, 5, 6, and 7, in terms of alkali-silica and other oxides. The alkaline nature of sequence No. 3 is clearly evident, as well as the calc-alkaline nature of the younger andesites and dacites.

The oldest plutonic intrusions, ranging from quartz diorite to quartz monzonite, cut Maestrichtian and older rocks. They provided a source for Eocene sediments, in which detrital quartz first becomes common. Because Eocene rocks are conformable with probable Paleocene and Maestrichtian strata in several parts of the island, plutonic intrusion probably occurred within the Maestrichtian. Three isotopic dates on zircons (lead-alpha method) and biotite (K-Ar method) from the plutonic rocks average 65 million years (U.S. Geological Survey, Isotope Geology Branch, determinations by T.W. Stearn and others, personal communication, 1962). A younger period of plutonic intrusion is believed to follow or accompany Eocene vulcanism. Chemical analyses of the plutonic rocks are included in Figures 4 to 7; they also belong to the calc-alkaline suite.

Most of the rocks in Puerto Rico show no evidence of deep burial. Metamorphism is only as high as the zeolite grade except near the batholiths where minerals of greenschist facies have developed. Borders of the batholiths and adjacent country rocks are foliated in several places, features suggesting forceful intrusion. In at least one area, plutonic rocks have intruded a formation only slightly older than the intrusion, allowing at the time of emplacement not more than 1,000 metres of well known rocks between the top of the pluton and the earth's surface. In most areas, however, the plutons were emplaced in sequence No. 2 under a known stratigraphic cover of 5,000 to 7,000 metres.

TECTONIC CHARACTERISTICS

The pre-Oligocene rocks of Puerto Rico are intensely faulted, as shown in Figures 2 and 8. Vertical faults with apparent vertical movements are abundant and closely spaced. In several areas they show differential vertical movements in which the centre of the island rose relative to

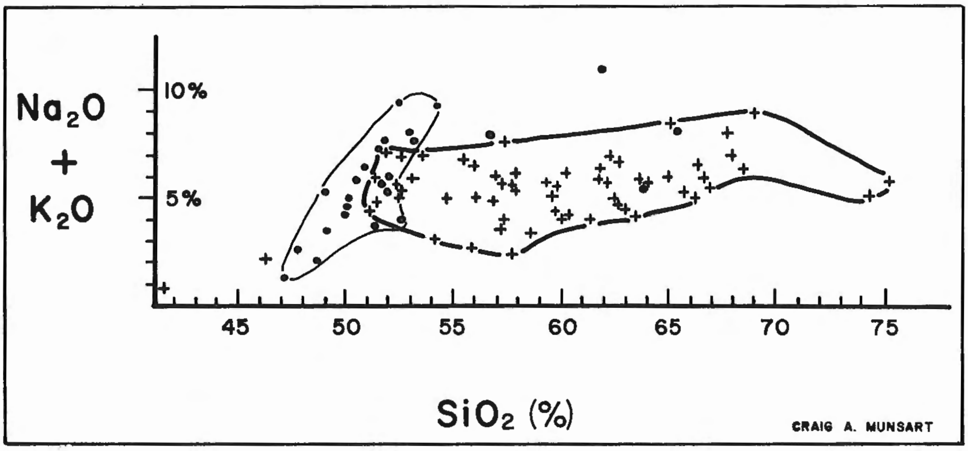

Figure 4. Alkali-silica plot of Puerto Rican chemical analyses. Analyses of rocks from the sequence No. 3 are shown as dots; those from younger sequences as crosses. The two analyses with low silica represent basic facies of the plutonic rocks.

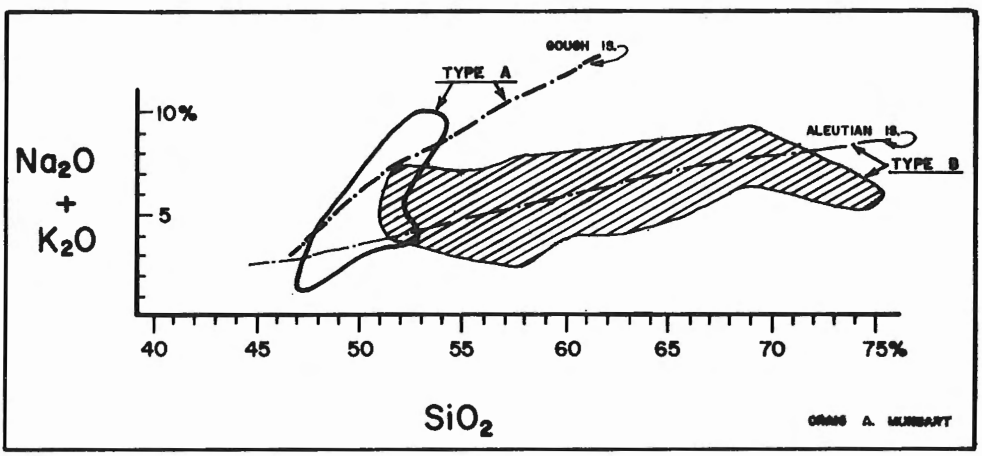

Figure 5. Generalized alkali-silica plot of Puerto Rican rock analyses. Type A: field of sequence No. 3, Puerto Rican analyses, compared with a visual best-fit curve for average analyses from Gough Island (Le Maitre, 1962), an alkali basalt suite; Type B: field of younger sequences, Puerto Rican analyses, compared with a visual best-fit curve for 154 analyses from the Aleutian Islands (Coats, 1951, 1952; U.S. Geol. Survey), a calc-alkaline rock suite.

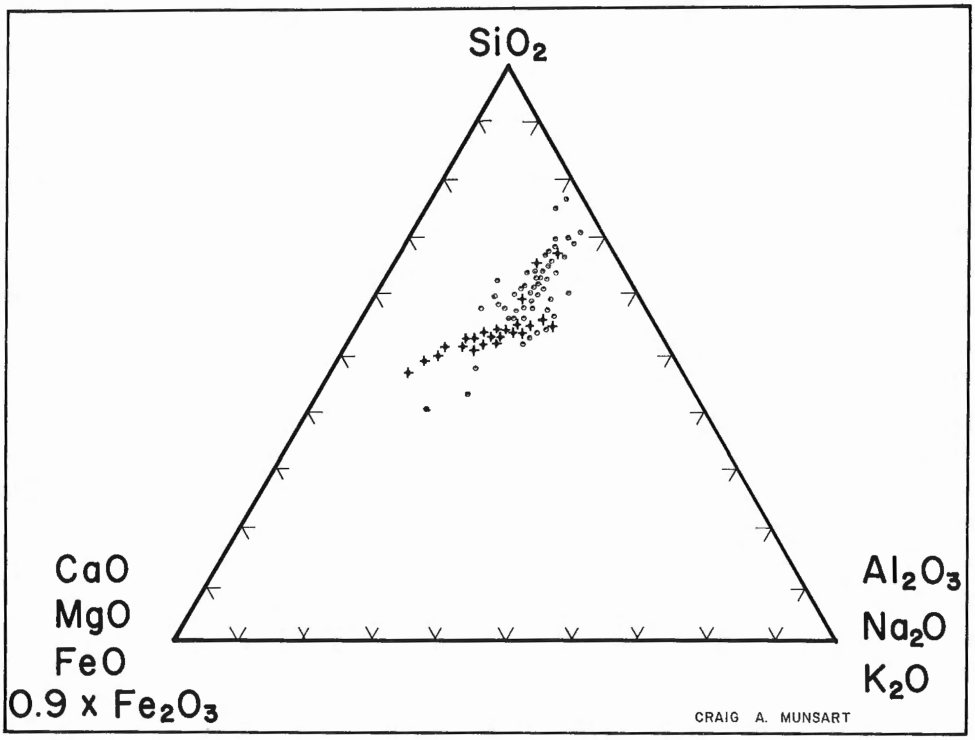

Figure 6. Puerto Rican rock analyses plotted on an eight-oxide triangular diagram. Sequence No. 3 analyses shown as crosses; analyses of younger sequences as circles. Note that the symbols are reversed from those used in Figure 4.

the northern and southern parts; they thus may be related to the uplift that has brought Puerto Rico above sea-level. Some transcurrent faults have been mapped; most trend east and have left-lateral movements. Two major fault zones crossing the island, shown as heavy lines in Figure 2, have transcurrent movement probably of the order of tens of kilometres. The exact amount is not yet known because lithologic and stratigraphic correlation across the zones is very difficult to establish. Both zones are deflected to the northwest near the centre of the island, probably because of the buttressing effect of the batholith in that area.

Steep reverse faults and some low-angle faults occur near the serpentinite in southwestern Puerto Rico. Gently dipping surfaces showing

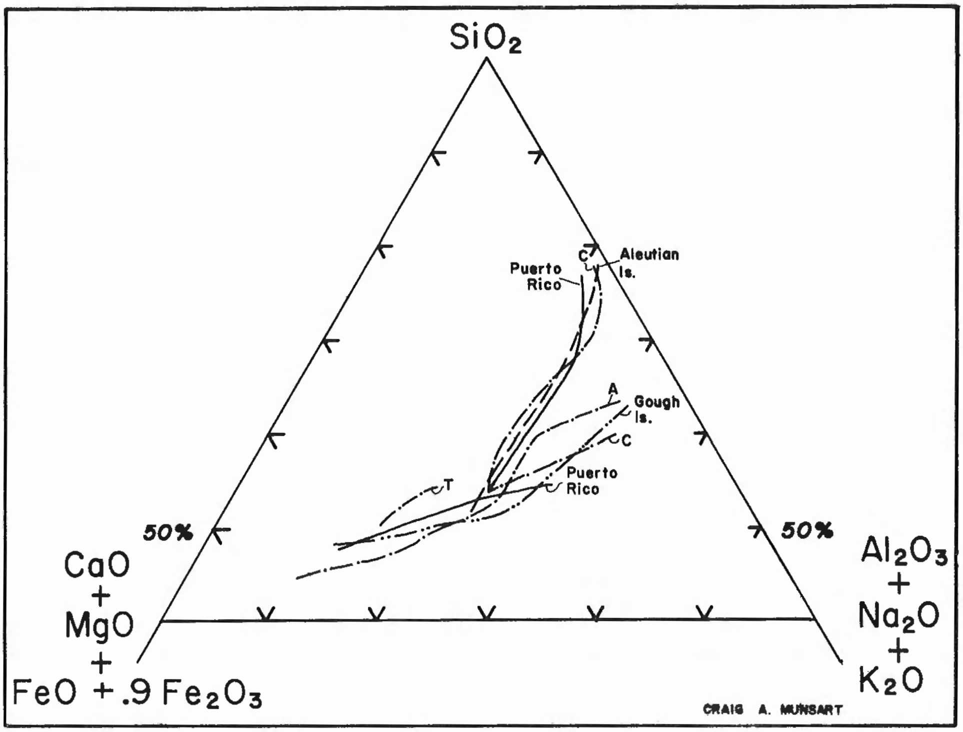

Figure 7. Generalized eight-oxide triangular plot of Puerto Rican rock analyses, enlarged to show only the field of 40-100% SiO_2. Shows visual best-fit curves for sequence No. 3, Puerto Rican analyses, other Puerto Rican analyses, Aleutian Island calc-alkaline analyses, and Gough Island alkalic analyses (see Figure 5 for references), plus average alkalic (A), calc-alkalic (C....C), and tholeiitic (T) analyses of Nockolds (1954).

evidence of dip-slip movements occur in southwestern Puerto Rico (Mattson, 1960) and south-central Puerto Rico (Glover and Mattson, 1960). They are interpreted as gravitational movements which took place before complete consolidation of the sediments. Blocks as long as 1 to 2 kilometres have moved. The southwestern blocks moved during Maestrichtian and perhaps early Tertiary times; those in south-central Puerto Rico moved during early Tertiary times. In both areas the movement pattern seems to be from south to north.

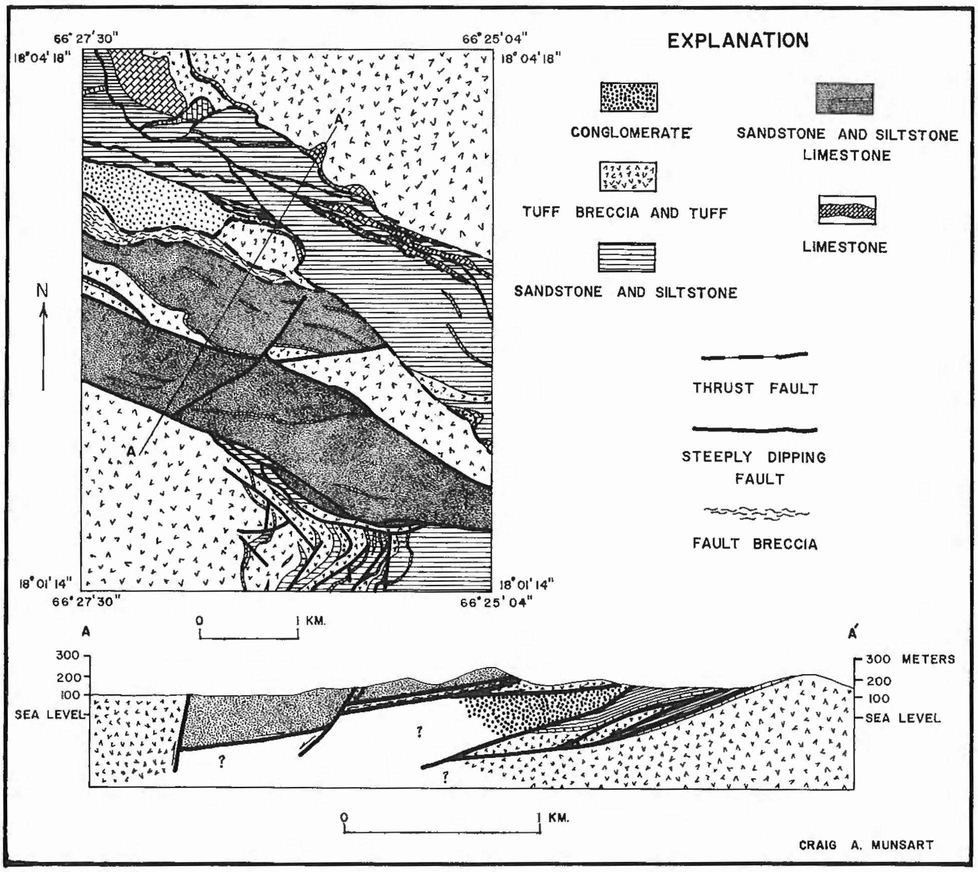

Figure 8. Geological map and cross-section of an area east of Ponce, Puerto Rico. (From Glover and Mattson, 1960) The thrust faults shown on the map are interpreted as planes of gravitational movement. Lithologic units are listed in approximate order of geological age; several units occur at more than one level.

Figure 8 shows an area in south-central Puerto Rico, in which the complexity of the geology is fairly typical of those areas where marker units are abundant enough to permit detailed mapping. Normal faults, transcurrent faults (part of the major southern Puerto Rico fault zone), and gently dipping surfaces showing dip-slip movements (called thrust faults on the illustration) are all shown.

Folds in the pre-Oligocene strata are remarkably broad and gentle, in most places with limbs dipping from 20 to 40 degrees. The axes are from 10 to 20 kilometres apart. One major anticline occurs in the central part of the island, lying approximately parallel with and between the two major fault zones. South of this anticline is a synclinal zone and south and southwest of the synclinal zone is another anticlinal area. This southwestern anticlinal area has different characteristics from the rest of Puerto Rico: within it are several anticlines with serpentinite in their cores, and between the anticlines are rather tight synclines in which bedding dips of 40 degrees to vertical are common. Some beds are overturned to the south. Strata lying above the serpentinite in this area constitute perhaps 10 to 30 per cent of the thickness measured elsewhere on the island. The tighter folds and steeper dips may have developed because of this very thin section.

The Table summarizes present-day knowledge of the sedimentary, volcanic, and igneous rocks of Puerto Rico.

DISCUSSION

The lack of detrital quartz in the older rocks, the presence of serpentinite basement in part of the island, and the location of the island within an oceanic area with no record of any nearby continental landmass or borderland, all suggest that the crust beneath Puerto Rico may be of oceanic character. However, geophysical data indicate a probable crustal thickness of about 30 kilometres for the central part of the island (see, for example, Talwani, 1964), comparable to continental crustal thicknesses. Stratigraphic thickness in single tectonic areas on the island is not more than about 6 to 8 kilometres. Thus, roughly the lower 22 kilometres of crust are not yet identified. Talwani (1964, his Figure 10) showed this same division of the crust beneath the island, that is, an upper 8-kilometre layer with characteristics similar to the 5.5 km/sec layer of oceanic crust, and a lower 22-kilometre layer with characteristics similar to the 7.0 km/sec oceanic crustal layer. My estimates of thicknesses were derived independently from those of Talwani, and by an entirely different approach. Both sets are somewhat subjective, but it is interesting that they are approximately the same. I suggest that the lower crustal layer beneath Puerto Rico is serpentinite, and that it is similar to the lower oceanic crustal layer.

Table – Sequences of sedimentary and volcanic rocks in Puerto Rico

Age of sequence	1. Albian or older (Lower Cret. or older)	2. Albian (latest Lower Cret.)	3. Albian to Santonian (latest Lower Cret. to Upper Cret.)	4. Santonian to Maestrichtian (Upper Cret.)	5. Maestrichtian to Eocene (Upper Cret. to Eocene)	6. Oligocene Miocene	7. Miocene to present
Approximate range of thickness	more than 300 m	zero to more than 5,000 m	250 to 2,700 m	700 to more than 4,000 m	zero to more than 2,700 m	zero to more than 1,700 m	variable
Area of best exposure	southwest	east, southeast	central	southwest, south-central	south-central	north coast	north coast
Character of lower contact	unknown	unknown	disconformity or slight angular unconformity	disconformity to slight angular unconformity	angular unconformity	angular unconformity	slight angular unconformity
Sedimentary and volcanic rock types	spilite; bedded chert; hornblende schist of basaltic composition	andesite; spilite and keratophyre (?); rare limestone and clastic sedimentary rocks	basalt and andesite lava, including pillow lava; pyroclastic rocks; thicken to north. Siltstone, mudstone, minor limestone, thicken to south	southwest: fine-grained limestone. West: lava, pyroclastic rocks, mudstone, minor limestone. South-central: conglomerate, lava, pyroclastic rocks, minor mudstone and limestone	dacitic and andesitic volcanic rocks: lava and pyroclastic rocks; algal limestone, rudist limestone, some clastic rocks	limestone, some sandstone, marly clay, silt, and conglomerate	sand, cemented dune sand, alluvial deposits
Depositional environment	marine vulcanism; deep-water sedimentation	volcanic areas; shallow marine (?)	marine volcanic activity in north-central P.R.; wide-spread marine deposition to south	volcanic centres in central and western P.R.; shallow-water marine, less volcanic to SW. Subaerial erosion of volcanic areas in central P.R.	shallow marine with common volcanic activity. Volcanoes in SW, NW, and south-central P.R.	shallow marine and non-marine erosion of deformed volcanic island; reef formation	coastal, non-marine; some river terrace deposits
Igneous intrusive activity; metamorphism	emplacement of serpentinized peridotite at this time or earlier; metamorphism to gneiss of amphibole grade	possible small volcanic intrusions	possible small volcanic intrusions	intrusion of and metamorphism by plutons of granodiorite and quartz monzonite at end of sequence	dacite dykes and small stocks; these are cut by small porphyritic quartz diorite (?) stocks and dykes	none known	none known
Tectonic activity during and immediately following	uplift; erosion; folding	unknown	faulting; possible broad folding; uplift and erosion	subsidence followed by uplift; faulting and broad folding; tectonic intrusion of small bodies of sheared serpentinite	subsidence followed by uplift; folding, erosion; gravity-sliding of large blocks	uplift and erosion followed by subsidence; faulting	uplift, erosion, minor faulting

A related problem is the origin of the volcanic and batholithic magmas; these cannot be derived from fusion of granitic crust if no such crust exists beneath Puerto Rico. The petrochemistry of relatively few stratigraphic sequences in Puerto Rico has been studied. But, thus far, it seems possible that partial fusion of peridotite in the mantle produced the initial volcanic liquids, and that successive refusions of these extrusive volcanic piles and their roots formed younger andesitic volcanic liquids and the batholithic magma. Perhaps three such refusions have occurred: in the Albian, Santonian, and Maestrichtian.

The localization and shaping of the island arc of the Greater Antilles must have been determined by some fundamental process. Tensional fractures, compressional folds, horizontal fault movements, and fortuitous drifting of continental fragments have all been suggested recently. With the evidence at hand, I favour the following: the alignment of volcanoes and thick sedimentation along a linear zone, perhaps (as suggested by Hess, in press) the locus of downward movement in a large convection cell, in Cretaceous and early Tertiary times; deformation of at least the eastern Greater Antilles by drag-folding along a major west-trending fracture zone in which the movement is dominantly horizontal and left-lateral. The fracture zone is topographically expressed by the Bartlett Trough and the Puerto Rico Trench (Fig. 1), and could be the somewhat distorted eastward continuation of the Clarion Fracture Zone, or a northeastern branch of the Clipperton Fracture Zone. Thus the initiation of vulcanism and to some extent the topographic relief of ridge and trench may be due to the plunge of convection currents, while the actual present location of the zone may be the result of folding due to differential horizontal movement of the blocks. Formation of the trench apparently followed the volcanic activity and deformation of the strata to form the island. This separation in time reflects two different tectonic styles: the first, volcanic and compressional with dominant vertical movements; and the second, non-volcanic with possible horizontal movement in addition to vertical movements. Perhaps two different causes have been operative here, and theories of origin should not try to connect them.

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DISCUSSION

Prof. H. Kuno (Japan)

I have three questions: 1. What is the relation in space and time between the alkali rock series and the other less alkaline series? 2. Have you any analyses of non-porphyritic basalts? 3. Why do you believe there are no granitic rocks beneath the island?

Dr. Mattson

The alkali rock series is sequence No. 3 on Figure 3 and the Table. It occurs in central Puerto Rico with younger calc-alkaline volcanic rocks lying to the north and south. Sequence No. 2 is perhaps spilitic in character (see text); it outcrops in the same area as the alkalic sequence. The sequence Nos. 4 and 5 are calc-alkaline, although sequence No. 4 is represented by only a few analyses and thus may be misidentified. In light of Kuno's paper describing a correlation of magma types with a dipping zone of earthquake epicentres near Japan (this volume; comment added in proof), it is interesting to note here that in the Puerto Rico area M. Ewing (paper presented at 4th Caribbean Geological Conference, Trinidad, 1965) reported a vertical zone of epicentres beneath the trench and island, a possible explanation for the occurrence of several magma types in the same small area of Puerto Rico.

In answer to the second question: there are no analyses of non-porphyritic rocks, and therefore the data are not, strictly speaking, representative of the original liquids.

In answer to the third question: there is no direct evidence of a granitic crust in the area of Puerto Rico. No quartzo-feldspathic basement is exposed; there is no detrital debris, such as granite pebbles and quartz grains, that might have been derived from such a crust. All sediments are derived from volcanic materials or by organic processes (limestones) until Eocene when the plutonic rocks first became exposed to erosion. These plutonic rocks, quartz diorite to quartz monzonite, could be considered evidence for a granitic crust, but I prefer to derive them by successive partial fusions of the lower parts of the volcanic pile.

GEOLOGICAL STUDIES OF THE WEST INDIES[1]

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University of Miami

Abstract

Dredging and seismic reflection profiles show that the Aves Ridge is at least partly volcanic in origin but vertical movements appear to have been slight and only one small and shallow guyot has been found. Reflection lines in the northern Lesser Antilles indicate that the younger vulcanism has not migrated westward but that it was initiated on a line diverging westward from the original volcanic arc. Other reflection lines do not show the South Caribbean Fault north of Trinidad but do show the Tertiary sediments which outcrop in Barbados are more extensively distributed on the Barbados Ridge. It is suggested that these sediments were derived from the north flank of an east-west trending Late Cretaceous mountain range in northern Trinidad but that they are separated from the central basin of Trinidad to the south. A relationship may exist between the filling of a trench and its later compression and uplift.

INTRODUCTION

The Atlantic Ocean and the Indian Ocean share the distinction of having very few island arc-trench systems. The West Indies island arc is one of the most complicated and perplexing tectonic features of the ocean basins.

Although literature on the area is extensive, many parts of the region are poorly known. Most recent studies have been devoted to the Puerto Rico Trench, while the volcanic island area has received considerably less attention. In this latter area therefore, we devoted most of our efforts. Our first cruise, approximately three years ago (1963), was short and primarily a reconnaissance of certain selected areas. Our second, longer cruise about two years ago (1964), was combined with the field examination of islands of particular interest. We now have enough data to propose some new ideas for testing.

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[1]Contribution No. 642 from the Marine Laboratory, Institute of Marine Science, University of Miami, Miami, Florida.

GEOLOGICAL CHARACTERISTICS

Figure 1 shows a chart of the Lesser Antilles. Most obvious of the geographic features is the curved row of volcanic islands extending from Grenada in the south to Saba on the north. In the northern part, a second row of islands with low relief diverges from the arc of volcanic islands, starting with the eastern islands of Guadaloupe and Marie Galante and extending northward to Anguilla and Sombrero Islands. This outer row of islands consists generally of eroded and intruded volcanic rocks overlain by shallow-water, marine limestones and tuffs of Eocene to Miocene age. On the whole they indicate a history of vulcanism and intrusion, followed by erosion and shallow subsidence, then accumulation of the limestones and tuffs, tilting and re-emergence or uplift in varying degrees. Farther south, similar limestones are exposed along the eastern shore of Martinique. The banks between Marie Galante and Martinique are thought to be submerged structures similar to those exposed on the islands. Efforts to sample these banks have been unsuccessful.

Barbados is geologically unrelated to the islands of the main arc. Beneath a capping of reef limestones are exposed a series of spectacularly folded and faulted sedimentary rocks. The oldest are the Scotland flysch sediments of Eocene age. These are overlain by progressively finer, less deformed, and more pelagic sediments, some of which are rather similar to modern pelagic carbonate sediments. The youngest rocks in this group are in the Bissex Hills Formation of probable early Miocene age. Deformational structures strike predominantly east-northeast, about 60 degrees from the trend of the island arc. The coarser parts of the flysch sediments contain abundant rounded pebbles of milky quartz as much as a centimetre and more in diameter and most exhibit graded bedding, flute casts, load casts and a variety of the other structures typical of turbidites. Similar rocks have been found to depths of about 15,000 feet beneath Barbados in oil exploration holes (Baadsgaard, 1960).

The Island of Tobago consists in general of rocks very similar to those exposed in the north range of Trinidad. In both places, the rocks strike east-northeasterly and consist of low-grade metamorphic and volcanic rocks principally of early Cretaceous age. On Tobago they are capped locally by younger marine sediments.

GRAVITY DATA

The axis of the negative gravity anomaly of the West Indian island arc parallels and lies seaward of the volcanic island arc, and coincides with the Barbados Ridge and passes through the island of Barbados (Hess, 1933). Gravity anomalies are generally positive over the island arc; and a small positive anomaly band lies parallel with and seaward of the belt of negative anomalies.

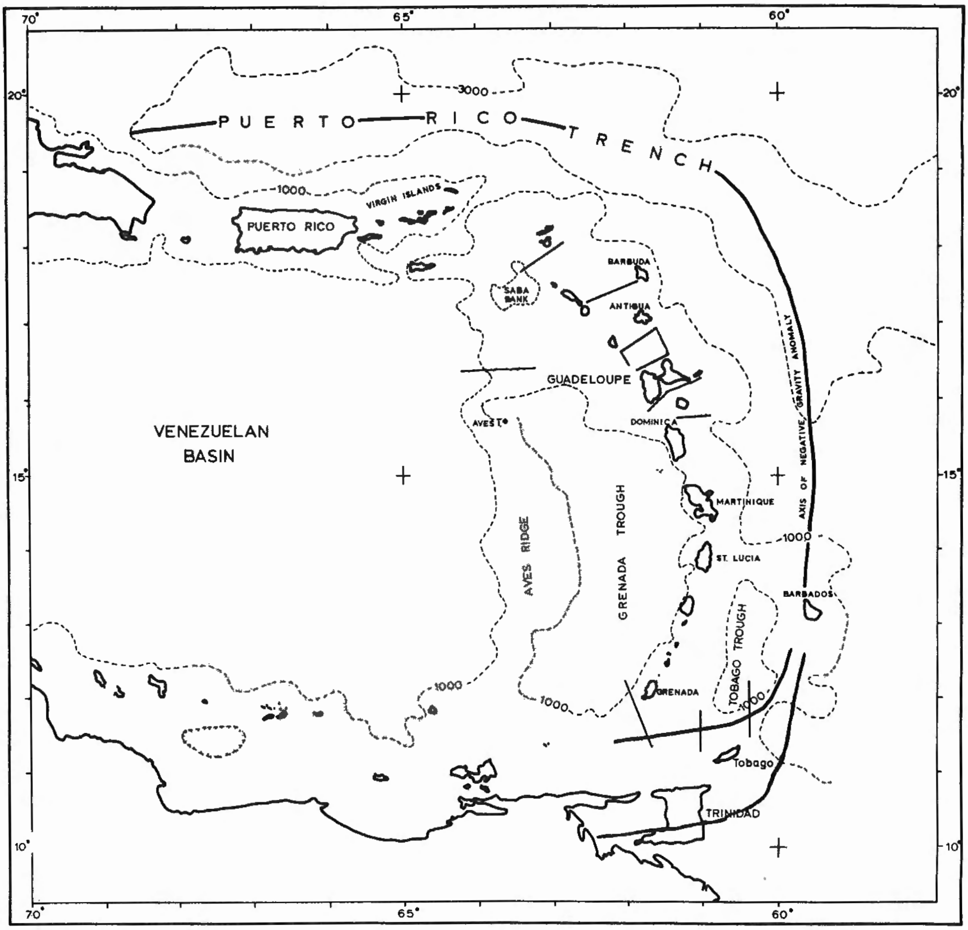

Figure 1. Island arc of Lesser Antilles. Locations of Arcer Profiles of Figures 3, 5, and 6 are shown.

New and unpublished British gravity data by Masson-Smith and Andrew (1965) (Fig. 2) indicate that the axis of the negative gravity curves westward north of Tobago and a pronounced negative anomaly trough extends westward between Grenada and South America approximately along the continental slope north of Trinidad and Venezuela. A near-zero or slightly positive gravity anomaly seems to occur along the north coasts of Trinidad and Venezuela.

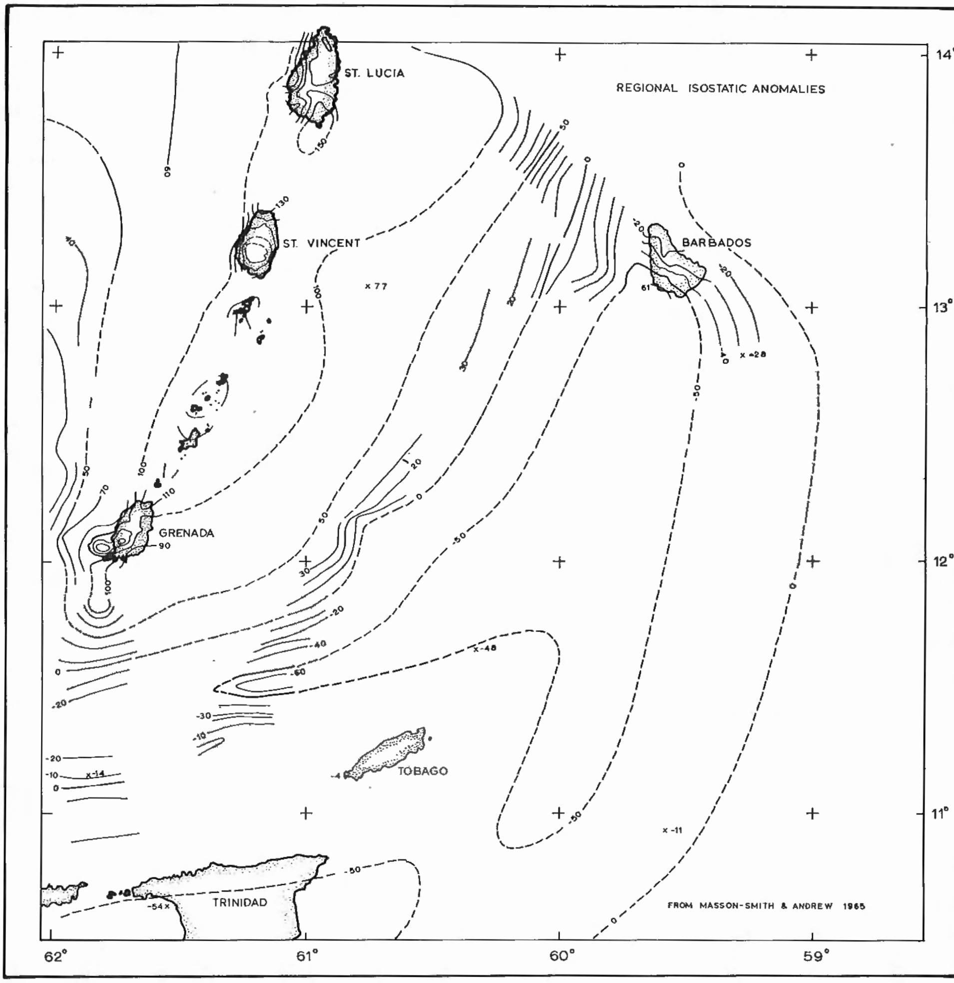

Figure 2. West Indian gravity data. (After Masson-Smith and Andrew, 1965)

SEISMIC DATA

A series of seismic reflection profiles using an electric arc source was made in the northern part of the Lesser Antilles island arc. Figure 3 shows sections redrawn from these profiles. The northernmost section begins off Saba and the southern one off Dominica. The profiles all extend easterly across the arc, that is from left to right in Figure 3, but they have different vertical scales. In the western part of the sections are the younger volcanic rocks. On the best records, these volcanics appear to be cut by many faults. Two small parasitic cones are outlined on the west end of the Basse Terre-La Desirade section. The eastern ends of the sections cover the more contorted older sediments and igneous rocks. The central parts of the northern sections show the basin between the islands filled with young marine sediments. The many bedding surfaces detected in these sediments probably represent volcanic debris from adjacent islands. Dipping westward beneath these young marine sediments is an erosion surface on top of the older rocks of the outer arc. South of Guadeloupe the central basin appears to drain into either the Atlantic or the Caribbean and a distinct trough appears. Figure 4 shows an idealized composite section of the northern profiles in Figure 3. It appears that the westward shift of vulcanism along the crest of the ridge was a clearly defined change in the site of activity and not a progressive westward migration of vulcanism. The earlier volcanic arc may coincide with the present-day vulcanism in the southern Antilles but the younger vulcanism was initiated farther to the west in the northern Antilles thereby widening the North Antillean Ridge.

A reflection profile across Aves Ridge north of Aves Island (Fig. 5) shows the Grenada Trough to be a basin containing a thick section of sediments. The ridge is evidently volcanic here and, while the volcano is nearly symmetrical, the ridge appears quite asymmetrical with its steeper and longer slope leading westward into the Venezuelan Basin and the gentle slope eastward into the Grenada Trough. A seamount southwest of Aves Island yielded basalt in a dredge haul and a small guyot was discovered at a depth of 16 fathoms south of Aves Island. The subsidence that produced this guyot and provided an opportunity for the growth of the coral cap on Aves Island appears not to have been widespread. Several other crossings of Aves Ridge in search of guyots have so far been unsuccessful. Vening Meinesz (1964, p. 76) considered Aves Ridge to be a "third arc" produced by a brief and small-scale compression by a small convection cell. The apparent absence of any evidence of large vertical movements and the lack of present-day seismic activity support this suggestion.

Figure 6 shows three more or less north-south profiles off the continental slope north of Trinidad and Tobago. The easternmost line off Tobago was obtained on our first cruise and appeared to confirm the "South Caribbean Fault" proposed by Barr (1958) and others, in the graben-like structure shown. On the next cruise, the other two profiles were obtained to investigate the continuity of this feature. While several minor faults appear in these records, the major fault could not be recognized. It appears that major recent transcurrent displacements in this region should be attributed to the El Pilar Fault which forms the southern boundary of the mountains of northern Trinidad and extends westward through Venezuela.

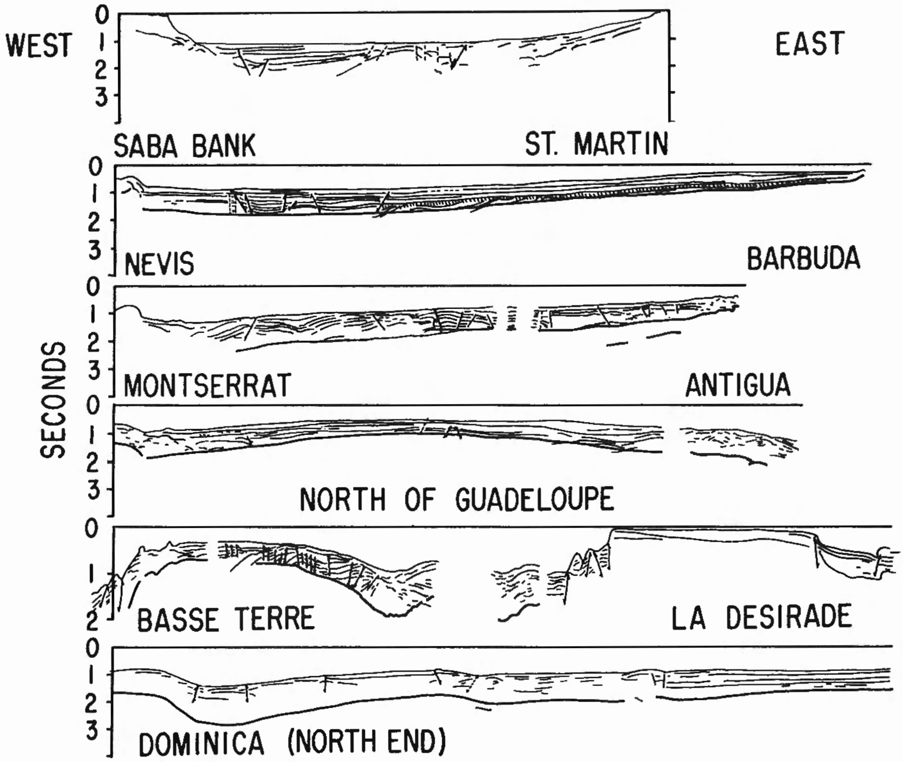

Figure 3. Profiles across northern Lesser Antilles. (Redrawn from Arcer Records)

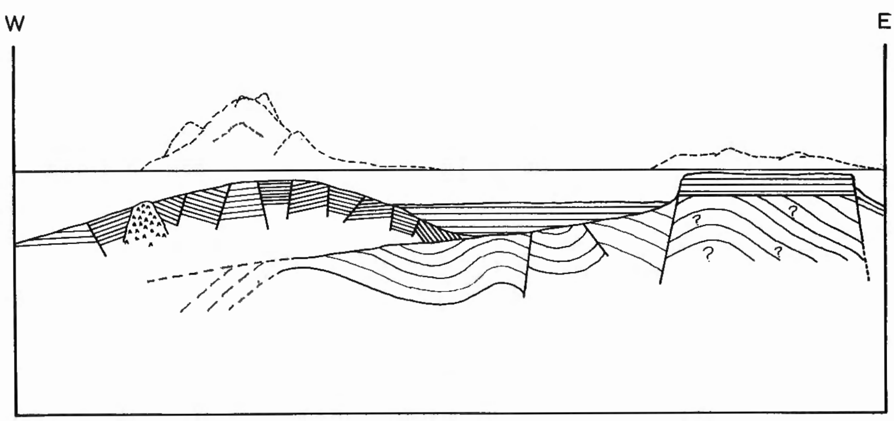

Figure 4. Idealized east-west profile across island arc.

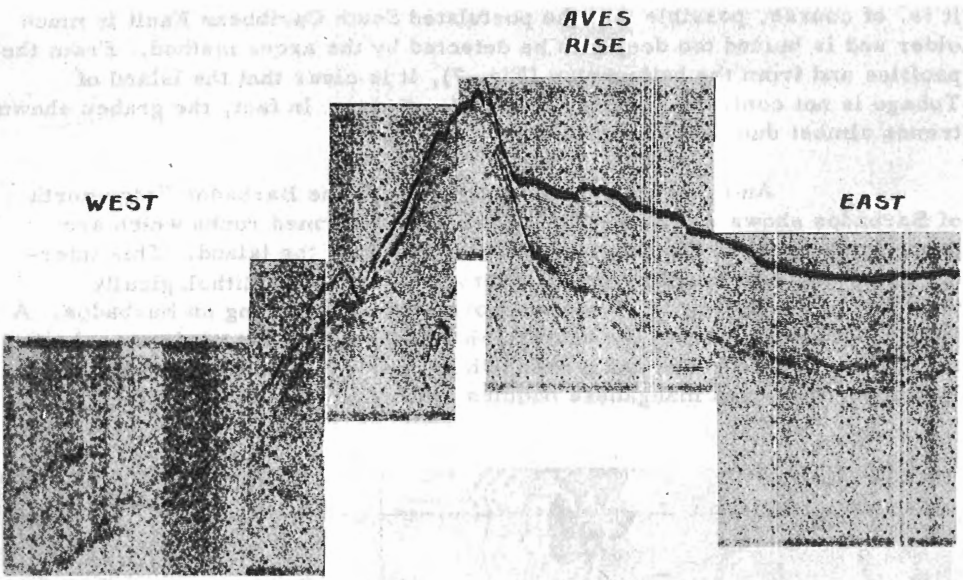

Figure 5. Arcer profile across Aves Ridge north of Aves Island.

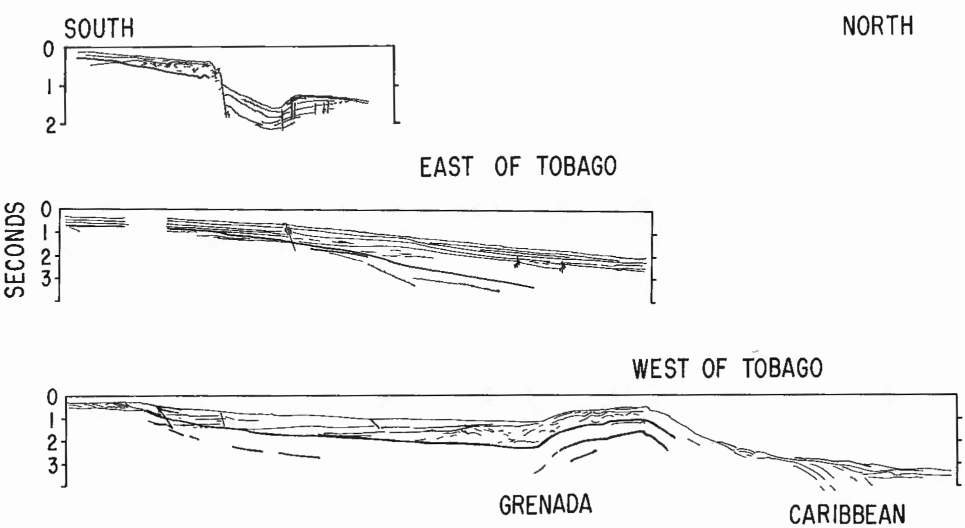

Figure 6. Profiles across southern Lesser Antilles.
(Redrawn from Arcer Records)

It is, of course, possible that the postulated South Caribbean Fault is much older and is buried too deeply to be detected by the arcer method. From the profiles and from the bathymetry (Fig. 7), it is clear that the Island of Tobago is not continuous with the Barbados Ridge. In fact, the graben shown trends almost due east.

An east-west profile made across the Barbados Ridge north of Barbados shows a thick section of strongly deformed rocks which are doubtless similar to the Tertiary rocks exposed on the island. This interpretation was confirmed by the recovery of flysch rocks lithologically identical to the Eocene St. Andrews Formation outcropping on Barbados. A north-south profile along the eastern side of the island also indicates these strongly deformed rocks and a dredge haul in 200 fathoms of water south of Barbados recovered manganese nodules embedded in a lithified limestone

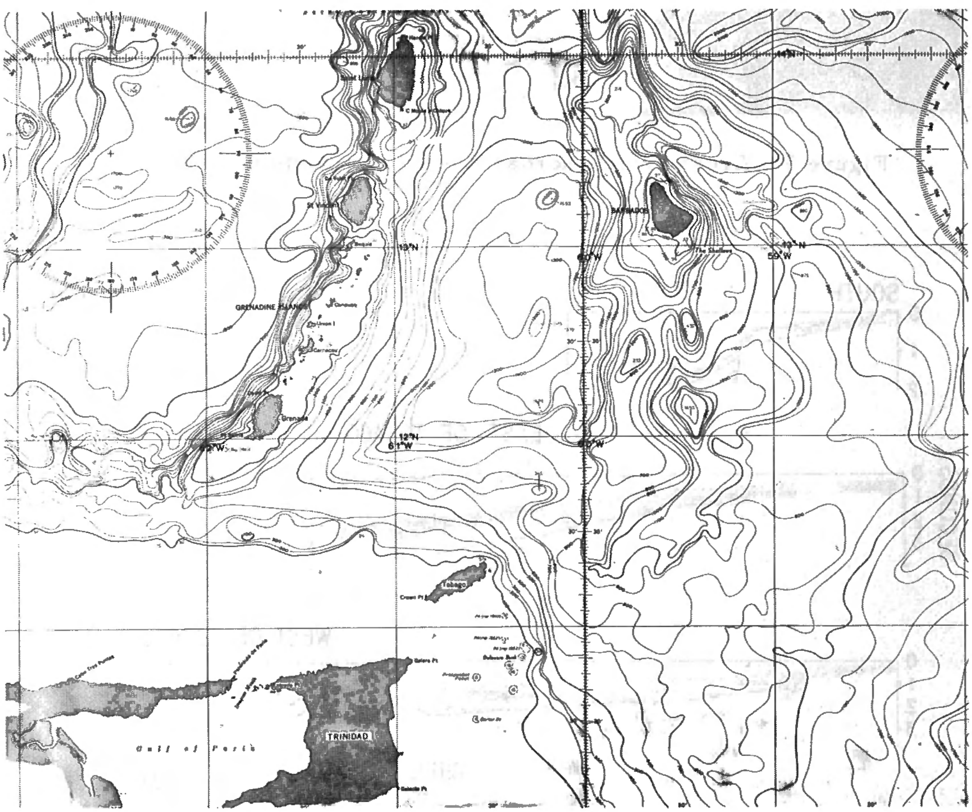

Figure 7. Bathymetric Chart, Trinidad to Barbados. (From Bottom Contour Charts 0703N and 0603N)

conglomerate. This material is being studied, but the limestone is suspected to represent a facies of the upper Oceanic or Bissex Hill Formation. As one might expect from the topography, the older sediments of Barbados Island occur extensively along the Barbados Ridge. It is clear that the ridge is not a simple elongate ridge, but rather is complicated by many cross-structures. A notable example is the double ridge with a total width of over 50 miles just north of the island.

MANGANESE NODULES

The Barbados manganese nodules (Fig. 8) were recovered at a depth of about 200 fathoms. They are very peculiar nodules because of their size and shape, the depth from which they were recovered, and the fact that they are firmly embedded in sediment. All are either nearly spherical cannon balls or flattened pancake-like objects. Some appear slightly eroded; and there is no evidence of recent manganese accumulation.

DISCUSSION

A number of authors, notably Hess and Barr, have debated the relationship between the filled, compressed, and uplifted trench sediments on Barbados, the rocks of similar age in the central basin of Trinidad, and the projected trend of the Northern Range of Trinidad. Tobago and the mountains in northern Trinidad are structurally and geologically similar. It is believed that the northeasterly elongated shape of Tobago is more probably the result of erosion and minor structural processes than of processes of fundamental significance. The trend of the graben off the northeastern corner of the Tobago Shelf is, like the strike of the structure of the Northern Range of Trinidad, only very slightly north of due east. The absence of an abrupt curve to the northeast and north is also confirmed by recent gravity data and by the bathymetry. Therefore, it appears that a simple relationship between Trinidad and Barbados is improbable as suggested by Barr (1958). However, Barr suggested that a major transcurrent fault extends along the southern edge of the Caribbean. He proposed that this fault parallels the continental shelf-edge north of Trinidad and Venezuela, and occurs between the shelf-edge and the end of the Grenada Ridge. It has been shown that recent data do not support the existence of this fault. Rather it would appear that neither a connection nor a dramatic boundary exists between these Barbados, and Trinidad and Tobago features.

If the Northern Range of Trinidad is not directly related to Barbados (and it certainly cannot be connected to the volcanic island arc), one must then consider the possibility that this tectonic feature simply dies out at the edge of the continental block. While this suggestion may be

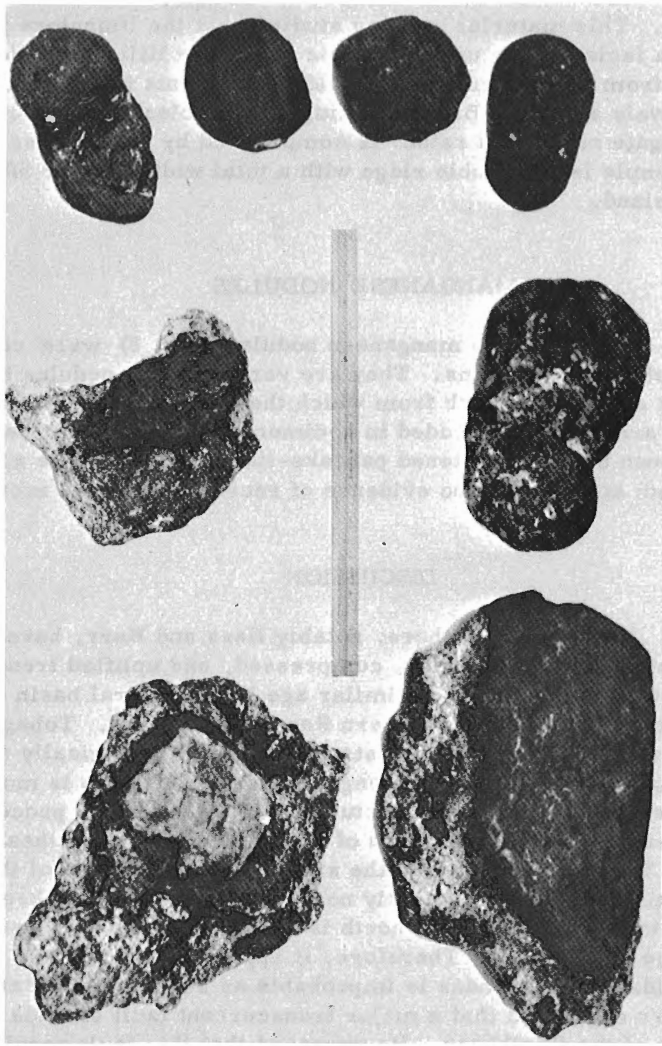

Figure 8. Manganese nodules from dredge hauls near and south of Barbados. One-foot ruler for scale.

surprising, the same situation obtains at the north end of the Appalachians, both ends of the Pyrenees, the western end of the Atlas Mountains, and probably in other places as well. Assuming this model to be true for the moment and following to some extent the ideas of Senn (1940), one might interpret the flysch sediments exposed on Barbados and detected elsewhere along the Barbados Ridge to be turbidity current sediments which filled a then much more extensive Antillean Trench from its southern end during degradation of a large landmass that may have included much of what is now the shelf off Trinidad, Tobago, and Venezuela. At least some of the chaotic deformation of the older rocks of Barbados is doubtless attributable to penecontemporaneous sliding and slumping. The manganese nodules grew on the unlithified top of the pelagic sediments in the trench, probably after the start of compressional deformation and uplift but before they reached the present shallow depth and before the associated sediment was lithified. Detritus from the southern flank of this suggested peninsular landmass would help fill the parallel basin of central Trinidad. These events may have followed a period of mountain building in the late Cretaceous; and remnants of these mountains may be the northern ranges of Trinidad and Venezuela.

It was shown (Hurley, 1960) that modern filling of the eastern half of the Aleutian Trench is principally by axial flow from east to west along the trench floor and that the amount of fill is influenced strongly by pinching and partial damming of the trench by a low cross-ridge supporting a row of very large volcanoes. Similarly, the axial fill of the Caribbean Trench may have been limited by deformation related to the Barracuda Fault Scarp, and this damming may have left more or less unfilled the only surviving topographic expression of this trench, that now called the Puerto Rico Trench. It has been shown (Ewing and Ewing, 1962), however, that the comparatively small amount of sedimentary fill in the Puerto Rico Trench is essentially undeformed. Thus there exists a trench, the continuity of which is undeniably demonstrated by the belt of negative gravity anomalies, in which the northern end is only slightly filled with sediment and has apparently undergone little or no deformation while the southern end apparently received large amounts of sediment which were later, as Hess (1933) described it, "squeezed upward like toothpaste out of a tube", by the subsequent closing of the tectogene.

One can, therefore, conclude that the trench-producing mechanism can permit widely varying stages of activity along its axis at any given time and that the later compression of the Southern Antilles Trench is not genetically related to the active sedimentation there. A second possible explanation is that some relationship exists between the trench-filling sedimentation and the subsequent deformation processes. Perhaps the filling of a trench at some rate or to some extent triggers the process leading to later compression and uplift. This is not to suggest that the sedimentation influences mantle convection cells that may produce the tectogene but perhaps sedimentation does alter the response of the crust to these forces. Examples of other trenches partly filled and compressed may be Timor in the Mesozoic Java-Timor Trench, and a Mesozoic trench in continuity with the modern Aleutian Trench may be represented by rocks of Kodiak Island and the Kenai

Peninsula, as suggested by Menard and Dietz (1951). An extension of this hypothesis may help solve the old problem of finding modern geosynclines. If the filling process, where it occurs, triggers the subsequent compression and mountain building events, then the modern trenches are either young geosynclines being filled, or old, unsuccessful, crustal attempts to build a geosynclinal prism of sediments. Further study of the Caribbean Trench between Barbados and the modern Puerto Rico Trench should provide one test of this hypothesis.

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MARINE GEOPHYSICAL INVESTIGATIONS IN THE WEST INDIES[1]

J.B. Hersey
Woods Hole Oceanographic Institution

Abstract

The ocean area between northeastern South America and the Nares Deep has been the object of intensive gravity, seismic, and bathymetric investigations since 1930. The early gravity observations of Vening Meinesz, Ewing, and Hess here and in the East Indies stimulated two decades of theorizing about the structure of island arcs and foredeeps. The seismic refraction studies of the late forties and fifties have shown that the Nares Deep and adjacent outer ridge have the characteristic thin crustal layer and associated structures of typical ocean basins. The Caribbean Sea has a slightly thicker crust, consisting of two layers, a shallower one of 6.0-6.7 km/sec compressional wave velocity and a deeper one of 7.0-7.5 km/sec. The crustal layer deepens and is overlain by a complex suite of layers having lower velocities in both the Greater and Lesser Antilles and beneath the foredeep.

Since 1960 seismic reflection profiling over the Nares Deep, the outer ridge, and the Puerto Rico Trench have revealed detail in the associated low-velocity layers which corroborate earlier refraction observations and show two contrasting bodies of stratified sediment and rock. These lie unconformably on a surface of high relief which corresponds to the top of the 5.2-5.5 km/sec layer (just above the 6.5-6.7 km/sec crustal layer). The shallowest major group of sediments, called the transparent layer, appears to be older than the formation of the trench. Its topography, structure, and distribution suggest that it may be the remnant of a continental rise which formed northward from Puerto Rico before the Puerto Rico Trench existed.

INTRODUCTION

This is a review of marine geophysical studies in the West Indies. Results of recent work to be discussed are all either published or in press and represent contributions from many American laboratories, mostly on the east coast of the United States - principally the Lamont Geological Observatory of Columbia University, the Woods Hole Oceanographic Institution, the Marine Laboratory of the University of Miami, and the Department of Oceanography of Texas A and M University.

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[1]Woods Hole Oceanographic Institution Contribution No. 1768.

The very early work of Vening Meinesz, Ewing, and Hess set the stage for a long series of intensely interesting and productive research in the West Indies, and also initiated a great deal of speculation about matters that we have been considering in this symposium. This work, conducted in the 1930's, consisted largely of measurements of gravity and of the depth of water. It was, however, followed by a rather long gap during which the Second World War and various other diversions kept geophysicists away from the West Indies. In 1946 and 1947, a few seismic reflection observations were recorded north of Puerto Rico (Hersey and Ewing, 1949), and in 1949 seismic refraction measurements were begun in the same area (Hersey et al., 1952). Through about the next 7 or 8 years this work went on intensively (see, for example, Ewing et al., 1954; Officer et al., 1952; Officer et al., 1959; and Officer et al., 1957). In the early 1960's, we gained the ability to make continuous measurements of gravity and total magnetic field and, most recently, good continuous seismic reflection profiles.

The seismic refraction method has several limitations: 1) it tends to make the structure of the earth appear layered, whether it is or not; 2) in the deep ocean it is a rather unsatisfactory method for studying shallow structures. Low-velocity layers which are comparatively thin or even quite thick can be almost entirely masked; 3) in general, low-velocity layers which lie beneath higher velocity layers remain completely undetected; and 4) the seismic refraction method, as ordinarily applied, does not provide data about velocity gradients. In spite of these shortcomings a great deal was learned by this method about West Indian structure.

EARLY INVESTIGATIONS

Figure 1 shows the locations of the early refraction profiles. There were many profiles near Puerto Rico, the Virgin Islands, and along the Lesser Antilles, and a few just off the coast of South America. From these studies we learned that the ocean area north and east of the foredeep bordering the Greater and Lesser Antilles has the typical thin crust of the ocean basins, with the Mohorovicic discontinuity lying at about 10 to 11 kilometres below sea-level. The crust is thick throughout both the Greater Antilles and the Lesser Antilles. It is again thin in the interior of the Caribbean where it is, however, somewhat different from the open ocean. This information is summarized in Figures 2A and 2B. The Moho discontinuity is shallow beneath the open ocean and then deepens beneath the Lesser Antilles and the eastern part of the Puerto Rico Trench.

The usual oceanic crust consists of a crustal layer having a velocity of about 6.5 to 6.7 km/sec underlying shallower layers with velocities ranging from about 4.0 to 5.5 km/sec. By comparison, the crustal layer in the Venezuelan Basin consists of two parts: a shallower 6.0 to 6.5 km/sec

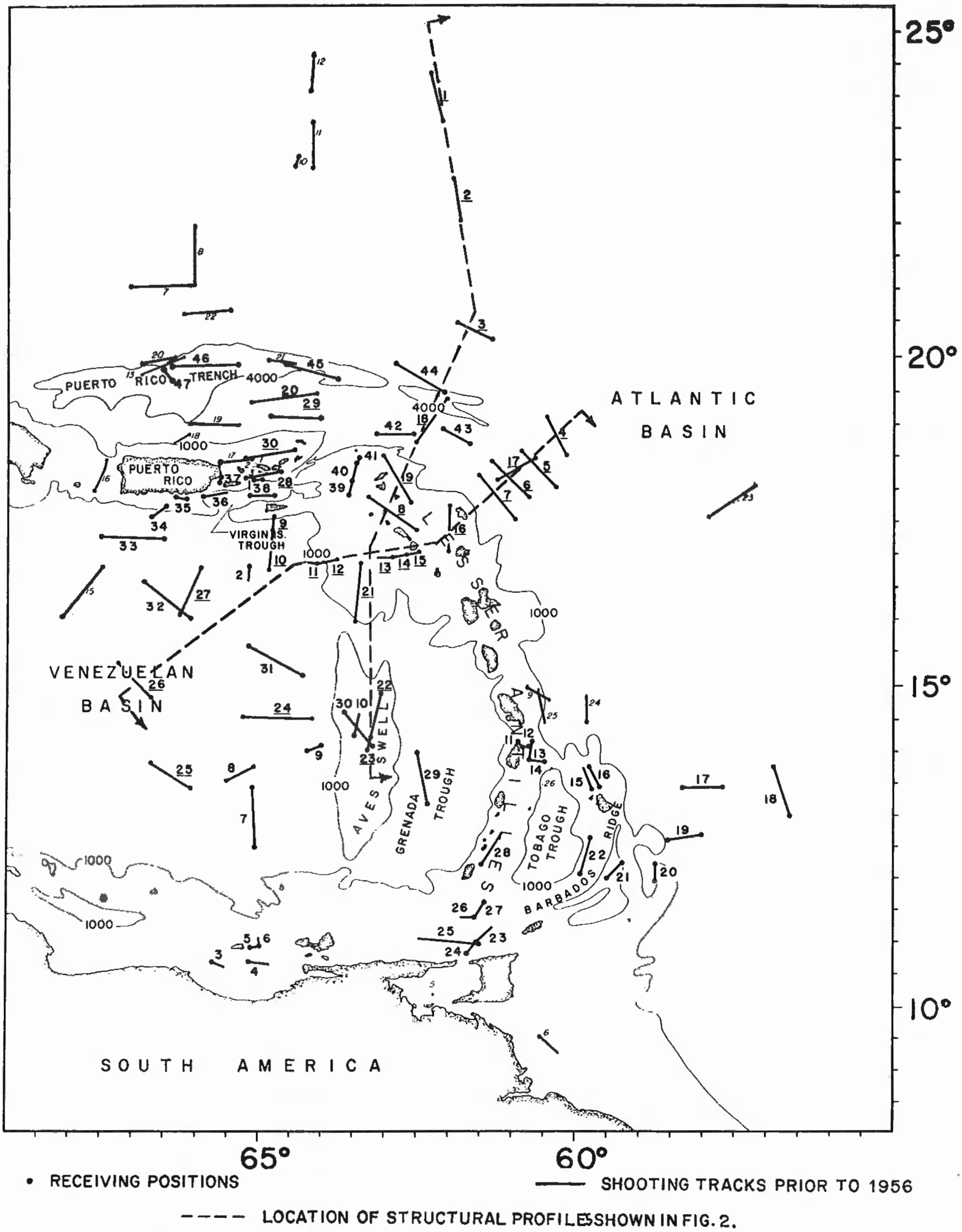


Figure 1. Locations of seismic refraction stations in the Eastern Caribbean. Depth contours are in fathoms. (After Officer et al., 1959)

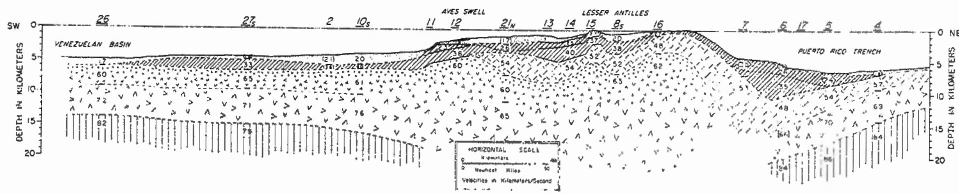


Figure 2A. Structure section: Venezuela Basin to the north wall of the Puerto Rico Trench. (After Officer et al., 1959)

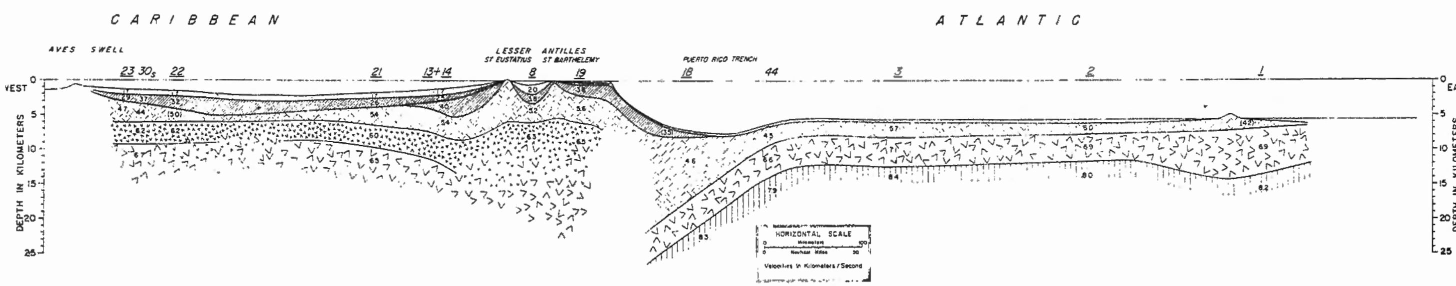


Figure 2B. Structure section: Aves Swell through the Lesser Antilles to the Puerto Rico Trench and outer ridge. (After Officer et al., 1959) layer and a deeper 7.0 to 7.6 km/sec layer underlain by the mantle which has velocities about 8.0 km/sec or more (Figure 2A). The structure sections here produced as Figures 2A and 2B were constructed by Officer et al. (1955). Their work was followed by a study of gravity and the available seismic refraction results by Talwani et al. (1959), which resulted in the section shown in Figure 3. This is Talwani's section through the outer ridge, the Puerto Rico Trench, the island of Puerto Rico, and the Venezuelan Basin. North of the Puerto Rico Trench, the crustal layer varies by 2 kilometres in thickness. There is a layer of lower velocity (5.5 km/sec) and lower density (2.7 gm/cc), corresponding approximately to layer 2, which is shown in a very generalized form here. The Puerto Rico Trench will not be discussed further in this paper because it is the subject of another paper in this symposium (see Bunce, this volume).

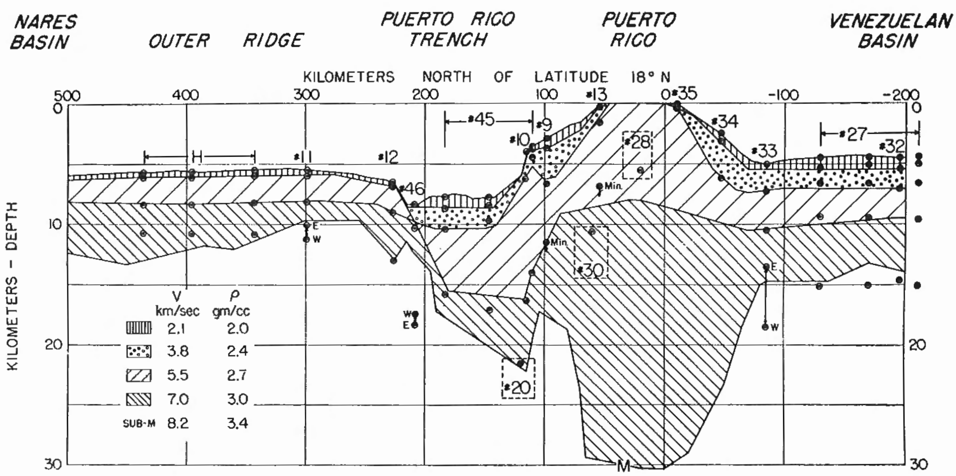
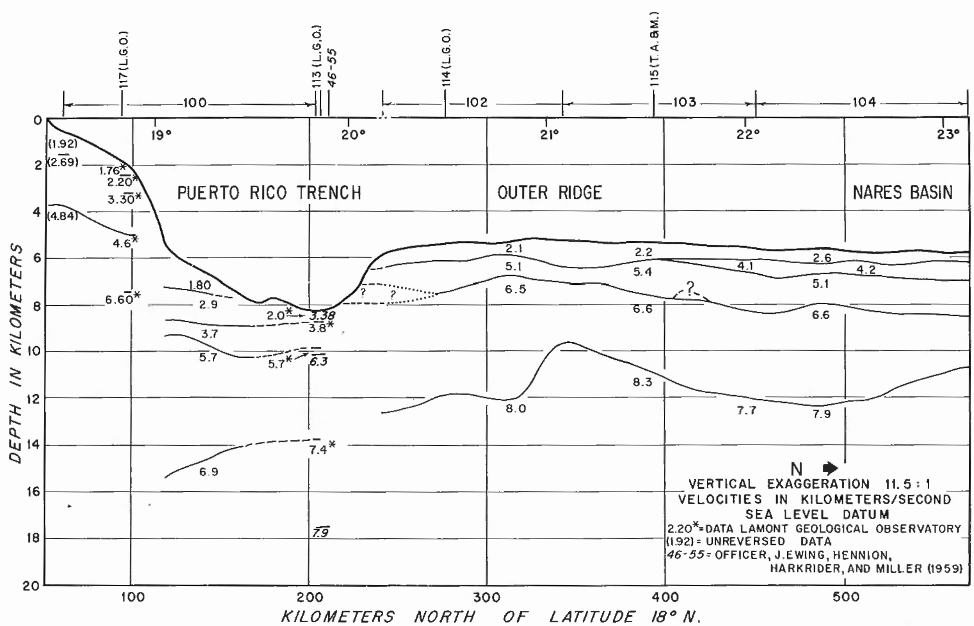


Figure 3. A crustal structure section from the Venezuelan Basin through Puerto Rico, the Puerto Rico Trench, and the outer ridge. (After Talwani et al., 1959)

Figure 3 contains the interesting suggestion of a local, very shallow depth (less than 10 kilometres) to the Moho discontinuity at one place below the outer ridge. In 1960 a more detailed survey using the seismic refraction method was conducted by a combination of several east coast laboratories to investigate this shallow place as a possible Mohole drilling site. One of the results of this study was the section analyzed by Bunce and Fahlquist (1962), shown in Figure 4. The principal difference between the Talwani section of Figure 3 and the Bunce and Fahlquist section of Figure 4 is the greater detail in crustal structure of Bunce and Fahlquist. The Moho discontinuity again appears shallow below the outer ridge and was traced south to a point close to the north wall of the Puerto Rico Trench. Beneath the north wall the Moho discontinuity drops to considerably greater depths.



STRUCTURE SECTION-PUERTO RICO TRENCH TO NARES BASIN
LONGITUDE 66° 30' W.

Figure 4. A crustal section from the south wall of the Puerto Rico Trench, across the Trench and the outer ridge to the Nares Basin. (After Bunce and Fahlquist, 1962)

RECENT INVESTIGATIONS

The foregoing research was completed several years ago. In the balance of this paper, recent results, largely on the outer ridge and in the Nares Basin, will be discussed. These results relate particularly to the structures in the layers of lower velocity which, beneath Nares Basin according to the profile of Figure 4, consist of a quite thin 4.1 km/sec layer, underlain by a thicker layer with a velocity of a little more than 5.0 km/sec, and overlain by a layer with a very low velocity ordinarily interpreted as unconsolidated sediment. It is in sections like this, where the structure varies considerably along the profile, that refraction profiles can lead us astray. Would the layers of the refraction profile appear as layers to another method of observation? It was quite exciting when the early development of continuous reflection profiling permitted us to look at this section by means of an independent seismic method.

Figure 5 shows the location of continuous seismic profiles recorded by Ewing and Ewing (1962), Savit et al. (1964), and Bunce and Hersey (1966) between Peurto Rico and the northern boundary of the Nares Basin. With the section along longitude 66°30'W, we had an excellent opportunity to compare the results of the reflection and refraction measurements.

Figure 6 shows the reflection profile recorded in 1962 that corresponds to refraction profile 104 of Bunce and Fahlquist (1962) (cf. north end of section produced here as Figures 4 and 5). The Nares Basin is very flat with sea-floor slopes of the order of less than 1:1,000. It is underlain by uniform layers to a depth of 0.15-0.24 sec below the bottom reflection (7.75 sec on the travel-time scale). These layers correspond to the 2.6 km/sec layer of the refraction profile (Fig. 4). The details of this section in the original data show that the section below 7.8 sec represents layered rock or sediment, probably somewhat broken up but nevertheless layered, and interrupted by masses of acoustically opaque material which rise from greater depths. The second set of layers correspond closely to the 4.2 km/sec layer, and the material below about 8.15 sec (Fig. 6), including the interrupting mass, is the 5.1 to 5.4 km/sec material. The section of Bunce and Fahlquist (Fig. 4) implied that the 4.2 km/sec material is not found over all the outer ridge. Reflection measurements, however, clearly indicate that patches of this material are to be found, in places, over all the ridge, lying between high parts of the deeper material.

Figure 7 represents a north-south section south of that in Figure 6, and includes the topmost slope of the north wall of the Puerto Rico Trench. Bunce and Hersey (1966) have suggested that the 4.2 km/sec layer corresponds to the layered material represented between 7.7 and 7.9 sec, measured at the edge of the north wall. Lying above it is a layer which corresponds to the so-called transparent layer of Ewing and Ewing (1962) and Savit et al. (1964).

Photographs taken along the north wall early in 1960 revealed a conglomerate or breccia containing very large blocks of rock, indicating that rocks of this type outcrop on the walls of the Puerto Rico Trench (Hersey, 1962). Up to the present writing, several tons of these rocks have been dredged, thus providing the opportunity to learn a great deal about them. The first few rocks which were dredged suggested that the layered rock of Figure 7 could be the 4.2 km/sec layer; they consist of indurated sediments and basalt, presumably interbedded in situ. By dredging farther

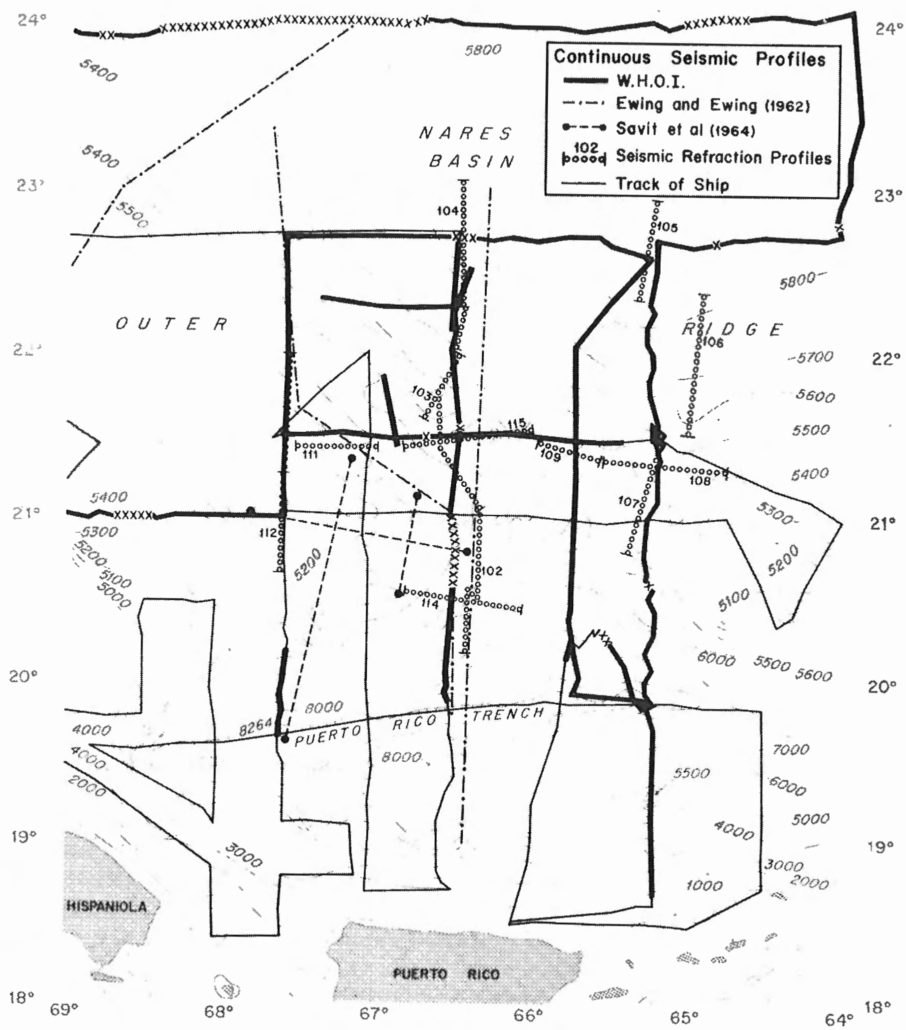


Figure 5. The location of continuous geophysical observations from the R/V CHAIN as reported by Bunce and Hersey (1966) indicated as "W.H.O.I.". This chart also shows the location of reflection profiles by Ewing and Ewing (1962) and Savit et al. (1964), as well as the location of refraction profiles made in 1959 and reported by Bunce and Fahlquist (1962). In addition to continuous reflection profiles, echo-sounding and gravity data were recorded along the entire track of CHAIN. Bathymetric contours are in metres, based on an unpublished chart by R.M. Pratt.

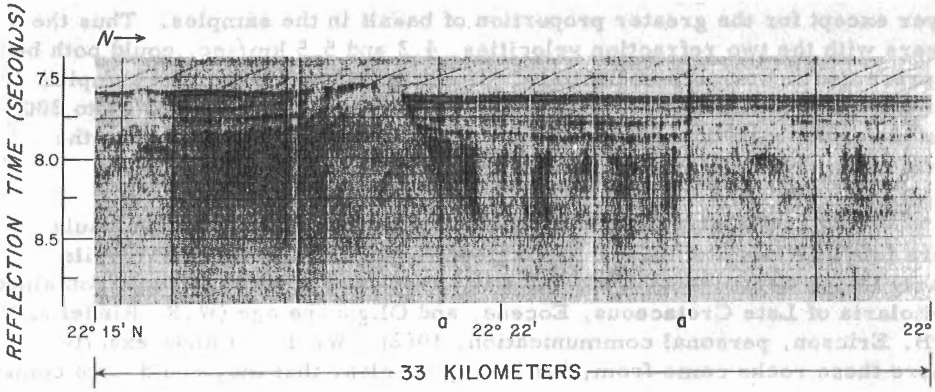


Figure 6. The northernmost section of the reflection profile made along longitude 66°30'W for comparison with refraction profile 104 of Bunce and Fahlquist (1962). (See Figures 4 and 5) (After Bunce and Hersey, 1966)

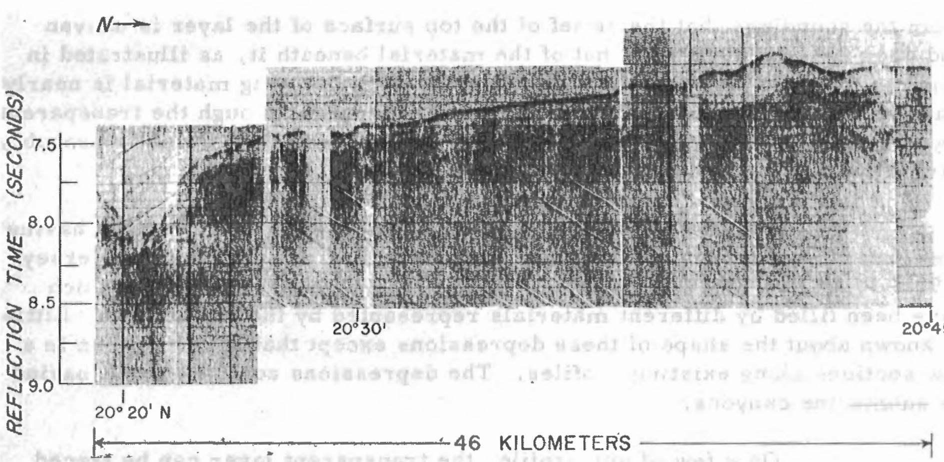


Figure 7. A continuous reflection recording from the top of the north wall northward over part of the outer ridge. (After Bunce and Hersey, 1966)

downslope on the north wall during a subsequent cruise, we obtained a large suite of rock samples having velocities ranging above 5.0 km/sec. The rock types are not strikingly different from those identified with the 4.2 km/sec layer except for the greater proportion of basalt in the samples. Thus the layers with the two refraction velocities, 4.2 and 5.5 km/sec, could both be represented in our rock collections. We do not know whether we sampled the crustal layer, although serpentinite was dredged from within 100 to 200 metres of the base of a steep declivity about 300 to 400 metres above the floor of the trench (Bowin et al., in press).

The sedimentary rocks and mudstones in our dredge hauls were fossiliferous. A limestone fragment contained Cenomanian fossils (early Upper Cretaceous) (Todd and Low, 1964); and other fragments contained radiolaria of Late Cretaceous, Eocene, and Oligocene age (W.R. Riedel and D.B. Ericson, personal communication, 1962). We do not know exactly where these rocks came from, but it is quite clear that they could have come from the transparent layer by rolling downhill or they could have come from the layered section but not from any deeper structure. Thus the transparent layer could be at least as young as Oligocene, or at least as old as Late Cretaceous.

For the balance of this paper, let us concentrate on the significance of the transparent layer, which is shown in Figures 8 and 9. It is very extensive over the outer ridge, but in the Nares Basin the corresponding shallowest structure is different; it is not transparent, contains several reflecting layers within it, and is probably of different origin. The transparent layer covers most of the outer ridge, but thins northerly toward the Nares Basin and southerly toward the Puerto Rico Trench. It is apparent from the soundings that the relief of the top surface of the layer is uneven and does not correlate with that of the material beneath it, as illustrated in Figures 8 and 9. In Figure 9, the immediately underlying material is nearly flat over a long distance. Deeper material protrudes through the transparent layer near a' to form a small hill or ridge, 1,200 feet high, which is probably part of the 5.2 km/sec layer.

In the transparent layer we have found many reflectors having the form shown in Figure 10. These were interpreted by Bunce and Hersey (1966) to be pre-existing depressions in the transparent material which have been filled by different materials represented by the reflections. Little is known about the shape of these depressions except that they are seen in a few sections along existing profiles. The depressions could be small basins or submarine canyons.

On a few of our profiles the transparent layer can be traced to where it underlies the flat-lying sediments of the deepest part of the Puerto Rico Trench. Since the transparent layer has to be Oligocene or

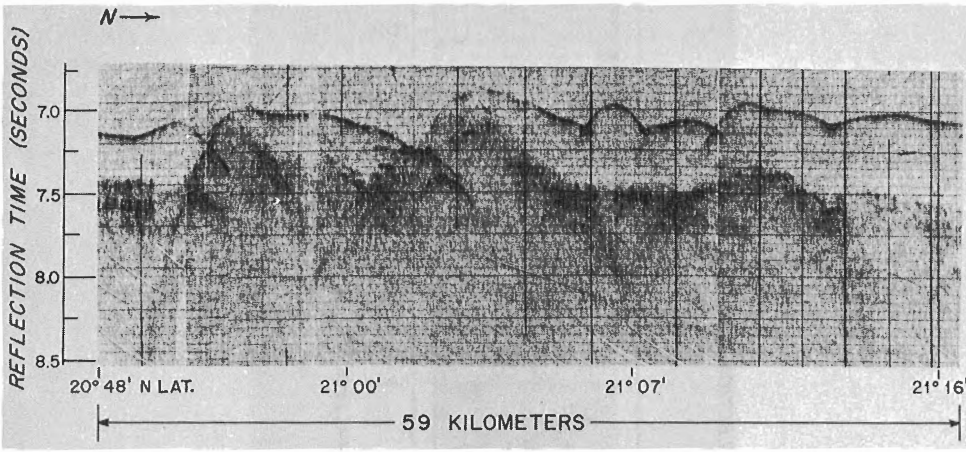


Figure 8. The transparent layer on the outer ridge as recorded along a north-south section along longitude 65°12'W. Note the apparent lack of correlation between the sea-floor relief and that of the underlying surface. (After Bunce and Hersey, 1966)

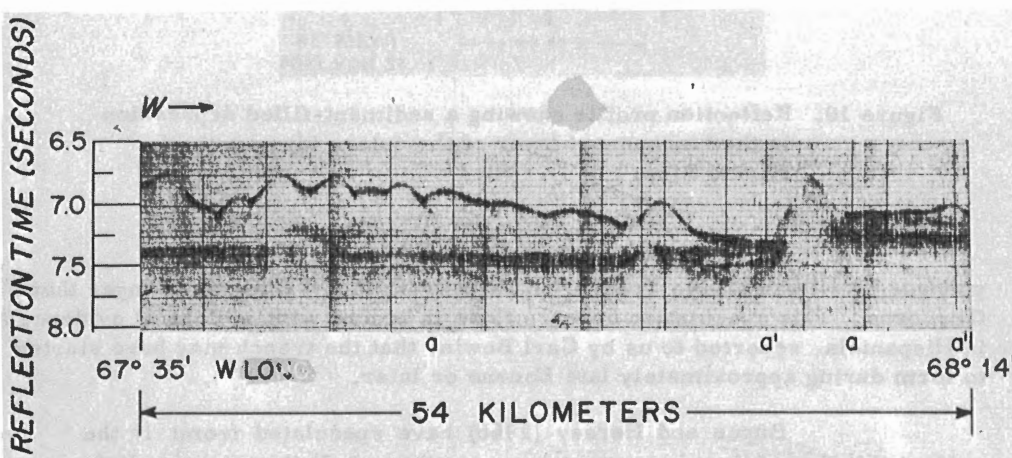


Figure 9. Reflection profile along latitude 21°N on the outer ridge. (After Bunce and Hersey, 1966)

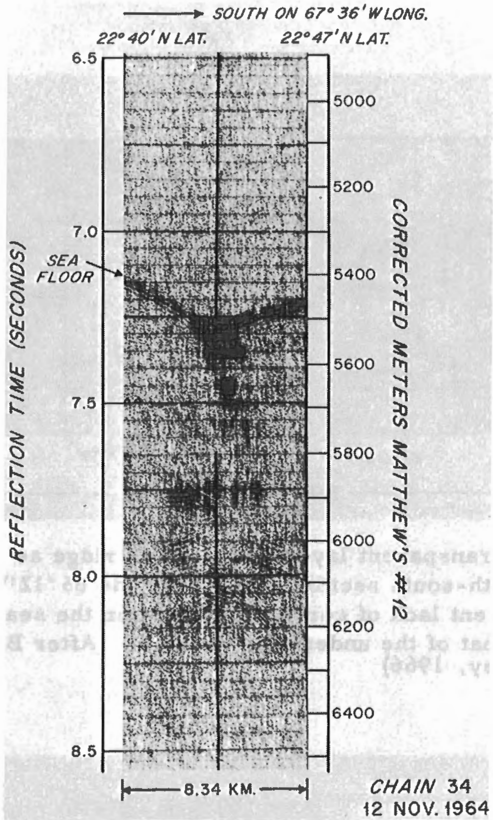


Figure 10. Reflection profile showing a sediment-filled depression in the transparent layer of the outer ridge north of Puerto Rico.

younger, the Puerto Rico Trench, in its present form, must be younger than Oligocene. This speculation appears to be in accord with geological evidence in Hispaniola, reported to us by Carl Bowin, that the trench may have started to form during approximately late Eocene or later.

Bunce and Hersey (1966) have speculated from: 1) the evident thinning of the transparent layer northward; 2) its uneven relief, independent of the relief of underlying rock surfaces; 3) the occurrence in it of sediment-filled depressions; and 4) its extension southward below the floor of the Puerto Rico Trench, that the transparent layer is a remnant of a continental rise made of sediment, but possibly largely volcanic, that was derived from land where Puerto Rico and Hispaniola are now located.

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THE PUERTO RICO TRENCH[1]

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Abstract

The results of recent marine geophysical investigations have been integrated with those of several earlier studies in an effort to define the structure of the Puerto Rico Trench. The observations include seismic refraction and continuous seismic reflection profiles, measurements of gravity, and bathymetry.

The floor of the trench is an abyssal plain elongate east-west, 8.3 kilometres deep (depth corrected for velocity of sound), and sloping gently to the south. The shallow sedimentary layers of the sea floor revealed by short-pulse echo sounding are uniform across the axis but thicken towards the western end. The deeper sedimentary layers both tilt and thicken to the south. A continuous reflection profile approximately along the axis of the trench shows between 1.5 and 2.0 kilometres of layered sediments overlying a rough basement surface. North and south of the plain, the basement rises to form the bounding slopes. The crustal structure section shows a difference between the compressional wave velocities of material underlying the trench and of that underlying the outer ridge.

Much of the seismic activity of the area is located beneath the south slope and occurs as shallow-focus earthquakes. The minimum free-air gravity anomaly lies south of the axis of the trench, toward the south slope. The trench may be a downfaulted or downwarped structure with activity continuing along the southern margin.

An acoustically transparent sediment layer beneath the bottom reflection can be traced in places continuously down the north slope and beneath the upper section of abyssal plain sediments. The trench must be younger than this layer. Eocene rocks were collected from the layer by recent dredge hauls on the north slope of the trench. Thus the deformation which formed the trench may be no older than Eocene.

INTRODUCTION

The Puerto Rico Trench has been the subject of marine geophysical investigations since the pendulum-gravity observations made by

[1]Contribution No. 1718 of the Woods Hole Oceanographic Institution.

Vening Meinesz revealed the large negative gravity anomaly associated with it. Talwani recently (1964) has presented an excellent review of the studies and the progression of ideas on the origin and structure of the trench.

The Puerto Rico Trench lies north of and parallel with the northeast part of the Antilles island arc (Fig. 1). Its axis is deepest in the region north of Puerto Rico and shallows as it curves to the southeast. The extent and type of recent investigations of the area made by the Woods Hole Oceanographic Institution are shown in Figure 2. Observations made recently by other institutions are not shown. This paper presents material drawn primarily from the results of investigations conducted since 1962.

SEISMIC REFLECTION PROFILES

The north slope or wall of the trench shows rugged topography superposed on an average regional southward slope of about 5 degrees. Hersey (1962) suggested that multiple normal faulting appeared to dominate the structure of the north wall. A layer of homogeneous, acoustically transparent sediment (the "transparent" layer) that underlies the bottom reflector extends from the outer ridge to the north almost without break down the slope and beneath the sediments of the trench (Hersey, 1966). The south slope differs from the north. Two reflection profiles show a thick section (over 0.5 sec) of uniformly layered sediments extending down the south slope from the shelf but terminating abruptly at a pronounced break in slope located at about the 3,600-metre bathymetric contour. No subbottom reflectors are observed between the slope break and the 7.0 to 7.5 kilometre depth. Below 7.5 kilometres, a shallow (less than 0.25 sec) reflecting surface was detected in places, as well as sediment pockets described by Ewing and Ewing (1962).

The floor of the trench, 8.3 kilometres deep (depth corrected for velocity of sound in water), is an abyssal plain that slopes gently southward. The southward gradient, measured on many crossings, varies little from a value of 1:1,000. Echo soundings made with very short pulses reveal thinly layered sediments. The layers are continuous over the length of the plain. They thicken slightly from east to west (Fig. 4), and become more numerous near the abrupt western boundary, but show no apparent southward thickening. A reflection profile made with the continuous seismic profiler (CSP) along the axis of the trench shows deeper subbottom structures beneath the abyssal plain. A section of the recorded profile appears in Figure 3.

Two seismic refraction profiles were made in the trench during earlier investigations (Officer et al., 1959, Profile 46-55; Bunce and Fahlquist, 1962, Profile 113). The locations and orientations of the profiles are shown in Figure 2, and the results in the structure section of Figure 5.

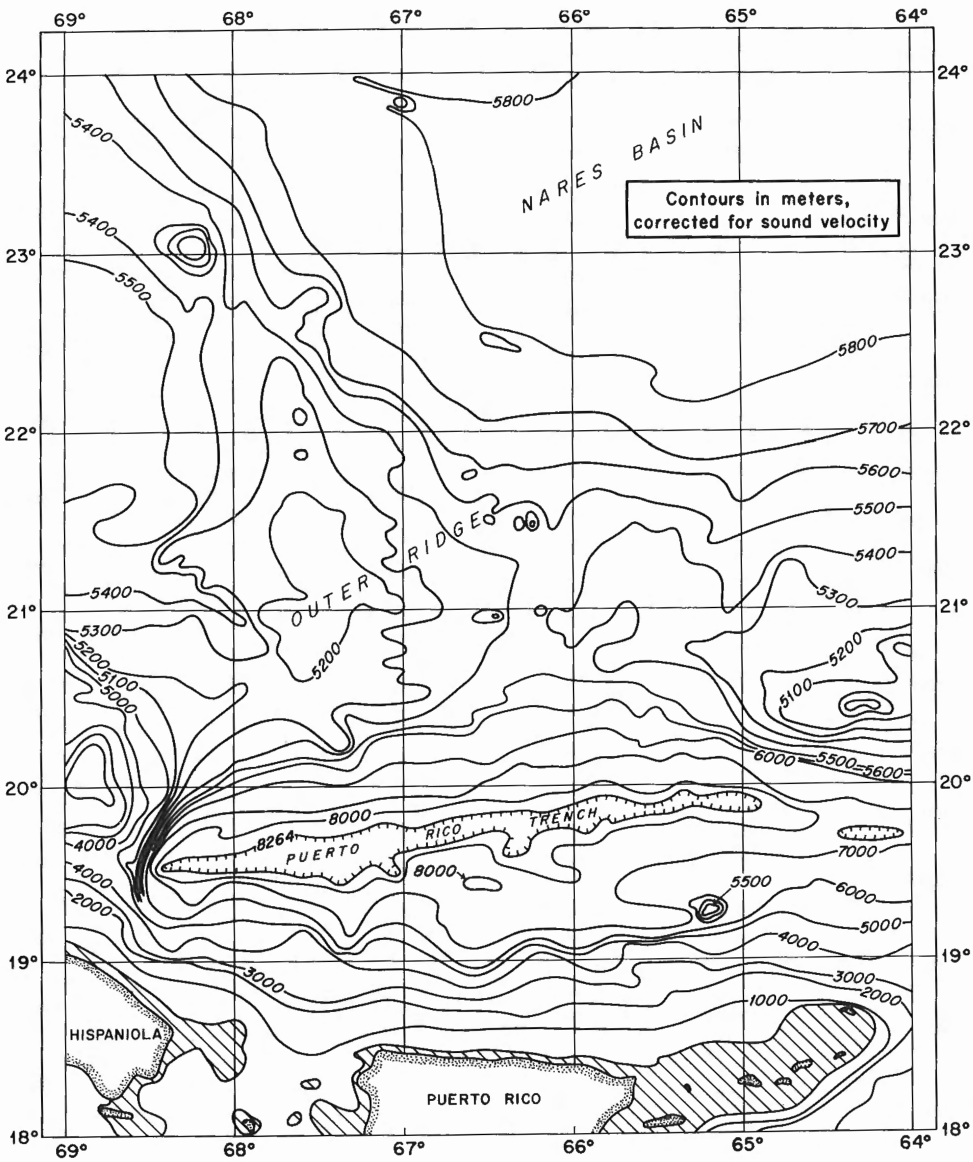

Figure 1. Chart of ocean area north of Puerto Rico and Hispaniola. Contours compiled from various sources.

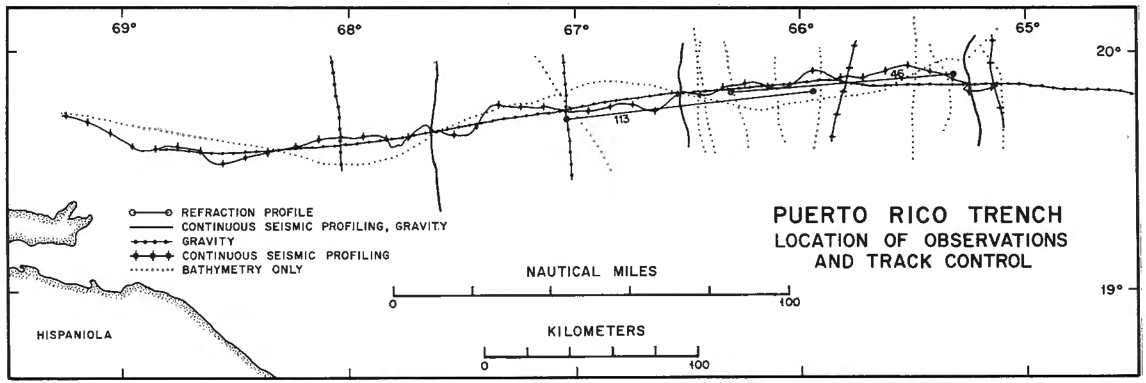

Figure 2. Puerto Rico Trench area showing the location of recent observations made by the Woods Hole Oceanographic Institution.

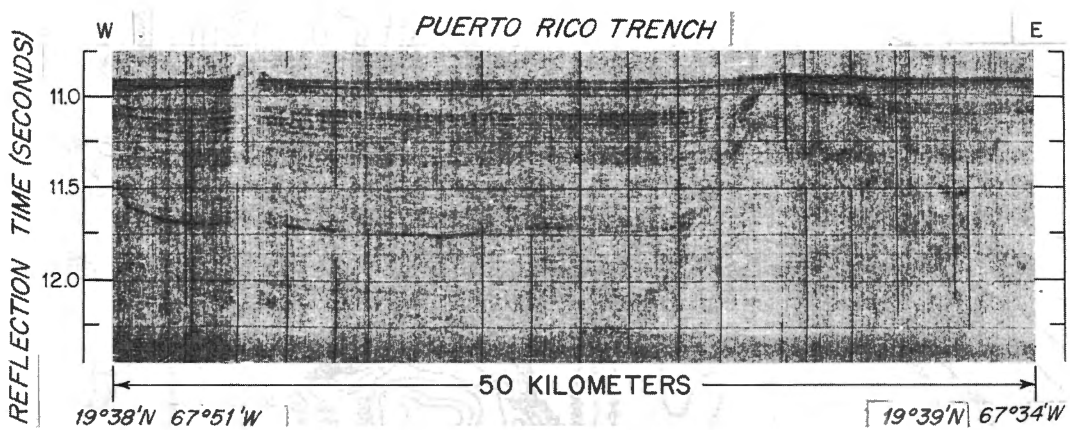

Figure 3. Abyssal plain of the Puerto Rico Trench; section of continuous seismic profile between longitudes 67°34'W and 67°51'W.

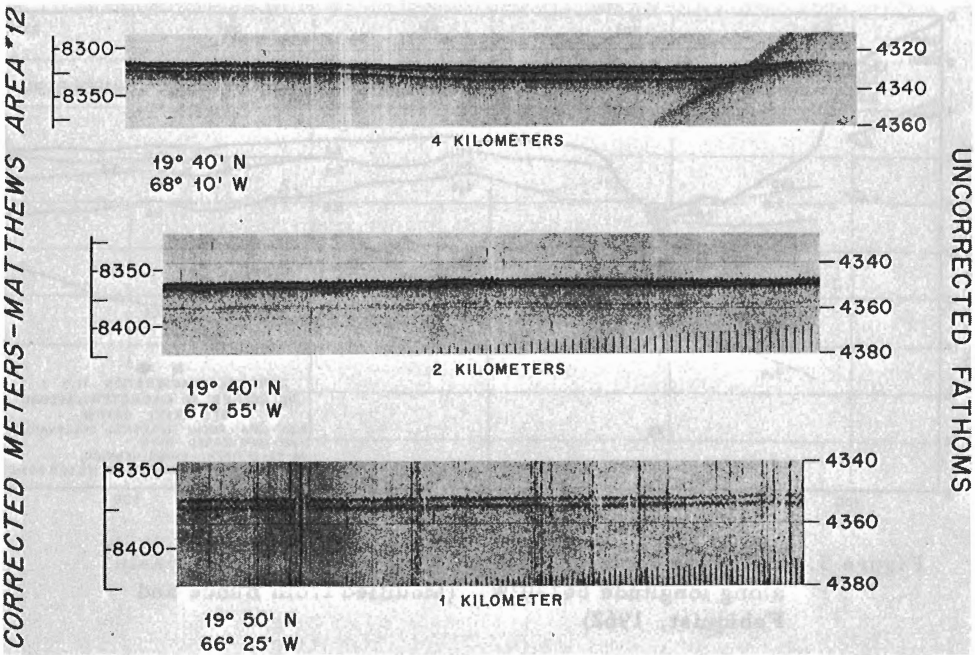

Figure 4. Abyssal plain of the Puerto Rico Trench; echo-sounding profiles.

The layers charted by CSP along the trench floor can be correlated with layers whose velocities and thicknesses are known from seismic refraction. The almost horizontal reflectors between the bottom reflection and a strong reflecting horizon at 11.70 sec are interpreted as sedimentary layers and are correlated with the material of 2.0 km/sec velocity (Fig. 5).

In the western section of the trench the reflector at 11.70 sec is identified as the top of the 3.8 km/sec velocity layer. This reflector shallows to the east and in places appears as a rough surface. The 3.8 km/sec material of Profile 113 also shallows to the east. At several places beneath the floor of the trench a deeper reflecting horizon can be detected. This appears to be a rough surface which rises both to the north and south to form the slopes bounding the abyssal plain (Fig. 3, east). Beneath the trench floor, this surface correlates moderately well with the top of the 5.7 km/sec material.

Hersey (1966), in his discussion of the transparent layer of the outer ridge, pointedout that in places it can be traced almost continuously

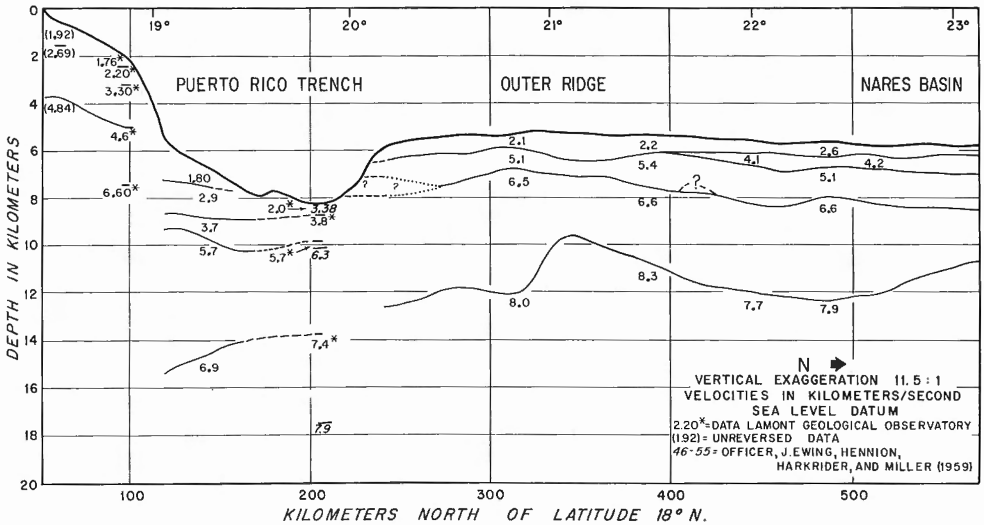

Figure 5. Structure section: Puerto Rico Trench to Nares Basin along longitude 66°30'W. (Modified from Bunce and Fahlquist, 1962)

down the north slope and beneath the sediments of the abyssal plain. There it appears to pass into the region of the 3.8 km/sec material below the ponded sediments. This interpretation results from correlation of earlier profiles crossing the trench with the east-west profile along the axis. The single profile along the trench does not show a completely transparent layer continuously; echoes suggesting layered material appear in places in this depth interval. The reflectivity characteristics and the probable composition of the transparent layer of the outer ridge have been discussed by Ewing and Ewing (1962), Savit et al. (1964), and Bunce and Hersey (1966). Within the layer are beds of slight acoustical contrast which, however, vary laterally. This variation, and the different types of acoustic source used for reflection profiling, produce the observed changes of reflection character.

The continuity of the transparent layer on the slope and beneath the upper section of sediments of the trench is evidence that the layer is older than the formation of the trench. Future investigations should include tracks planned to define the relationship of material of the north wall to that of the trench as a continuous function of the reflection profiling.

SEISMIC REFRACTION PROFILES

The seismic refraction profiles indicate an interesting deep structure. A brief description of the methods used to obtain the profiles is necessary for their explanation. The earlier profile of the two (46-55), was a reversed profile made by the two-ship method. It passes over part of the eastern section of the trench onto the north slope. Thus, the mantle of 7.9 km/sec velocity and the overlying velocity-layer of 6.3 km/sec may be partly representative of the outer ridge crustal layers. The later profile (113) was made by four ships, of which three occupied receiving positions while the fourth ship did the shooting. The entire profile was made over the abyssal plain of the trench. No velocity close to that of normal mantle material (8.0 km/sec) was observed on this reversed profile although it was 129 kilometres long.

Profile 113 shows vertical offsets of approximately 2 kilometres in the upper surface of the 7.4 km/sec velocity-layer. This structure was well defined by the reversed and overlapping profiles obtained from the three receiving locations. However, the attitude of the surfaces along which the offsets occurred cannot be determined from the available data. They simply provide evidence for structural complexity beneath the trench.

GRAVITY AND MAGNETIC DATA

The negative gravity anomaly associated with the trench is well known. The free-air gravity anomaly and bathymetric profiles across the trench at five longitudes are shown in Figure 6. The displacement of the axis of the gravity minimum southward from the axis of the topographic deep and toward the south slope, noted by Officer et al. (1957, p. 368), is evident in all five profiles. This relation may be associated with a thick wedge of sediments under the south slope.

The seismicity of the area known as the Caribbean Loop has been reviewed in a number of treatises on island arc-trench structures, most recently by Sykes and Ewing (1965). They point out that in the western section of the trench much of the activity consists of shallow-focus earthquakes located beneath the south slope. Some activity occurs in the trench itself, while several epicentres follow a north-northwest trending line located south of the trench axis and defined by 19.3°N, 65°W and 19.5°N, 66°W. The abrupt termination at the west end of the trench lies north of the projected point of convergence of two seismic belts at the eastern end of Hispaniola (Sykes and Ewing, 1965).

The lack of a characteristic magnetic anomaly associated with the trench was pointed out originally by Ewing and Heezen (1955) and has been further substantiated by the more recent work of Van Voorhis and Davis (1964).

DISCUSSION AND CONCLUSIONS

The resemblance of the structure of the trench to a downfaulted block (Fig. 5) has been pointed out by Bunce and Fahlquist (1962) and Talwani (1964). The former based their hypothesis on the depth relationship between the 6.6 km/sec velocity-layer on both sides of the trench, the greatly different velocity-structure beneath the trench, and the abrupt change in velocity pattern beneath the margins of the trench.

Ewing and Ewing (1962) described the tilt to the south of the deeper sediments of the abyssal plain, their upturn at the southern margin, and the southward dip of the basement rocks. They suggested, in explanation, that the north side of the trench and the abyssal plain have subsided and the plain tilted to the south.

The hypothesis that the trench is a downfaulted structure depends upon the assumption that the 6.6 km/sec velocity-layer is the same on both sides of the trench, and that the 5.7 or 6.3 km/sec velocity-material beneath the trench represents an altered form of this material (Bunce and Fahlquist, 1962). Further, the change in velocity-structure occurring beneath each margin of the trench was interpreted simply as a lack of evidence for a transitional or velocity gradient zone.

An alternate hypothesis is that the trench is a downwarped structure. The relatively gentle slopes of the two sides of the trench (shown in natural scale in Figure 7) would support such an origin. In addition, the thickness of the layers underlying the outer ridge and trench are not appreciably different. The wedge of sediments beneath the south slope may be accounted for by down-slope deposition from the island arc. The 6.6 km/sec velocity layer may not be the same on each side of the trench; for instance, it may comprise metamorphic rocks to the south and oceanic crustal rocks to the north. In any case, gradual depression or downwarp of the structure does not require that this layer be homogeneous across the area.

The existence of the transparent layer of the outer ridge beneath the uniform sedimentary layers of the trench is evidence that the trench was formed after this layer was deposited. Eocene rocks have been dredged from the region of the transparent layer on the north wall (Bowin et al., 1966; Hersey, 1966). Thus the trench may be as old as Eocene. The seismicity associated with the south slope suggests possible continuing

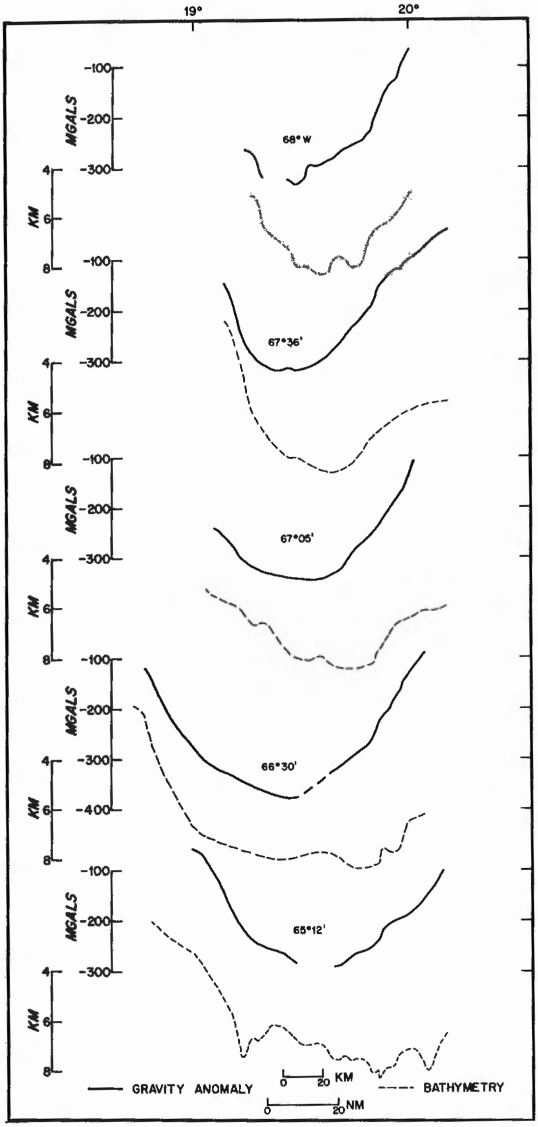

Figure 6. Profiles of observed free-air gravity anomaly and bathymetry across the Puerto Rico Trench between longitudes 65°12'W and 68°00'W.

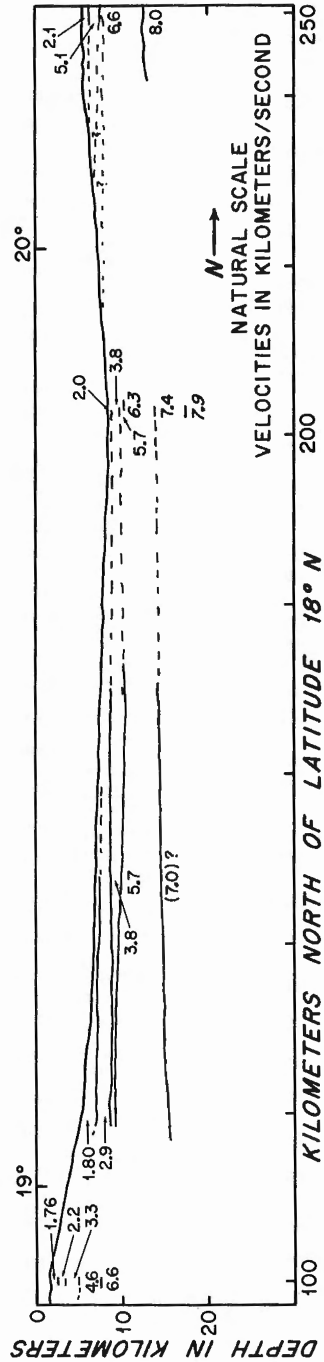

Figure 7. Structure section, natural scale, across the Puerto Rico Trench along longitude 66°30'W.

activity in this area although, as Sykes and Ewing (1965) point out, "The zone of intense seismic activity may be concentrated at depths of several tens of kilometers and may not be directly related to movements along the trench walls". Whether the forces of deformation are still in process, or exactly what the causative forces are, is a question still not answered.

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DISCUSSION

Dr. G.G. Shor (USA)

What is the age of the trench?

Miss Bunce

The trench may be as old as Eocene. As Dr. Hersey pointed out, the transparent layer is Eocene.

Prof. J.T. Wilson (Canada)

Why is so much attention devoted to the north side of the trench, which appears not to be a normal island arc? So little is devoted to the west side, which appears to be a very much better example of an island arc.

Miss Bunce

The north side attracts most attention, I think, first because of the tremendous vertical exaggeration which you see on the bathymetry and on the reflection profile; secondly, because the reflection profile reveals outcrops, which we have dredged; and, thirdly, because San Juan is a good port and you always cross the trench from north to south and from south to north and thus very rarely get around to the east and west ends.

Prof. Wilson

It is difficult to find a true island arc.

Miss Bunce

I suspect that all but a few investigations use San Juan as the port in the Caribbean region.

(Note in proof: We have recently made some investigations of the south slope. We plan studies of the eastern and western boundaries of the trench, and of the south slope during 1966).

GRAVITY ANOMALY BELTS IN THE CARIBBEAN[1]

Manik Talwani
Lamont Geological Observatory

Summary

Continuous gravity data obtained on Lamont Geological Observatory Research Vessels VEMA and ROBERT D. CONRAD have been used, together with earlier submarine pendulum measurements, to delineate the prominent free-air gravity anomaly belts in the Caribbean. The negative anomaly belt associated with the Puerto Rico Trench continues westward and appears to connect with the negative anomaly associated with the Cayman Trench. The submarine ridge which connects the northwest end of Hispaniola with the southeast end of Cuba either does not interrupt this belt or, if it does so, the interruption is minor. Continuity of the free-air gravity belt would favour a similar origin for the two trenches.

Eastwards, the negative free-air anomaly belt of the Puerto Rico Trench departs from the topographic trench and continues through Barbados into Trinidad and Venezuela. This belt lies immediately to the east and on the ocean side of a positive belt associated with the Lesser Antillean island arc. The positive belt also curves around and terminates at the Island of Margarita off the north coast of Venezuela.

Off the north coast of South America is another set of positive and negative free-air anomaly belts. The positive anomaly belt passes through the islands of Aruba, Curaçao, Bonaire, and Los Roques. Westwards it continues into the Guajira Peninsula of Colombia. Eastward it curves into the Aves Swell and continues northwards possibly as far as Saba Bank. The major negative anomaly belt off the north coast of South America generally lies on the continental slope or at the foot of it. It continues at least as far west as Panama, and is terminated at its eastern end by the Aves Swell. Negative anomaly belts exist in Colombia and Venezuela but there does not appear to be a clear connection of the negative anomaly belts on land with the negative belt offshore.

Other important gravity features in the Caribbean area are the negative anomalies associated with the Muertos Trench south of Puerto Rico, with the Anegada Trough, and with the continental margin off the Guianas. Positive gravity anomalies exist over the Beata Ridge.

[1]For bathymetric charts of Caribbean area, see Figure 1 of Mattson and Figures 1 and 7 of Hurley, both papers elsewhere in this volume - Ed.

FORMATION OF THE SCOTIA AND CARIBBEAN ARCS[1]

Warren Hamilton
U.S. Geological Survey

Abstract

Continental connections existed between North and South America and between South America and Antarctica at the beginning of Tertiary time, and probably consisted of narrow Mesozoic eugeosynclinal belts whose fragments now form the larger islands of the Caribbean and Scotia arcs. If the continents are regarded as having drifted westward into the Pacific Ocean basin, then the two arcs can be pictured as formed by the disruption of the narrow bridges, which lagged behind the continents.

SCOTIA ARC

The island-sprinkled submarine ridge of the Scotia Arc connects South America and the Antarctic Peninsula of Antarctica by a hairpin curve that extends 2,300 kilometres east of the direct line, only 800 kilometres long, between the two continents (Figure). A submarine ridge extends at least part of the way along the direct line between them.

Southernmost South America consists chiefly of Jurassic and Lower Cretaceous marine volcanic rocks, siltstone, and greywacke, which were deformed, metamorphosed to a low grade, and intruded by granitic rocks of the Andean batholith, mostly about the middle of Cretaceous time; cobbles of the metamorphic and granitic rocks are abundant in unmetamorphosed Upper Cretaceous conglomerates (Feruglio, 1949; Cristi, 1956). High-grade metamorphic rocks are commonly considered to be pre-Jurassic.

South Georgia is the largest island of the Scotia Arc and lies on its northern limb. The island consists of a thick sequence of tuffaceous greywacke interlayered with basalt and spilite, and quartzose greywacke (Trendall, 1959). Sedimentary structures imply deposition of the greywacke by turbidity currents which moved west-northwestward down a long submarine slope. Rocks high in the sequence are dated as Early Cretaceous; they were deformed, metamorphosed to a low grade, and intruded by granite and gabbro presumably in later Cretaceous time.

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[1]Publication authorized by the Director, U.S. Geological Survey. Work done in cooperation with the Office of Antarctic Programs, National Science Foundation.

Figure Relation of the Caribbean and Scotia arcs to width of continental masses. The continents bent where they were narrow at the beginning of Cenozoic time, and ruptured where they were narrowest.

The South Sandwich Islands, which form the outer eastern bend of the Scotia Arc, are young volcanoes of andesitic basalt, andesite, and dacite (Tyrrell, 1945), such as are typical of volcanic island arcs elsewhere in the world. A submarine trench lies along the outer side of the bend.

The South Orkney Islands on the south limb of the arc consist of sedimentary rocks that were highly deformed and partly metamorphosed during Late Triassic or Early Jurassic time (Matthews, 1959; Miller, 1960). Fold axes and metamorphic structures trend northerly directly across the submarine ridge of the arc, suggesting that the folding and metamorphism are unrelated to the formation of the arc. Probably all the sedimentary rocks were deposited on land or in shallow water (Matthews, 1959).

The Antarctic Peninsula is formed mostly of metavolcanic rocks and quartz diorite. The pre-granitic rocks are Jurassic and Cretaceous, wherever they have been dated by fossils, although some workers infer that some complexes elsewhere on the peninsula are older. Major batholithic intrusion occurred during middle or Late Cretaceous time (Halpern, 1962). The remanent magnetic field direction in the Cretaceous batholithic rocks of the northern half of the peninsula (Blundell, 1962) shows a progressive clockwise swing totalling about 25 degrees, along the peninsula from latitude 68°S northeastward to the northeast tip[1]. The peninsula itself curves about 40 degrees clockwise in the same interval - so its shape may be due largely to bending since Cretaceous time.

The shallow-water Cenozoic brachiopods of South America and the Antarctic Peninsula are more similar than are those of any other pair of the southern lands, South America, Australia, New Zealand, and Antarctica; the similarity suggests that South America and Antarctica were joined by a continuous coastline in early Tertiary time (Allan, 1963). Early Tertiary beech-podocarp land floras of southern South America are quite similar to those of Antarctica. No fossil land animals have yet been found in Antarctica, however.

The Scotia Arc can be explained in terms of lateral disruption of continental crust (Hawkes, 1962; Hamilton, 1963, 1964). The geometry

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[1]This interpretation is made by the writer from Blundell's data. Of the 12 areas along the peninsula for which he presented data, two (Nobby Nunatak and Birdsend Bluff) yielded results so scattered as to be ambiguous, and they have not been used here; and palaeomagnetic bearings from another locality (Barchans) differ by about 40 degrees from the closely grouped bearings from four neighbouring localities and so also are not used. Bearings of the remaining nine groups of measurements average about N 20°W near lat. 68°S, north at lat. 65°S, and N 5°E at lat. 63°30'S.

and geology of southernmost South America and the north limb of the Scotia Arc eastward to South Georgia, and of the Antarctic Peninsula and the south limb eastward to the South Orkneys, permit the interpretation that the arc was produced by tensional thinning and fragmentation of a narrow belt of continental rock which, in Cretaceous and earliest Tertiary time, directly connected South America and the Antarctic Peninsula. Crustal structure of the Scotia Sea is oceanic although that of the ridge of the Scotia Arc is more nearly continental (Ewing and Ewing, 1959). The young volcanoes of the South Sandwich Islands apparently have grown across an oceanic gap between the disrupted ends of the initially continental belt. Long, straight channels along the south side of Tierra del Fuego and along the north end of the Antarctic Peninsula perhaps mark strike-slip faults whereby the Scotia Sea block has moved relatively eastward.

CARIBBEAN ARC

The belt of intense late Mesozoic deformation in western North America trends generally southeastward through northern and central Mexico, but in the southern part of Mexico and in Guatemala, Honduras, and Nicaragua the belt arcs eastward and northeastward toward the Greater Antilles. Cretaceous, Jurassic, and Palaeozoic rocks are known in eastern Central America (e.g. McBirney, 1963, and Woodring, 1954, p. 721-725), and late Precambrian crystalline rocks occur in southern Mexico at least as far east as central Oaxaca (Fries and Rincon-Orta, 1965). The islands of the Greater Antilles are composed largely of Cretaceous eugeosynclinal rocks, intruded by serpentinite and by quartz diorite and allied plutonic rocks; Tertiary deposits are mostly thin and post-orogenic, although they form thick sections locally, and in places are much deformed (Woodring, 1954, p. 721-729). Eugeosynclinal rocks at least as old as Early Jurassic occur in Cuba, where schists and marbles may be still older (Judoley et al., 1964).

Columbia and northern Venezuela present a mirror image of the geology of southern Mexico and Central America. Palaeozoic rocks are overlain by geosynclinal Jurassic and Cretaceous strata, and structures arc from northward to eastward closer to the Caribbean.

The lower Tertiary conglomerates of southern Oriente Province, southeastern Cuba, were derived from the south – the site of the present Cayman Trench – from a terrane like that of Hispaniola (Lewis and Straczek, 1955, p. 245). The southeast-trending tectonic and lithologic belts of eastern Cuba are truncated by the Oriente coast, but belts like them reappear in Hispaniola and Puerto Rico. Hess and Maxwell (1953) interpreted such evidence to indicate that Jamaica, Hispaniola, and Puerto Rico have moved eastward past southern Cuba along a left-lateral fault marked by the Cayman Trench. Symmetrical to these left-lateral structures of the north limb of the arc, right-lateral faults trend eastward across the south limb in northern Venezuela, according to Rod (1956), and the en echelon pattern of folds demonstrates similar right-lateral shear (Bucher, 1952).

Continuous land existed between North and South America in the Paleocene and early Eocene, for the land mammals of the two continents are very similar (Simpson, 1940). From Eocene to late Pliocene, however, the mammals of South America evolved in complete isolation: no land connection existed. The present Panamanian volcanic bridge between the continents emerged in the late Pliocene, and since that time there has been great exchange of animals (Simpson, 1940). The vulcanism which has produced the small islands of the Lesser Antilles, and that which has produced the isthmus of Costa Rica and Panama, may have developed upon what was previously oceanic crust.

Among the interpretations of these relationships are a number of variants on the theme that the Greater Antilles represent fragments of a late Mesozoic geosynclinal belt which connected the Americas at the beginning of Cenozoic time. Such explanations have been made by Alberding (1957), Bucher (1952), Hess and Maxwell (1953), North (1965), Rod (1956), and Staub (1965). Some such explanation does indeed appear to be required.

MECHANISM

The very similar Caribbean and Scotia arcs are each explicable in terms of the bending and disruption of a narrow belt of upper Mesozoic eugeosynclinal rocks which more directly connected the continents at the beginning of Cenozoic time. Any specific theory should be applicable to both arcs, and should explain the symmetry of the northern and southern limbs of each.

The separation of the Americas and Antarctica from the Mid-Atlantic Ridge and the Atlantic-Indian Ridge probably indicates motion of the continents since Triassic time, as most advocates of drift assume[1]. The northern parts of both North and South America are closer to the Mid-Atlantic Ridge than are the southern parts: each continent has rotated slightly

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[1]Convection currents are frequently called upon to explain the movement of the continents away from the mid-ocean ridges. Were such currents operative, however, they should have affected the Caribbean and Scotia regions as well as the adjoining continents, and should not have varied with continental geometry in the manner indicated by the deformation.

clockwise as it moved westward, and the southern part of North America has moved westward relative to northern South America[1].

The breadth of the continental plates, as they existed at the end of Mesozoic time, apparently controlled the pattern of Cenozoic deformation (Figure). The broad continental plates moved independently of one another, but narrow parts of the plates bent, and the narrowest parts ruptured. The strength of a continental plate must vary with its width. An obvious inference from the geometry of Caribbean and Scotia deformation is that the three continents bent where they were weak and broke where they were weakest. Integration of this inference with that of motion of the three continents toward the Pacific Ocean basin yields the speculation that the continents moved over the mantle as independent plates, and that they were not carried passively on top of moving mantle material. (The same conclusion can be reached from consideration of the intricacies of motion patterns shown by Cenozoic deformation in many other parts of the world.) The narrowest parts of the continents lagged behind and were disrupted.

The distribution of Tertiary and Upper Cretaceous sediments in the western Atlantic, however, places severe limits on the amount of westward drift of North and South America that can be postulated to have occurred since middle Cretaceous time. Oligocene sediments occur on the deep-sea fan of the Hudson submarine canyon near the foot of the continental slope off New York, and Upper Cretaceous fossils occur on a seamount 450 kilometres southeast of the foot of the slope off New York; and upper Oligocene sediments occur in the north wall of the Cayman Trench (Ericson et al., 1961, p. 238, 240). If the Greater Antilles have indeed lagged behind the westward-drifting American continents, then much of the lag indicated by the U-shape of the arc antedates the middle of Cretaceous time, although the final disruption of the arc did not occur until Eocene time.

Alternatively, the bending and fragmentation of the narrow parts of the Mesozoic belt might have been caused by drift of those parts independent of the broad adjacent continents, or by eastward ejection of Pacific mantle that carried with it the narrow continental masses. Such explanations appear less likely.

The young volcanic island arcs and flanking trenches that close on the east the U's of the Caribbean and Scotia arcs may have developed where Pacific and Atlantic crust and mantle came in contact when the continental connection was broken.

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[1]North (1965) explained the disruption of the Caribbean Arc in terms of relative movements of the two Americas, but his hypothesis does not account for the eastward swing of the geosynclinal belt of northern South America, nor for the character of the very similar Scotia Arc.

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DISCUSSION

Dr. H.P. Laubscher (Switzerland)

The gap between continents that have drifted apart can be filled by rising convection currents at the mid-ocean ridges. Where the currents go down, there are deep-focus earthquake belts which extend about the world. Where the currents come together, you have a surplus of mass which has to be shoved down somewhere. So we don't get rid of convection currents after all.

Dr. Hamilton

Many people have drawn idealized cross-sections showing convection currents rising and spreading beneath mid-ocean ridges and descending along deep-focus earthquake belts – but it does not appear possible to relate such speculation to the earth's actual tectonic geometry. The Mid-Atlantic Ridge is the type example of the rising and diverging part of a convection cell cited by most advocates of mantle convection. There is, however, no place where this hypothetical convection call can be postulated to descend on either the east or west sides (with the exceptions of the east ends of the Caribbean and Scotia Arcs, which represent only a trifling proportion of the length of the Mid-Atlantic Ridge). Conversely, there is no ridge to match the Kamchatka-Kuril-Japan-Mariana Trench. Convection cannot explain most strike-slip faulting known on the continents, nor can it explain many other tectonic features. And it is by no means established that deep-focus earthquakes are due to shear along planes dipping under continents or island arcs, although this is commonly assumed to be so.

Isostatic rebound following deglaciation has a half-life of only something like 800 years. The upper mantle obviously flows very readily, horizontally as well as vertically, and the rapid rate indicates a strength probably no greater than 10^{21} poises, and perhaps only 10^{20} poises if flow is limited to a thin layer. So if the crust is pulled apart by any process, mantle material should flow into the gap. The medial ridges of at least the Atlantic and Indian Oceans do apparently represent pull-apart features, but they need not have anything to do with convection. One alternative explanation is that the ridges are raised above belts of high heat flow, and that the flanks slide gravitationally toward the deep ocean floors.

Prof. S.K. Runcorn (UK)

Deep-focus earthquakes and the processes of ascension obviously imply some causal connection between the motion of continents at the surface and motions beneath the surface. You were quite right in drawing attention to the importance of isotasy as proof that there is the possibility of both horizontal and vertical flow beneath the rigid crust. After that point, when you get into the evidence of the hypothesis of Wegener's interpretation, you are demonstrably wrong.

Dr. Hamilton

I agree that Wegener's forces won't work, but I think that his basic concept of crustal rafts moving independently over the deeper mantle is more generally correct than is the common assumption that continents float passively on top of moving mantle material.

Prof. Runcorn

Well, obviously, there has got to be some force which will move the continents, and your last statement, which pictured a raft moving independently of what's underneath, of course, is nonsense.

Dr. Hamilton

Perhaps. But inertial forces derived from the rotation of the earth may provide a mechanism for independent drift of crustal rafts. As the core is fluid, it must be possible for the rotational velocities and orientations of spin axes of the core and mantle to change interdependently, so long as the sum of their products of angular momentum and moments of inertia remains constant, as in nested gyroscopes. The data of late Cenozoic palaeomagnetism can be interpreted in just these terms: the wanderings of the dipole axis mark wanderings of the axis of the core relative to the mantle, and the palaeomagnetic reversals mark epochs during which the core revolved faster than the mantle, rather than slower as is now the case. If such interchange of momentum does indeed occur, then wherever the strength across a layer in the upper mantle, or between mantle and crust, is less than the stresses produced by changes in velocity or axial orientation of the mantle, the overlying material should slide over the deeper mantle. A small change in velocity or axial orientation of the mantle shell could be compensated in momentum by a large motion of a proportionately tiny crustal fragment. Irregularities in movement patterns might be explicable, in such terms, as due to variations in strength of the uncoupling layer. Different sorts of motion could be expected to result from different depths of uncoupling.

D. SESSION ON ARCTIC CONTINENTAL MARGINS

THE NORTHERN MARGIN OF NORTH AMERICA: A PROGRESS REPORT ON INVESTIGATIONS AND PROBLEMS

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Summary

Knowledge of the nature of the northern margin of the North American Continent, and of its structural relationship to the crust under the Arctic Ocean, is still largely speculative. Until very recently, reliable information from the region has been so sparse that attempts at interpretation or general description have been based mainly on analogy with other areas or extrapolation of limited local observations. In the past decade there has been a tremendous increase in geophysical and geological investigation of the Arctic margins of North America and Eurasia, but emphasis is still on data collection rather than analysis, and the observations are too few to permit meaningful interpretation or even an assessment of their own significance. Nevertheless, the unexpected nature of some of the evidence indicates that traditional ideas of the structure and behaviour of the earth's crust at the northern edge of the continent may need revision.

Two general themes are highlighted by the accumulating evidence in nearly every field of study: 1) the crust beneath the Arctic Ocean is complex, with a behaviour neither typically oceanic nor typically continental, but some features indicative of each, and thus with a perhaps complicated and obscure transition to the typical continental crustal block of North America; and 2) the northern edge of the North American block itself is a region of much greater recent and present crustal and tectonic activity than had heretofore been realized.

Northern North America fits well, in gross pattern, the concentric structure of the traditional concept of an idealized continent, with a central stable craton bounded by a complex geosyncline which has been involved in repeated orogenies to form a fold belt, and a younger flanking sedimentary basin that has been folded, uplifted, eroded, and covered in turn by coastal plain and shelf deposits. The similarity to the east coast of North America is striking, and on a globe the Arctic Ocean may be viewed as a large bay at the north end of the Atlantic Ocean.

The nature of the crust under the Arctic Ocean has been the subject of much discussion. In general geological inference is in harmony with the interpretation that the depression occupies a sundered or ruptured continental mass, with postulated shear or fracture contacts at the edge of the North American continent. Most of the geophysical information suggests that a typical oceanic-type crust is present, which passes into the North American block by marked crustal thickening. A third possibility, advocated by some cosmogenists, is that the Arctic Ocean basin is underlain by a remnant of the primordial crust of the earth, which escaped differentiation into thickened continental-type masses in an oceanic crust matrix; the major continental blocks of the earth are conceived as being crowded around this remnant as a result of a common poleward component of continental drift.

Seismic studies in the Canadian archipelago show the crust to be about 38 kilometres thick under the geosynclinal belt, thinning to 30 kilometres under the continental shelf. Analysis of earthquake waves that arrive in North America after having passed under the Arctic Ocean indicates that the waves have travelled through oceanic-type crust whose thickness is of the order of 15 kilometres or less. There is thus an implied discrete boundary to the continental block.

Gravity surveys show an interrupted but nearly continuous positive free-air anomaly near the outer edge of the continental shelf off both Alaska and the Canadian Arctic Islands. The anomaly is consistent with a pronounced thinning of the crust, from 30 to less than 20 kilometres, under the continental slope.

The residual magnetic field has been mapped over a large part of the continental shelf and slope adjacent to the Canadian archipelago, and widely spaced aeromagnetic profiles run across the ocean beyond. Pronounced magnetic irregularities are confined to the geosynclinal belt and sedimentary basin; most of the continental shelf is magnetically very uniform; there are indications of greater irregularity over the continental slope, leading to an area of strong irregularly spaced anomalies over the floor of the basin and the Alpha Rise beyond it. The significance of this pattern of magnetic anomalies is not at present known, but it does indicate a distinct difference between the continental block and the crust beneath the ocean basin.

Local areas on the north edge of the continental block are anomalous, from a geophysical point of view, and their interpretation may add much to our understanding of the nature of the continental margin. Near Alert at the northeast corner of the archipelago a very high level of irregular magnetic activity has been observed in a zone with a north-northeast axis. Magnetotelluric measurements show exceptionally high electrical conductivity close to the surface, and the zone coincides with a positive Bouguer gravity anomaly. The phenomena appear to be indicative of unusually high electromagnetic conductivity at a shallow depth; it is tempting to postulate a local pronounced thinning of the crust and consequent anomalously high temperature gradient, but there is no independent evidence of this to date. The zone is subparallel to but not coincident with a postulated major crustal shear between Ellesmere Island and Greenland, which is marked by, among other phenomena, an apparent hiatus in a zone of earthquake epicentres that extends through Baffin Bay and, after the interruption, continues into the Arctic Ocean.

Near Mould Bay, at the western edge of the archipelago, the vertical fluctuations of the magnetic field are curiously dampened, in comparison with the horizontal variations, over an area at least 60 by 100 kilometres, with apparently well-defined limits. Seismic energy received within this area by waves travelling beneath the crust from sources to the east is attenuated by a factor of as much as ten compared with the energy received along a similar path from comparable sources to the north; waves travelling through the granitic layer arrive with about equal energy from each direction. Here again it is tempting to invoke a positive crustal temperature anomaly, but measurements of geothermal heat flow in the ocean floor show anomalously low values to the south of the area of the magnetic anomaly, and normal to slightly high values within and to the west of it. Local seismic activity is marked within the area; and several hundred small earthquakes originated there within a two-month period in 1965. The area has suffered block faulting since apparently prior to the Tertiary period, and may be a place where the continental margin is making geological history before our very eyes.

MAGNETIC DATA CONFIRM THAT THE NANSEN-AMUNDSEN BASIN IS OF NORMAL OCEANIC TYPE[1]

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Abstract

The Nansen-Amundsen Basin of the Arctic Ocean is a typical ocean basin with characteristic linear magnetic anomalies similar to those found in the Pacific Ocean Basin. The Eurasian continental shelf anomalies, indicating the continuity of structure from land, end at the continental slope. A zone of magnetic anomalies with lower amplitudes occurs along the slope and probably represents a sediment-filled trench. The western basinward slope of the Lomonosov Ridge resembles magnetically a submerged continental slope with a similar filled trench. The Nansen-Amundsen Basin contains a Mid-Arctic Ridge similar to the Mid-Atlantic Ridge.

The results of aeromagnetic surveys in the Arctic Ocean, partly published earlier by Demenitskaya et al. (1962, 1964) may be used as a basis for a comparative geophysical study of the western (Spitsbergen side) Arctic Basin and other oceans.

Discontinuous "cluster" magnetic anomalies of a characteristic shape can be traced along almost the entire boundary between the Eurasian continent and the Arctic Basin and marginal seas, and are associated with the edge of the shelf. The anomalies are similar to those found off the east coast of North America (Drake et al., 1959; King et al., 1961; Drake et al., 1963), near Chukchi Cap (Hunkins et al., 1962), and elsewhere. They probably resulted from strongly magnetized material intruded into fissures parallel with the continental slope.

Magnetic anomalies over the Arctic shelf and islands attest to the continuity of structure from adjacent land areas. The shelf anomalies end at the continental slope. The slope separates the shelf anomalies from the Arctic Basin anomalies. Direct geological implications of this relationship are the lack of continuity between the Lomonosov Ridge and the Verkhoyansk Fold Belt, and between the Mendeleev Ridge and the east-west structures on the adjacent part of the Chukchi shelf.

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[1]By title

A zone of magnetic anomalies with lower amplitudes was traced along the seaward boundary of the Spitsbergen-Severnaya Zemlya continental slope. The writers believe that the zone marks a structural trench which is filled with sediments and thus is not reflected in the seabottom topography. The supposed trench lies beneath the lower edge of the continental slope and may have a structure similar to other buried trenches in the Atlantic Ocean.

On the opposite side of the Nansen-Amundsen Basin, along the base of the Lomonosov Ridge, is a similar trench structure. The western basinward slope of the ridge resembles a submerged continental slope because "cluster" magnetic anomalies are associated with the ridge slope.

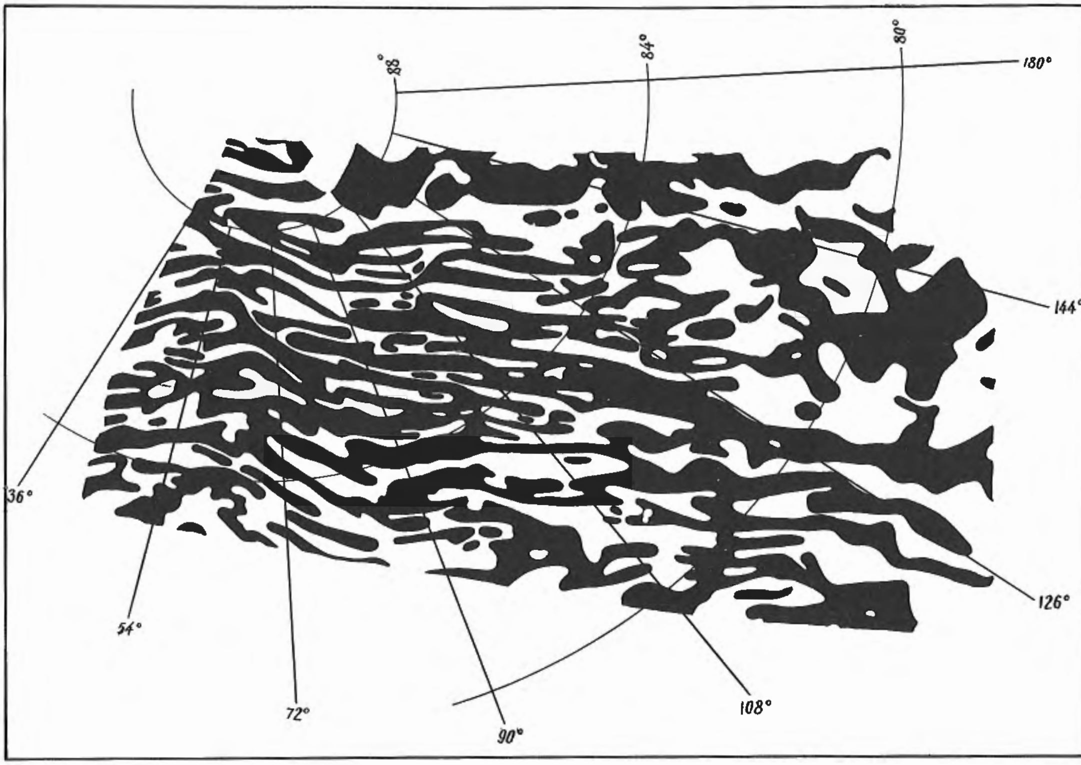

Figure 1. Preliminary magnetic anomaly map of Nansen-Amundsen Basin.

The structure of the Nansen-Amundsen Basin shows clear features of symmetry. Filled trenches occur on the Spitsbergen-Severnaya Zemlya side and the Lomonosov sides of the basin, and a rifted Mid-Arctic Ridge occurs in the middle of the basin. The basinal area coincides with an area of regular, almost linear magnetic anomalies (Fig. 1) which are similar

Figure 2. Magnetic anomaly map of Pacific Basin off the west coast of North America. (After Raff and Mason, 1961)

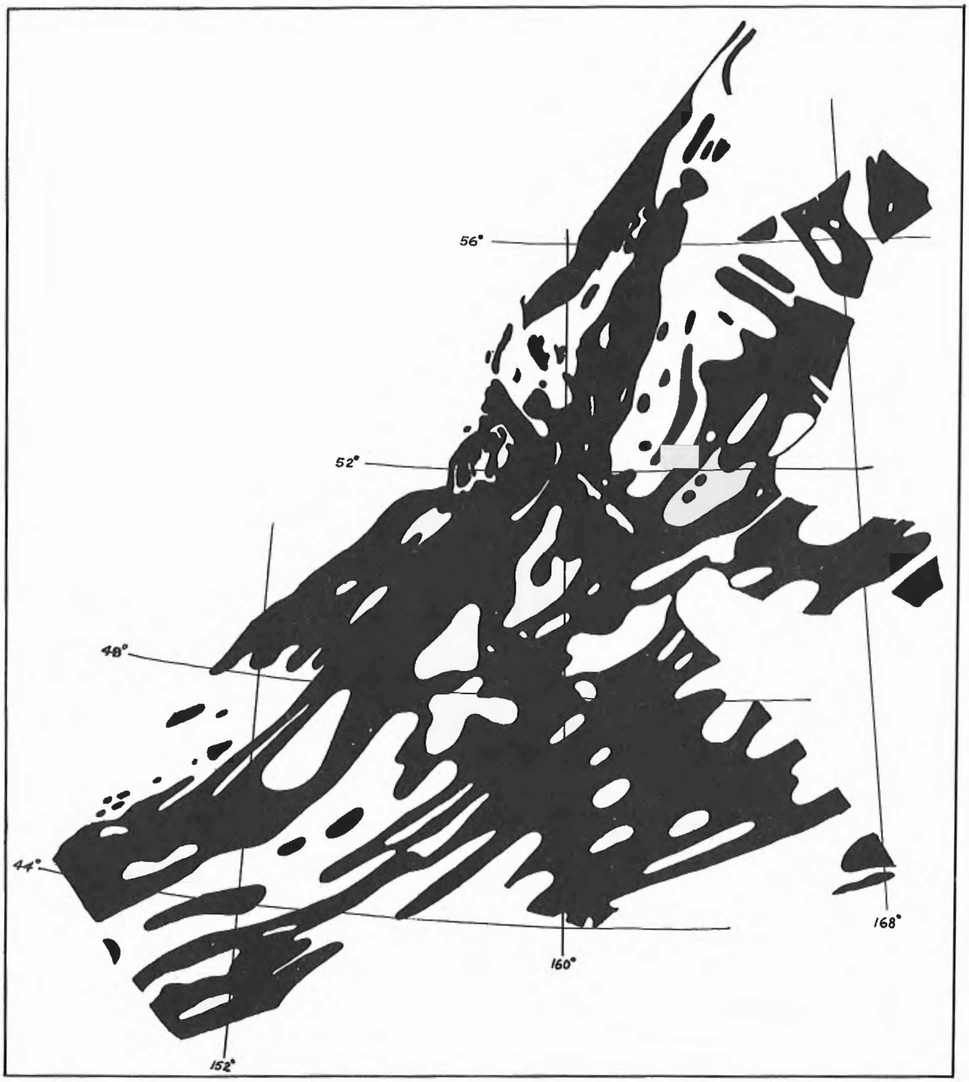

Figure 3. Magnetic anomaly map, northwestern part of Pacific Ocean. (After Soloviev and Gainanov, 1963)

to those of the Pacific Ocean Basin (Gainanov and Soloviev, 1963; Mason, 1958; Mason and Raff, 1961; Raff and Mason, 1961; Raff, 1962; Soloviev and Gainanov, 1963; Vacquier et al., 1961). The degree of linearity of the magnetic field within the Arctic Basin is somewhat lower than that within the northeastern part of the Pacific (Fig. 2) and higher than that within the northwestern part (Fig. 3). These differences may be due either to different geological features in the Arctic than in the Pacific, or to different ages of the crust.

The mid-Arctic rift can be located by its characteristic magnetic field. It is believed that the characteristic pattern of anomalies, similar to those described over the mid-Atlantic rift by Ewing et al. (1957), Keen (1963), and Vacquier and Von Herzen (1964), constitutes more critical and more definitive evidence of a rift than does the location of an earthquake epicentre belt.

Thus the Nansen-Amundsen Basin is a typical ocean basin, underlain mainly by oceanic crust and in the southern part by suboceanic crust. The Mid-Arctic Ridge is probably underlain by anomalous mantle. The basin as a whole, and its separate morphological provinces, are smaller than the Atlantic Ocean. Structurally, the Nansen-Amundsen Basin is similar to the Atlantic as indicated by the transverse faults, locally with small strike-slip offsets shown by the magnetic anomaly fields.

The western (Spitsbergen side) and eastern (Alaskan side) Arctic basins have different crustal structure, a difference also supported by the magnetic anomaly field and its quantitative evaluation. In general, the results of calculations of the anomaly-source depths confirm and modify the conclusions about crustal thickness made by Demenitskaya et al. (1964).

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THE ARCTIC CONTINENTAL SHELF NORTH OF ALASKA[1]

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Lamont Geological Observatory

Abstract

North of Alaska, the shelf ranges from a normal type off Point Barrow to a "continental borderland" type north of the Chukchi Sea. Northwest of Barrow, seismic refraction results indicate a layer with a compressional-wave velocity of 7.4 km/sec which rises from a depth of 32 kilometres at Barrow to 20 kilometres near the edge of the shelf. The Cretaceous rocks of the Arctic coastal plain apparently thicken seaward from 1.1 kilometres at Barrow to 6 kilometres near the edge of the shelf.

The Chukchi Cap is evidently a feature of continental origin north of the Chukchi Sea, although it is now separated from the shelf by a saddle. The Chukchi Cap is 150 kilometres in diameter at the 500-metre contour. The shallowest sounding recorded for the Cap is 246 metres. A continuous 1,000-gamma positive magnetic anomaly borders the western and northern margins of the Cap. The anomaly is interpreted as an effect of a buried basement ridge similar to that found along the continental margin of eastern North America.

INTRODUCTION

Scientific exploration of the Arctic Ocean has advanced rapidly in the past two decades. Expeditions using drifting ice stations, aircraft, and submarines have all contributed to the present understanding of topography and geological structure in the Arctic Basin. Two decades ago, the Arctic Ocean was believed to consist of only one basin. Since that time knowledge of the Arctic Ocean has expanded through efforts of Soviet and American expeditions. Today the bathymetry of the Arctic Ocean is known in broad outline (Fig. 1). The Lomonosov Ridge and Alpha Rise cross the Arctic Ocean and divide it into three basins. The continental margin north of Alaska is bounded by the Canada Basin.

PHYSIOGRAPHY

The continental margin north of Alaska is complex and includes several different physiographic provinces. The shelf width itself

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[1]Lamont Geological Observatory Contribution No. 971.

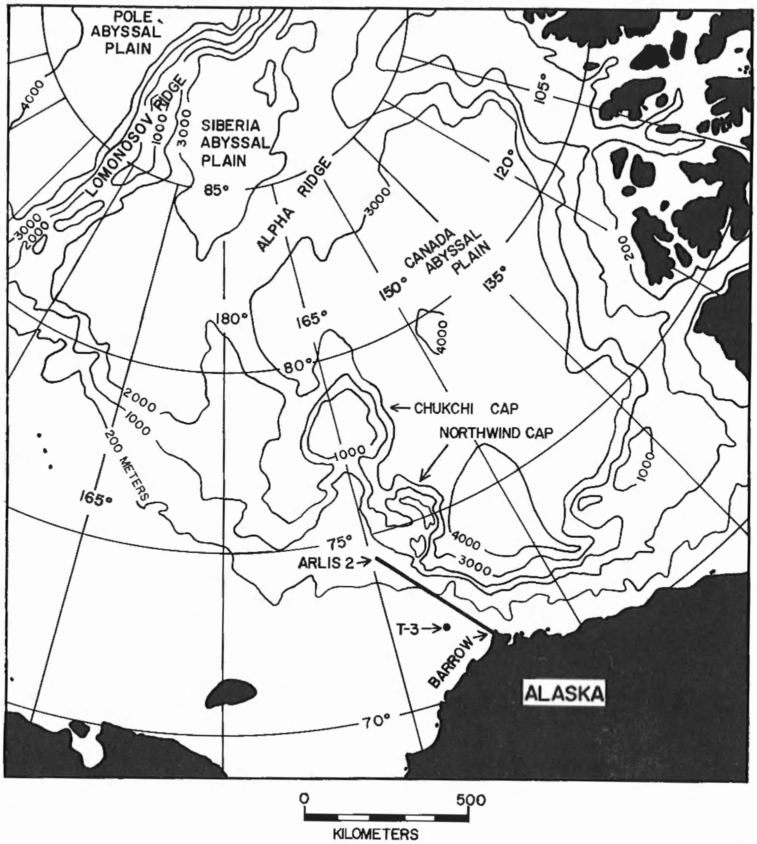

Figure 1. Bathymetric chart of the Arctic Ocean. Solid line indicates seismic refraction profile between Barrow and Arlis 2.

varies by a factor of 10, ranging from 75 kilometres north of Barrow to 750 kilometres in the Chukchi Sea. The narrow margin north of Barrow is similar to that of other oceans. The lower part of the continental slope has a gradient of one to two degrees. At the foot of the slope lies a gentle continental rise which joins the Canada Abyssal Plain. The plain covers an area of 200,000 square kilometres at a depth of about 3,800 metres.

North of the broad Chukchi shelf lies an area of intermediate and rugged topography. This area has some resemblance to the continental borderland off southern California (Fisher et al., 1958). The lower continental slope in this region is a steep scarp with gradients as high as 23 degrees. The region contrasts markedly with the Barrow shelf and slope to the east. North and west of this borderland is a submarine plateau about 150 kilometres in diameter. The flat top of the plateau is less than 300 metres deep.

GEOLOGY

The geological structure of the emerged portion of the Arctic continental shelf in northern Alaska has been investigated with seismic and gravity methods (Woolsen et al., 1962). A large asymmetric sedimentary basin lies beneath the region. Its deepest part occurs near its southern margin where it is flanked by the thrust-block mountains of the Brooks Range. The axis of the basin trends east, parallel with the Brooks Range. The basin is filled mainly with Cretaceous sedimentary rocks. They range in thickness from 5,000 to 7,000 metres near the southern margin, to 500 metres near Point Barrow. At Point Barrow, a basement high is associated with a complex, plug-like, disturbed zone.

Apparently the Cretaceous rocks extend seaward beneath the submerged part of the continental shelf. This is indicated by extrapolating surface geology and by seismic refraction methods. However, no offshore wells have yet conclusively demonstrated this continuity.

SEISMIC REFRACTION PROFILE

In 1961, a reversed seismic refraction profile, 426 kilometres long, was completed along the edge of the continental shelf northwest of Point Barrow (Kutschale et al., 1963). Receiving stations were located at Barrow and on ice stations Arlis 2 and T-3 (Fig. 1). Nine shots, ranging up to 1,500 lb., were fired between the stations by the U.S.S. STATEN ISLAND. The travel-time curves are shown in Figure 2. The deepest layer determined from data of both receiving stations had a compressional-wave velocity of 7.4 km/sec. This velocity-layer is 32 kilometres deep at Point Barrow and 20 kilometres deep at Arlis 2 near the edge of the shelf (Fig. 3). An 8.5 km/sec layer was detected at Barrow but not at Arlis 2. If the boundary surface is actually horizontal, then the layer lies at a depth of 55 kilometres. A velocity of 7.4 km/sec has been observed elsewhere in the world, principally beneath mid-ocean ridges and continental margins. Other layers and their depths at Barrow are 6.7 km/sec at 15 kilometres, 6.2 km/sec at 6 kilometres, and 4.9 km/sec at 1.1 kilometres. The 4.9 km/sec layer presumably represents basement. Resting upon the basement is a layer with a compressional-wave velocity of 3.0 km/sec. This layer corresponds to the Cretaceous sands and shales at Barrow where a test well has provided

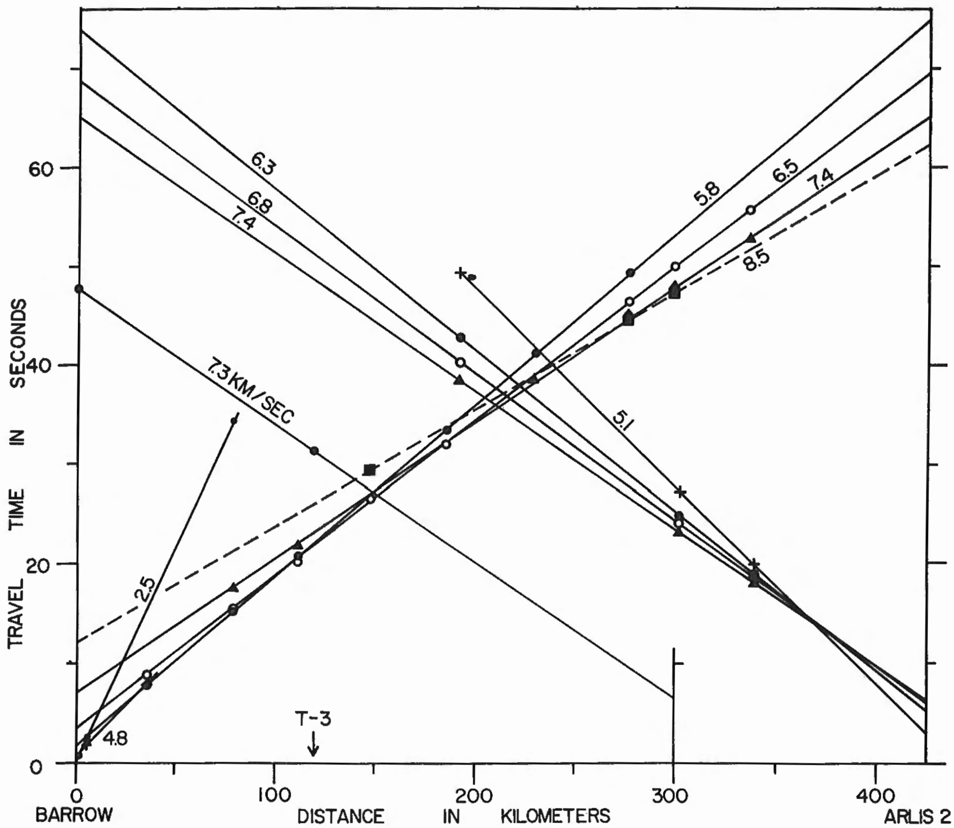

Figure 2. Travel-time curves for seismic refraction profile along line shown in Figure 1.

seismic velocities of the geological formations. The basement increases in depth from 1.1 kilometres at Barrow to 6 kilometres at Arlis 2's position.

MAGNETIC AND GRAVITY SURVEYS

Magnetic and gravity surveys indicate that the basement on the continental shelf has local irregularities not detected by the refraction survey. A 1,000-gamma positive magnetic anomaly on the shelf trends parallel with the Alaskan coast but is inclined to the continental margin. The anomaly can be interpreted as a buried basement high which just reaches the

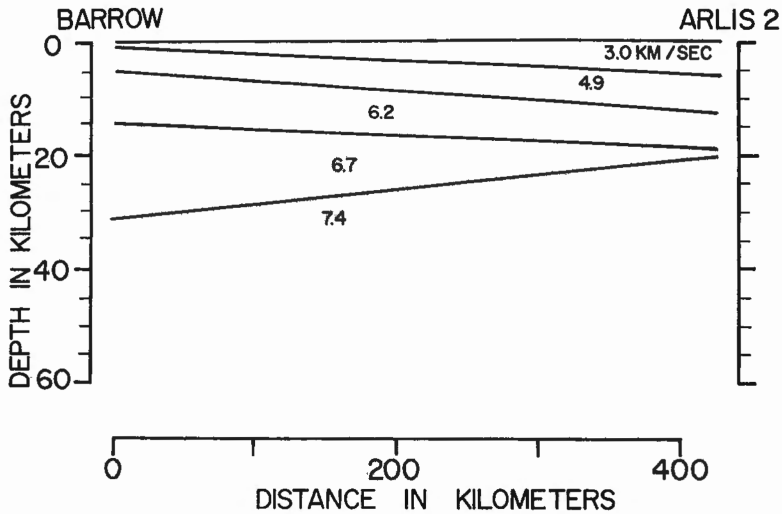

Figure 3. Cross-section showing interfaces determined by seismic refraction methods along the line between Barrow and Arlis 2

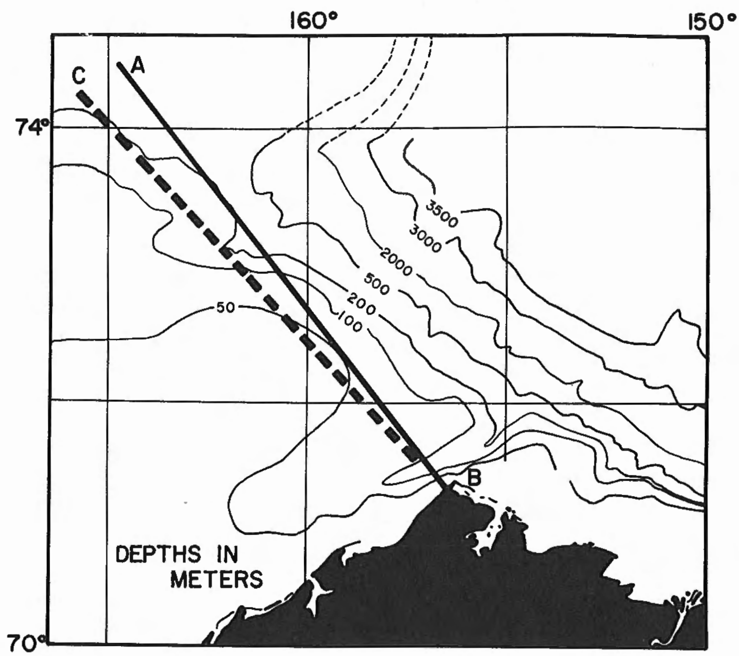

Figure 4. Bathymetric chart showing location of refraction profile (A-B) and aeromagnetic profile (B-C) between Barrow and Arlis 2.

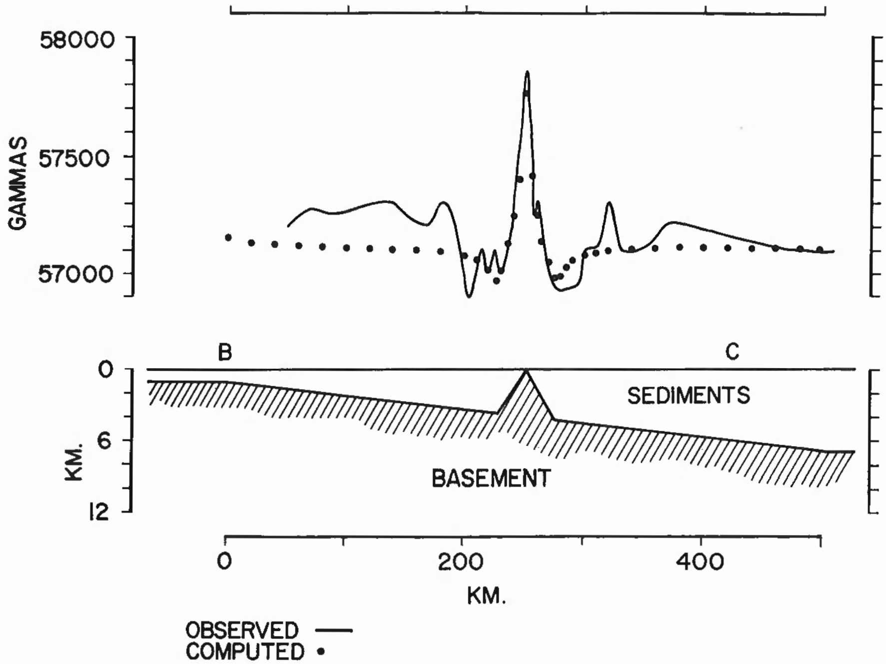

Figure 5. Interpretation of magnetic anomaly on Arctic continental shelf. Solid line is observed anomaly; dotted line is anomaly calculated from the model.

surface (Figs. 4 and 5). Its relief is 4 kilometres if the magnetic susceptibility is assumed to be 0.01 emu for the basement and zero for the sediments.

The Chukchi Cap is evidently continental in origin although it is now separated from the continent by a saddle. Depths of 300 metres and less to the Cap's upper surface are similar to the shelf depths. Along its western margin is a continuous positive magnetic anomaly of about 1,000 gammas. The anomaly maximum falls over about the 1,000-metre depth contour (Figs. 6 and 7). The anomaly and its associated submarine topography are similar to those observed along the Atlantic coast of the United States. There, with both magnetic and seismic information available, the anomaly is believed to be caused by a buried basement ridge beneath the continental slope. A similar interpretation was made for the Chukchi Cap anomaly (Shaver and Hunkins, 1964). It requires a layer about 12 kilometres thick of non-magnetic material beneath the upper surface of the Cap. Presumably, a large part of this layer consists of sediments. The anomaly along the western side of the Cap trends perpendicular to the present continental margin. If it is a relic of an old continental margin, it must have once been parallel with the coast. If so, one hypothesis which would account for its present location would have the Chukchi Cap block located originally along the Alaskan coast east of Barrow and then rotated a quarter-turn counterclockwise into its present position. This would explain the lack of shelf anomalies east of Barrow. It would also explain the "borderland" between the shelf and the Cap as a shear zone which formed during the rotation of the Chukchi Cap block.

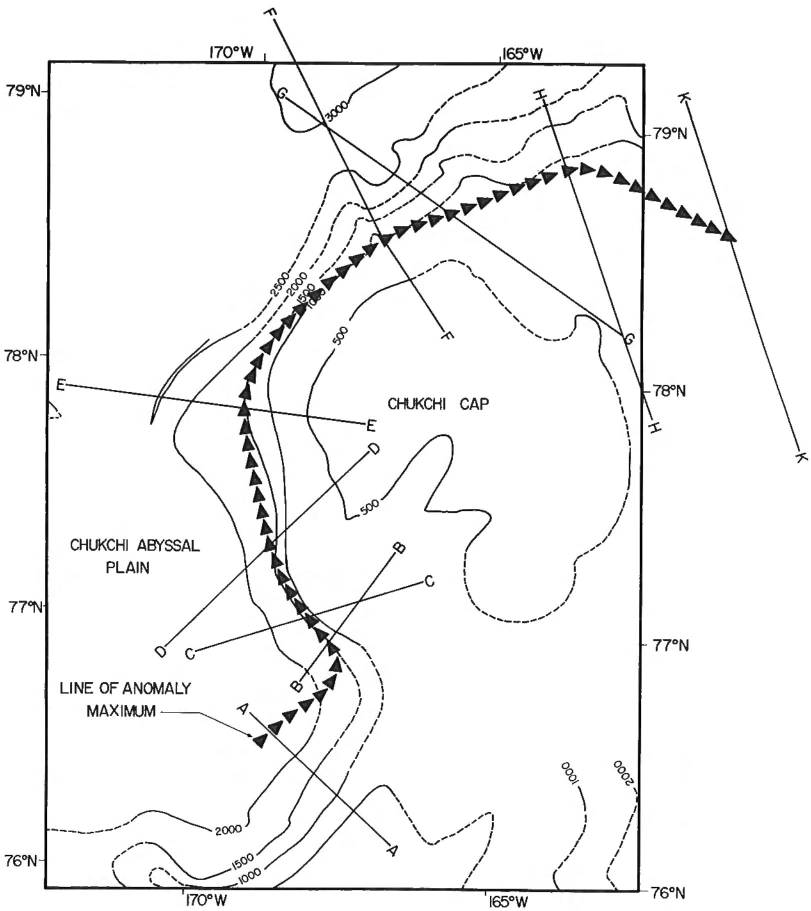

Figure 6. Bathymetric chart showing trend of large magnetic anomaly along western boundary of the Chukchi Cap.

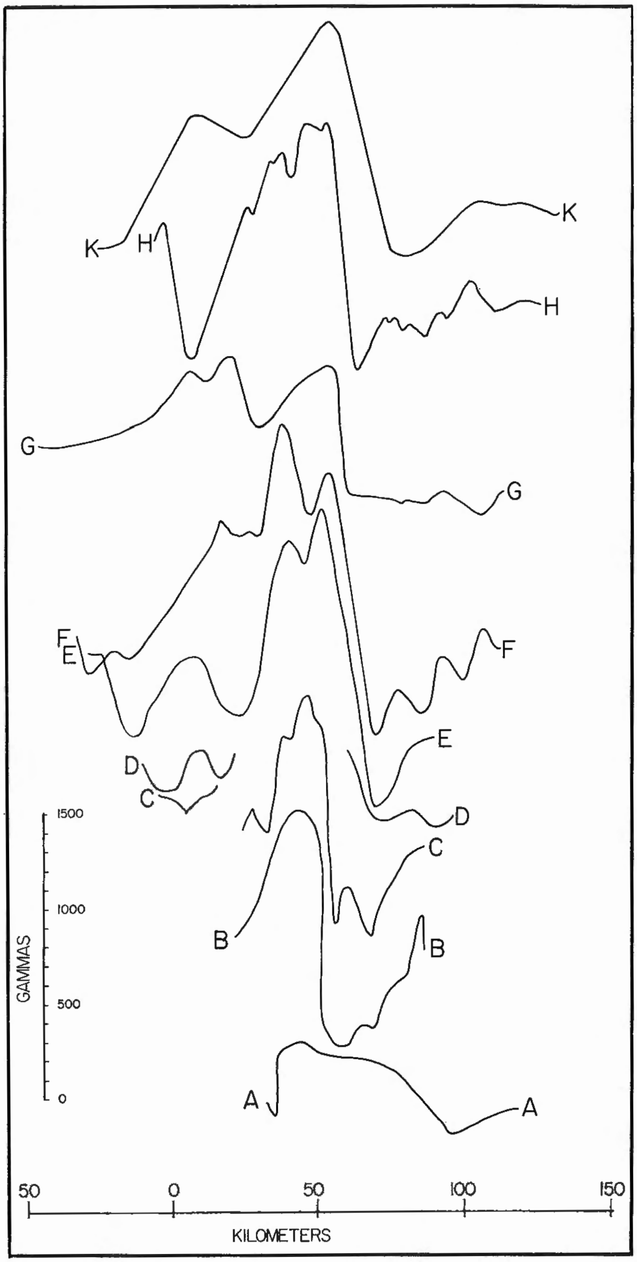

Figure 7. Magnetic profiles across the western part of the Chukchi Cap. Locations of profiles are shown in Figure 6.

ACKNOWLEDGMENTS

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DISCUSSION

Prof. J. Tuzo Wilson (Canada)

Do you have any material that was dredged, cored, or obtained in any other way, which would give any indication of the age of any of these features?

Dr. Hunkins

We do not have any dredged rock which would provide important criteria. We do have many samples of unconsolidated sediments, but no bedrock which would suggest the age of these features.

E. SESSION ON PACIFIC AND INDIAN ISLAND ARCS

THE ALEUTIAN ARC AND ALASKA CONTINENTAL MARGIN[1]

C.A. Burk
Mobil Oil Corp.

Abstract

The Alaska Peninsula is of special geological interest since it represents the continental margin of southern Alaska as well as a part of the Aleutian island arc. The volcanic-rich Tertiary sediments of the Aleutian Islands are abundant also throughout the Alaska Peninsula, where they overlie Cretaceous sandstones and shales and a thick sequence of Jurassic arkosic strata. Permo-Triassic carbonate and volcanic rocks are exposed locally and represent the oldest dated rocks of the Alaska Peninsula. The Shumagin-Kodiak Shelf separates the Alaska Peninsula from the Aleutian Trench and consists of a thick sequence of late Mesozoic turbidites, intruded by ultramafic rocks and overlain by remnants of coarse Tertiary debris. The Mesozoic structural and stratigraphic history of the Shumagin Shelf was thus distinct from that of the Alaska Peninsula.

A major uplift closely followed intrusion of early Jurassic granitic batholiths in the Alaska Peninsula. The Shumagin-Kodiak Shelf was uplifted immediately following intrusion of earliest Tertiary granodiorites. A third period of major plutonism was marked by intrusion of quartz diorite and granodiorite in the Alaska Peninsula region. The major tectonic deformation occurred during the Pliocene.

The Alaska Peninsula may thus have existed as early as mid-Jurassic. The Shumagin-Kodiak Shelf is no older than Tertiary, but it is not known whether this area was previously a trench, continental rise, or slope. It seems likely that the Aleutian Trench is no older than Tertiary, and may be much younger. The volcanic arc of the Alaska Peninsula and Aleutian Islands developed in earliest Tertiary.

The structural configuration of the Shumagin-Kodiak Shelf, and the presence of Mesozoic turbidites and ultramafic rocks along the northern borders of the Bering Sea Basin, suggest that the history of these shelves

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[1]Much of the information presented here is discussed in greater detail in Burk (1965). The writer acknowledges gratefully the kind permission of the Geological Society of America to include in this report several illustrations from that publication.

is similar and that the Aleutian arc was superimposed on this framework in early Tertiary, extending across both oceanic and continental crust. The occurrence of upper Palaeozoic sedimentary rocks at one locality in the Aleutian Islands (Adak Island) remains to be explained, however.

ALEUTIAN ISLANDS

The Aleutian volcanic arc is one of the earth's major structural features, extending for nearly 2,000 miles from the Kamchatka Peninsula into southern Alaska. It is bordered on the south by the Aleutian Trench and on the north by the Bering Sea basin and shelf and by the Alaska mainland. At least 75 major volcanoes have been recognized in this arc. The Aleutian Islands form a perfect small circle of 1,200 kilometres radius. They consist of volcanic rocks, sedimentary debris derived from such rocks, and quartz-dioritic plutons. These rocks are only gently deformed by folds and steep faults. All of the volcanoes in these islands are concentrated along the northern concave edge of the arc.

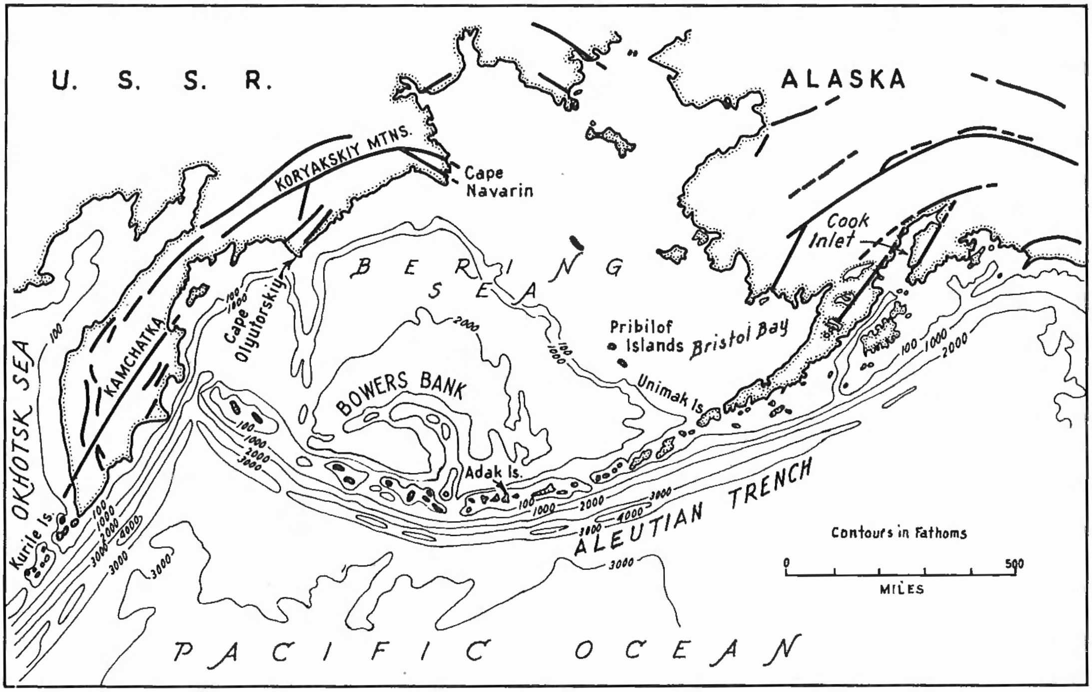

Figure 1. Bathymetric map of the Bering Sea and adjacent areas showing principal faults.

The Tertiary volcanic and sedimentary rocks are of marine and non-marine origin. Some contain fossils at least as old as Oligocene; older volcanic rocks are probably of earlier Tertiary age. The thickness and structure of these rocks are poorly known. The Aleutian Islands as a whole have received very little field investigation; the area is remote, access is difficult, and the weather is unpleasant. Much structural speculation has been based on bathymetric charts of this region, but these interpretations often bear little relationship to what is known from the exposed geology.

The volcanic-rich Tertiary rocks found in the Aleutian Islands are present also throughout the Alaska Peninsula, where the geology is better known and where a sequence of Mesozoic rocks provides a basis for interpreting the earlier history of this arc.

ALASKA PENINSULA

Northeast of Unimak Island the Aleutian arc constitutes the Pacific continental margin of Alaska. All of the active and recently active volcanoes are confined to the Alaska Peninsula and to the mountains north and west of Cook Inlet. The oldest dated rocks of the Alaska Peninsula are fossiliferous Permo-Triassic carbonate and volcanic strata, which are conformably overlain by Lower Jurassic volcanic-rich clastic sediments. All of these rocks were intruded near the head of the Alaska Peninsula by an early Jurassic granitic batholith (Fig. 2). Similar plutons of the same age (about 165 m.y.) occur to the northeast for at least 600 kilometres to the Talkeetna Mountains (Grantz et al., 1963).

Rapid uplift and erosion of these plutonic rocks constitute the first indication of a structural ridge in the present position of the Aleutian arc. Arkose-rich sediments accumulated to great thicknesses throughout the Alaska Peninsula from Middle Jurassic into Early Cretaceous (Fig. 2). Rocks of possibly the same age to the north and south are deep-water flysch and greywacke sequences (Fig. 3). Rocks of mid-Cretaceous age (Aptian to Campanian) are absent on the Alaska Peninsula, but this interval was one of only very gentle deformation. A thin sequence of uppermost Cretaceous clastic rocks has transgressed across strata as old as Upper Jurassic.

Lower Tertiary rocks consist of volcanic flows, sills, and clastic debris, indicating that active vulcanism extended throughout the area. These strata were gently deformed and intruded along the Alaska Peninsula by a series of mid-Tertiary quartz-dioritic plutons, and again the area was uplifted. Debris from these plutons and all older rocks is abundant in a locally thick Miocene sequence.

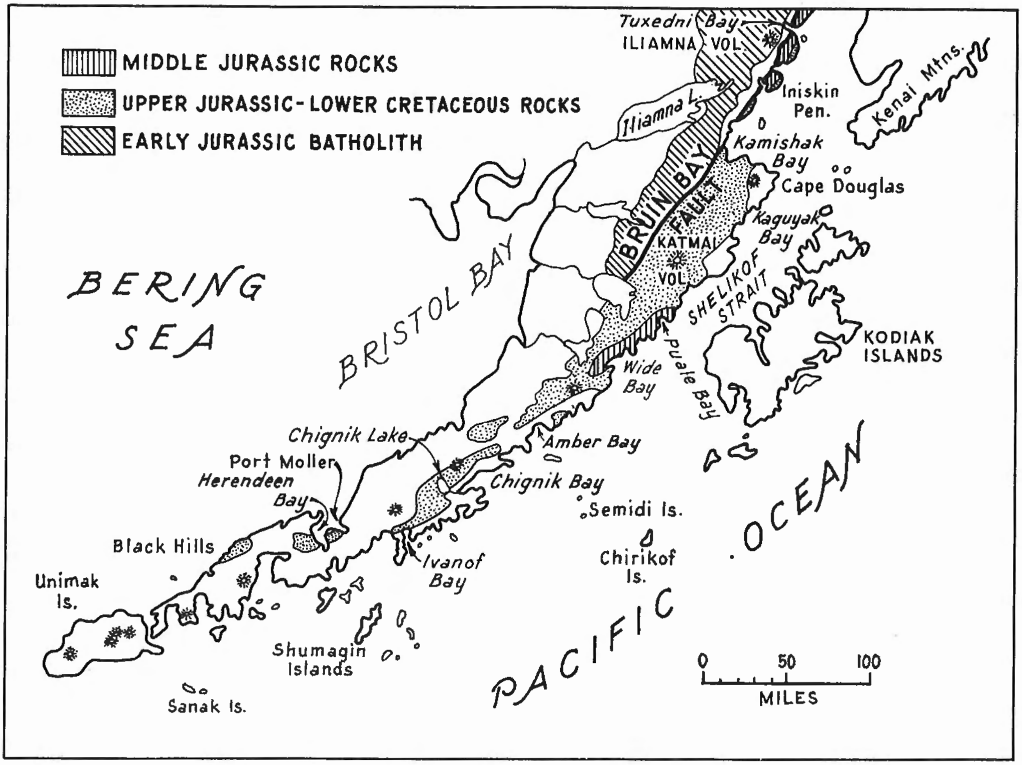

Figure 2. Generalized exposures of Middle and Upper Jurassic rocks of the Alaska Peninsula area.

The present complex structural configuration of the Alaska Peninsula was created largely during a short interval within the Pliocene. Marine Pliocene sediments along the coasts and pre-Pleistocene volcanic rocks in the mountains unconformably overlie Miocene and all older strata.

SHUMAGIN-KODIAK SHELF

The geology of the broad shelf which separates the Alaska Peninsula from the Aleutian Trench is distinct in most respects from that of adjacent areas. Rocks exposed on the islands consist largely of a thick sequence of volcanic-rich turbidites which have been intruded locally by dunite, peridotite, and other ultramafic rocks. The age of this flysch sequence is problematical, but at least part of it is Late Cretaceous and part may be as old as Late Jurassic; most of the sequence is probably Cretaceous.

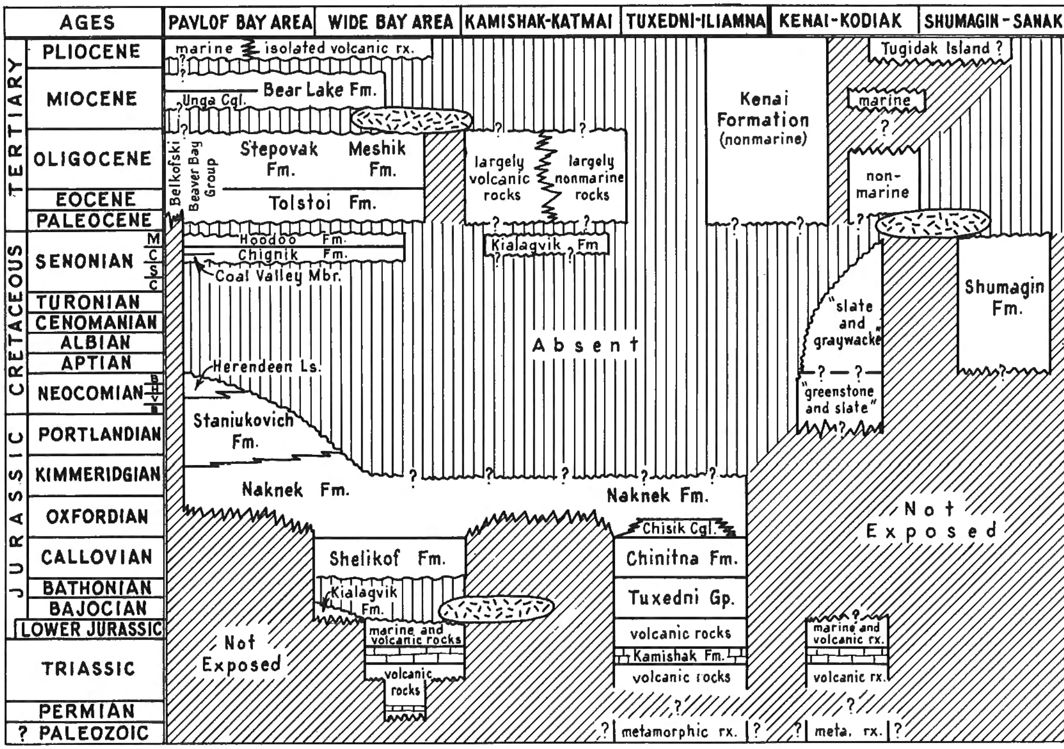

Figure 3. Simplified stratigraphic relationships in the Alaska Peninsula area.

The strata lack the bimodal grain distribution characteristic of greywackes. Strata rich in volcanic rocks and intruded by ultramafic bodies may be the oldest rocks in the sequence. The structure of these rocks is very complex, with many close, steep folds of short wave-length, but some of the deformation was penecontemporaneous with the rapid deposition of the sediments.

The flysch sequence of the Shumagin-Kodiak Shelf was intruded during earliest Tertiary (60 m.y.) by many granodioritic plutons and then rapidly uplifted to form the continental margin. These rocks are unconformably overlain by Palaeogene strata similar to those known on the Alaska Peninsula, and also by isolated exposures of less-deformed Miocene sedimentary rocks. There is no indication as yet of Tertiary vulcanism anywhere in the belt of the flysch sequence of the Shumagin-Kodiak Shelf. The present Aleutian Trench is probably no older than the adjacent shelf (early Tertiary) and it may be much younger.

STRUCTURAL HISTORY

Of the five principal periods of deformation affecting the Alaska Peninsula and the adjacent continental margin, three were associated with plutonic intrusion followed by rapid uplift (early Jurassic, early Tertiary, and mid-Tertiary), but only minor tectonic warping was involved. The mid-Cretaceous deformation is represented by a great hiatus on the Alaska Peninsula and probably by the thick flysch accumulation of the Shumagin-Kodiak Shelf (Fig. 3). Pliocene deformation created essentially all of the structures we observe today.

The structural history of the Aleutian Islands is only poorly known, but the overall Tertiary history would appear to be compatible with that of the Alaska Peninsula. Although the structure is locally very complex its overall aspect is not one of tight compressional folds, overturned anticlines, and thrust faults considered to be characteristic of Alpine-type orogenies. The fundamental structure appears to involve deep faults bounding wedges of crustal rocks, and the degree of deformation seems to reflect the structural competence of the rocks involved.

Although there are many long, straight faults within the Aleutian arc, little strike-slip displacement can be demonstrated with confidence. The Bruin Bay fault, which borders the southern edge of the early Jurassic batholith at the head of the Alaska Peninsula (Fig. 2), was active through the late Jurassic, during which time it separated the uplifted plutonic rocks from the accumulating arkosic debris. All of its known displacement is dip-slip. Juhle (1955) has reported that cobbles of a distinctive granophyric quartz monzonite are present in Jurassic sediments a few miles east of stocks of identical rock in the early Jurassic batholith. This would seem to preclude any significant strike-slip movement along this major fault.

Similar long faults adjacent to Cook Inlet have been credited with strike-slip movement (e.g. Hill, 1963), but there is little supporting evidence available. The same may be said of the large faults on Kodiak Island. All of these, however, exhibit obvious and significant dip-slip displacements. The amount of strike-slip displacements of other postulated faults in the Aleutian Islands (e.g. Adak and Unalaska) are also uncertain; many steep normal and reverse faults have been recognized and described throughout these islands.

Many of the young volcanoes show prominent local fractures and alignments trending both normal to and parallel with the strike of the arc and at various intermediate angles, but little is obvious from them regarding broader structural features. The plutonic rocks appear to be restricted both in time and space. The widespread early Jurassic batholiths are confined to the upper Alaska Peninsula and its projection to the northeast. The early

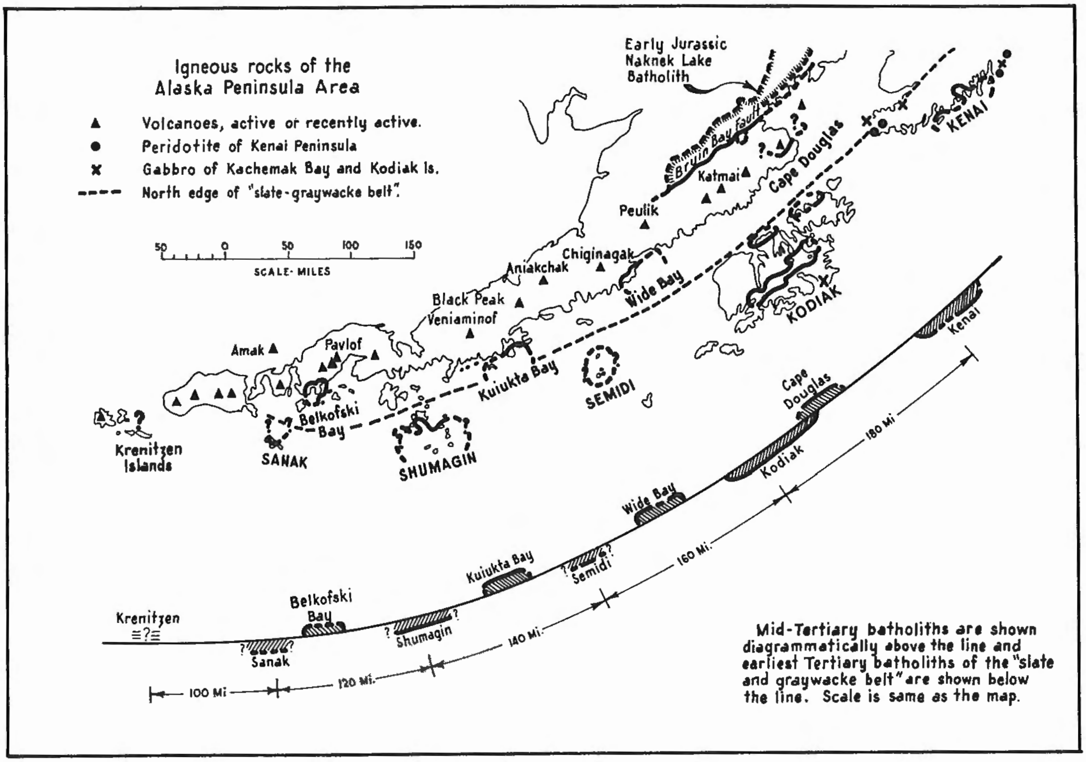

Figure 4. Generalized map showing apparent areal relationships of the principal igneous rocks of the Alaska Peninsula.

Tertiary plutons are confined to the Shumagin-Kodiak Shelf and show a fairly regular spacing. The mid-Tertiary plutons appear to be restricted to a linear belt on the Alaska Peninsula with an apparent regular spacing that alternates with the earlier plutons of the adjacent shelf (Fig. 4). This apparent distribution requires further checking in the field, but the pattern appears to reflect fundamental structures within the crust which cannot easily be explained. The geology of most of the Aleutian Islands is too poorly known to define similar patterns, but none is apparent at the present time.

THE BORDERS OF THE BERING SEA

Although the structure of the Shumagin-Kodiak flysch sequence is locally very complex, the trend of the rocks and of the fold axes for more than 600 miles along this shelf and on the Kenai Peninsula closely parallels the present shelf-edge. It is not known whether these sediments were deposited in a Cretaceous oceanic trench or as a continental rise (or both), but much of the present structure is penecontemporaneous with sedimentation and probably reflects the depositional strike of the original deposits. The flysch sequence of the Sanak Islands (Fig. 2) diverges sharply and strikes westward towards Unimak Island and towards the edge of the Bering Sea Shelf beyond. Unimak Island unfortunately is entirely unmapped, but the Pribilof Islands (Fig. 1) of the Bering Sea Shelf contain a basement of ultramafic rocks similar to those found on the Shumagin-Kodiak Shelf. Cretaceous turbidites containing ultramafic rocks have been described along the eastern coast of Kamchatka and the Bering Sea coast as far north as Cape Navarin (e.g. Nalivkin, 1960).

It seems possible that the late Mesozoic history of the northern shelves bordering the Bering Sea and the eastern margin of Kamchatka Peninsula were similar to that of the Shumagin-Kodiak Shelf. If this is true, the Aleutian volcanic arc would represent a Tertiary feature superimposed on the older framework, extending across oceanic and continental crust, and developing coincident with the formation of the present Shumagin-Kodiak Shelf. It should be noted, however, that other explanations are readily available and that almost nothing is known about the rocks comprising the Bering Sea Shelf.

Another anomaly regarding the origin of the Aleutian arc is the presence of a small, isolated exposure of volcanic sandstones on Adak Island (Fig. 1) containing a rich flora of late Palaeozoic plants (Coats, 1956). This may simply represent a very old seamount now incorporated in the Aleutian Islands, or it may have a broader significance regarding the age and origin of these islands. Much more detailed mapping is necessary throughout the Aleutian Islands before a confident interpretation can be advanced.

SIGNIFICANCE OF THE BERING SEA REGION

Many individual problems of obvious importance are apparent throughout the Aleutian arc. Certainly Unimak Island should be mapped geologically; most of the Aleutian Islands have received only cursory attention; the geology associated with the late Palaeozoic plants of Adak Island should be investigated in greater detail; and an attempt should be made to determine the depositional environment and age of the flysch sequence of the Shumagin-Kodiak Shelf and the related ultramafic rocks. The Bering Sea Basin and Shelves should be investigated in detail by geophysics and sampling. Many other opportunities exist for studies of general importance.

However, the broader significance of the Bering Sea area lies in the opportunity to examine and relate many fundamental features of the earth. In this relatively small region we can study a major oceanic trench, an island arc which spans both oceanic and continental crust, the margins of two major continents (and perhaps fossil margins or trenches as well), and even aseismic ridges (Bowers Bank). A most profitable investigation would incorporate marine geophysical studies of the oceanic basins and adjacent shelves with an expanded effort in mapping the exposed geology surrounding this area in an effort to relate all of these features in time as well as space.

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DISCUSSION

Dr. G.G. Shor (USA)

Is it possible that you are attaching too much importance to the ultramafics and their relationship to the coastline in southern Alaska? The Bering Sea Shelf is covered by a great deal of sediments and there may be other explanations for the isolated ultramafic exposure in the Pribilof Islands.

Dr. Burk

There are actually many possible explanations. It is not unreasonable, for instance, that several Mesozoic troughs containing flysch and ultramafics (such as the Kuskokwim trough) may trend normal to the Bering Sea Shelf. The suggestion that this shelf, like the Shumagin-Kodiak Shelf, may have been the site of flysch accumulation at the Mesozoic continental margin or in a Mesozoic oceanic trench was offered here because it is as reasonable as any other explanation presently available. It is a suggestion which I believe warrants further investigation. Carefully planned geophysical surveys along the whole border of the Bering Sea, from the Alaska Peninsula to Siberia, should be very rewarding – especially when it is tied to additional field geology and perhaps eventually to shallow oceanic drilling as well.

Dr. D.C. Krause (USA)

It seems to me that the late Palaeozoic exposure on Adak Island is completely at variance with everything else around the Pacific Basin, and as such it assumes a great deal of importance. Is it buried in volcanics or greywacke? What does it occur in?

Dr. Burk

These outcrops were discovered and described by R.R. Coats of the USGS, who seems to have a knack for finding such anomalies. The fossiliferous exposures occur on the northern edge of Adak in volcanic sandstone associated with flows and other volcanics. The fossil leaves are abundant and well-preserved; there should be no problem regarding their identification. These exposures are isolated by tundra lowlands from the Finger Bay Volcanics farther south, which at one time were considered to be Palaeozoic or early Mesozoic, but a Tertiary age seems most reasonable now. Consequently, the relationship between the Palaeozoic and exposures elsewhere on the island is unknown. The fossils apparently are not from glacial erratics. We may be crediting these Palaeozoic rocks with more than their true significance, but they are indeed anomalous and certainly they must be accounted for. To me, an especially important aspect of their occurrence is that they are presumably shallow-water or non-marine Palaeozoic deposits bordered on both the north and south by apparently normal oceanic crust.

CONTINENTAL MARGINS AND ISLAND ARCS OF WESTERN NORTH AMERICA[1]

George G. Shor, Jr.
Scripps Institution of Oceanography

Abstract

The Aleutian island arc shows a structure that can be interpreted as caused by growth of a volcanic ridge atop a welt of thickened oceanic crust, trapping of sediments behind the arc, and regional isostatic compensation with downbowing of the ocean floor to the south.

Off Southeast Alaska, a basement ridge, analogous to the island arc, occurs beneath the shelf break, and a filled trench with landward-dipping sediments exists beneath the continental rise. Structure along the Middle American Trench is similar, with downbowed sediments on the seaward flank of the trench and a buried basement ridge at the shelf-edge. It is suggested that these represent successive stages of continental accretion. Many other areas must exist where the continental mass has grown in the same manner, requiring palaeogeographic theories to take into account changes in size and shape of the continents.

INTRODUCTION

The only parts of the coast of western North America that have the typical Pacific border trenches are: the Aleutian Trench; a filled trench or geosyncline off Southeast Alaska; a very small trough near Cedros Island, Mexico; and the Middle America Trench.

ALEUTIAN ARC

The Aleutian arc has the complete sequence of trench, volcanic arc with intermediate- and deep-focus earthquakes, and a back basin which catches sediment from the continents. The Aleutian Basin (Fig. 1) has a simple, uniformly layered structure. The shallow layers represent a

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[1]Contribution from the Scripps Institution of Oceanography, University of California, San Diego.

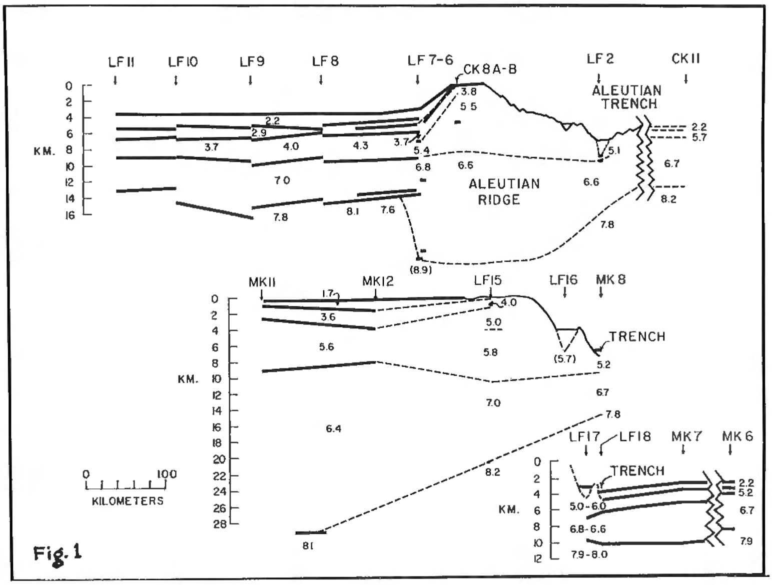
much-thickened sedimentary section. Cores from this material include sand suggestive of turbidity-current deposition; recent reflection work by Lamont Geological Observatory (Ewing et al., 1965) shows a thick sequence of closely spaced uniform layers, also interpretable as turbidites. The deeper material shows the same layering as in the Pacific Basin, although the mantle velocity may be slightly lower than normal. The mantle velocity is probably uniform within the Aleutian Basin; differences between stations represent the experimental error. The entire deeper section is depressed, indicative of isostatic compensation to the sedimentary load. Located as it is adjacent to a plentiful sediment supply from the coasts of Alaska and Siberia, the basin will in time be filled, sink, and become an addition to the continental mass.

The Aleutian Ridge (Fig. 1) is best described as a welt of thickened oceanic crust on which is superimposed a chain of volcanoes. On the south side of the ridge, the Aleutian Bench represents a sediment-filled fault-trough. The trench itself in the area near Adak Island may have the structure of a graben. Eastward along the trench (Fig. 2) the trench shallows and the sediments thin to a basement sill near Unimak Pass. Apparently the trench consists of two sections separated by a sill. Sediments entering the trench from the east end have filled the eastern section and flowed over the sill into the deeper western section.

Near Kodiak Island (Fig. 3), the structure of the shelf is complex, but definitely shows a slight structural high near the shelf break. The sediments on the seaward flank of the trench dip uniformly toward the trench and are covered by nearly flat sediments filling the trench bottom. The topographic axis of the trench is not structurally significant, because it represents merely the channel along which the present-day sediment flow takes place. It is usually close to the landward wall of the trench. The trench structure in this area cannot be considered a graben, since no fault occurs on the seaward side.

MIDDLE AMERICA TRENCH

A reflection record taken at the north end of the Middle America Trench shows a structure nearly identical to the Aleutian Trench near Kodiak Island. Here again sediments on the seaward side dip uniformly toward land under the flat-lying sediments of the trench floor. On this record (Fig. 4), a slight amount of deformation of the latest trench sediments can be detected. This one-sided structure may be typical of the end of a trench and is evidence that the fault on the landward side of the trench is of primary importance, while faults, if any, on the seaward side are formed subsequent to the formation of the trench itself.



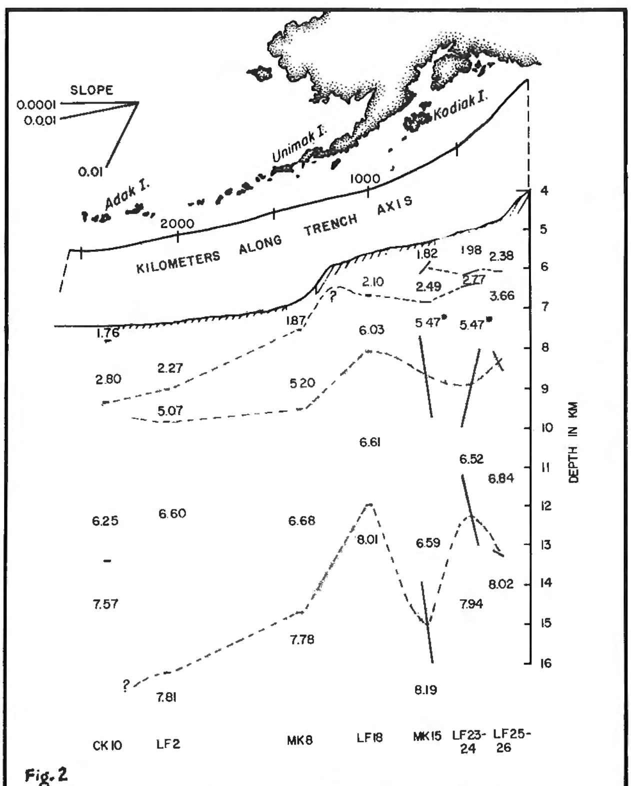


Figure 1. Crustal profile through part of the Aleutian Basin (on left), the Aleutian Ridge and Trench, showing layers with seismic velocities in km/sec.

Figure 2. Crustal profile along axis of Aleutian Trench. Note basement sill opposite Unimak Island.

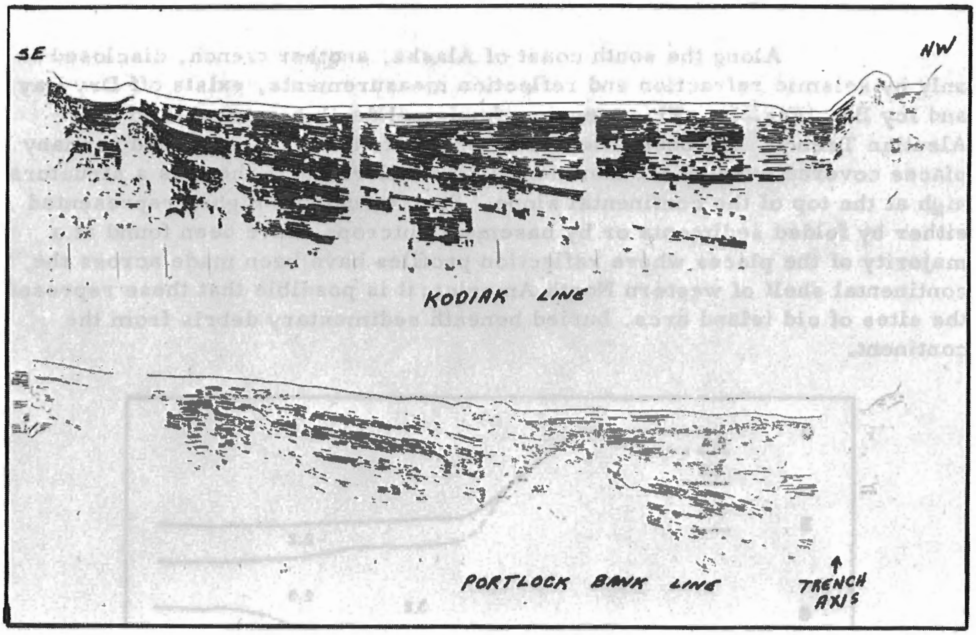


Figure 3. Seismic reflection record across Aleutian Trench (and seaward) near Kodiak Island.

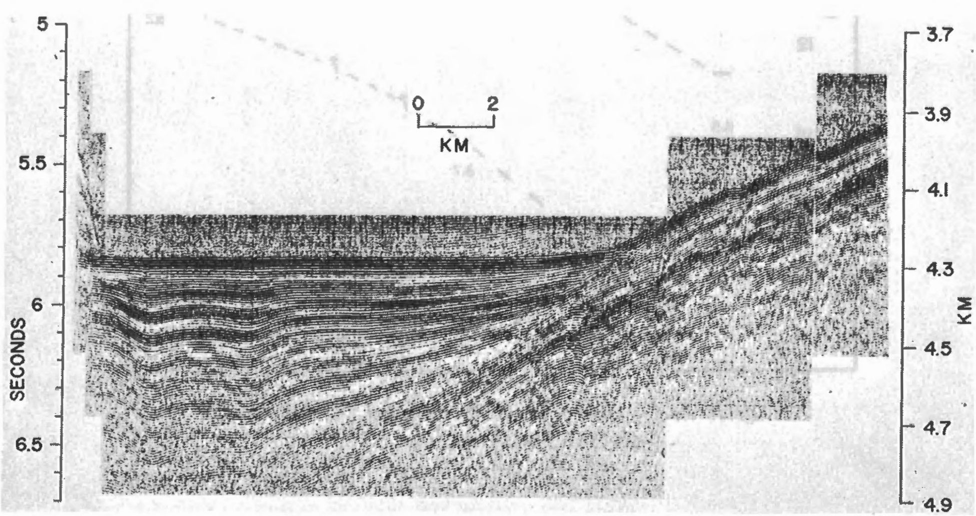


Figure 4. Seismic reflection record across north end of Middle America Trench.

FILLED TRENCH OFF SOUTHEAST ALASKA

Along the south coast of Alaska, another trench, disclosed only by seismic refraction and reflection measurements, exists off Dry Bay and Icy Bay (Fig. 5). This trench, of original depth comparable to the Aleutian Trench, has been filled with sediments from the coast and in many places covered over by the continental rise. Here again there is a structural high at the top of the continental slope. Such structural highs, represented either by folded sediments or by basement outcrops, have been found at a majority of the places where reflection profiles have been made across the continental shelf of western North America; it is possible that these represent the sites of old island arcs, buried beneath sedimentary debris from the continent.

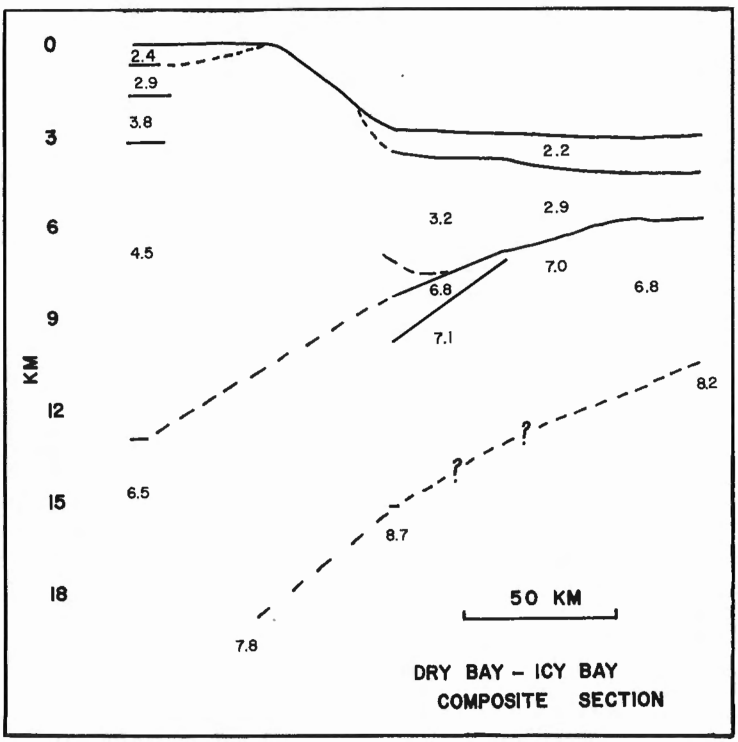


Figure 5. Crustal profile across filled trench off Southeast Alaska.

CONCLUSIONS

Additional work has been done along the coasts of British Columbia, Washington, Oregon, and California; no sign of a buried trench has been found in these areas, although some may be hidden beneath the continental rise. In all of the trenches studied, the evidence favours an origin by tension or vertical movements of the crust. No crumpling of the sediments or overthrust faulting is apparent.

The similarity of structure of the coast of Mexico and Southeast Alaska to the Aleutian arc-Bering Sea sequence suggests that all these areas may have a common origin. Sediment trapped behind an island arc changes an oceanic area to a continental area. The sedimentary sequence sinks and is metamorphosed to form part of the continental mass. Many other areas of such continental accretion must exist.

This work has been supported by the Office of Naval Research and the National Science Foundation.

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DISCUSSION

Dr. B.C. Heezen (USA)

A few years ago I ran a profile across the Tonga-Kermadec Trench. The records could have been mixed with yours; those of the Kermadec Trench look exactly the same. The sediments are truncated without any disturbance. However, in the Tonga Trench there is a fault on both sides. But in the Kermadec Trench it looks like the same downwarp. I think it's the same pattern as the Tonga, in many respects.

Dr. Shor

In my opinion, the downwarp comes first and if you go out far enough you finally find a fault on the outside. But the basic structure is the downwarp against the fault.

Dr. J. Healy (USA)

If I average the mantle velocities shown for the Aleutian Trench, they come to something like 7.8 km/sec.

Dr. Shor

The values shown on the slide are, in some cases, the results of reverse profiles; some of them are splits, some of them are separates. To get the average, I averaged the actual observed velocities without regard to reversals. One is not necessarily dealing with plane layers along refraction profiles in the trench; in fact, the dip is probably quite variable.

Dr. Healy

But this procedure will tend to produce a higher velocity.

Dr. Shor

I have averaged not velocity, but the reciprocal of velocity. This procedure favours a lower velocity.

Dr. Healy

My second question is have you any measurements of mantle velocity in the oceans where you have extended out for distances of 100 or 200 kilometres, and have a long segment of mantle arrivals?

Dr. Shor

Not in this area. Russ Raitt made some very long profiles in the Indian Ocean. I do not know exactly where; Bob Fisher may know. But, as I recall the results, they did not show an increase of velocities as you went outward. In other words he did not detect a higher velocity material. We do not have any such long profiles in the North Pacific.

Dr. Healy

Just one more question. Is the reason that we don't usually see this increased velocity in the ocean simply a matter of convenience or do you lose the first arrival? Are you forced to stop or do you stop by choice?

Dr. Shor

I normally stop by choice; Russ Raitt normally shoots until he is forced to stop. And it is a question of whether you want to make a few very long lines or many shorter ones. A reversed profile in the oceans with a 40-mile reversal takes about 1,600 pounds of powder and the results are fairly detailed. For longer profiles, up to many tons of explosives are needed and you are faced with running out of explosives. In profiles 80 to 100 miles long, the charges have to be so large that they cannot be handled conveniently. And they have not produced any significant information thus far.

PRELIMINARY RESULTS OF A SYSTEMATIC GEOPHYSICAL SURVEY SOUTH OF THE ALASKA PENINSULA

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Abstract

Results of a closely spaced grid survey of the magnetic and gravity fields and the bottom topography is presented for an area located between latitudes 45° and 55°N and between longitudes 155°30' and 158°30'W.

Three positive magnetic anomaly bands run nearly parallel (within 10°) with the bathymetric contours in the area of the northeast-trending Aleutian Trench. South of latitude 51°N the magnetic anomalies form high and low bands aligned north-northwest. The longest band in the survey area is 650 kilometres. The bands most probably continue southward and join the striations discovered by investigators of Scripps Institution. Based on the magnetic anomaly pattern, two major crustal discontinuities are apparent: one at the top of the southern trench wall, and the other near the southern edge of the outer ridge. It is suggested that the magnetic anomalies represent fracture zones with associated magnetic minerals.

The lack of correlation between the magnetic data and gravity data may be attributed to one or more of: 1) small or negligible increase in density in the area of the inferred fracture zones; 2) limited (± 10 mgal) instrument accuracy; and 3) widely spaced sampling interval.

A model of crustal structure is presented in the area of the Aleutian Trench, based on magnetic, gravity, and limited seismic information.

INTRODUCTION

About 10 years ago the U.S. Coast and Geodetic Survey and the Scripps Institution of Oceanography conducted a special bathymetric and marine magnetic survey off the west coast of the United States. This cooperation led to the discovery of the Mendocino, Pioneer, and the other fracture zones of the northeastern Pacific Ocean. It was realized that systematic surveys could map sea-bottom topography and reveal hitherto unknown patterns in the magnetic and gravity fields, which could become significant in the understanding of the structure of the crust and upper mantle.

To achieve the understanding of the oceans of the world through their systematic exploration, the U.S. National Plan for Ocean Surveys was formulated.[1] Part of the plan is the marine geophysical program of the Coast and Geodetic Survey, which started in 1961. The program calls for the systematic exploration of the North Pacific between longitudes 150° and 180°W. The area is divided into smaller sections. Within the section described here, the ship's tracklines were run north-south and were spaced approximately 10 nautical miles apart, except for occasional check-lines. The ship's position was determined by LORAN C. The depth of water and the magnetic and gravity field variations were recorded continuously.

In this paper, these data will be discussed in the area located between longitudes 155° and 159°W and from the continental shelf south to latitude 45°N (Fig. 1).

MAGNETIC INTENSITY MAPS

The maps of Figures 1A and 1B show the advantage of a systematic survey, and demonstrate the possibilities for interpretation when data for the entire North Pacific become available for study. Although this sample shows new and interesting results with possibly far reaching implications, in the most critical places the mapped area appears to be too narrow; therefore, it must be stressed that some of our conclusions are only preliminary, and their verification must await study of the area to the west and some detailed, systematic seismic investigations.

In Figure 1B, there is a distinct pattern of parallel, north-northwest aligned bands of magnetic highs and lows. An east-west trackline near latitude 50°N, described by Fabiano and Alldredge (1961), reveals that bands of highs and lows also exist to the east and west of the present area.

To construct the magnetic anomaly map (Fig. 1B), we prepared a regional total intensity chart on the basis of our own magnetic survey. This chart compared well with a chart prepared by Cain and Neilon (1963), but because too few observations were available at the time of its publication the C&GS World Total Intensity Chart for the epoch of 1955 (corrected to 1961) showed considerable deviations (Fig. 2).

Figure 2 shows how well the regional total intensity based on our survey fits the data, and indicates that it is correctly defined. The importance of this will be shown later in this report. On the basis of the

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[1]Detailed description is in ICO Pamphlet No. 7, May 1963: National Plan for Ocean Surveys.

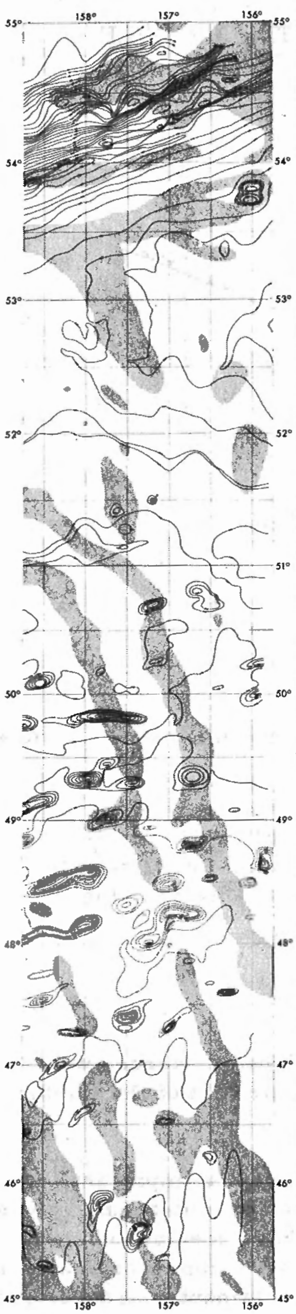

Fig. 1A

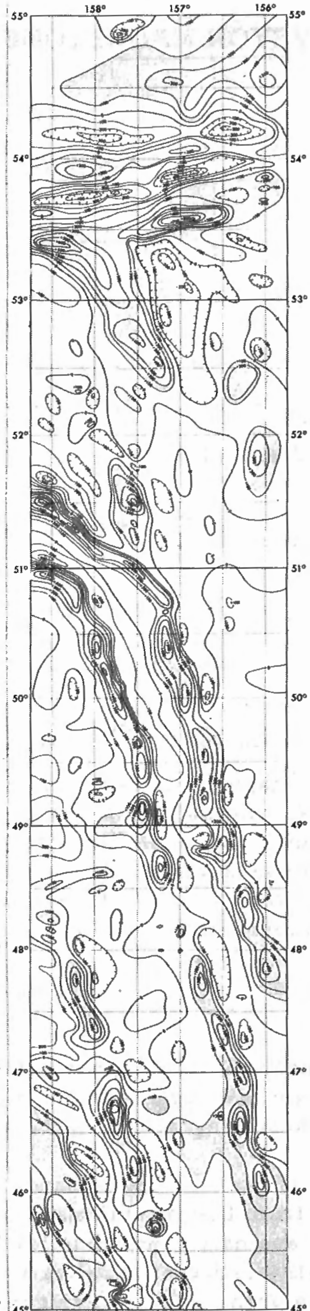

Fig. 1B

Figure 1A. Positive magnetic anomalies (shaded areas of Fig. 1B) superimposed on bathymetric chart. Contour interval 50 fathoms (100 fathoms over some seamounts).

Figure 1B. Total magnetic intensity map. Contour interval 100 gammas. Areas above 100 gammas are shaded.

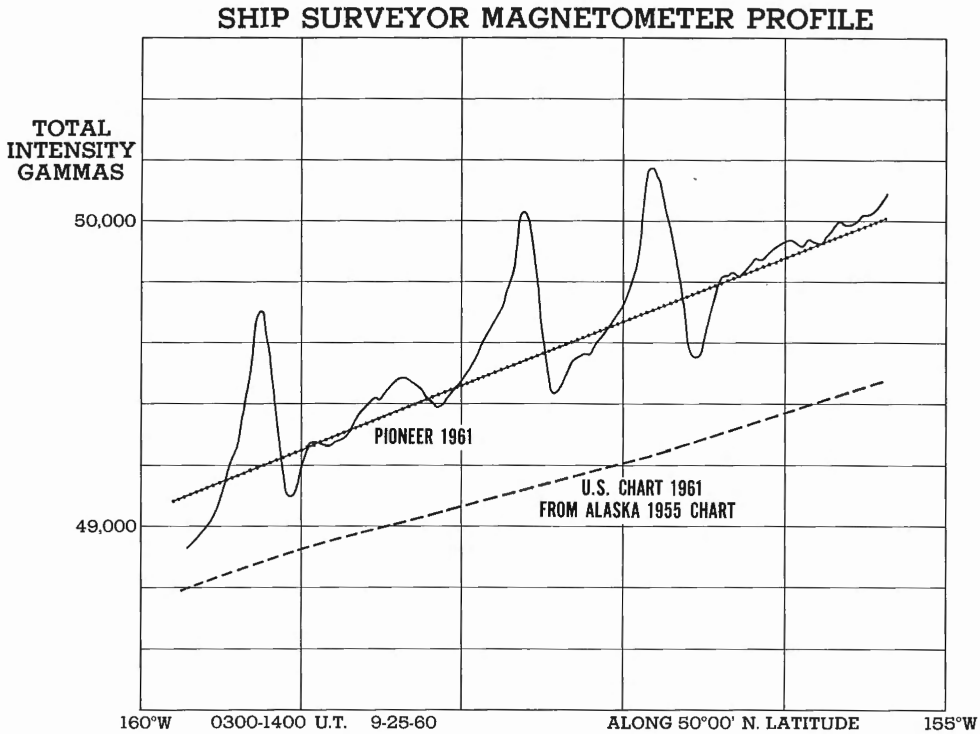

Figure 2. Profile of total magnetic intensity across area of Figure 1B along lat. 50°N. Dotted line demonstrates the fit of the regional total intensity (from the PIONEER 1961 survey) to an actual profile. Dashed line is regional total intensity based on U.S. C&GS World Total Intensity Chart for the epoch of 1955 (corrected to 1961).

total magnetic intensity anomaly chart and other published evidence, we believe that one can extrapolate and suggest that a major part of the North Pacific is characterized by these magnetic striations.

The existence of these anomaly bands is quite important, because they are located far from continental margins and mid-oceanic ridge systems, with which similar anomaly bands thus far have been associated. The anomaly bands trend north-northwest parallel with the Emperor Seamount Chain and the western margin of the North American continent, but these are located 1,500 nautical miles to the west and 900 nautical miles to the east, respectively. It appears that either parallel anomaly bands occur much farther from the centre of these features (mid-oceanic ridge systems, continental margins), or the anomaly bands must have a new geological explanation.

From Figures 1A and 1B, we can conclude that: 1) there is no relationship between the sea-bottom topography and the magnetic anomaly bands; and 2) some of the seamounts apparently have no magnetic effect, while other seamounts have either normal or reversed magnetization (or at least a direction of remanent magnetization that is significantly different from the present dipole direction).

MAGNETIC DISCONTINUITIES

From Figures 1A and 1B and the four profiles (selected approximately 5 degrees apart) from our systematic survey of the Aleutian Trench (Fig. 3), we conclude that a major crustal discontinuity occurs at the top of the southern wall of the trench, and is indicated by a magnetic anomaly band. Figure 3 shows the four profiles, one each at longitudes 166°W, 170°W, 175°W, and 179°W. The upper trace is the gravity free-air anomaly. The minimum is broad and overlaps the Aleutian Bench. The middle trace is the magnetic anomaly with the regional or normal field removed; and the shaded trace is the sea-bottom topography. These profiles were prepared for comparison with the aeromagnetic profiles, published by Keller et al. (1954). Some of their profiles are very similar to ours, but the location of the profiles had to be adjusted slightly to correct for the navigational errors of the aircraft tracks.

As can be seen from Figure 3, neighbouring profiles are similar. A characteristic large magnetic anomaly occurs along the top of the southern trench wall in all profiles. The north-northwest trending anomaly bands appear to terminate at, or are cut by, this trench anomaly. Two of these bands, however, do not reach the trench wall. The striations bend sharply toward the west, and the band which is terminated by the trench anomaly appears to be broken up in the area between latitudes 51°N and 52°N in Figures 1A and 1B. Thus, another crustal discontinuity may be present in this area. Along the east-west trackline near latitude 50°N (Fabriano and Alldredge, 1961), the eastern positive magnetic anomaly band is wider than other bands and may, therefore, be a continuation of the band that reaches the south wall of the trench. If so, a westward movement of about 220 kilometres is suggested for the area north of latitude 51°30'N relative to the stable ocean floor to the south. If the bands are not the same, then not only the distance of westward movement, but also the entire nature of the discontinuity is unknown. The fact that a bend and not a complete breakage is is present here, as was found over the Mendocino escarpment, may indicate

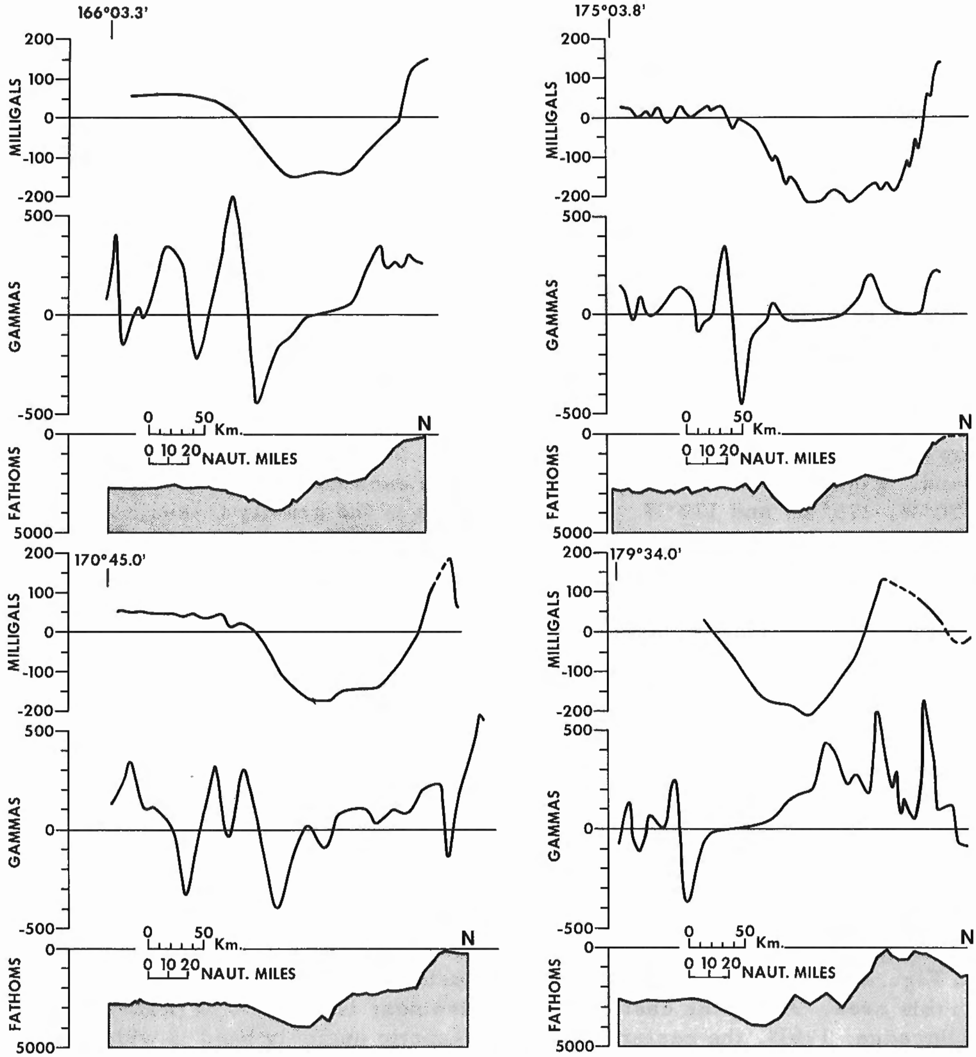

Figure 3. Four profiles aligned approximately north-south across the Aleutian Trench showing sea-bottom topography, gravity, and magnetic variations. Longitude of southern end of each profile appears in upper left corner.

that the westward displacement cannot be much larger than the suggested 220 kilometres. However, until we have the data contoured for the area to the west, the westerly displacement along this second discontinuity is speculative. If it can be proved that there is a westward displacement along the southern edge of the outer ridge, it may have a further interesting implication. Seismologists studying the Alaskan and the North and South American earthquakes concluded that right-lateral movements are associated with the earthquakes, and a counterclockwise rotation of the Pacific Basin has been postulated. Since this hypothesis was raised, the Philippine left-lateral faults were discovered. The magnetic pattern south of the Aleutian Trench may indicate that the right-lateral movement, or westward movement of the ocean basin, is restricted to an area only 150-200 miles wide. It must involve only the continental margin and the outer ridge, while the ocean floor remained stable. The absence of earthquakes at the southern margin of the outer ridge seems to indicate that the present-day displacements do not occur even this far south. Perhaps the indicated displacement took place in the early phase of the trench formation, while the present displacements are restricted to the trench and the island arc.

ORIGIN OF MAGNETIC STRIATIONS

More regional surveys and systematic seismic surveys are needed to understand what the magnetic striations themselves represent. Scripps investigators studied the magnetic striations off the west coast of the United States and found no differences in the seismic structure of the magnetic high and low areas. More studies are needed to determine whether this characteristic represents only the local situation, or whether it can be accepted generally. Raff (1961) and Mason (1958) suggested lava flows as one explanation of the anomalies, but pointed out that the linear pattern must have a further explanation. They suggested that the magnetic patterns resemble stress patterns, and that what we see may be a fossil record of ancient stresses.

Figure 4 is an east-west section across two magnetic bands. In preparing the basement model, it was assumed that the magnetic body is two-dimensional and perpendicular to the section, and that its magnetization is induced by the earth's present magnetic field. The figure shows that two magnetic bodies, separated by non-magnetic material, can reproduce the observed anomalies without introducing a reversely magnetized area between them. An apparent susceptibility of 10^{-2} cgs was used in the calculation. If, in the model, separate magnetic bodies with the same depth to the top, but a shallower base were assumed, then for each 1 per cent decrease in thickness of the body, a 3 per cent increase in susceptibility would be required. If reverse magnetization and the same effective susceptibility for the area between the present magnetic bodies were assumed, the negative anomalies

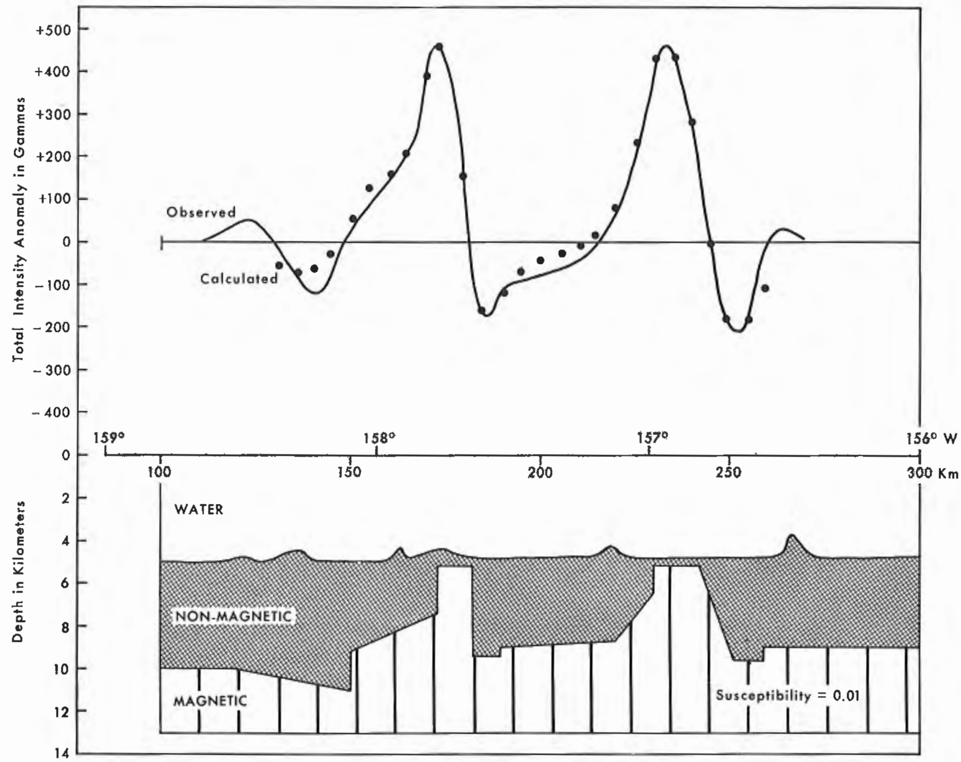

Figure 4. Observed and calculated total magnetic intensity profiles across two magnetic anomaly bands, and "magnetic basement" model.

clearly would be too large; this effect could be eliminated only by decreasing the normal field and reducing the assumed effective susceptibilities. However, as it has been shown earlier, the normal field is well established for this area, and hence the above suggestion is improbable.

These magnetic bodies may represent either ridges in the basement rock material or zones within the basement rock complex containing more magnetic minerals than the neighbouring rock mass. This latter interpretation was also suggested by Drake et al. (1963). The minerals may be associated with fracture zones, and if brecciation is marked along the fractures, the average density of the area would be unchanged, a state required by the gravity measurements available in the area.

GRAVITY ANOMALY MAP

Figure 5 is the free-air gravity anomaly map from latitudes 55°N to 49°N, and Figure 6 the strip southward to latitude 45°N. The isogals parallel the bottom topography of the Aleutian Trench and Ridge, but farther south, except in the area between latitudes 48°N and 49°N where there are a number of high seamounts, there is very little, if any, correlation with the bottom topography, and certainly none with the magnetic anomaly bands. There are three possible causes for the lack of correlation in the southern area:

1) The wide spacing of the sampling interval may be the most important cause. In 1961 we did not have the "direct gravity read-out" LaCoste-Romberg meters and we had to measure slopes on the straight-line portions of the record. Under optimum conditions this procedure allowed four readings of gravity values per hour, which represent a sample every 4 nautical miles. Actually, three samples per hour was more typical of the conditions that existed during most of this survey. It is quite possible, therefore, that we did not have gravity values over a number of the seamounts.

2) Perhaps the gravity measurements (estimated at $\pm$ 10 mgal) were not accurate enough to detect small density changes. The magnetic anomaly bands are large enough to be well sampled by our method.

3) Perhaps the inferred fracture zones with magnetic minerals are not denser than other parts of the crust. Such was found to be the case south of the Aleutian Trench over the previously mentioned magnetic discontinuity ("trench anomaly"), where generally the data quality and the controls are the best for the whole area.

We believe that while the first suggested cause is the best explanation for the absence of correlation between the bottom topography and the free-air map, the combination of the second and third causes is the best probable explanation for the absence of correlation between the gravity and the magnetic anomalies.

MODELS OF CRUSTAL STRUCTURE

Figure 7 shows a profile of the total magnetic intensity anomaly across the Aleutian Trench, and a "magnetic basement" model computed as before. The assumed induced magnetization provides a good fit between computed and observed values. A better fit of the small anomaly over the continental slope would have resulted had we assumed a body (consisting of 5.4 km/sec material) similar but smaller than the one in the centre

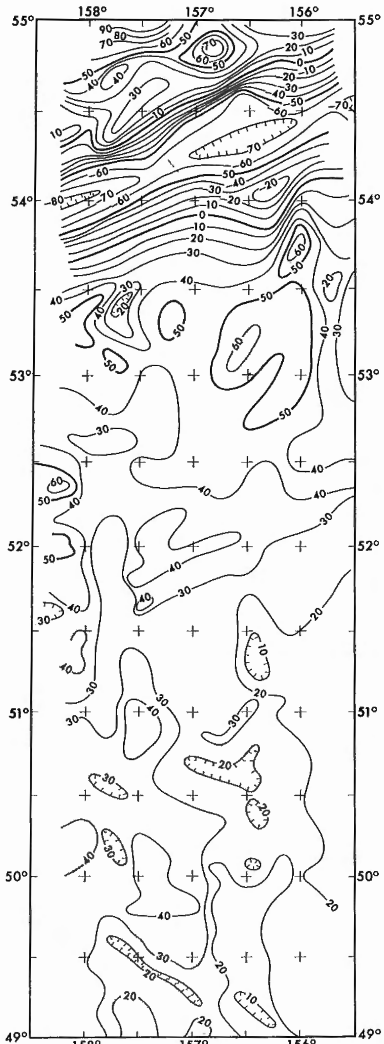

Fig. 5

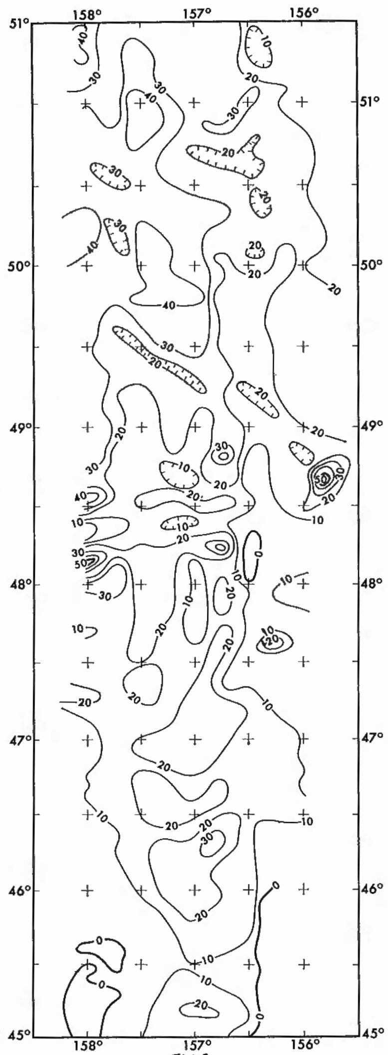

Fig. 6

Figure 5. Free-air gravity map of Aleutian Trench and outer ridge southwest of Kodiak Island. Contour interval 10 gammas.

Figure 6. Free-air gravity map of area south of outer ridge. Contour interval 10 gammas. Figures 5 and 6 overlap between latitudes 49°N and 51°30'N.

of the trench. This anomaly parallels the shelf break and becomes much larger farther east, where magnetic anomalies are 500 gammas and gravity anomalies are as high as +160 mgals. It probably represents a "basement ridge" typically found under continental margins. The fit is poor near latitude 53°N, even though the assumed top of the magnetic material was lowered to 10 kilometres. The magnetic map of Figure 1B shows that the top of the magnetic material lies above 10 kilometres, because the negative anomaly is caused by a different body located southwest of the area. This feature also shows up in Figure 8, which is a model of possible crustal structure along the same profile. The magnetic horizon is everywhere within the 5.4 km/sec seismic layer, with the exception of the area near latitude 53°30'N, where it was not necessary to lower the top of the magnetic material.

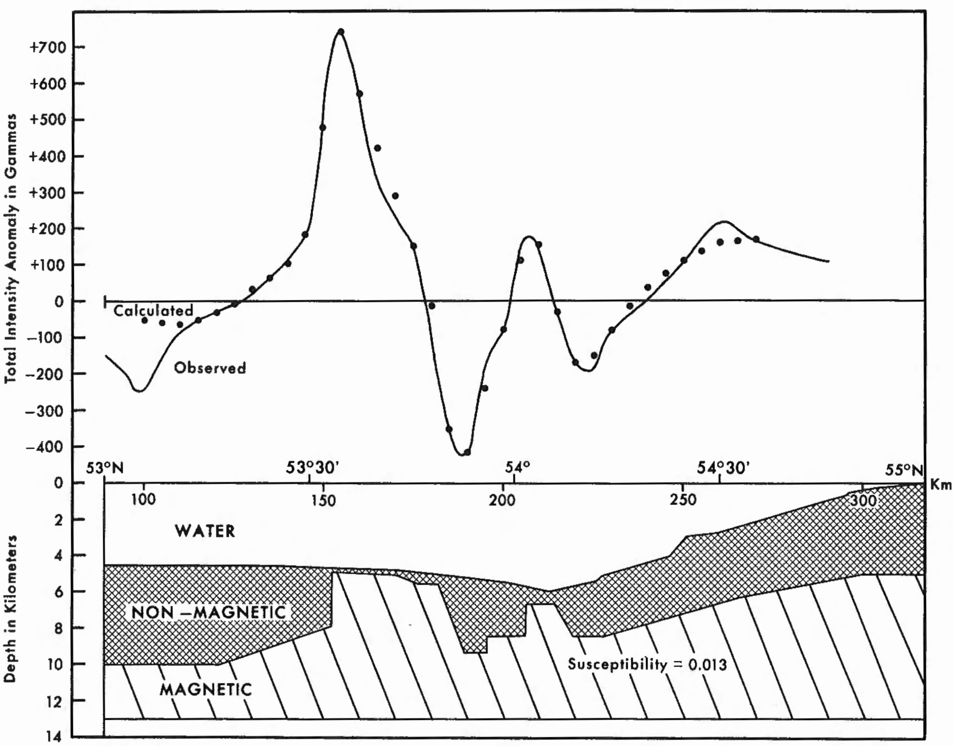

Figure 7. Observed and calculated total magnetic intensity profiles across the Aleutian Trench and "magnetic basement" model southwest of Kodiak Island.

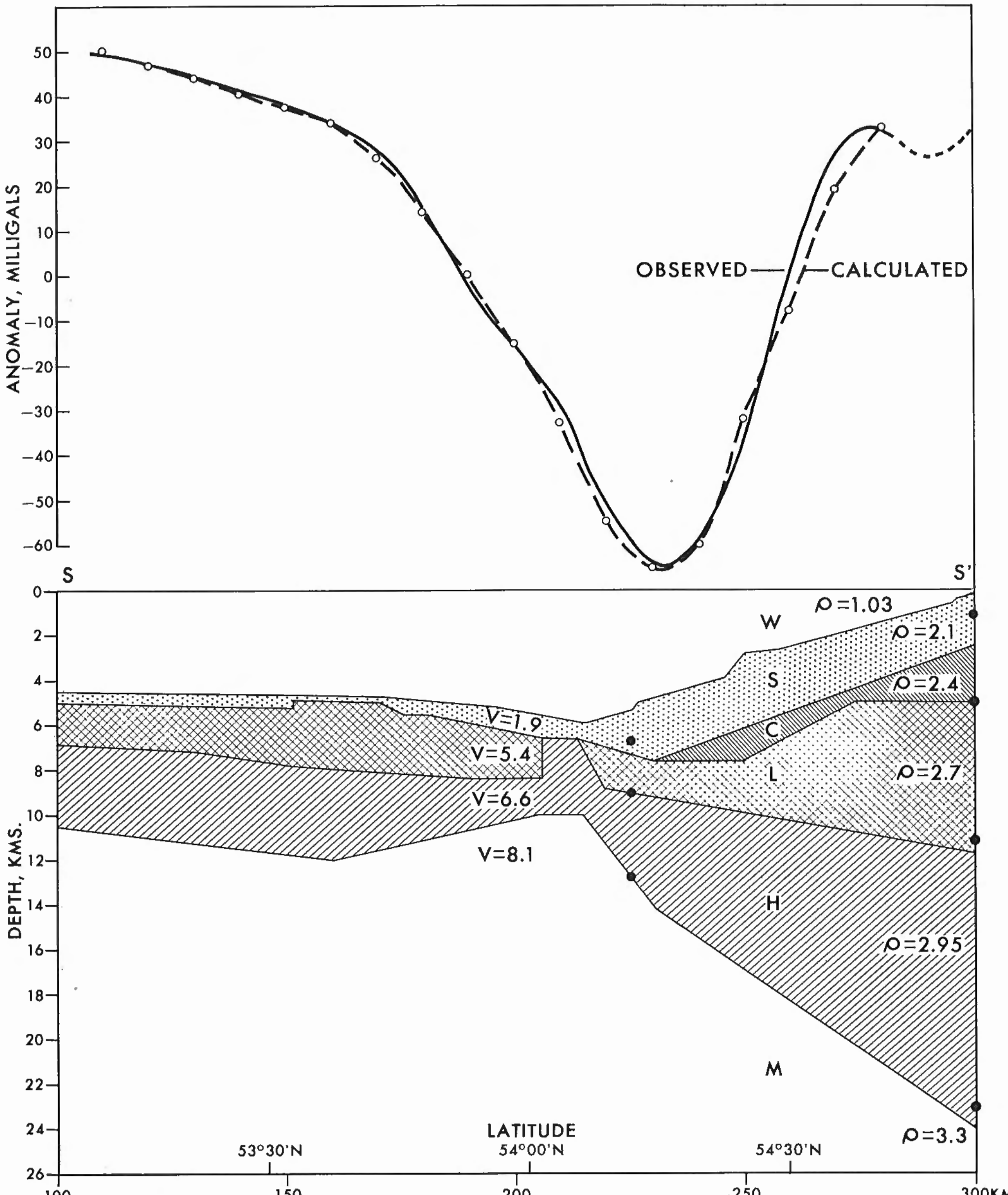

Figure 8. Model of crustal structure across the Aleutian Trench southwest of Kodiak Island calculated from gravity, seismic, and magnetic data. Profiles are observed and calculated free-air gravity values.

The magnetic body between 150 and 180 kilometres on Figure 7 must be interpreted as a magnetization discontinuity or a zone containing magnetic minerals within the 5.4 km/sec layer, because when in the first gravity calculation we used the 6.6 km/sec layer (similar to the body in the centre of the trench), a large positive gravity anomaly appeared over the magnetic body which is not present in the measured profile. We could have compensated for it by depressing the 6.6 km/sec layer into the mantle, but since we lack seismic control south of the trench, we preferred to keep the layers smooth as in the earlier interpretation.

In the model of crustal structure of Figure 8, the black dots indicate control points on horizons interpolated from the seismic profiles of Shor (1962), located approximately 50 kilometres to the east and 50 kilometres to the west of our survey area. The control points were connected with straight lines and, just as it was indicated by the magnetic anomalies, a ridge-like feature, most likely in the 5.4 km/sec layer, must be postulated to obtain a better fit of the gravity values over the continental shelf.

The interesting part of this structure is that we were able to introduce the high-density 2.95 gm/cc layer under the magnetic anomaly in the centre of the trench, and still had to raise the mantle interface quite high to fit the free-air data.

If we had assumed an average crustal density and ignored the interpolated seismic horizons, we would still face the same problems: a high-density structure under the continental shelf and the top of the mantle even higher than in Figure 8. Right now, both the 2.95 and 3.3 gm/cc layers are compensating for the effect of water (or mass deficiency) in the trench. Since using an average crustal density in our calculations would eliminate the 2.95-2.7 gm/cc contrast under the trench, the top of the mantle would have to be raised slightly. In view of the seismic control near the centre of the trench, we do not believe that raising the mantle any higher would be justified. We suggested (Peter et al., 1965) that there is a fissure (100 miles long and 10 miles wide) under the trench, and that the area between the 150 and 180 kilometres is more likely a fracture zone without appreciable increase in crustal density. Of course, this is only one of many possible interpretations. The crustal structure changes farther west, as can be seen in magnetic and gravity profiles of Figure 3.

In Figure 8, the gravity minimum lies north of the present-day trench and probably is located over the original structural trench axis which, by sediment filling derived from the north, moved southward. In other words, the gravity anomaly shows the location of the structural axis of the trench, which may not be the same as the present topographic axis.

SUMMARY

The U.S. Coast and Geodetic Survey is committed to the Ocean Survey Plan, and will continue with the systematic exploration of the North Pacific. With the expansion of our survey fleet, similar systematic surveys will be initiated in other oceanic areas.

Perhaps we have carried our interpretation of the magnetic bands too far and have presented what may be a one-sided view. The objectives of this report were not an undisputable geophysical interpreation, but to show: 1) that the magnetic anomalies are distributed in an orderly fashion in the Northeast Pacific; 2) that there are no readily apparent geological explanations for the cause of the parallelism, in contrast to parallel magnetic bands of mid-oceanic ridges and continental margins; and 3) how these bands change direction as they approach the Aleutian Trench.

Also I would like to suggest: 1) that a search for these anomaly bands be initiated in other oceans; and 2) that a detailed study be initiated to find a geological explanation for these bands.

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DISCUSSION

Dr. E. Irving (Canada) stated that numerous results from basalts showed an average remanent intensity value for continental basalts of about 2×10^{-3} gauss/cm^3 and for basalts from oceanic islands about 5×10^{-3} gauss/cm^3. Oceanic anomalies require intensities of the latter magnitude or higher. They may arise from basalt, but they may also, as Dr. Ringwood has privately suggested, be caused by low-grade metamorphic rocks (glaucophane schist facies) which are rich in magnetite. It would be interesting to make comparisons here with results from Precambrian greenstones to see if they have the required high intensities.

Prof. T. Nagata (Japan)

The apparent susceptibility of basalt of about 10^{-2} cgs units requires approximately 4.2 per cent volume content of magnetite. This percentage is not weight content. Is this right, Dr. Kuno?

Prof. H. Kuno (Japan)

Yes, oceanic basalts have about 5 per cent volume of magnetite and titaniferous magnetite.

Prof. T.F. Gaskell (UK)

May I ask Mr. Peter what is the present form of this United States national plan for ocean surveys? Does this include the universities, or is it primarily a plan of the U.S. Coast and Geodetic Survey group?

Mr. Peter

I am not sure that I should attempt to answer this question, because I do not know all the details. The Ocean Survey Plan was first suggested by the National Academy of Sciences Committee on Oceanography, and was accepted by the Interagency Committee on Oceanography. The plan called for a coordinated effort of the U.S. Government agencies to explore the oceans of the world. It is true that the program progresses very slowly and, to date, only the Coast and Geodetic Survey is actively engaged in pursuing the program.

THE PERU-CHILE TRENCH[1]

Dennis E. Hayes
Lamont Geological Observatory

Summary

Twenty-six profiles of topography, free-air gravity anomaly, and total intensity magnetic anomaly across the Peru-Chile Trench are shown in Figure 1 and their locations in Figure 2.

The Peru-Chile Trench extends as a continuous topographic deep approximately from latitude 4°N to 40°S. Seismic reflection profiles and a well-defined negative gravity belt indicate that the trench structure continues at least as far south as the Drake Passage near latitutde 56°S and longitude 70°W. East of this area the trench structure is terminated or is interrupted by a northerly trending topographic ridge. The trench structure is also interrupted near latitude 5°N. A strong negative gravity anomaly belt can be traced around the Gulf of Panama to about latitude 8°N and longitude 80°W, but it is not thought to represent a continuation of the Peru-Chile Trench structure.

A second negative gravity belt has been observed west of central Colombia and west of central Peru in water less than 1,000 metres deep. This belt correlates with the extension of the axis of the Bolivar Geosyncline. The axis of thickest sediment lies onshore in Ecuador, in northern Peru, and in southern Peru where the geosyncline terminates. It is probable that this negative belt is continuous from latitude 9°N to 20°S.

The Carnegie Ridge (near lat. 0°) and the Nasca Ridge (near lat. 15°S) are prominent submarine features lying transverse to the Peru-Chile Trench. The Carnegie Ridge strongly alters the character of the trench and serves to define a unique province of the trench. For this reason the ridge is presumed to be younger than, or contemporaneous with, the trench. The Nasca Ridge does not greatly alter the character of the trench. It is a broad ridge and gravity measurements indicate that it is essentially isostatically compensated.

There is a remarkable contrast in the amount of sediment present in different parts of the trench. Most of the trench falls into either the sediment-free province (lat. 8°S to 32°S) or the sedimentary province

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[1] Read by Dr. J.L. Worzel.
Lamont Geological Observatory Contribution No. 973.

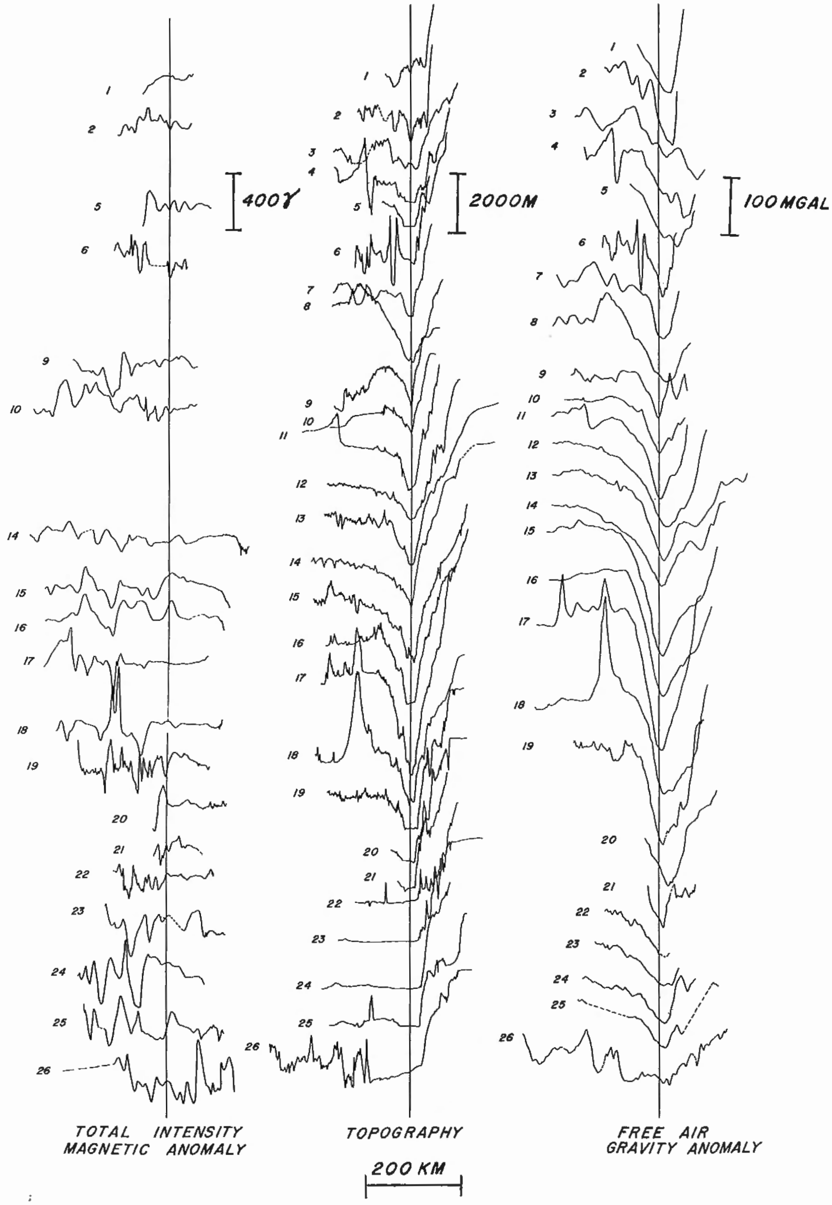

Figure 1. Projected profiles of topography, free-air gravity anomaly, and total intensity magnetic anomaly aligned with respect to the topographic trench axis. The locations of the profiles are shown in Figure 2.

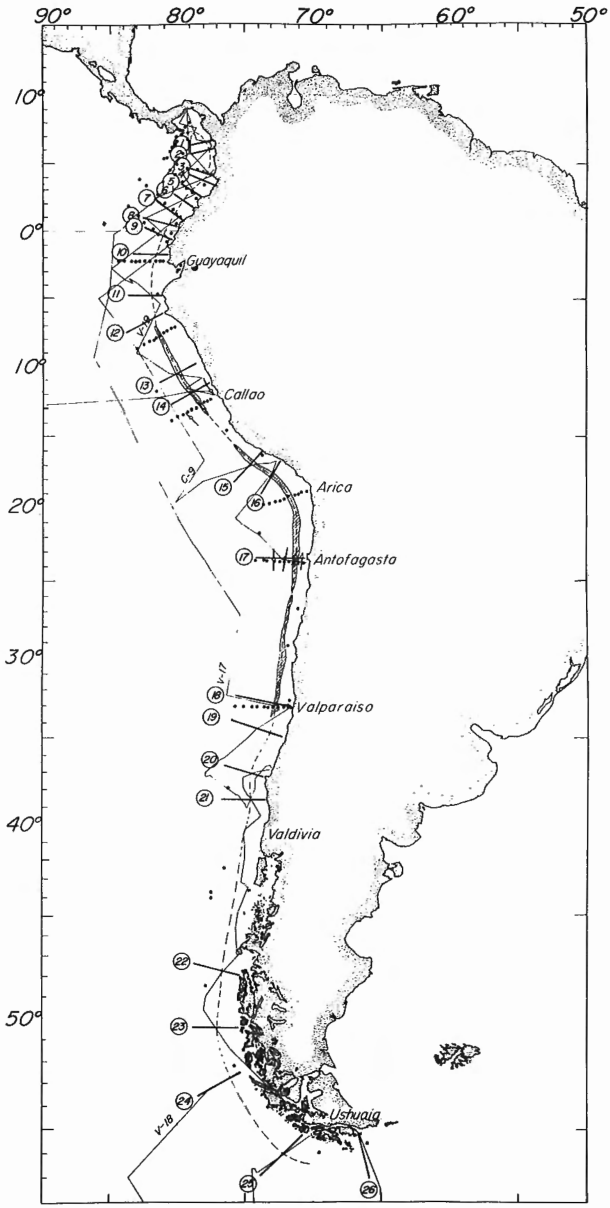

Figure 2. Map showing the locations of the projected profiles.

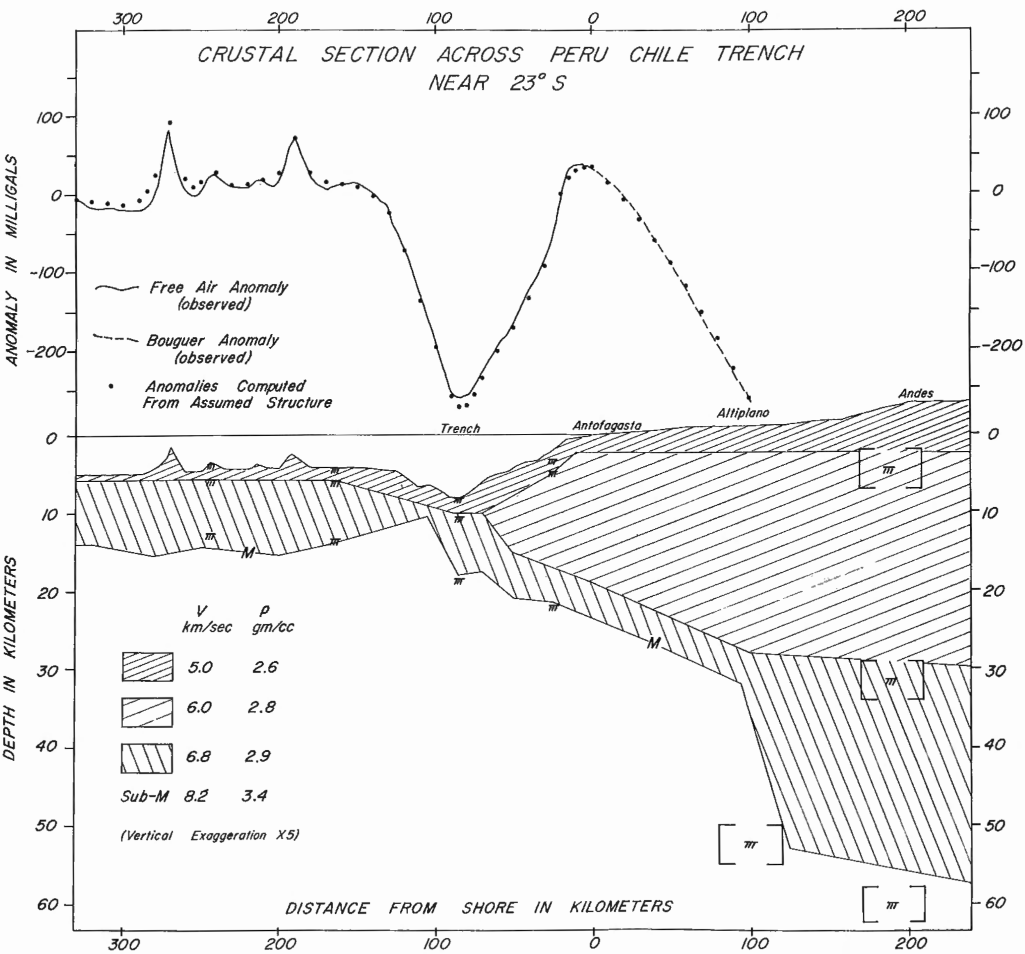

Figure 3. Deduced crustal section near Antofagasta, Chile. Seismic refraction results are from Fisher and Raitt (1962) and layer depths are indicated by small hachured lines. Bouguer anomaly is from Wuenschel (1952).

(lat. 33°S to 57°S). In the opinion of the writer the accumulation of sediment in the trench is probably related to both the quantity of sediment supplied by the continent and the effectiveness of sedimentary traps on the continental slope.

Studies incorporating seismic refraction (Fisher and Raitt, 1962) and reflection measurements (Ewing, 1963), and gravity measurements indicate a pronounced crustal thinning beneath the offshore flank of the trench (see Fig. 3). Crustal thicknesses beneath the topographic axis of the trench appear to be normal for the transition region of an ocean-continent margin. It is suggested that the trench may have originated by high-angle normal faulting near the base of the continental slope accompanied by a downward flexure of the crust farther offshore.

Gravity data indicate that there are no marked changes in the longitudinal crustal structure of the entire western continental margin of South America.

Magnetic anomalies cannot be correlated over large distances. The magnetic signature is considerably smoother over the shoreward flank of the trench than over the offshore flank. This points to a sharp contrast in the magnetization of the material underlying the two flanks of the trench. The relatively large amplitudes of some observed magnetic anomalies strongly suggest that they are not produced primarily by induced magnetization of bodies in the crust. In certain areas the observed anomalies correlate well with the basement topography. There is good evidence that some of these anomalies are caused by remanent magnetization in a direction opposite to the earth's present ambient field.

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DISCUSSION

Prof. S.K. Runcorn (UK)

Do you think that the magnetization of the material below the trench is explained quantitatively by the rise in temperature which you would get?

Dr. Worzel

I suspect that this is probably the case. Due to its greater depth and perhaps to the tectonic processes in progress, the magnetization has been destroyed. As you saw from our calculation it should show up unless the Curie Point has been exceeded.

Prof. Runcorn

Yes. In order to calculate the rough order of magnitude, what was the depth of the trench on the upper end?

Dr. Worzel

It varies so much that it's hard to say - about 6 kilometres in the region I think you are talking about.

Prof. Runcorn

Yes. If you take the geothermal gradient as 25°C per kilometre, then this is about 150°C which makes quite a bit of difference to the magnetization.

Prof. T. Nagata (Japan) pointed out a confusion between susceptibility and J.

Dr. Worzel agreed that he had misread his notes and had referred to "susceptibility" when he had meant "magnetization" or J.

Dr. E. Irving (Canada)

It is rather interesting to see these values of magnetization appearing in such interpretations. They are a good deal higher than the average continental basalt.

Dr. Worzel

This is the only way we can arrive at a satisfactory fit of the observed data.

ON THE DEEP STRUCTURE IN THE KURIL-KAMCHATKA REGION[1]

P.S. Weizman
Institute for Physics of the Earth,
Academy of Sciences of the U.S.S.R.

Abstract

A short outline of the deep structure of the transition zone between Asia and the Pacific Ocean is given. Crustal structure, obtained by the DSS method, is compared with other geophysical data and with seismicity and vulcanism. A comparison is also made with the crustal structure of the zone of transition between the Pacific Ocean and South America from published data. It is shown that on the east and west the Pacific "crust-mantle" block is separated from the continental blocks of Asia and South America by zones of earthquake foci concentrations.

INTRODUCTION

The Kuril-Kamchatka region is a part of the transition zone between the Asian continent and the Pacific Ocean, a zone of the most complex type. This transition zone was studied during the International Geophysical Year by an expedition of the Academy of Sciences of the USSR. The investigations were in part envisaged by the late Acad. G.A. Gamburzev who attached great importance to the study of seismically active regions along the junction of major earth structures, in particular the Kuril-Kamchatka region.

The expedition, headed by E.I. Galperin, carried out observations by the Deep Seismic Sounding (DSS) method. I.P. Kosminskaya supervised the processing of the data.

The interpretation of the seismic data involved integration of gravimetric, magnetometric, seismological, and geological data, taken from the works of, and in close contact with, V.V. Beloussov, Gainanov, Soloviov, Fedotof, Bogdasarova, and others. The results were compared with the published data on the zone where the Pacific Ocean joins the South American continent.

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[1]Read by Prof. V.A. Magnitsky.

METHOD

In the observations at sea, stationary recording sites and a mobile shooting point were used. Submarines equipped with recording instruments operated as seismic receiving stations. A hydrophone for recording wave compressions was mounted outside the submarine hull. A surface ship equipped with instruments for recording sound waves and for the determination of shooting times was used as a mobile shooting point. Three submarines operated during the working cycle (lasting about a day) and gathered data on about 250 kilometres of profile with a complete system of reversed and overlapping time-distance curves.

The conditions for observing the reciprocity principle, according to kinematic and dynamic principles, are more completely fulfilled at sea than on land, because of the equal directional characteristics of the receiver and of the energy source at sea. Hence the dynamic features of the recorded waves were used with confidence in the correlation of events.

RESULTS

Investigation of the crustal structure by the DSS method was carried out in regions of different structures. The crust considered here has a complex layering and is extremely heterogeneous in the horizontal direction. In spite of the complex layering, the continental crust, as is well known, is divided into three and the oceanic crust into two fundamental layer-complexes. The boundaries between different layer-complexes are designated K_1, K_2, M.

The seismic records show a great variety of travel paths of waves, both in number, as well as in their combinations. The amplitude and frequency characteristics of the waves are very variable.

Figure 1 shows several profiles of crustal structure across the zone between Kamchatka and Japan.

Judging from the DSS data, the Kuril-Kamchatka region comprises two essentially different zones.

Zone 1 includes the shelf and the western slope of the deep-water trench. In the seismic records three distinct wave groups were recorded: P^o, P^*, and P^M. In some cases P^M_r waves appear to have been recorded. For this zone, relatively large arrival times of P-waves and a complicated, non-linear form of the time-distance curve are characteristic. A particularly complicated wave pattern was observed at the western slope of the deep-water trench, where, because of the eastward pinch out of the layer-complex 1, of the disappearance of the K_1 surface, and of a general thinning of the entire crust, the K_2 and M surfaces rise sharply. Under the western slope of the trench and near the continental edge, the crust is thickened. This is most clearly expressed in the southern and northern parts of the region, where the crustal thickness reaches 30 to 35 kilometres. In the middle of the region the crust seems to be more typically subcontinental.

Zone 2 contains the eastern slope of the deep-water trench, the border ridge, and part of the ocean floor. The wave pattern is simpler there. Generally, two wave groups were recorded: P^* and P^M. Small arrival times are characteristic of this zone. The latter part of some of the records obtained over the sea contains waves of the PSP type, which apparently pass over the topmost part of layer-complex 2 as transverse waves. Over the eastern slope of the trench no waves of the PSP type were recorded. Oceanic crust was found in zone 2. It consists of a thin (0.5-1.5 kilometres) sedimentary layer and an underlying, relatively thin (4-10 kilometres) basaltic layer (layer-complex 2). Near the eastern slope of the trench the crust thickens slightly. Deep troughs accompanying the deep-water trench were discovered in the K_2 and M surfaces. The higher the trough in the crust the farther its axis is displaced to the east.

The boundary between zones 1 and 2 is the axis of the deep-water trench and is apparently complicated by deep faults.

INTERPRETATION

Seismic data permitted construction of cross-sections, albeit somewhat schematic and with smooth lines. They do not show the assumed faults and steep contacts between blocks of different structures, although steep slopes of the dividing boundaries were obtained.

Figure 2 shows the depth to M surface (and hence crustal thickness). Within the band of thickened crust beneath the western slope of the deep-water trench, two regions of the greatest downwarping of M surface are distinctly outlined in the southern and northern parts of the belt. In the

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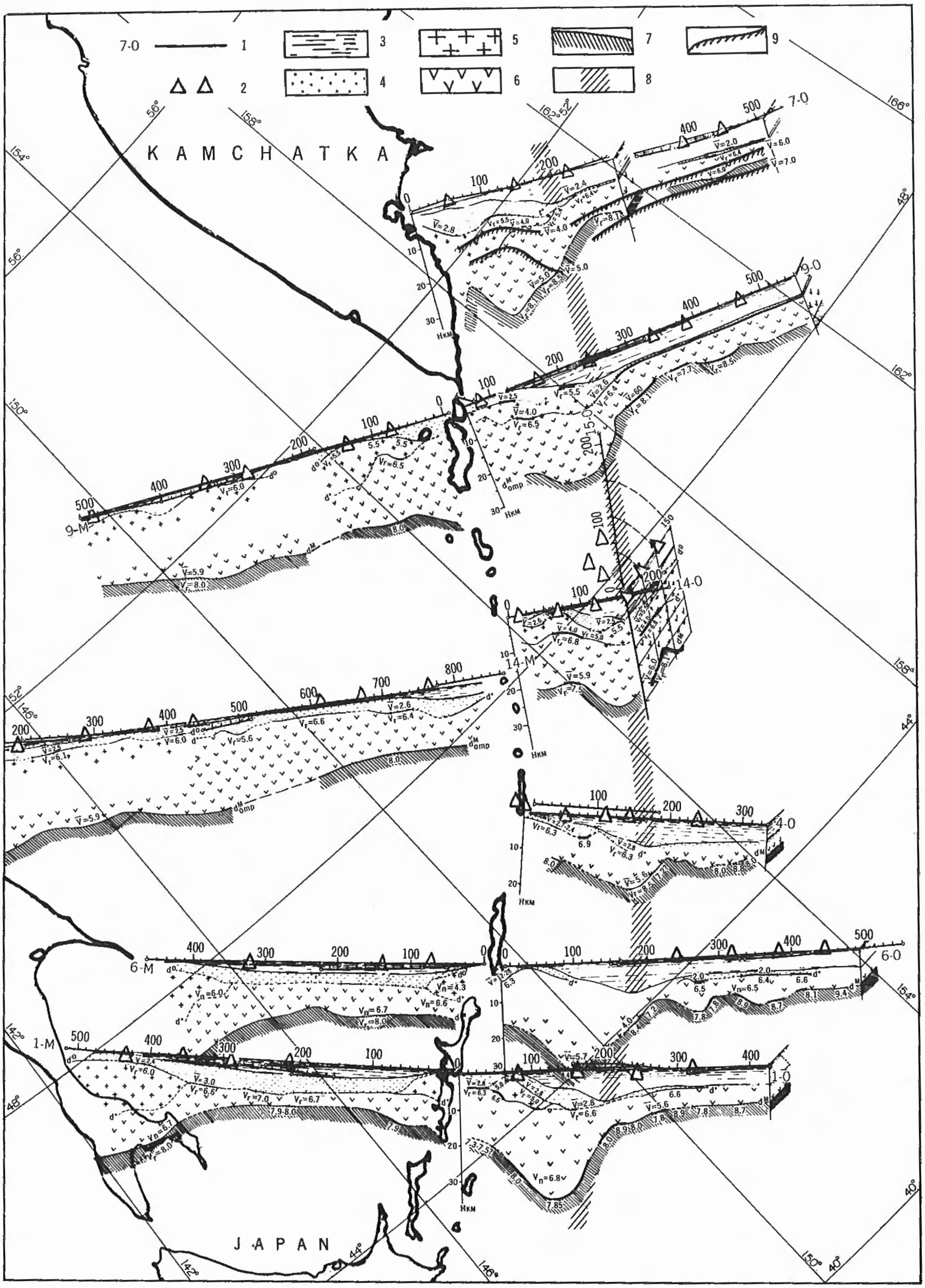
Figure 1. Schematic crustal structure along DSS profiles, Kuril-Kamchatka region. 1 - DSS profile lines (shooting line); 2 - receiving stations; 3 - water; 4 - sediments; 5 - layer-complex 1; 6 - layer-complex 2; 7 - M surface; 8 - axis of deep-water trench; 9 - lines of equal average velocities. Seismic boundaries drawn from reversed systems are shown by thick lines, from single profiles by thin lines, and from least certain data and from interpolated data by dashed lines. Horizontal to vertical scale 1:5.


KAMCHATKA
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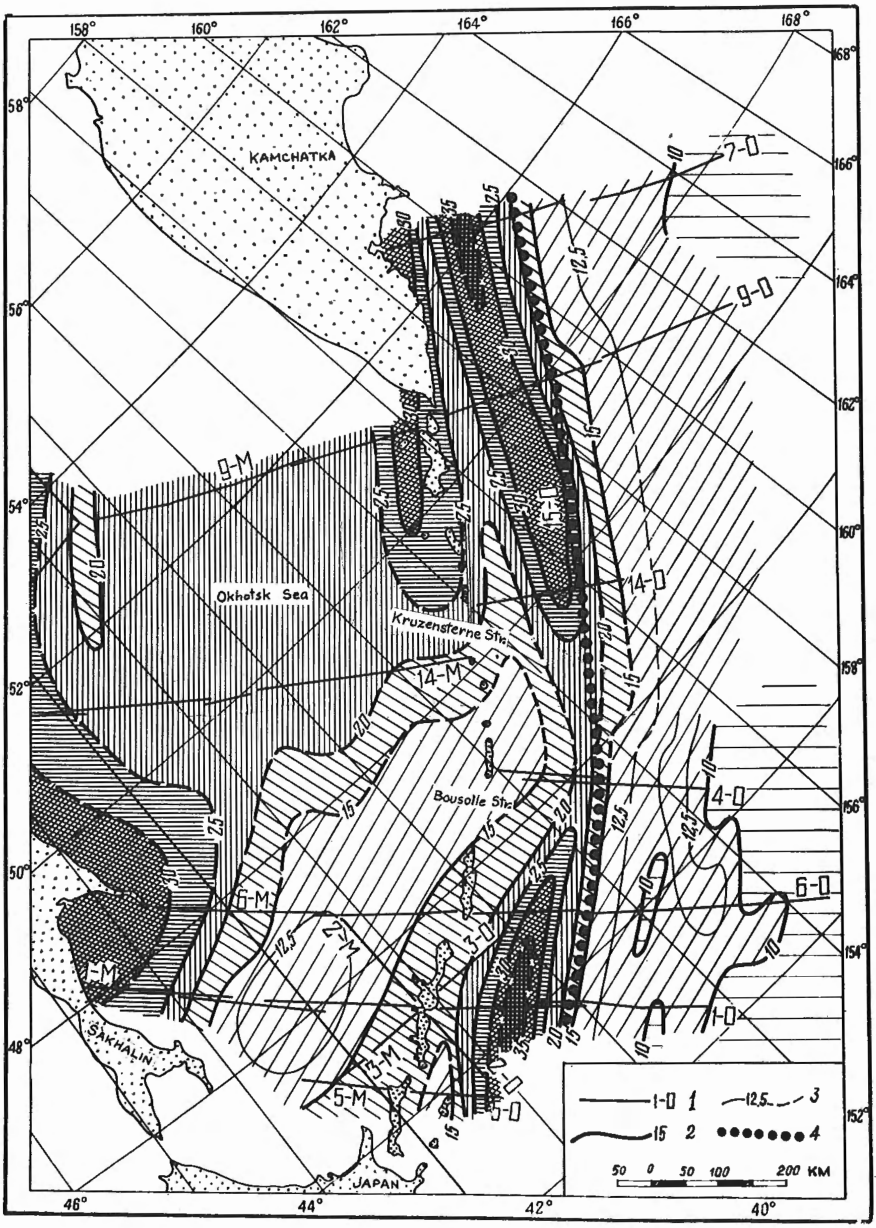

Figure 2. Chart showing depth to M surface, Kuril-Kamchatka region. 1 - DSS profile lines; 2 and 3 contours on M surface in kilometres; 4 - axis of deep-water trench.

central part of the region, along the longitudinal line of maximum depths to M surface, is a region of relatively shallow depths to the M surface. This region is confined to the narrowest part of the band of thickened crust. There, the M surface forms a culmination of a peculiar kind. The belt between the island arc and the axis of the deep-water trench can be thus divided into three different parts on the basis of crustal structure. The parts are separated on the island-arc side by the Bousolle and Kruzensterne Straits. These parts differ also in the mode of recent movements. All the islands of both Kuril ranges lie to the west of the line of maximum depths to M surface. By comparing crustal structures constructed by the DSS method, certain features of the geophysical fields (magnetic and gravity), and data on recent movements, vulcanism, and seismicity, the following conclusions can be drawn: 1) adjacent to zones with maximum rates of recent uplift, which according to the geologists are confined to the southern and northern parts of the island arc, there exist the zones of the greatest crustal thickness; 2) the most seismically active areas are in the southern and northern parts of the arc where the crust is thickest; 3) recent vulcanism is more intense in the middle part of the island arc, where the crust is thinnest along the belt; and 4) the gravity minimum is confined to the western slope of the deep-water trench, and the maximum gradient, to the trench axis. A large and broad positive anomaly was observed in the ocean east of the trench.

The crustal sections constructed from the DSS results were compared with the distribution of earthquake foci depths taken from the "Atlas of Earthquakes in the USSR" and from data obtained at high-sensitivity seismic stations. The deepest earthquakes, with foci as much as about 650 kilometres deep, occur in the western part of the Okhotsk Sea. This region is separated at depth by an interval of about 100 kilometres from a zone of foci concentration which extends continuously along the entire Kuril-Kamchatka region. Within this zone the foci occupy practically all depths from the surface to about 200 kilometres. The zone projects to the earth's surface in the belt lying between the island arc and the axis of the deep-water trench.

According to published data of other authors, similar regularities in the distribution of earthquake foci are characteristic of a number of the world's island arc systems and deep-water trenches. A cross-section through the Pacific Ocean, based on our and other published data, is shown in Figure 3, extending from the Kuril-Kamchatka zone to the Andes Mountain range in South America. The distinctly outlined Pacific block consists of crust and upper mantle and is separated on the east and west from the continental blocks of Asia and South America by shift zones or zones of earthquake foci concentration. These zones are confined in the west to trenches and island arcs and in the east to trenches and coastal mountain ranges; the eastern zones invariably dip beneath the continent. Earthquakes rarely occur on the ocean side of the trenches.

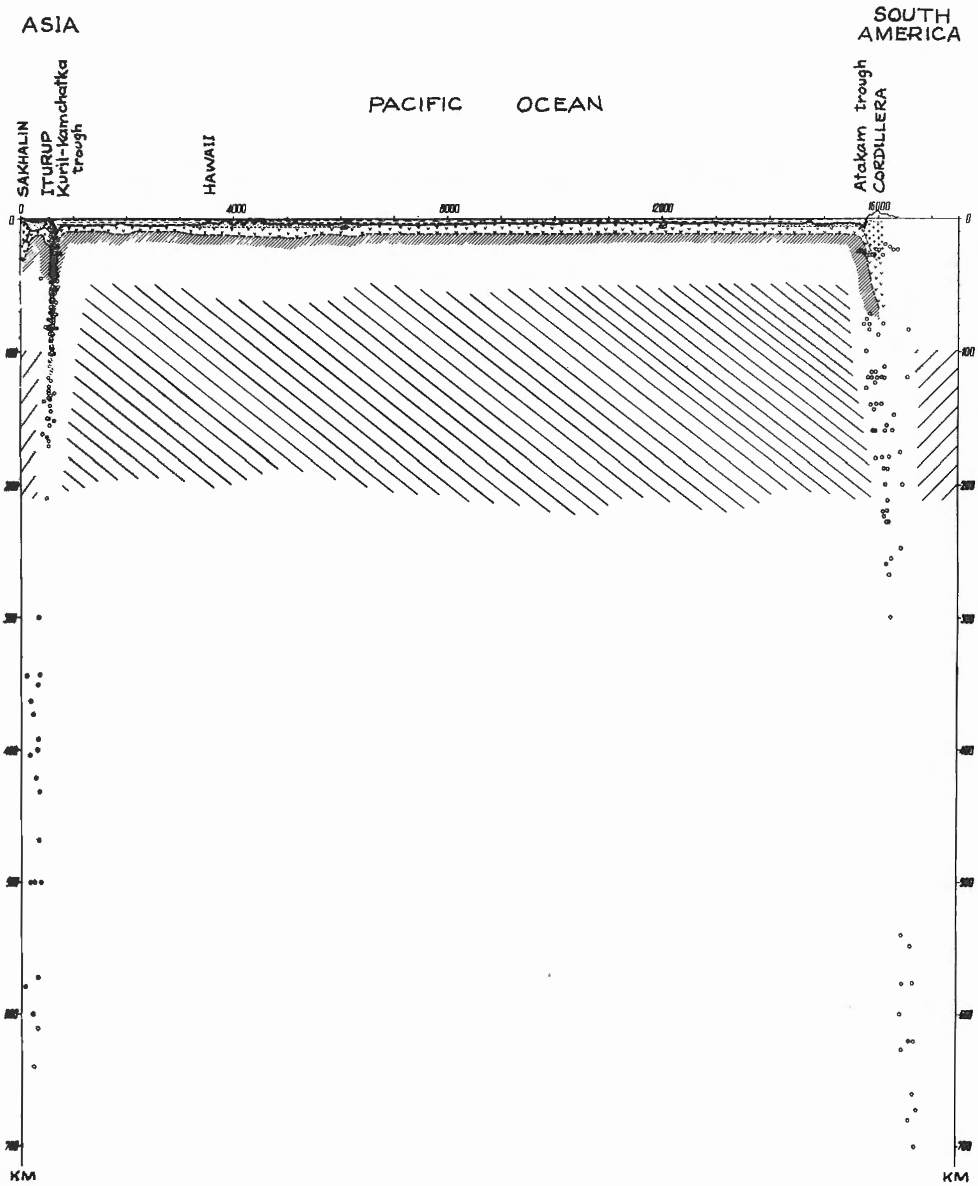

Figure 3. Cross-section through the Pacific Ocean extending from Kuril-Kamchatka region to the Andes Mountain range in South America. The shaded areas show the location of the low-velocity zones (from Gutenberg) under the ocean and continents.

The above data suggest that blocks of the first order correspond to large continental and oceanic areas. We call such blocks of crust and upper mantle, "crust-mantle" blocks. The crust-mantle blocks differ essentially not only in crustal structure, which might vary considerably within one block and differ widely in different blocks, but also in properties of the mantle. In the cross-section of Figure 3, low-velocity zones for continents and oceans are shown as drawn from Gutenberg's averaged data. There are reasons to believe (based on published data) that in the Kuril-Kamchatka region the earthquake foci concentration zone to a depth of about 200 kilometres is itself also a low-velocity zone. We suggest that within the oceanic and continental blocks there may exist local variations of depth to, and thickness of, the low-velocity zone.

Zones of concentration of earthquake foci, or shift zones, separating oceanic and continental crust-mantle blocks, can be regarded as the deepest planetary fractures. Similar, shallower fractures, separating seismically stable blocks, can be followed within the oceanic and continental blocks themselves. This and other evidence support the model of the block structure on various scales of the complexly layered crust and upper mantle.

DISCUSSION

Dr. B.D. Loncarevic (Canada)

Dr. Magnitsky, yesterday you mentioned that in this work some evidence of layering in the upper mantle was found. Could you expand on this? In what region, and what is the evidence of layering?

Prof. Magnitsky

I have already shown that it was in the southeastern part of Figure 2. But these data were not included in this paper, which was written before they were received. These measurements were made on the last expedition. I have only a personal communication from Dr. Kosminskaya about them. (See: Lukk, A.A. and Nersesov, I.L. 1965. The structure of the upper portion of the Earth's mantle from observations of earthquakes with intermediate depth of foci. Dokl. Akad. Nauk. SSR 162, no. 3, 559-562, in Russian.)

SEDIMENTS AND STRUCTURE OF THE JAPAN TRENCH[1]

W.J. Ludwig[2], J.I. Ewing[3], M. Ewing[3], S. Murauchi[4], T. Asanuma[4], N. Den[5], H. Hotta[5], S. Asano[6], M. Hayakawa[7], K. Ichikawa[7], and I. Noguchi[8]

Summary

Seismic reflection profiles recorded east of Honshu show a fairly uniform thickness of acoustically transparent and presumably homogeneous sediment along the outer ridge and east slope of the Japan Trench. The sediments continue to the bottom of the trench where they abut the foot of the west slope. In several localities the transparent sediments of the east slope end abruptly as a perched ledge slightly above the bottom of the trench, suggesting post-depositional subsidence or extension of the sea floor near the trench axis.

Seismic refraction measurements indicate that the east slope of the trench is a normal ocean floor which has been depressed. A succession of graben and step faults detected by the reflection technique along the entire eastern slope suggests that the process which formed the trench is

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[1]For the complete paper, see: Ludwig, W.J., Ewing, J.I., Ewing, M., Murauchi, S., Den, N., Asano, S., Hotta, H., Hayakawa, M., Asanuma, T., Ichikawa, K. and Noguchi, I. 1966. Sediments and structure of the Japan Trench. J. Geophys. Res. 71, 2121-2137.

[2]Speaker; Lamont Geological Observatory

[3]Lamont Geological Observatory

[4]National Science Museum, Japan

[5]Geophysical Institute, Hokkaido University

[6]Earthquake Research Institute, University of Tokyo

[7]Geological Survey of Japan

[8]Japan Maritime Safety Board

still going on. The faults are interpreted to be normal-antithetic and caused by tensional forces introduced in the convex side of the oceanic crustal plate as it is being further depressed, possibly in response to the load exerted by the weight of the island margin.

Refraction profiles shot along the upper part of the west slope (continental slope) show that its foundation is composed of material with seismic velocity of about 5.8 km/sec; the depth to the M-discontinuity is approximately 26 kilometres. A tentative interpretation of one profile shot along the lower part of the west slope of the trench indicates that the contact between the rocks of the island arc and oceanic section lies west of the present topographic axis of the trench. A thick wedge of low-velocity sediment detected near the foot of the west slope suggests that the topographic axis of the trench has been displaced seaward by outbuilding of the island margin and that the maximum depth of the trench has decreased.

GEOTHERMAL AND MAGNETIC SURVEY OFF THE COAST OF SUMATRA[1]

Victor Vacquier
Scripps Institution of Oceanography

and

P.T. Taylor[2]
Lamont Geological Observatory

Summary

Total magnetic intensity and terrestrial heat flow were observed along profiles off the coast of Sumatra. The topographic swell just seaward of the trench was found to have a heat flow value of greater than 1.5×10^{-6} cal/cm^{2}sec compared to a value of less than 1.0×10^{-6} cal/cm^{2}sec both in the Sumatra Trench and seaward of the swell. The magnetic anomalies trend mostly east-west and do not follow the curve of the Indonesian island arc.

The heat flow pattern has three distinct features. First of these features is the high heat flow found across the ninety-east ridge. The second is a narrow band of high heat flow parallel with Sumatra and flanked by broad areas of low heat flow. The third is an area of high heat flow running roughly east-west along latitude 04°30'S.

Several possibilities were considered for the origin of the magnetic and heat flow data.

As only one heat flow profile was made across the ninety-east ridge, the data are considered too scant for a reasonable interpretation and, therefore, will not be discussed here.

Several possible origins are considered for the narrow band of high heat flow flanked by broader areas of low heat flow. Among these are sedimentation-erosion, sea depth and topography of the submarine surface, thermal conductivity refraction effect, and geothermal convection currents.

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[1]Complete paper has been submitted to Bull. Earthquake Res. Inst. Tokyo Univ. for publication.

[2]Speaker.

The third geothermal feature, a large high heat flow anomaly running east-west along latitude 04°30'S, coincides with a magnetic anomaly of greater than 400 gammas. Serpentinization and vulcanism are suggested possible sources of the heat flow anomaly.

This work has been supported by the Office of Naval Research under contract Nonr 2216(05) and by the National Science Foundation under grant NSF-G22255.

DISCUSSION

Prof. S.K. Runcorn (UK)

It seems to me that one of the difficulties in interpreting the geothermal results in a situation like this is that it's unlikely that thermal equilibrium exists. If you have a crust with a uniform heat flow and then suddenly a trench is produced by any mechanism at all, isn't it probable that thermal equilibrium will not be reached? For example, the thermal time constant in, say, a hundred kilometres of rock is something of the order of two or three hundred million years and, unless these features are older than that, then you are not dealing with an equilibrium situation.

Dr. Taylor

One of the purposes of measuring heat flow is to try to determine the mechanism operating. High heat flow in an area would indicate that some type of force acted in that region, and low heat flow, another type. I do not see your point exactly, Dr. Runcorn.

Prof. Runcorn

Well, I think it is simply this. If the upper part of the earth has such a long thermal time constant, you cannot assume thermal equilibrium in your crustal models unless the features are very old, greater than many hundreds of millions of years.

Dr. Taylor

If the convection current hypothesis is correct the high heat flow may indicate a fossil cell, that is, a cell which existed in the past and has since ceased, so that we are now detecting the heat flow presently reaching the surface from that previously existing cell. And the same could be true of serpentinization in the transverse anomaly. If it occurred in the past and is no longer operating, we are still detecting the heat flow from it. Yes, that is true.

Dr. J.L. Worzel(USA)

Did you make any quantitative estimates of the heat flow in this convection cell?

Dr. Taylor

Yes, I did. I worked backwards actually. I took the heat flow anomaly and worked back to see what thickness of convection cell would be required to produce this anomaly and which results were consistent with the anomaly measured. T. Rikitake and K. Horai have a graph which shows the thickness of convecting layer necessary to produce a given heat flow anomaly for a given crustal thickness. I took my quantitative results from that graph.

Mr. Peter (USA)

Isn't this convection cell rather smaller than the ones usually postulated?

Dr. Taylor

Yes, it is. But the size of the convection current was obtained from the existing heat flow data. It's like trying to determine the thickness of an anomaly from a magnetic map.

Prof. Runcorn

I think that you are trying to explain heat flow anomalies of this kind by looking for small convection patterns. But I am not sure whether this is a valid argument. Because if you imagine that the crust is essentially a rigid layer and you have a very large convection cell underneath, it is quite possible mechanically to cause this layer to yield. Yet the size of the stress system which is producing the downbuckle may be very much larger than the lateral dimensions of the downbuckled part.

Dr. Taylor

I did not investigate the dimensions of the trench in developing the dimensions of the convection current. The dimension of the interpreted convection current was derived only from the quantity of heat brought by convection at a given crustal thickness. The paper by Rikitake and Horai is "Studies in the thermal state of the Earth; Bull. Earthquake Res. Inst., Tokyo Univ. 38, 403-419, 1960.

Dr. Worzel

Does not the transverse anomaly give you certain problems with the convection hypothesis?

Dr. Taylor

Yes. If it is caused by serpentinization, it may be coming from material above the 500-degree isotherm which I would not like to speculate on.

GRAVITY SURVEYS IN THE BRITISH SOLOMON ISLANDS - A NARRATIVE[1]

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Abstract

A gravity survey of the Guadalcanal Plains by Day in 1960 and the linking of the Solomons airfields to the world gravity network by Laudon in 1961, led to the recognition of large anomalies. A joint venture during 1963-64 by the University of Wisconsin, the U.S. Army Map Service, Far East, and the Solomons Department of Geological Surveys, established over 2,000 stations at intervals around the coastlines and across the mountains of all major islands. With the help of the University of Tasmania and the Australian authorities, another 500 stations were established in the Territory of Papua and New Guinea and in West Irian. The work in the Solomons was carried out vigorously and proved difficult, hazardous, and exciting. Arrangements to follow-up with a gravity survey of the surrounding seas was postponed by the damage to H.M.S. COOK in 1963. A sea reconnaissance by U.S.S. WANDANK produced support for funds in 1964, and Hydrographer of the Royal Navy kindly made H.M.S. DAMPIER available from October to December, 1965. An area from New Ireland and New Britain in the west to the Santa Cruz Group in the east, about 1,500 miles long and of varying width, was recently completed: a joint venture involving the Royal Navy, the Institute of Geophysics, Hawaii, National Science Foundation, U.S. Office of Naval Research, and the Solomons Geological Surveys. Aerial geophysical surveys also began late in 1965 with electromagnetic and magnetic methods covering major islands of the Protectorate; the magnetic runs over the seas between the islands will support the gravity data. Correlation of land gravity with other geological and geophysical data is remarkable. Sea results are still awaited and should soon be forthcoming.

BACKGROUND

The idea of a gravity survey of the anomalous Solomons chain of islands was first discussed in 1949 with Professor Charles Marshall of the University of Sydney. Two years later, in 1951, with the impending receipt of a Worden Gravity Meter, plans were made for logistic support of a geophysicist by the Solomons Geological Survey, and a vessel was allocated

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[1] By title.

for four months. Unfortunately, the instrument arrived in Sydney out of adjustment, and shortly afterwards the geophysicist resigned. The project did not eventuate. Also in 1951, Dr. George Woollard was scheduled to visit the Protectorate and tie the gravity of the airfields to the world gravity network. However, he became ill in New Guinea, and his visit was cancelled. Linking the Solomons to the world gravity network had to wait for another ten years.

The possiblity of arranging a gravity survey of the surrounding seas by pendulum equipment in a submarine - the then only known way - was raised officially from time to time, and discussed personally with officers of the Australian Departments of External Affairs and National Development late in 1956. The proposal was discussed in 1957 with Professor Vening Meinesz in Holland, Dr. Anderson of the Geophysical Institute in Copenhagen, Mr. B.C. Browne of Cambridge, and by correspondence with Captain G.S. Ritchie, D.S.C., of the Hydrographic Department of the Admiralty. The project did not come about. Unfortunately no approach had been made to the Royal Society - this might have made a difference.

Meanwhile, the submarine H.M.S. TELEMACHUS, and U.S.S. CAPITAINE and BERGALL made gravity observations in the southwest Pacific; they passed through the New Hebrides and Ellice Islands, and to the west of the Solomons, as well as the Fiji and Tonga areas. The TELEMACHUS made one crossing of the Tonga Trench, and two of the Kermadec Trench. No information of use in the study of the anomalous Solomons region was forthcoming.

In 1960 Oil Search Limited of Australia arranged a reconnaissance examination of Guadalcanal's sedimentary sequence, and made a gravity survey of the plains. The latter survey was made by Dr. Alan Day of the University of Sydney, using a Worden Gravity Meter at stations previously marked out by the staff of the Geological Survey - at 2,000-foot centres on all roads and foot trails in the area. A ship was made available for coastline and offshore island observations. The Bouguer anomalies indicated that the basin area was divided into two parts by a gravity high extending northward from Gold Ridge in the centre of Guadalcanal to Tetere on the coast. The survey brought out what were believed to be the steepest gravity gradients known in the world; they are associated with an upfaulted block of basement ultrabasic rocks and amphibolite schists, thinly covered by Cenozoic sediments, and flanked by sedimentary basins about 9,000 feet deep on the west and 22,000 feet deep on the east. This explained the apparently anomalous stratigraphic correlations of the eastern and western parts of Guadalcanal. The occurrence of economic minerals along the gravity high itself - gold, silver, stibnite, arsenic, magnetite, copper sulphides, etc. - suggested some genetic relationship with this structure.

However, the division of the basin into two parts further reduced the chances of economic accumulations of petroleum in such a small area, and Oil Search Limited withdrew its interest.

In 1961 Dr. George P. Woollard, as principal research worker on the University of Wisconsin World Gravity Project, sent Mr. Thomas S. Laudon to the Solomons by air to make observations of all airfields with gravity and geodetic meters. Laudon stayed overnight in Honiara and established a base gravity station in the Geological Survey Department. He left next morning with all available local information, and was apparently impressed with the gravity anomalies he had encountered. He had the honour of being the first American earth scientist to visit the Solomons since the war and to make a contribution to our knowledge of the islands. The following were the final gravity values:

Henderson Airfield, Guadalcanal	978.2742 cm/sec^2 or gal
Honiara, Guadalcanal Geological Survey Dept.	978.2444 gal
Yandina Airfield, Russell Islands	978.2598 gal
Munda Airfield, New Georgia	978.2541 gal
Buka Island Airport	978.3016 gal

Several weeks after Mr. Laudon's visit the detailed proposals for a land gravity survey were under discussion, and the following logistic support was offered by the Solomons Marine and Geological Departments: a small ship, fuel and lubricants, master and crew salaries and supplies; at least one educated and trained Solomon Islander assistant; semi-skilled bushmen labourers and bearers (at least six for each geophysicist in the expedition); a Land Rover and driver on Guadalcanal as required; watertight patrol cannisters, packboards, tents, tables, chairs, cots, sandfly nets; office laboratory, and workshop facilities; services of instrument-maker technician; maps; and free accommodation for scientists in Honiara.

Support for the project was also provided by the University of Queensland, which offered a geophysicist and equipment.

In October 1961 a Research Proposal was submitted by Dr. George P. Woollard and T.S. Laudon from the Geophysical and Polar Research Centre of the University of Wisconsin to the National Science Foundation, Division of Earth Sciences. Dr. Woollard briefly summarized the current state of information. This is worth reproducing at length lest we forget the situation that existed prior to the collection and collation of all this valuable data applying to the New Guinea-Solomons region.

Dr. G.P. Woollard's Summary

"Knowledge of the earth's crustal structure in the Solomon Islands and the Bismarck Islands of Melanesia resides today primarily in the realm of hypothesis. Different theories regarding the nature of this key area have been advanced over the years, but they remain largely untested due to a lack of geological and geophysical data. Umbgrove (1945, p. 209) discussing Pacific island arcs states: 'For lack of sufficient data, the entire region extending from New Guinea to Samoa has to be left out of consideration.', and Glaessner 1950 (p. 870) writes: 'Various hypotheses have been advanced in explanation of these structural conditions, but most investigators agree that further geophysical data, and above all more geological field observations, are required in this key area.' This situation remains largely unchanged as regards geophysical work at present, although local agencies have been doing extensive geological work.

"In discussions of the structure and tectonics of the Pacific Margin, information regarding this part of Melanesia is restricted mainly to records of earthquakes, bathymetric data, and scattered geologic and vulcanologic observations. These records show the area to be one of very great volcanic and seismic activity. Twenty-seven centres of volcanic activity occur in the Solomon, Bismarck, and Admiralty Islands, and in the volcanic arc off the northeast coast of New Guinea. Concerning the seismicity of the area, Gutenberg and Richter (1949, p. 50) state: 'In the region of the Solomon and Bismarck Islands, seismicity reaches a high level (with a relatively large number of class b shocks of magnitude 7.0-7.7) probably exceeded only in the Japanese area.'

"The Melanesian geotectonic province is defined on the basis of a set of distinct physical characteristics by which it differs from the 'normal' Pacific island arc provinces as defined by Gutenberg and Richter (1941) and modified by Hess (1948). Glaessner (1950) summarized the Melanesian characteristics as being:

(a) Sigmoidal structural trends, with resulting absence of ordered outward convexity of the island arcs.
(b) Rounded deep nuclear basins.
(c) Lack of separation of volcanic and non-volcanic island arcs.
(d) Confused, instead of ordered, distribution of earthquake epicentres.

The conditions mentioned above, specifically the high degree of seismic and volcanic activity associated with island arcs and oceanic troughs, leads to the expectation that a knowledge of the gravity field might well lead to a better understanding of this extremely interesting and anomalous area. This expectation seems to be borne out by the applicants' work in this area and by the reports of the small amount of gravity work that has been done by other groups. A report of the Lamont Geological Observatory submarine gravity cruise in this area, tells of observing a large negative gravity anomaly on crossing the axis of the zone of earthquake epicentres between Bougainville and Rabaul (Anonymous, 1949). Day (1960) in a petroleum exploration gravity survey report on the Guadalcanal Plains refers to a large positive gradient of 120 milligals relief, with gradients on the flanks of up to 9.5 milligals/km. These two reports, plus the applicants' observations, cover the entire amount of gravity work that has been done in the area so far as is known, but despite this paucity of data they confirm the existence of an extremely interesting and significant gravity field.

"Since 1950, geologic, and vulcanologic and station seismic work have been in progress in the area. This work is being done by the Vulcanological Observatory in Rabaul and the Geological Survey Department in the British Solomon Islands. In addition thousands of miles of magnetic observations were obtained in the Solomon Islands region in 1958 by H.M.S. COOK of the Hydrographic Survey Department, British Royal Navy (Grover, 1960).

"The lack of gravity and magnetic studies can be attributed primarily to the isolated location of the area, and the difficulties, inherent in working in areas of rugged terrain, covered mostly by tropical rain forest.

"When one considers the role played by gravity studies, in particular in unravelling the geotectonic pictures in almost every other part of the world, but especially in complex areas such as Indonesia, to which parts of this area bear a strong resemblance, it is evident that a gravity study here would be extremely valuable. A companion magnetic study would aid materially in the interpretation of the gravity data, particularly the contribution of near-surface geologic effects.

"In March 1961, as part of the University of Wisconsin World Geodetic Gravity Program, gravity base stations were established at thirty airports in the British Solomon Islands Protectorate, the Territory of New Guinea, and Netherlands New Guinea, using two geodetic Worden gravity meters (Nos. 14 and 291). Ties to local landmarks and survey points were carried out wherever time permitted. In all, observations were made at 66 stations.

"This traverse was tied at both ends to University of Wisconsin pendulum stations by direct two-way ties between Brisbane and Port Moresby on the east and between Mokmer and Manila on the west.

"The study was undertaken for the purpose of observing, if possible, the effect on the gravity field to be expected from the ellipticity of the equator reported by Kaula (1961), Kozai (1961), and Issak (1961) from studies of satellite orbital perturbations."

After discussing further aspects of the islands of New Guinea and New Britain areas, and the Planet Trough, and suggesting that anomalies would be comparable to those of Indonesia, Dr. Woollard pointed out that:

"It is not possible to differentiate a volcanic and a non-volcanic island arc in the Solomons. Furthermore, the distribution of earthquake foci is confused in this area, rather than ordered as in other circum-Pacific areas. The volcanic axis of the Solomons runs just about up the centre of the group. Gutenberg and Richter (1954) have suggested that the Solomons are a "reverse" island arc, i.e. fronting on ocean deeps away from the Pacific, with reverse order of the regional features in relation to the Pacific Basin. Unfortunately, no observations were made northwest of the volcanic axis, away from the ocean deeps.

"Considerable oil exploration gravity work has been completed in the area of the Gulf of Papua, and in Netherlands New Guinea where Shell Oil Company (N.N.G.P.M.) carried out gravity observations at over 49,000 stations. The observations made by the University of Wisconsin at oil company base stations in Port Moresby, Honiara, Sarmi, Mokmer, and Jefman, plus a few additional observations, will make it possible for all of the oil company gravity stations to be put on the Potsdam datum and the University of Wisconsin world gravity standard, so that these data can be integrated with the proposed work to yield a much larger body of data."

PLANNING

The initial proposal to include the New Guinea and New Britain areas as well as the Solomons was modified in March 1962, to limit the first year's work to the Solomons only, in view of the support that had been offered. On the 9th August 1962, news was received confirming the National Science Foundation's approval of the Wisconsin proposal for which the sum of $22,400 was granted.

During the Chief Geologist's visit to Wisconsin in mid-1962 details of the land project were discussed, and basic plans made for the sea phase to follow. The latter was also discussed with officers of the Hydrographic Department of the Royal Navy in London, and both projects with Professor S. Warren Carey in Hobart, Tasmania.

Professor Carey had recently been given the responsibility of coordinating gravity measurements made by oil companies in Australian Papua-New Guinea, and to arrange further measurements to produce a gravity map of the entire territory. He was in a position to offer help with the gravity survey of Bougainville, and was subsequently kept fully informed of all developments.

LAND GRAVITY SURVEY

On the 5th March 1963, Dr. Thomas Laudon and Mr. Perry Parks, Jr., arrived in Honiara from Wisconsin, with two La Coste and Romberg Gravity Meters (G-1 and G-19) and four Wallace and Tiernan Altimeters: the land gravity survey began. At the end of March, Dr. Laudon made a quick flying visit to West New Guinea to occupy base stations there and in Australian New Guinea, in order to tie in with the existing gravity net-work, the data produced by the Dutch Oil companies in past years. This was successfully accomplished during the UNTEA administration, and Laudon returned to Honiara, together with two trained observers from the American Army Map Service, Far East (Pfc Morris Bierig and Pfc John Brewer) who were to join in the project and double the speed of data collection. They brought with them two temperature-controlled Texas Instruments Elevation Meters of great precision for the several mountain crossings of Guadalcanal and four more Wallace and Tiernan Altimeters, as well as three PRC-10 radio units.

The Government of Papua and New Guinea also extended its support to other observers from the U.S. Army Map Service and the University of Tasmania, who made gravity observations in Bougainville, and also in the nearby Shortland Islands at the request of the Protectorate Government. We were glad of this assistance as it saved an extra trip of several hundred miles by the small ship allocated to our gravity team. The inclusion of Bougainville meant that the Solomons region was being dealt with as one geographical unit regardless of political boundaries.

The University of Queensland was unable to send its geo-physicist owing to illness, but kindly provided a base recording magneto-meter in view of the proposal to make Jalander Magnetometer readings simultaneously with the gravity observations.

By the end of April three crossings of the Guadalcanal mountains, and three of Malaita had been accomplished. Four trained and partly-trained educated Solomon Islander geological assistants had already mastered the art of altimetry on the leap-frog system from coast to coast, and up to 25 experienced and enthusiastic bushmen bearers from Guadalcanal were involved. Coastline observations at one-mile intervals were proceeding simultaneously in good weather. The toughness of the Guadalcanal country resulted in all Americans losing their surplus adipose on their first expedi-tions, and one reported that he had "never felt better for years in spite of the two worst blistered feet in the Pacific". Expensive footwear succumbed in an astonishingly short time, and preconceived ideas with regard to the use-fulness of certain types of boots were disposed of. They were always a problem.

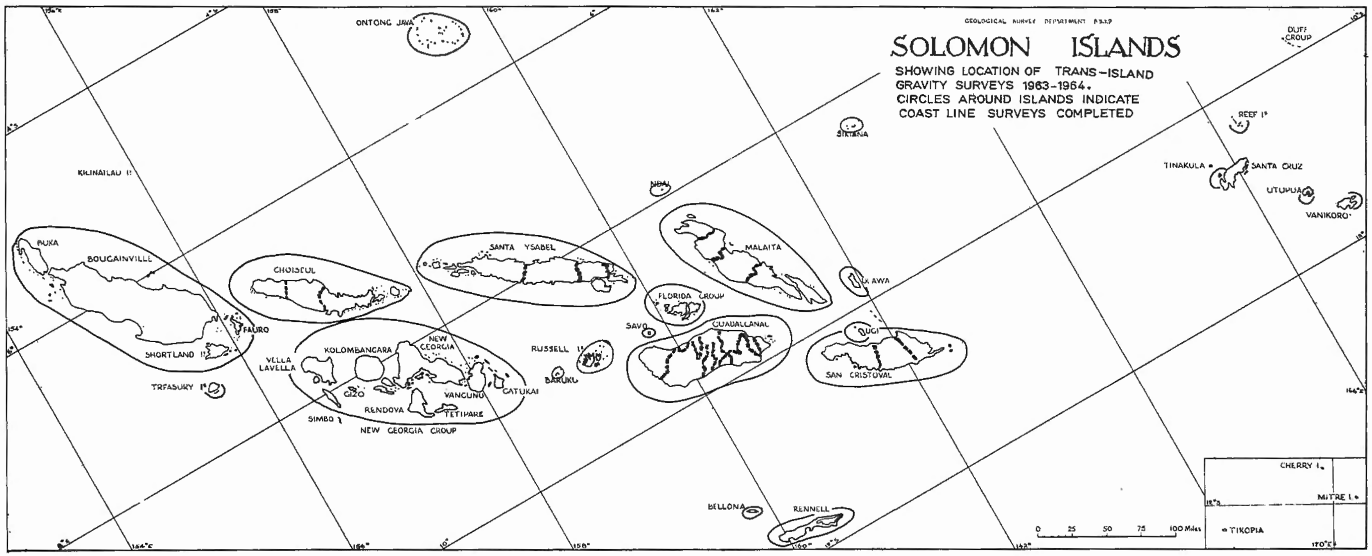

Figure 1. Solomon Islands showing the location of the trans-island gravity surveys 1963-1964.

Dr. T.S. Laudon in his progress report on the operations described the conditions in the following terms:

"The investigators' optimistic estimates of probable progress were based on a lack of appreciation of the difficulties inherent in working in the Solomons, the result of neither having worked under tropical jungle conditions before. It is difficult to express these conditions adequately; they must be experienced to be appreciated. Torrential rains drenched the field parties for hours daily and necessitated repeatedly reading the instruments under conditions that in any other environment would be considered impossible for gravity work, and under which the usual procedure would be to leave the gravity meter sealed in its protective case and wait for better weather. Infection, fever, diarrhea, fungus, scorpions, centipedes, poisonous plants and flash floods were constant problems while working in the bush. Parks was hospitalized twice during his stay in the Solomons and Laudon has been hospitalized twice since leaving, in unsuccessful attempts to shake off the lingering effects of maladies contracted there. The only suitable short description of the terrain of the Solomon Islands is "unbelievable".

"The execution of the field program was a joint cooperative effort throughout. The contribution of the British Solomon Islands Geological Survey Department to the success of the operation cannot be over-emphasized. Not only was the help of that Department many times greater than that promised in the research proposal, it would be impossible for any organization to carry out an operation such as ours in the Solomon Islands without similar aid from the Geological Survey. The corps of trained geological assistants and bushmen who participated in the field work of this project, many of whom have been with the Survey for over twelve years, formed such a well coordinated team that they not only thoroughly attended to the many facets of living in the bush, thereby making it possible for us to devote all our energy to the gathering of the data, but they also participated in the actual observing and recording of the data thereby speeding up the work immeasurably. No individual or agency, arriving in the Solomons, could hope to assemble such a team on its own, and it is doubtful that any other department of the Government could provide a comparable team."

With no advance preparation, 30 to 35 stations per day at one-mile intervals were possible by Land Rover. If stations were previously surveyed in and marked, and a guide provided, it was possible to observe up to 60 stations per day by Land Rover. By small ship it was found that 10 to 20 stations could be occupied, depending on the difficulties of landing. On foot trails only 6 to 12 stations per day were possible without previous preparation, depending on whether rough mountains were involved.

Advance preparation helped immensely. Accurate maps with survey points shown on them permitted fairly accurate planning of operations. Personal knowledge of the Lands Department and American post-war

Figure 2. Bush group in mid-Malaita. Photograph by Dr. T.S. Laudon.

Figure 3. Knee deep in mangrove swamp, Mr. Perry Parks, Jr., prepares the base plate for the La Coste and Romberg gravity meter.

triangulation stations along the coast proved invaluable; the Master of small-ship HYGEIA was able to take her roughly to the position, and guides who had worked on the recent tellurometer survey of the region were able to take the party directly to the spot even where it was unidentifiable through complete overgrowth of dense vegetation. Wherever possible such known survey points were located at the commencement and at the completion of coast-to-coast observations.

The Texas Instruments Elevation Meters on loan from the American Army were used for altitude measurements on some crossings of the mountain ranges and claimed greater precision with a special suspension, and temperature-control by rechargeable flashlight battery cell heating units. They were the size of small milk cans, weighed about 20 lb., and were carried and operated by Messrs. Bierig and Brewer. In addition, four matched pairs of Wallace and Tiernan Altimeters were available, two of which were carried by each of two Solomon Islander Assistants trained to make the necessary observations, employing the "leap frog" method. Walkie-talkies proved ineffective in this close jungle country and readings were taken at set times. Working from dawn to dusk those engaged in altimetry usually moved at the double with enthusiasm. The readings of the two different altimeter systems were compared.

On shipboard operations it was found necessary to have one or two sure-footed islanders who would carry the valuable gravity-meter (worth at least $10,000), and act quickly when landing by dinghy between breakers; and a boat's crew who could be sure to do the right thing at the right time - to choose the correct wave interval to get the party ashore, and the boat up the beach out of reach of the following dumping waves. This had its exciting moments and much had to be left to the judgement of the islanders involved. Fortunately for the valuable gravity meters, orders shouted in the heat of the moment by a horrified geophysicist were either obeyed or ignored by the islander as he judged the situation: either he would wade frantically from the sea and race up the beach out of reach of the thundering breaker, or make a dash armpit and chin-deep for the dinghy, gravimeter held above his head where eager hands would take it from him, and backs bend to the oars to get out beyond the rapidly approaching wave with its top threatening to curl. When each landing and withdrawal seawards had been successfully accomplished, the whoops, shouts, and laughter of the islanders - and geophysicists - would relieve the tension. Far from being a dull routine buiness like most operations involving the collection of gravity observations, this work proved to be highly adventurous. One American newspaper quoted Laudon as saying "it was one adventure from start to finish".

In order to recharge batteries for the meters it was necessary to have a special installation aboard ship to make use of its generator system, and to have a portable generator ashore at the coast rendezvous to meet a party after each island crossing. Sometimes it proved possible to utilize charging units available at Mission Stations, where the visitors were invariably accorded every kindness and assistance. At the Catholic Mission at Tangarare on the west coast of Guadalcanal, the visitors had the privilege of being the first audience to a choir of seventy Solomon Islanders who had been rigorously and thoroughly trained for a whole year in preparation for the coming consecration of their new church. While the visitors relaxed on the church steps in the sunset, the choir sang the Mass so beautifully that all confessed lumps in their throats and tears in their eyes, Protestants and all.

The necessity to carry several fully-charged small sealed batteries on each island crossing – one for each day's march – was modified with the arrival of a new lightweight gasoline-driven generator weighing only 12 lb. complete, and capable of being lifted by one finger – measuring about 12 inches long, 8 inches wide, and 9 inches high – and with an output of 300 watts, with takeoff for 240 volts AC or 12 volts DC. This equipment is now standard issue for Geological Survey radio tranceiver stations in country difficult of access.

By the end of May, two island crossings of San Cristoval had been completed. The need to use the same ship to collect these large land-parties, and the consistently heavy southeast seas of the southern coast, meant that the shoreline work was not keeping pace with the mountain crossing work. Repeatedly heavy seas and the fear of losing instruments and personnel precluded some shoreline operations. It became apparent that more time would have to be spent on the coastal work if the project was to be completed in a reasonable time, and the station interval was extended to two miles instead of one mile, except where anomalies were apparent. The work was not straightforward, as advantage had to be taken of spells of good weather. Only about 50 per cent of the coastline of Guadalcanal had been completed, and 50 per cent of Malaita, with the most interesting anomalous areas as yet untouched because of the weather. However, the field results had justified expectations and one big gravity anomaly after another was being revealed.

During June, two mountain crossings were being made on Santa Isabel, as well as coastline work. Off the northeast coast about noon on the 12th, a serious mishap occurred. John Brewer was going ashore with gravity meter G-1, considered to be the finest geodetic gravity meter ever made and worth many times its initial value of $10,000 owing to the tens of thousands of miles of gravity traverses to its credit, from Pole to Pole. It is said to be irreplaceable, being some times more accurate than other gravity meters. The aluminium dinghy left the ship in a heavy swell, and when 450 yards off shore in deep water over a deeply-submerged reef, a large wave broke behind, swamping the dinghy over the stern. The following breaker threw everybody out, and bushman Pende holding the gravimeter was thrown onto a rowlock and dropped the meter overboard. It was grabbed by bushman Tanise Nosi, obeying orders to save the meter first in any emergency. Repeatedly swept by successive breakers the dinghy crew supported Brewer who could not swim. The immediate shock over, the islanders turned the dinghy over so that it floated on its own trapped air. The precious gravimeter was then placed on top and held by bushmen Pende and Tanise, one on each side holding it with one hand, and swimming with the other, being submerged by passing breakers. After about 25 minutes without any progress against the current, their plight was seen from the shore and an islander came out by two-man dugout canoe from the Komago Village. To his astonishment he was peremptorily ordered by Tanise to take the gravimeter ashore and never mind the obvious plight of the master; and he did this, sending a larger canoe out to rescue the party and tow the dinghy ashore.

Although partially immersed in salt water inside its aluminium carrying case, and with loosened glass allowing water to enter the inside of the meter case itself, the meter was found to read quite normally when emptied and tested ashore. There was no tear or serious damage to this quite irreplaceable instrument. The expedition continued.

Dr. Tom Laudon departed by air for Wisconsin on the 12th June. After completing trans-island crossings on Choiseul, and some coastal work on that island and Isabel, Mr. Perry Parks returned to Honiara where special meter maintenance measures were taken in accordance with instructions telegraphed from the United States. When the lid was afterwards tightened and pressure was brought to bear on one of the levels, some maladjustment to the instrument resulted, most unfortunately. Mr. Parks and gravity meter G-1 departed by air on the 17th July, visiting Rabaul, Buin, Moresby, and Tokyo on the way home to Wisconsin (whose University team required his services in the Arctic beginning in October). As the work was progressing so well, and only shoreline work remained to complete the survey, an appeal was made to Dr. Woollard offering continued support if gravity meter G-19 could remain; he concurred with the proposal. Similarly the Army Map Service, Far East, agreed to extend the tours of duty for Bierig and Brewer. The gaps in shoreline work were filled in on all the island groups in the months that followed. The rates of progress were recorded as follows:

10 April-12 May'63	276 gravity stations of which 97 were vertically controlled by altimetry.
12 May-10 June	220 stations on Malaita, San Cristobal, Ugi, Three Sisters, and Ulawa. Altimetry at 68 stations on San Cristobal.
10 June-11 July	229 stations of which 122 were vertically controlled by altimetry.

11 July-5 August	96 stations on Malaita, before the HYGEIA, pounded by heavy seas, limped to port in a leaking condition and had to be slipped. She was replaced by VERONICA.
5 August-7 Sept.	181 stations including the Florida Group, San Jorge, Santa Ysabel, Russell Group, and Eastern District.
7 Sept.-15 Oct.	419 stations with elevations from high-water-mark - working in the Russells, Borokua, and New Georgia Group: mostly in sheltered lagoons with dinghy and outboard motor.
15 Oct.-15 Nov.	126 stations and 6 elevations by altimetry on New Georgia Group, Guadalcanal, Rennell, Bellona and Santa Ysabel.
15 Nov.-20 Dec.	395 stations and 183 elevations on Santa Isabel, Choiseul, and Guadalcanal.
21 Dec.-21 Jan.'64	71 stations and 26 elevations on Sikaiana, Ontong Java, Small Malaita, and Guadalcanal.

Pfc Brewer was relieved by Pfc Hattemer on the 10th December. Both Morris Bierig and Philip Hattemer took their last reading at Henderson airfield on the morning of the 22nd January 1964, when they departed for New Guinea and Tokyo.

Approximately 2,000 gravity stations were occupied in the course of the land gravity survey between the 5th March 1963, and the 21st January 1964. But office work in the Solomons continued on after the departure of the team.

The correlation of the readings with charted positions of the stations, and the allocation of latitudes and longitudes was made the responsibility of Supervising Draughtsman, Mr. Bill Lewis. Although an attempt had been made to microfilm all field books after each expedition, it was ascertained that some data had escaped us, and these had to be obtained from Wisconsin. The numbered stations were all copied by hand onto maps of the largest scale, usually 1:50,000. In some cases corrections of island position and shape had to be made from the tellurometer data, and from the results of the hydrographic survey by H.M.S. COOK in 1958. Two copies of all maps were sent to the University of Wisconsin, and two to the U.S. Army Map Service, Far East. The men of both these organizations exchanged visits and views, and all data. Computers were at their disposal for processing data.

Dr. George Woollard had by this time resigned from the Geophysical and Polar Research Centre of the University of Wisconsin, and assumed the Directorship of the Institute of Geophysics, University of Hawaii. In April 1964, he was elected President of the American Geophysical

Union. Dr. Tom Laudon had assumed a lectureship at Wisconsin State University, Oshkosh. Still their interest in the project continued.

In May 1964, another $6,400 was granted to the University of Wisconsin to permit processing of the considerable amount of data collected. Both Dr. Laudon and Mr. Parks were engaged on this work during the summer of 1964, and were visited by John Brewer and Lepisto (who made observations on Bougainville) of the Army Map Service.

PLANNING THE PROPOSED GRAVITY-MAGNETIC-BATHYMETRIC SURVEY OF THE SURROUNDING SEAS

Mention has been made in passing of discussions in 1962 with Dr. Woollard in Wisconsin, and officers of the Royal Navy Hydrographic Department in London. These discussions concerned the extension of the land surveys by a shipboard gravity-magnetic-bathymetric survey of the surrounding seas, a necessity if the land gravity work was to be integrated with the regional picture.

In the early 1960's it became no longer necessary to use pendulum equipment in submerged submarines in order to measure gravity. The new La Coste and Romberg Shipboard Gravity Meters had been developed well beyond the experimental stage, and had been used at sea with some success by the Scripps Institution of Oceanography and others. The tremendous advantages of continuous shipboard readings could not be ignored.

Although these shipboard instruments were very rare, it appeared from discussions in Wisconsin in July 1962 that an even greater difficulty was to find a suitable ship and funds. In the event of the British side being able to arrange a vessel, the American side would put forward a proposal for funds to cover scientific personnel, equipment, and computer time. It was made clear at the time that the Protectorate's logistic support of the land gravity surveys was to be its major contribution and that it was unlikely that local funds would be available to support the sea survey.

After discussion with Professor F. Vening Meinesz in Holland, the subject was raised in London with Captain G.S. Ritchie, D.S.C., and Lt-Cdr. J. Paton of the Hydrographic Department of the Admiralty. On my return to the Protectorate a firm proposal was submitted to the Hydrographer on the 2nd December 1963. The Protectorate's requirements for shore hydrographic work in deep-water harbours (for impending timber and mining developments) were also made known, and it was proposed that perhaps the survey personnel could be engaged on this work while the oceanographic survey of gravity, magnetism, and bathymetry was in progress.

Information regarding the La Coste and Romberg Shipboard Gravity Meters was also communicated, together with information on all known types of ship in which they had been operated with varying success. One meter had been operated in an 85-foot ship in the Gulf of Mexico, but was only effective in fairly calm weather; reasonable results were obtained with waves up to three feet high, but no more. Texas A. and M. College had been operating a meter on a 136-foot converted minesweeper of 250 tons, and enjoyed fairly good operation when running the ship in the best direction to reduce roll. Dr. J.C. Harrison of the Institute of Geophysics at University of California, Los Angeles, obtained very good results on the oceangoing tugs HORIZON and SPENCER BAIRD of the Scripps Institute of Oceanography; although listed as 550 tons, they actually had total laden displacements of about 950 tons, lying low in the water and possessing a deep draft of about 16 to 19 feet. Better results had been obtained on the ARGO which had a displacement of 1,700 tons. Evidence pointed to the need for a large vessel.

The Shipboard Gravity Meters were designed to deal with horizontal accelerations with periods up to 20 seconds. Longer periods could give gravity errors. Good manual steering might be in order, but when the helmsman gets tired the steering becomes poor. Running the ship slowly may reduce "fishtailing" so that effect could be overcome, but evidence pointed to the need for an automatic pilot. However, continuing improvements of the instrument were being made and it seemed likely that by the time the sea survey was begun, the characteristics of the ship would be less restrictive. (This proved to be so.)

The sea survey proposal was submitted by the Geophysical and Polar Research Centre, University of Wisconsin, to the National Science Foundation in mid-1963, naming Dr. George Woollard, Dr. T.S. Laudon, and Mr. J.C. Grover as Principal Researchers. The Foundation was later notified that, subject to funds becoming available, the Admiralty Board was prepared to allocate H.M.S. COOK to the gravity-magnetic-bathymetric survey early in 1964. It was not possible to obtain a decision on the financing from the Foundation until mid-December, and as this was the time that the ship was due for refit in Singapore, a tone of urgency developed. However, H.M.S. COOK struck an uncharted coral pinnacle in the Fiji Islands, and had to be slipped in Suva to make temporary repairs. She was then ordered to Britain for damage survey. We were advised that this would undoubtedly affect the project, as a decision was to be made whether the old ship was to be re-commissioned or not. New survey ships were being built at the time and the life of H.M.S. COOK in the best conditions was very limited. While awaiting the final decision, H.M.S. COOK (Cdr. F. Hunt, M.B.E.) flying her long paying-off pennant, passed through the Solomons on 13-14 December 1963, carried out some oceanographic surveys for us in the New Georgia Group, and discovered an entirely new submarine volcano beginning its activity several miles from Munda Bar, New Georgia. In America, the

National Science Foundation agreed to grant $70,000 for the Sea Project, and the Office of Naval Research agreed to loan one of the rare La Coste and Romberg Shipboard Gravity Meters; a Proton Precession Magnetometer unit had been specially built in Hawaii. Then came the announcement that H.M.S. COOK was not to be re-commissioned, and the sea survey was off.

This was a profound disappointment to all concerned, both Americans and British, even though it was not altogether unexpected. So much store had been set by this great geophysical project which hoped to solve once and for all the puzzle of the anomalous nature of the physiographic, vulcanological, seismic, and geological features of this island festoon, where the land gravity work had already produced such startling results in such a short time. The new bathymetric chart of the Pacific prepared by the U.S.S.R. published in 1963, recent U.S. measurements of bathymetry, the discovery of post-Miocene eclogites on Malaita in 1962-63, and considerations of subcrustal convection currents, all further added interest to the problem to such an extent that great concern was felt by all, and particularly our American colleagues, who had all arrangements on stand-by. Dr. Woollard was called from Hawaii to the Office of Naval Research of Washington, and further representations were made to Britain in the hope that an alternative vessel could be made available.

It was with great pleasure that all parties received the news in July 1964 that the Admiralty Board had approved the deployment of another vessel, H.M.S. DAMPIER, for the project. It was proposed to install the equipment during refitting in Singapore in August 1965, so that the ship could be available for the three months of October to December 1965 to carry out the project. Owing to other substantial commitments, it was not possible to consider extending the work to the Bismarck Sea or to the New Hebrides as well.

Late in November 1964, at short notice, it proved possible for Dr. George Woollard and Dr. John Rose to arrange a test run of the shipboard gravity meter on a smaller ship, U.S.S. WANDANK in the Solomon Sea, and although only part of the traversing produced usable results these were sufficiently conclusive to remove all objections to the provision of funds by the National Science Foundation. Dr. Woollard was battling all the way, with government policy reducing research funds on all sides.

In May, June, and July 1965, planning of the operation was under way, with, at first, a tendency to overestimate the ship's range between refuelling points. The Admiralty advised a delay in availability of H.M.S. DAMPIER which made it necessary to limit more severely the project in the Solomons-Santa Cruz area.

An examination of the structure of the region in the light of the latest bathymetric data led to the following conclusions:

(a) The South Solomons-Santa Cruz Trench "elbow" is almost entirely analogous to that of the New Britain Trench.

(b) It is of great interest because of its proximity and connection with the Vitiaz Trench north and east of Santa Cruz.

(c) The anomalous Ulawa sea-bed feature runs into the Vitiaz Trench.

(d) The Vitiaz Trench is surely the shredded remnant of the circum-Pacific Kermadec-West Melanesian-Mariana trench system.

(e) Three main ridges extend from New Guinea into the area:
   (i) the ridge New Britain-Bougainville-Choiseul-Malaita;
   (ii) the ridge Trobriands-Woodlark-New Georgia-Guadalcanal-San Cristobal;
   (iii) the ridge Louisiades-Rennell-New Hebrides.

   These ridges cause the trenches to become less apparent in the mid-Solomons and mid-New Hebrides areas.

The gravity-magnetic-bathymetric survey of the surrounding seas eventuated in October-December 1965 when H.M.S. DAMPIER (Commander M. Baker) was made available by the Royal Navy. With almost continuous running, calling at Manus Island and Port Moresby for fuel, a considerable area was covered from New Ireland in the north to the Vitiaz Trench in the Santa Cruz Group. Numerous traverses were run across the New Britain Trench which proved more conveniently situated than the South Solomons-Santa Cruz Trench.

John Rose of the Hawaii Institute of Geophysics, Jack Shallock of the U.S. Institute of Oceanography, and Bill Unger of the University of Wisconsin comprised the scientific staff for the operation.

Results were most encouraging, including that from bathymetry alone. From first discussions it would appear that more problems were raised than disposed of, but of such an interesting nature that further gravity and other oceanographic studies in the region will undoubtedly be made before long.

The aerial geophysical surveys of all main islands of the Protectorate began in November 1965, three methods being used: rotary field electromagnetic, proton precession magnetometric, and scintillometer. Country of very high relief is being excluded. Magnetic surveys are being systematically run between the islands so that the gravity data will have this support, in addition to that of the surface magnetic survey by H.M.S. COOK in 1958 in New Georgia Sound.

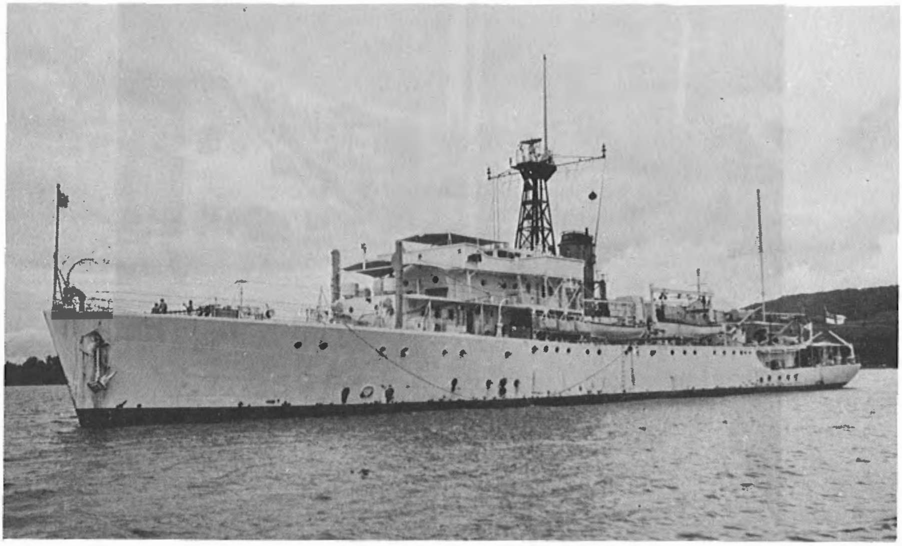

Figure 4. H.M.S. DAMPIER, equipped with La Coste and Romberg shipboard gravity meter and proton precession magnetometer on Solomons survey October-December 1965.

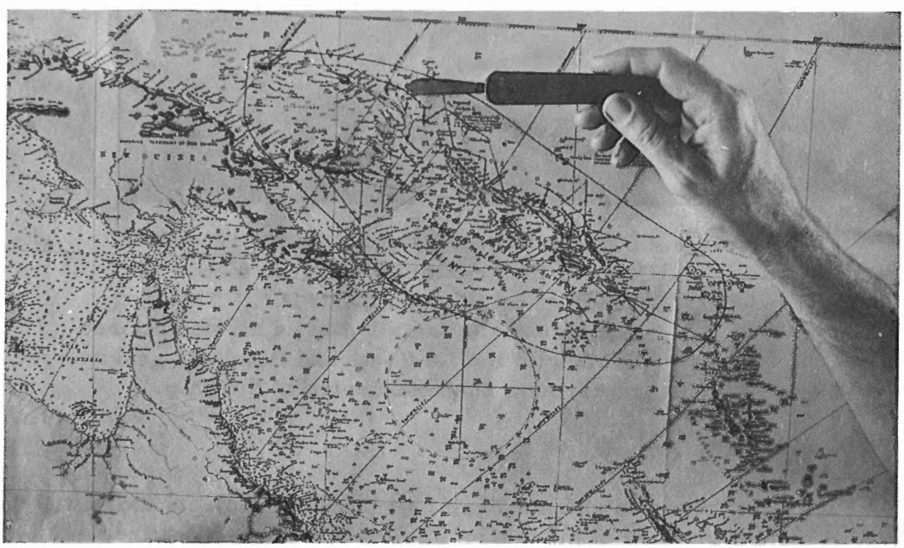

Figure 5. Chart showing area studied by H.M.S. DAMPIER October-December 1965.

Figure 6. Dr. John Rose at the shipboard recording station for gravity and magnetometer readings on H.M.S. DAMPIER. The equipment was installed in an air conditioned cabin with the La Coste and Romberg gravity meter near the metacentre of the ship.

These two sea and aerial geophysical projects alone will have involved the expenditure of more than $2,100,000 by the time they are completed.

The Solomon Islands represent one of the most anomalous of island structures in the world, and require detailed gravity, magnetic, seismic, and geological studies in order to be understood. The land gravity maps have recently been compiled, and their correlation with major geological features is remarkable. Ideas are beginning to crystallize after fifteen years of painstaking field work, and the gravity data from the surrounding seas should be published in the near future, making possible the discussion of a regional model.

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THE SEISMICITY OF THE TONGA-FIJI REGION[1]

Lynn R. Sykes
Lamont Geological Observatory

Summary

The spatial distribution of earthquakes in island arcs is an important source of information about the tectonic processes that occur in the upper mantle. In this investigation the hypocentres of about 500 earthquakes in the Tonga-Fiji region were relocated using an iterative, least-squares method. The Tonga-Fiji region is the most active area of the world for very deep earthquakes. Since these computations are much more accurate than those used in previous studies, the distribution of earthquake foci can now be used to resolve structural features with dimensions of about 20 kilometres and larger.

Near its northern end, the Tonga Trench curves abruptly to the west; the belts of shallow, intermediate, and deep earthquakes exhibit a similar curvature. Thus, the tectonic processes responsible for the origin of the earthquakes and the trench are intimately related for depths from 0 to 650 kilometres; theories that attempt to explain the abrupt curvature of the trench must also account for the configuration of the seismic belts. The distribution of hypocentres in the New Hebrides and Tonga-Fiji areas indicates that these arcs are part of a larger structural feature. Hypocentres in the Tonga-Fiji region are confined to a zone less than about 50 to 100 kilometres thick that dips under the arc. The dip does not appear to change significantly with depth. A zone of intense shallow-focus activity is centred over the inner margin of the Tonga Trench. Similar results were obtained for several other island arcs. A discontinuity in seismicity between the Tonga and Kermadec arcs can be traced from the surface to a depth of about 650 kilometres.

DISCUSSION

Dr. S. Suyehiro (Japan)

I understand that one of the objectives of this investigation is to determine the frequencey of occurrence of deep earthquakes and their magnitudes. Has Dr. Sykes reported anything on this matter?

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[1] Read by Dr. J. Dorman. This paper forms part of a more comprehensive paper: The seismicity and deep structure of island arcs. J. Geophys. Res. vol. 71, no. 12, pp. 2981-3006, 1966.

Dr. Dorman

Dr. Bryan Isacks of the Lamont Geological Observatory has investigated these topics and is preparing a paper "Distribution in time of small, deep and shallow earthquakes in the Fiji-Tonga region."

Dr. K. Wadati (Japan)

It is very interesting for us to know the seismicity of the Tonga-Fiji-Kermadec region. Invariably, the seismicity of these islands is very interesting. In the region of the Japanese Islands we have many deep earthquakes at depths between 300 and 400 kilometres, and only a few earthquakes at 300 kilometres. We call deep focus earthquakes, those deeper than 300 kilometres, and intermediate earthquakes those from 100 to 300 kilometres.

Dr. Dorman

I did not mean to imply that Dr. Sykes is trying to modify the terminology applied to shallow, intermediate, and deep earthquakes.

Dr. Wadati

The zone between 100 and 200 kilometres is seismically very active, and always associated with volcanoes. But in the Tonga-Fiji region there are no shallow depth earthquakes beneath the volcanoes. It is a very distinctive feature of this region. My next question is: Have you any information on the aftershocks of deep focus earthquakes?

Dr. Dorman

This is one of the objectives of our present field program in the Fiji-Tonga region. Since we will be able to record shocks of much smaller magnitude with high magnification instruments in the immediate area, we expect to have more information on aftershocks. I do not know whether Dr. Sykes has looked at that aspect yet. In this paper, he attempted to use all data that was available up to the beginning of this field program, and he chose a recent three-year interval simply because the quantity and quality of earthquake data have expanded greatly in recent years.

Dr. D.C. Krause (USA)

I think that this distribution of earthquakes is very interesting. Eiby has recently shown that a similar pattern of activity exists near New Zealand. An aseismic corridor occurs just north of New Zealand where the Kermadec and Hikurangi trenches meet.

Dr. Dorman

Yes. Well, Dr. Wadati has mentioned the situation in Japan and as more regions are investigated in this fashion, why I am sure that more differences than similarities will become apparent.

EVIDENCE OF PLEISTOCENE WARPING OF THE NEW SOUTH WALES CONTINENTAL SHELF

Charles V.G. Phipps
University of Sydney

Abstract

From detailed profiles of some 400 miles of the continental shelf of central and southern New South Wales, a number of well-defined submarine terraces have been recognized. Using the pattern of the shelf margin and the two lower terraces, a distinctive pattern of deformation of the outer shelf was found. This consists of a downwarped area limited on the north and south by ridges extending across the shelf. The extent of the deformation corresponds closely with the extent of the Sydney Permian-Triassic sedimentary basin on land, suggesting a genetic relationship. The depths of the deformed terraces indicate that this warping has occurred since the beginning of the rise in sea-level resulting from the melting of Wisconsin ice. Evidence is presented for similar patterns of deformation of the Gippsland Basin and of the Permian and Mesozoic basins in northern Australia and the north part of Western Australia.

INTRODUCTION

During 1963 and 1964 the Department of Geology and Geophysics of the University of Sydney, using the Royal Australian Navy ships GASCOYNE and KIMBLA, made some 60 traverses across the continental shelf of central and southern New South Wales. The program was aimed at determining the details of bathymetry not apparent from the Navy's hydrographic data, and the pattern of sedimentation on the shelf.

Traverses were run at five-mile intervals between Crowdy Head in the north and Batemans Bay in the south and at ten- to twenty-mile intervals south of Batemans Bay to Bass Strait (Fig. 1).

This paper deals with the bathymetric evidence, obtained from these traverses, which indicates Pleistocene warping of the outer continental shelf.

GENERAL BATHYMETRY OF THE CONTINENTAL SHELF

The general bathymetry of the shelf off New South Wales is remarkably uniform. The shelf may be divided into two distinct zones: a) an inner zone, and b) an outer shelf plain (Phipps, 1963).

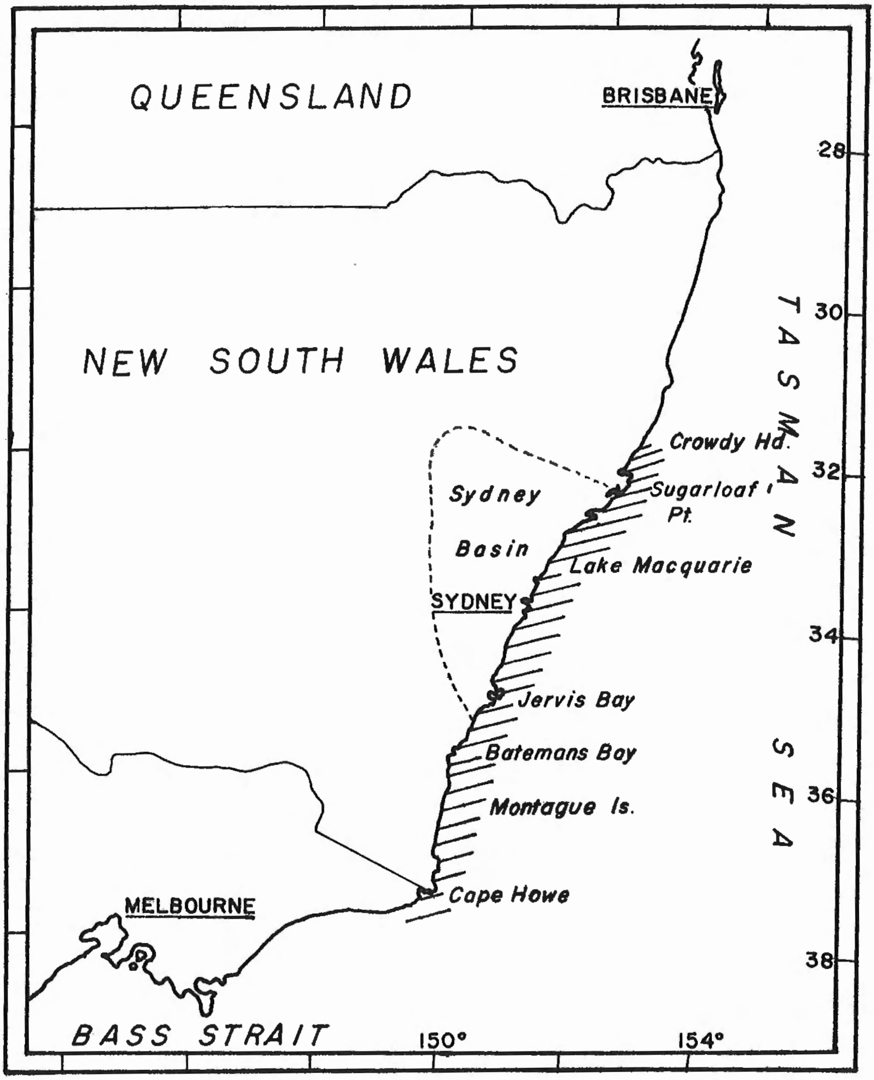

Figure 1. Continental shelf off central and southern New South Wales, indicating the principal study area.

The inner zone extends from the present shore to a depth of 65 to 70 fathoms. The slope within this zone is often irregular and reflects the infleunce of coastal geology. For example, the Triassic Hawkesbury Sandstone which forms the prominent cliffs around Sydney produces a distinct rough bottom compared with the more uniform slope associated with the underlying Narrabeen Group. The Permian volcanic flows, which occur some 70 miles south of Sydney, also produce steep slopes in the inner zone.

Many of the detailed features of the rock surface in the inner zone are partly or wholly masked by a thin cover of recent sediment varying from sands near the coast to fine silts and clay at the zone's outer limit (Shirley, 1964). The thickness of these recent sediments, where determined by coring, is less than 10 feet and generally only 1 foot to 2 feet. Areas of rock outcrop are common, especially on the outer shelf (Shirley, 1964).

The outer shelf plain, for the most part, is flat with very minor relief and a very gentle slope seawards. This plateau is covered with coarse sand which is overlapped by the finer silts of the inner zone. The sand covers a consolidated sandstone, found from the fauna it contains to be of shallow-water origin. Both the sand and the sandstone are considered to be Pleistocene.

SUBMARINE TERRACES

A number of submarine terraces have been recognized on the profiles. The most distinct and least obscured by more recent sediments occur at depths of 60 to 70 fathoms and 70 to 80 fathoms. A higher terrace at 50 to 55 fathoms depth is recognized in many of the traverses but tends to be masked by recent sediments (Fig. 2). The furthest seaward of these three terraces forms the outer shelf plain described above.

The fact that in a number of cases these submarine terraces have been cut into bedrock of different types indicates that they have been formed by an erosional process. As Emery (1961) pointed out, it does not seem possible that the submarine terraces found below the present wave base were formed when the sea was at its present level. It is concluded, therefore, that these features were formed during periods when eustatic sea-level remained stationary for a period of time during the general rise of sea-level as the Wisconsin ice-sheets melted. During these stillstands, agencies of coastal erosion modified the shelf then above wave base, and produced a multiplicity of shoreline profiles similar to those found along a present-day coast. Each set of these features associated with any one terrace was horizontal at the time of formation.

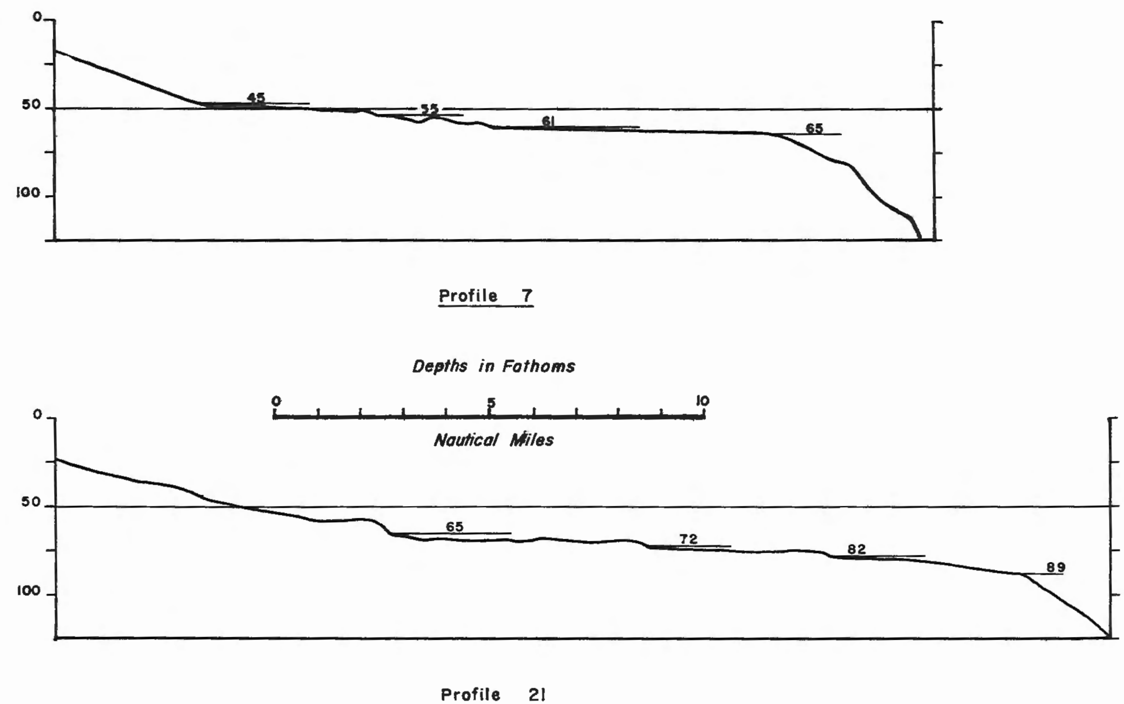

Figure 2. Selected profiles across the continental shelf, showing the maximum variation in depth of the submarine terrace pattern. The two lower terraces and the shelf margin have been used in this study. Depths in fathoms.

The exact positions of the old sea-levels on the profiles are often difficult to define accurately. A shoreline is often represented by a beach and offshore barrier, separated by a narrow channel, similar to many present-day beach profiles. In this case the top of the offshore barrier is assumed to mark sea-level to within $\pm$ 1 fathom. The varying degrees of uncertainty are represented on the plot of the depths of the terraces by a vertical line (Fig. 3). The curves are drawn through the midpoints of this line.

The shelf break is generally sharp and well defined but in some areas may be indistinct due to irregular rock outcrops such as those off Crowdy Head in the north. In other areas, there is no sharp change in slope but a gently curved profile between the shelf plain and the continental slope.

The pattern of the two lower terraces and the shelf break provides a means of relating the terraces along the shelf. If the sea-levels for each profile are plotted against depth rather than their relationship to the shelf margin and other terraces, a confusing pattern results. For example, the terrace occurring at a depth between 68 and 72 fathoms off the Sydney-Newcastle part of the shelf is not the same terrace as that which occurs at these depths further to the south (Fig. 3).

The three curves plotted on Figure 3 indicate that there has been downwarping of the outer part of the shelf between Sugarloaf Point in the north and Jervis Bay in the south. At either end of this downwarped part of the shelf are two prominent rises that extend across the shelf. Where these rises intersect the shelf margin, the shelf break rises from 83 to 65 fathoms in the north and 85 to 68 fathoms in the south.

The shelf rise off Jervis Bay strikes approximately north-northwest at an angle to the traverse lines. This relationship causes an offset of the curves representing the rise on the three terraces plotted. In addition to the rises off Jervis Bay and Sugarloaf Point, a third rise crosses the shelf just north of Newcastle, and a less marked rise occurs off Botany Bay near Sydney. These features do not appear to correspond to any geological feature on the mainland but may be the surface expression of structures in the basement rocks.

It is apparent from Figure 3 that the difference in depth between the lower terrace and the shelf margin varies from north to south. If the difference in depth is plotted (allowing for the fact that the shelf rise at Jervis Bay does not parallel the traverse lines), the difference in depth appears to vary systematically (Fig. 4). The difference in depth increases from 9 fathoms off Jervis Bay to 12 off Sydney, then decreases to 4 fathoms off Sugarloaf Point. This is a very minor variation over the distance of some

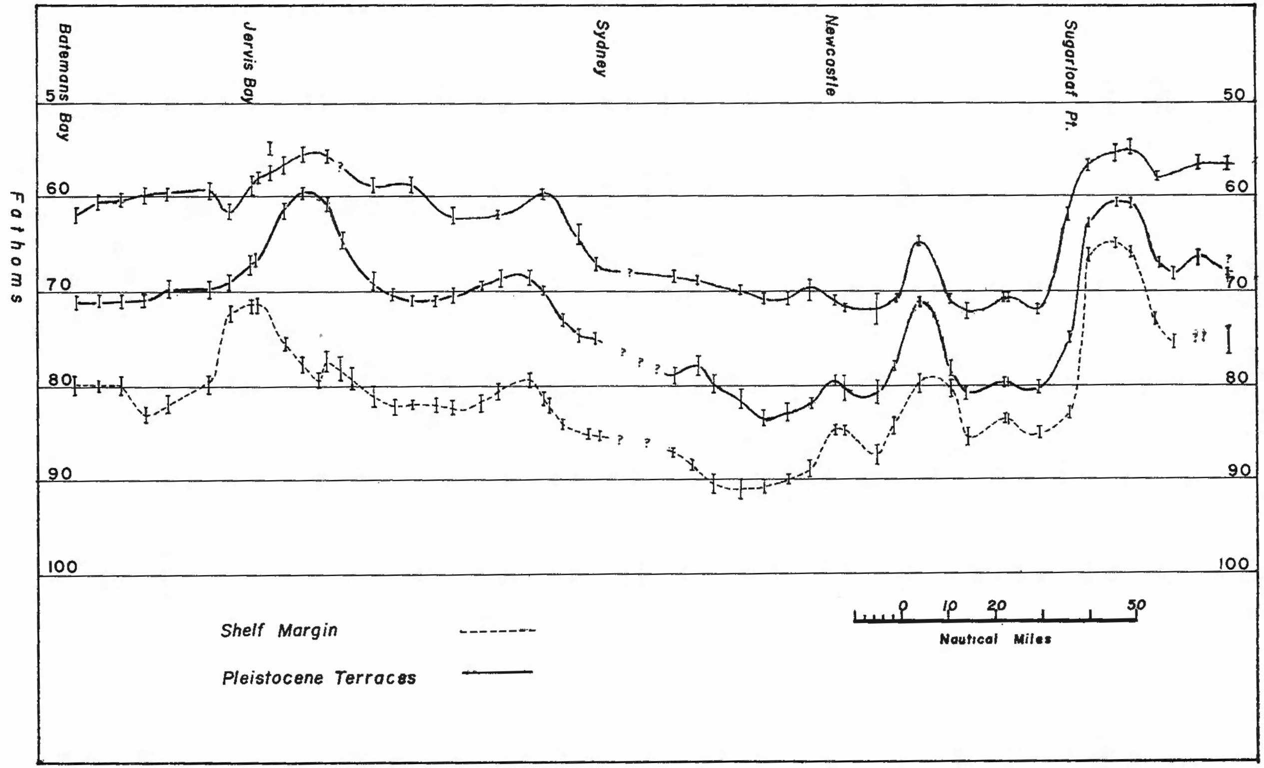

Figure 3. Depths to submarine terraces and shelf margin on the outer shelf zone.

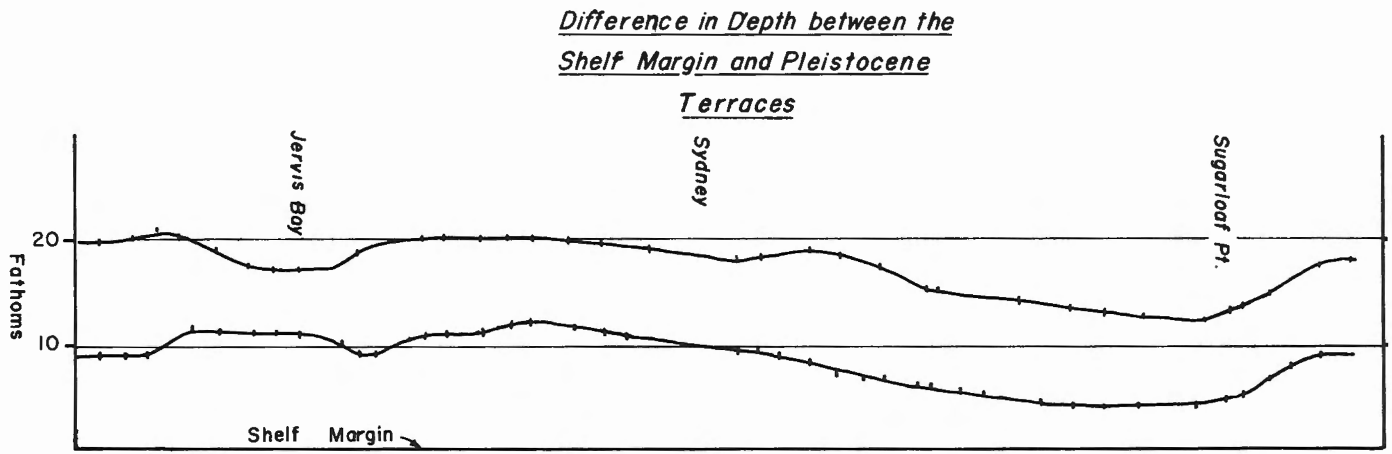

Figure 4. Height in fathoms of outer terraces above shelf margin. The variations in height can be explained by a westward tilting of the shelf during epeirogenic subsidence.

200 miles involved. The pattern of Figure 4 can be explained by a westward tilting of the shelf between Sydney and Sugarloaf Point.

Besides the downwarping of the area off the Sydney Basin, one other feature distinguishes this area from the shelf and slope to the north and south. The continental slope south of Jervis Bay and north of Sugarloaf Point is considerably steeper than in the area between. A slope of 1:8.5 has been measured off Montague Island (Phipps, 1963), and similar slopes occur in the area off Crowdy Head. Off the Sydney Basin the slopes are fairly uniform, about 1:15. In addition, the outer shelf plain is better developed off the Sydney Basin compared with the shelf to the north and south. This suggests that there is a more extensive wedge of sediment developed off the Sydney Basin than on adjacent parts of the shelf. Future seismic profiles will be necessary to confirm this suggestion.

The maximum variation in depth due to warping of the shelf margin and of the two terraces is as follows: shelf margin, 26 fathoms; outer terrace, 23 fathoms; inner terrace, 17 fathoms. These figures suggest that deformation decreased with decreasing age of the terraces. It follows that deformation started during the rise of sea-level and that some 36 feet of differential warping occurred between the formation of the lower terrace and the formation of the upper terrace.

The time when the depression of the shelf took place is uncertain except that it occurred after the formation of the 65-fathom terrace (Fig. 3). Data are not yet adequate enough to define warping on the higher (younger) terraces, as recent sediment cover has partly obscured them.

If the last rise in sea-level is assumed to have commenced around 20,000 years ago, a maximum period over which the warping of the shelf has taken place is established.

B. Thom (personal communication, 1966) has found that no deformation has occurred in a peat bed which he mapped along the coast just above present sea-level. The peat yielded a Carbon 14 age of about 3,000 years. However, if deformation of the continental margin is still in progress and has affected the coastal areas, the amount of warping over the past 3,000 years may well be difficult to detect.

If deformation of the shelf has taken place during the last 20,000 years the rate of warping in this tectonically inactive area, which is not being subjected to sediment load of any significance, is surprisingly fast. The source of the movement, which cannot be a surface effect, must represent a deepseated weakness of the continental margin.

The association of the distribution of the deformation of the shelf with the Sydney Permian-Triassic Basin must be significant. The Sugarloaf rise, although seaward of Carboniferous rocks on the mainland, may well correspond more exactly to the extent of Permian rocks beneath the Hunter Overthrust which has moved the Carboniferous over the Permian. The Jervis Bay rise trends south-southeast from Bancroft Head, the northern headland of Jervis Bay, and is parallel with the rather straight western margin of the Sydney Basin, considered by C. McIlroy (unpublished manuscript) to have possible structural significance. It appears that the crustal weakness which was responsible for the formation of the Sydney and the other Permian-Triassic basins mentioned below was still present in the late Pleistocene.

TECTONIC PATTERN

The tectonic pattern in the area of detailed study between Batemans Bay and Crowdy Head is a gentle downwarp of the shelf offshore from the Sydney Permian-Triassic Basin. The downwarp is bounded by broad shelf rises extending across the shelf at Jervis Bay in the south and Sugarloaf Point in the north. In the south, Permian rocks extend south from Jervis Bay along the Coast, but these are thin, and immediately north of Jervis Bay the thickness of the Permian increases. Although the shelf rises occur off coastal promontories where the shelf is narrow, it does not follow that wherever the shelf is narrow the shelf margin is shallow. For example, at Montague Island south of Batemans Bay, the shelf east of the island is very narrow (Fig. 5), only some three miles wide, and yet the depth of the shelf margin there is 76 fathoms. No satisfactory explanation for the epeirogenic development of these shelf rises can be suggested by the writer at the present time. It is considered more probable that they represent epeirogenic uplift of the shelf possibly associated with faulting at depth, rather than stable ridges left high as the shelf subsided on either side.

South of Batemans Bay, the shelf margin has a uniform depth of 76 to 80 fathoms as far as Cape Howe, where another rise is indicated (Fig. 5) and there the shelf margin is 65 fathoms deep. This rise occurs on the eastern side of the Tertiary Gippsland Basin. Examination of the charts off Bass Strait reveals a series of islands, principally of granite, extending from the western margin of the Gippsland Basin southeast to Flinders Island (Fig. 5), with a pattern similar to that off the Sydney Permian-Triassic Basin.

Fairbridge (1952) and van Andel and Veevers (1965) describe a series of basin depressions and shelf rises in the northern part of Australia (Fig. 6). Basin depressions, limited by shelf rises, extend from Cape York and Torres Strait westwards to the Canning Basin in Western

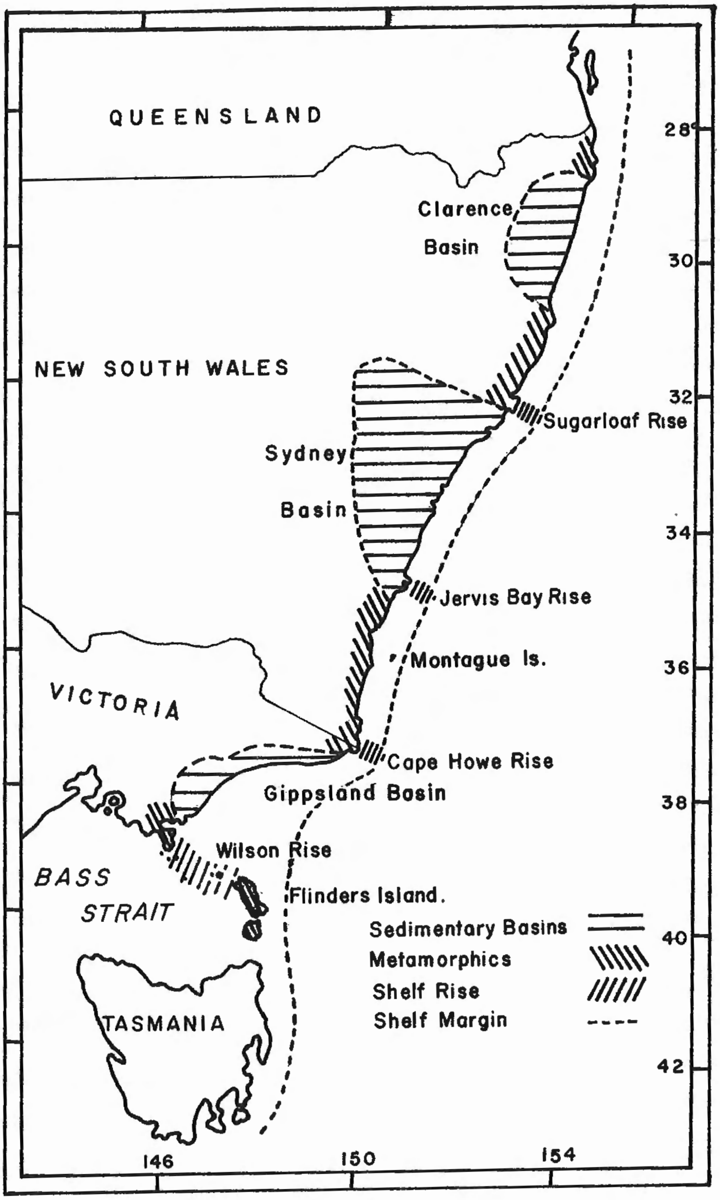

Figure 5. Relation of sedimentary basins on land to rises and depressions on the shelf off southeastern Australia. No data are available on the Clarence Basin.

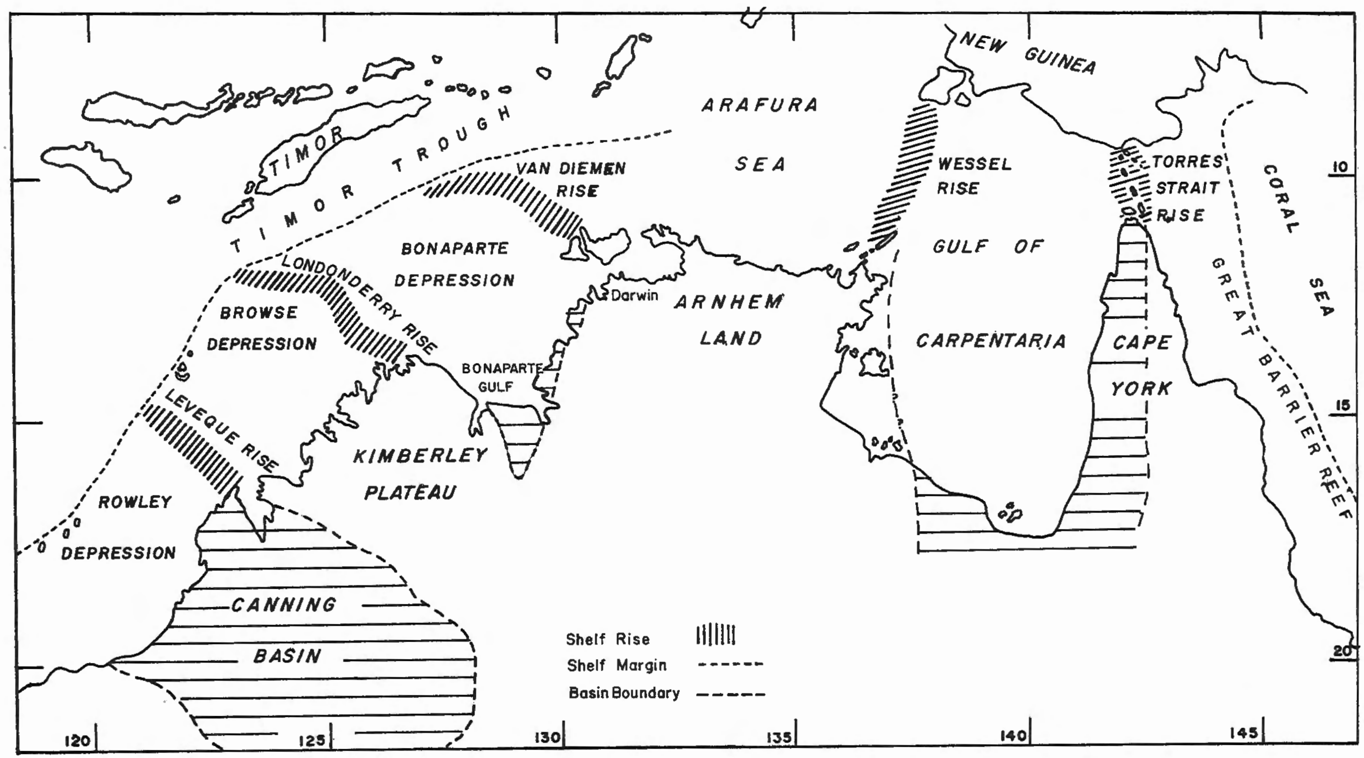

Figure 6. Rises on continental shelf of northern Australia. (After Fairbridge, 1962, and van Andel and Veevers, 1965.) This indicates the same relationship of post-Permian sedimentation to shelf rises as found off southeastern Australia.

Australia. In northern Australia the shelf is considerably wider than that on the east coast and the shelf margin is modified by reef development. The New Guinea geosyncline north of the Gulf of Carpentaria and the Arafura Sea, of course, mask the Australian continental margin in that area, so that the Wessel and Torres Strait rises extend to New Guinea.

CONCLUSIONS

Because of the world-wide distribution of the oceans, any halt in the rise in sea-level during the late Pleistocene and Holocene will have been reflected on all the continental shelves of the world. During any subsequent rise in sea-level, some of the shoreline features would be obliterated or highly modified by wave action whilst they remained above wave base; some, however, would be preserved, such as the drowned barriers described by Curray (1960) from the Gulf of Mexico. Obviously the erosional factors will differ depending on local conditions of waves and currents. However, terraces and shoreline features, produced during periods of sea-level stillstands during the eustatic rise, have been sufficiently well preserved to be used as data.

From evidence presented above on the depths of these originally horizontal features, it is concluded that the outer half of the continental shelf off central and southern New South Wales has been slowly depressed during the rise in sea-level possibly over the last 20,000 years. This downwarping has not been uniform; it has resulted in minor tilting of the shelf, in the development of prominent ridges extending across the shelf at either end of the depressed area, and in the development of minor ridges within the downwarped area. The rate of depression appears to have been remarkably fast for this type of coastline, if, as suggested, the deformation occurred during the last 20,000 years.

With the rise in sea-level after the melting of Pleistocene ice in higher latitudes, the load on the shelf areas would increase as a result of the increased weight of the water covering them. The added weight of water would be the equivalent of about 200 feet of sediment at the outer shelf edge and would not cause the 100-foot depression of the crust recorded above. The cause must lie within the structure of the continental margin itself. The close similarity in extent of the depressed areas with that of the sedimentary basins of Permian and younger age is significant and indicates that the crustal weakness that was responsible for the initial formation of these sedimentary basins has been active in late Pleistocene. It is well known that in the area of the Sydney Basin there was extensive uplift and warping in late Tertiary when the present Cumberland physiographic basin was formed. It is not unreasonable to expect that the type of earth movement found in this investigation should take place a relatively short time later.

The terraces and rises on the shelf off the Sydney Basin appear to have similar parallels further south off the Gippsland Basin in eastern Victoria and along the northern and northwestern coast of Australia. It follows that the Sydney area is not unique but rather an example of a much more general process going on in many areas around the Australian continent and probably in many other parts of the world.

This investigation has special importance to studies of Pleistocene features along the coastal areas and on other shelves. It is apparent that in any one area little significance can be attributed to the depths of submarine terraces from isolated and widely spaced traverses. To determine the actual depths of submarine terraces in relation to Pleistocene sea-level stands, it is essential that a relatively large part of a shelf be covered by traverses less than ten miles apart. These traverses should be directed away from coastal sedimentary basins to reduce the possibility of encountering epeirogenic movement similar to that described above. The correlation of raised beaches and terraces on land is often more difficult than on the continental shelves where, for the most part, erosional factors are minimal. Considerable care should be taken to ensure that the correlations are in fact made with the same feature. It would be wise in all studies of Pleistocene sea-level stands to assume that epeirogenic deformation of the area under consideration may have taken place.

ACKNOWLEDGMENTS

The writer is indebted to Captain A.H. Cooper, Royal Australian Navy Hydrographer, for arranging ship time; to the officers and crew of the Royal Australian Navy ships GASCOYNE and KIMBLA for their willing assistance in obtaining the initial data for this investigation; to Dr. J. Shirley for his assistance at sea; to Dr. R. Curtis for his assistance in the correlation of the initial data; and to Dr. F.P. Shepard of Scripps Institution of Oceanography for his helpful criticism of the manuscript.

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DISCUSSION

Dr. D.H. Matthews (UK)

A very brief question. I am not clear how you are using the term "basin" as in the Sydney Basin. Is this a tectonic basin of Permian-Triassic strata, or is this the modern physiographic lowland?

Dr. Phipps

This is a Permian basin that was developed during the Permian and extended through into the Triassic and possibly into the Early Cretaceous.

Dr. Matthews

And it's rejuvenated now?

Dr. Phipps

Yes.

Dr. G.G. Shor (USA)

I don't remember much about Daniel's work on the shelf, but we have refraction lines between Cape York and Arafura Sea along which we measured velocities up to 6 1/2 km/sec in a depth of ocean of 1 or 2 kilometres. So I think maybe it closes off on the north side, too.

Dr. Phipps

Yes, I think it does. We have some aeromagnetic data which suggest that the gulf depression is limited to the Gulf of Carpentaria and that there is a rise between the gulf near Cape York and the New Guinea geosyncline.

CRUST AND MANTLE RELATIONS IN THE HAWAIIAN AREA[1]

G.P. Woollard
Hawaii Institute of Geophysics

Abstract

An integrated series of gravity, magnetic, and seismic refraction studies has been made over the Hawaiian Ridge and adjacent Hawaiian Trench and Hawaiian Rise. These studies define significant differences in crustal structure and in overall crustal thickness in the three areas. The depth of the mantle changes progressively from about 21 kilometres beneath the ridge between Oahu and Molokai, to 15 kilometres beneath the trench, to 10 kilometres beneath the rise north of Maui and is as shallow as 9 kilometres at one site. The corresponding change in regional free-air gravity anomaly values are +190 mgal, -100 mgal and +30 mgal, respectively. No magnetic anomalies were observed except over centres of vulcanism and rifts on the islands, and over the Molokai fracture zone and its buried extension on the ocean floor. Seismic measurements over these areas of magnetic disturbance indicate material with a seismic velocity of 7.6-8.0 km/sec at depths ranging from 2 to 6 kilometres below sea-level. Over the Koolau caldera on Oahu, where a depth of only 2 kilometres was obtained to mantle-like material, there was, in addition to a marked dipole magnetic anomaly, a pronounced superimposed local Bouguer gravity anomaly of +115 mgal. This pattern of local gravity and magnetic disturbance in association with centres of vulcanism was found to be characteristic on all the islands throughout the length of the Hawaiian Ridge. Of the various geophysical methods, the magnetic method was the most useful for defining the primary fracture systems in the area, all of which appear to have been invaded by mantle material. Vulcanism appears to have been localized both at points of intersection between east- and southeast-trending fractures, and along what appear to be east-trending, en echelon fractures whose general alignment coincides with that of the Hawaiian Ridge. The ridge therefore appears to be fracture controlled, and the adjacent trench and rise are secondary features induced by subsidence beneath the load of volcanics deposited on the ocean floor to form the ridge. The shallow Moho depth of 9-10 kilometres on the rise is not due to a subnormal value of crustal thickness, but rather to crustal flexure.

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[1]By title.

GEOLOGICAL SETTING OF HAWAII

The Hawaiian Islands lie on the eastern end of a pronounced subsea ridge which strikes approximately west-northwest in the central Pacific region between the coral atoll of Kure near Midway Island and the island of Hawaii (Fig. 1). The volcanic mountains of Hawaii rise to approximately 13,500 feet (4,120 metres) above sea-level, whereas recent drilling on Midway indicates that volcanic rock is capped by 550 feet (166 metres) of coral. It thus appears that the west end of the ridge (Midway) has subsided at least 14,000 feet (4,300 metres), if it is assumed that the Midway volcanic mountains were originally as high as the Hawaiian mountains. Since available data suggest the volcanic rocks are progressively older from Hawaii to Midway, it follows that the inferred differential subsidence between Hawaii and Midway is apparently related to geological age.

Wilson (1963) postulated on the basis of this inferred age differential and subsidence that the ridge developed as a result of crustal migration away from a single volcanic source-area (Hawaii). The writer, however, feels that there is good evidence that the ridge developed progressively along a crustal shear zone along which vulcanism occurred at the intersections of cross-cutting fractures and along possible en echelon tear faults in the crust lying above the shear zone. This conclusion, as will be shown, is based on gravity, magnetic, and seismic studies as well as on an analysis of the pattern of primary volcanoes which led to the development of the ridge.

The ridge is flanked on the north by trench areas that have a depth in excess of 3,000 fathoms (5,500 metres). The trench areas are, in turn, flanked to the north by a bathymetric rise (the Hawaiian Rise, also known as the Hawaiian Arch) which may well represent a crustal flexure induced by the subsidence beneath the ridge. Two pronounced, essentially west-striking fracture systems, the Molokai and Murray fractures, intersect the ridge and pass through it. The more pronounced of the two, the Murray fracture, maintains its bathymetric expression essentially up to each flank of the ridge near Necker Island. The Molokai fracture loses its bathymetric identity on the Hawaiian Rise, but can be traced by its magnetic charcteristics completely through the rise, trench, and ridge areas.

GEOPHYSICAL STUDIES

Gravity and Seismic Studies

Vening Meinesz (1941) postulated that the Hawaiian Islands were composed of and underlain by dense ultramafic rocks, an hypothesis based on his submarine gravity measurements. This conclusion has not been

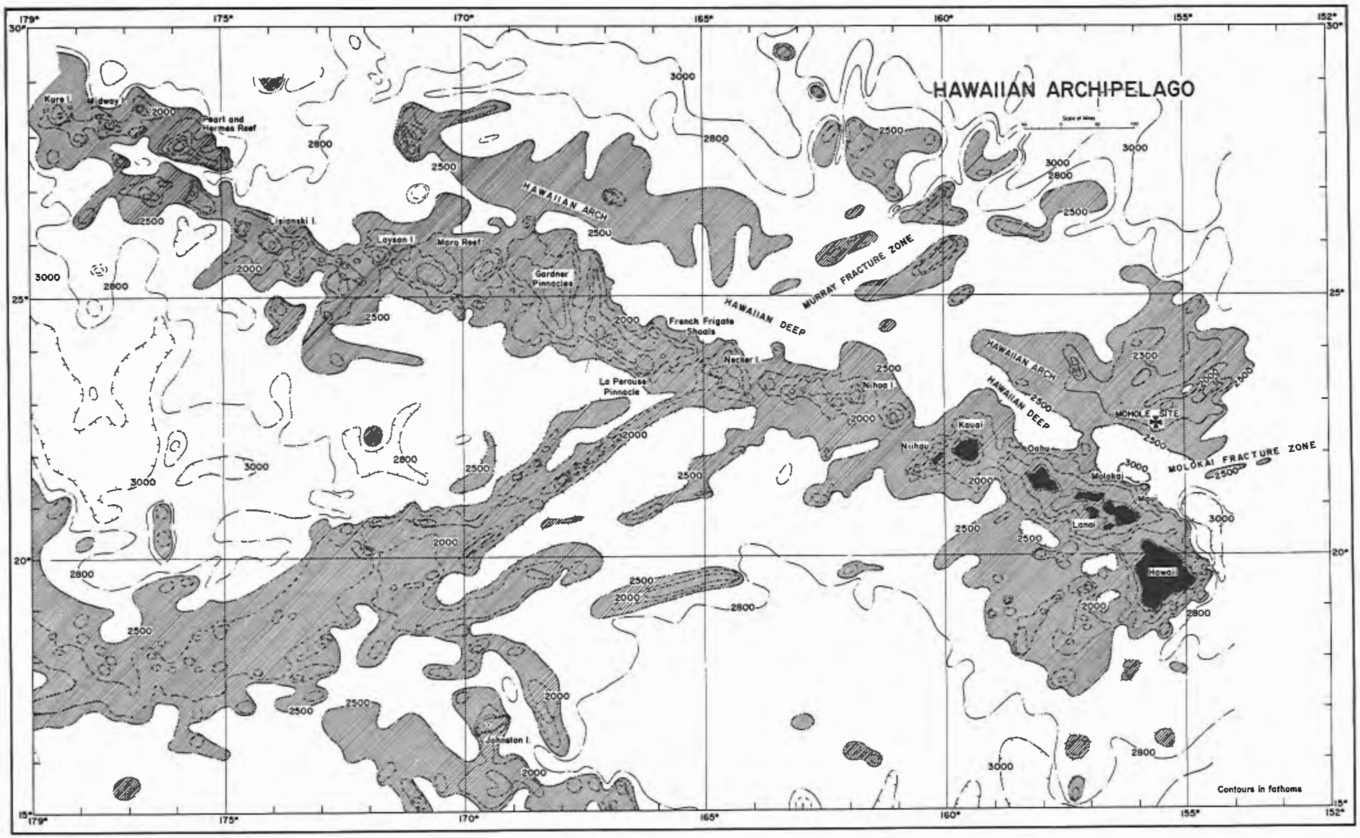

Figure 1. Bathymetric map of Hawaiian archipelago area from Hawaii to Midway.

substantiated by subsequent geological and geophysical studies. There is evidence that, at depths of lava emplacement 3,000 feet (1,000 metres) below sea-level, the tholeiitic basalts comprising the Hawaiian Islands have a density of about 2.9 gm/cc which in a subaerial environment is only about 2.3 gm/cc. As the mean density of the crust in the ocean is also about 2.9 gm/cc, the superimposed load of rock standing some 32,000 feet (10 kilometres) above the ocean floor on a base approximately 120 kilometres in width would be expected to have an appreciable gravity effect. The actual effect of the combined surface mass and its compensation at depth is a change in free-air gravity anomalies from +30 mgal over the Hawaiian Rise to -100 mgal in the Hawaiian Trench to +200 mgal at the coastline on the ridge (Fig. 2). Superimposed on this general pattern are the effects of the main volcanic feeder zones which supplied the lava to build the islands. These zones show up as: 1) lenticular fracture zones characterized by local gravity anomalies as high as +50 mgal and magnetic anomalies as high as 1,000 gammas; and 2) as central vents (pipe zones) marked by local gravity anomalies as high as +115 mgal and magnetic anomalies as high as 1,800 gammas. Figure 3 shows the change in Bouguer gravity anomalies noted on some of the islands.

In interpreting these data and in order to satisfy the gravity anomaly relations, the geological and mathematical restrictions, which must be observed, require the assumption of a density differential of approximately 0.4 gm/cc between the intrusive bodies and the crust, and the assumption of an expanded magma chamber of about 8 to 10 kilometres radius beneath each vent area extending down into the mantle. If the mean density of the country rock is as high as 2.9 gm/cc, then the intrusive rock must have a density of about 3.3 gm/cc.

To test this interpretation of the gravity data first advanced by Woollard (1951), seismic refraction measurements were carried out over the Koolau caldera on the island of Oahu and over the associated rift zone along the northern coast of the island. The following section was obtained in the caldera area:

Layer	Velocity	Thickness
1	1.7 km/sec	0.12 km
2	2.8	0.28
3	4.7	1.23
4	7.6	H = 1.63 km

The width of the area defined by the seismic measurements is about 6 kilometres, down to a depth of 3-4 kilometres where apparent reflections indicate a shoulder, on the northwest side, which adjoins the Koolau Rift zone. Refraction measurements along the rift from Kaneohe Bay to Kahuku Point resulted in the following section:

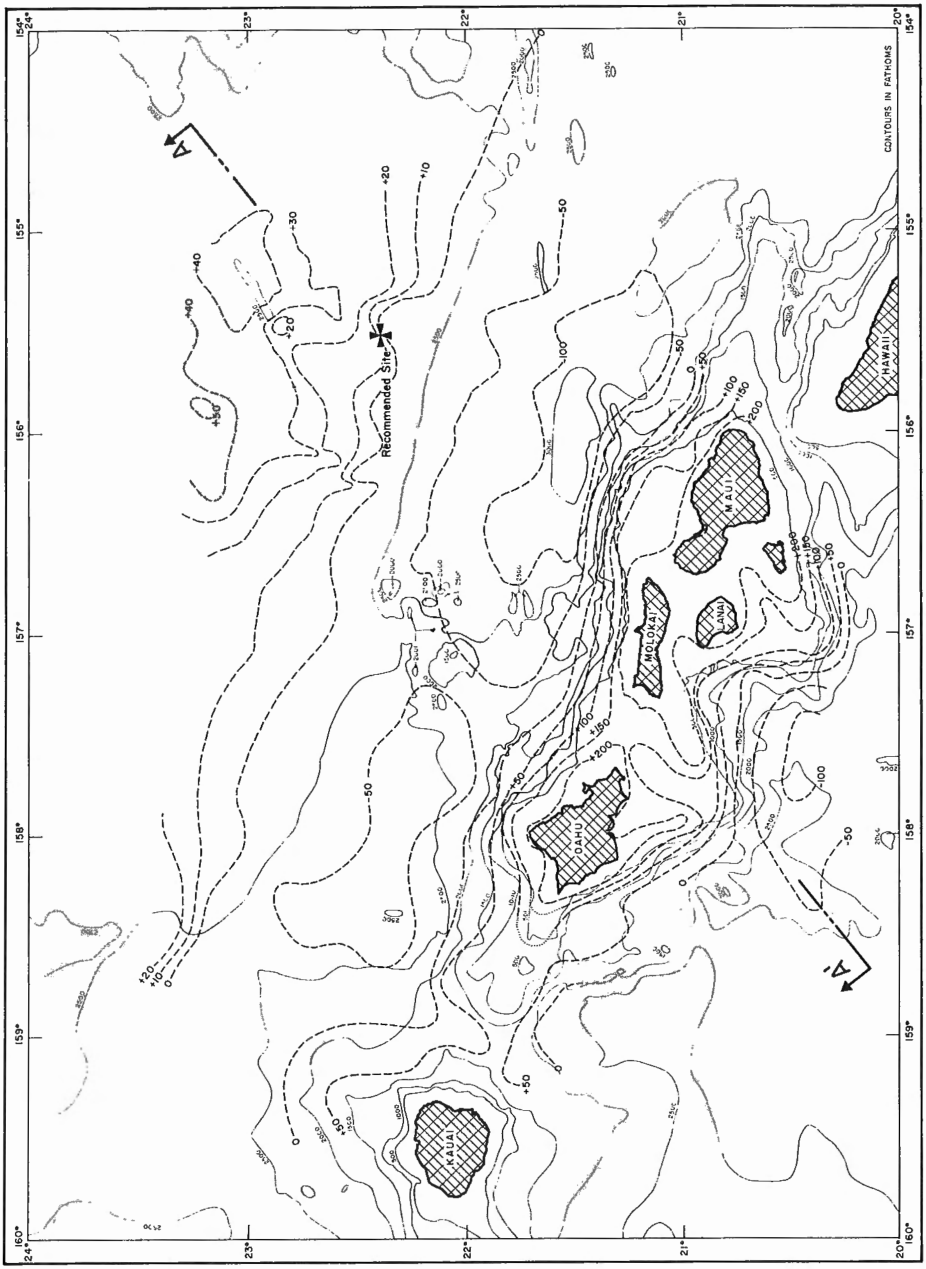

Figure 2. Free-air gravity anomaly map of the area adjacent to the Hawaiian Islands.

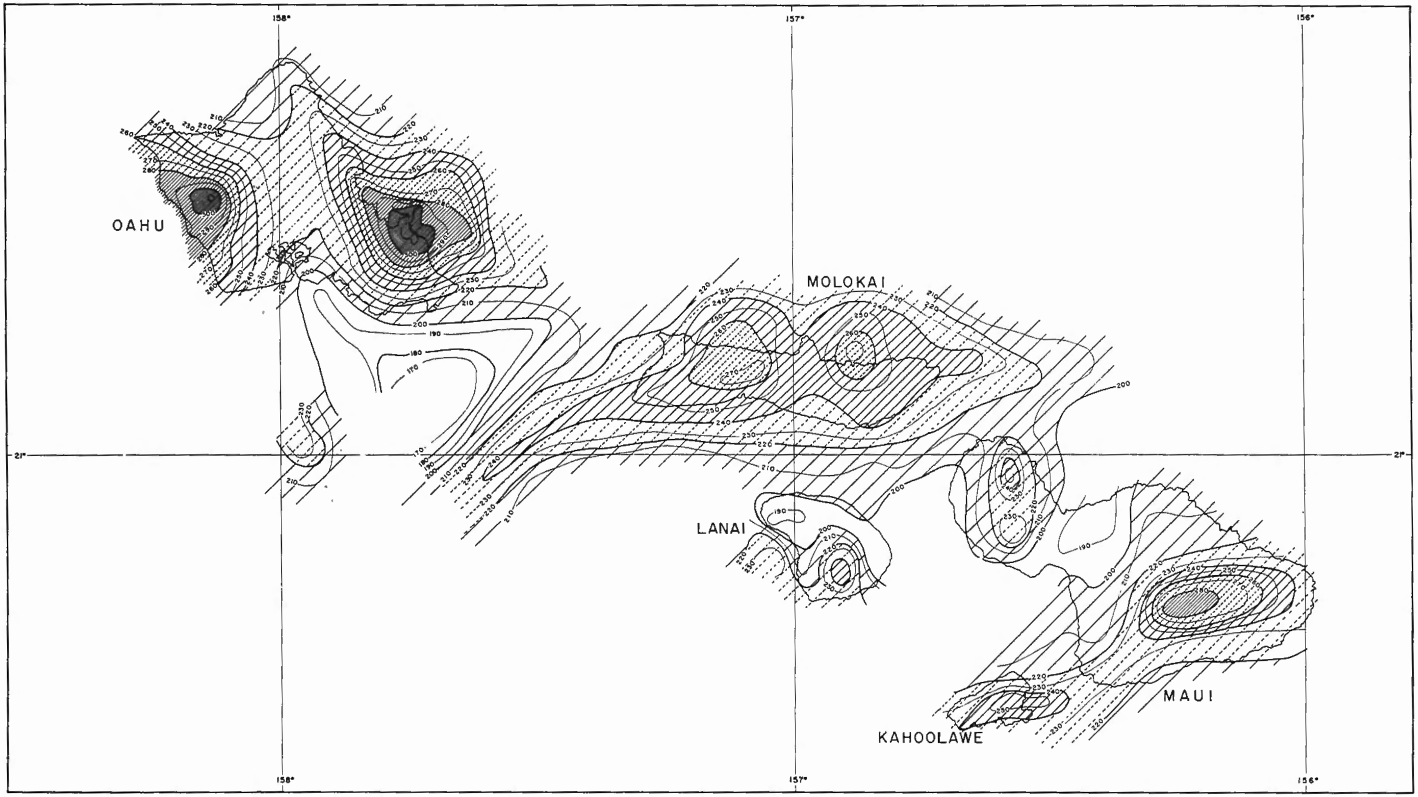

Figure 3. Bouguer gravity anomaly map of the islands of Oahu, Molokai, Lanai, and Maui.

Layer	Velocity	Thickness West End	Thickness East End
1	3.0 km/sec	1.3 km	0.7 km
2	4.1-4.7	2.5	1.2
3	5.7-6.1	1.6	2.8
4	7.6-7.7	H = 5.4 km	H = 4.7 km

Details on these seismic measurements and the analytical procedures used have been given by Furumoto et al. (1965), and by Adams and Furumoto (1965); they will not be discussed here.

It is of interest that the mass analysis made of the Koolau gravity anomaly by Strange, Woollard, and Rose (1965) defines a structure for the Koolau intrusive mass that is in good agreement with the seismic data. The anomaly has been described by Strange, Machesky, and Woollard (1965) and the derived section is as follows:

Layer	Radius	Intrusive Density	Thickness	Country Rock Density
1	3 km	2.3 gm/cc	0.2 km	2.3 gm/cc
2	3	2.9	1.3	2.3
3	6	3.2	1.5	2.6
4	9	3.2	6.5	2.8
5	9	3.3	4.0	2.9

Depth to 3.2 gm/cc material 1.5 km
Depth to base of model 13.5 km

It is obvious that the depth to the base, and the radius of the basal intrusive layer of the model, could be altered slightly and still satisfy the gravity anomaly pattern. The significant aspect of the model is the depth derived for the upper intrusive layer of 3.2 gm/cc material. It is noteworthy that, to fit the observed relations, the upper density contrast must be 0.6 gm/cc, from which it follows that the core density value could have been 3.3 gm/cc rather than the 3.2 gm/cc value assumed. Geologically, the important point of this analysis is that ultramafic material is indicated at a depth of only 1.5 kilometres and that this material obviously extends from this depth down to at least the normal depth of the mantle. Thus the high-density material does not represent a heavy mineral concentrate in a shallow magma chamber, developed through gravity settling of early formed minerals, but rather a continuous column of high-density rock at least 14 kilometres deep apparently extending to its source, the mantle. The fact that the intrusive does not have the typical mantle velocity of about 8.1 km/sec but rather only about 7.6-7.7 km/sec can be attributed to three factors: 1) the material was obviously emplaced in the upper levels of the crust as a magma because it is the source of the tholeiitic basalts. Because it was in the liquid state, most of the volatile constituents have escaped and were no longer present after recrystallization; 2) recrystallization took place in a regime of much lower pressure and presumably different temperature than in the mantle itself so that both the minerals and the structure of the mineral assemblage are presumably different from those that exist in the mantle source; and 3) in laboratory studies of rocks under confining pressures, although most of the compressibility effect which controls velocity values results from pressures equivalent to a depth of burial of 1 kilometre, the velocity value still increases as the pressure is raised from 1 kilobar to 10 kilobars. It is, therefore, not necessary to postulate that a velocity of 7.6-7.7 km/sec represents an admixture of crustal and mantle material, or that the high heat flow has reduced the velocity. But neither can we expect the 7.6-7.7 km/sec material necessarily to be completely representative of the parent mantle material.

In view of these subnormal depths to apparent mantle material in the intrusion on Oahu, and since there were no published data on the depth to the true mantle beneath oceanic islands, an attempt was made south of Oahu to measure the depth to the mantle beneath the central ridge. This measurement was made between Oahu and Molokai, and the profile was aligned more or less parallel with the strike of the ridge. This area was chosen because the gravity and magnetic data indicated that it was free of intrusive crustal rift and vent areas that might bias the results. The results for this measurement (Furumoto et al., 1965) are as follows:

Layer	Velocity	Thickness
1	Water	0.3 km
2	2.95 km/sec	2.3
3	4.97	7.1
4	6.81	11.4
5	8.8	H = 21.1 km

The depth to the mantle is so much greater than had been anticipated that the measurement was repeated on a somewhat different heading, but similar results were obtained.

A second indication of a thick crust was obtained from a line of measurements carried out across the island of Maui using large HE explosions (500 tons) detonated on the island of Kahoolawe by the U.S. Navy. No mantle velocity arrivals were obtained at the extreme end of the line, although the upper crustal section and the velocities were similar to those found off Oahu. On a conservative estimate, the depth to the mantle must exceed 18 kilometres.

These results contrast markedly with those reported by the U.S. Geological Survey on the island of Hawaii. H. Powers (personal communication, 1965) advised that the depth to the mantle there is between 12 and 16 kilometres. Somewhat similar results were obtained by Shor and Pollard (1964) at their seismic station No. 27, north of Maui, where the water depth is about 1.2 kilometres. This section was restudied for the National Science Foundation by J. Sides (personal communication, 1965) who reported his results as follows:

Layer	Velocity	Thickness
1	Water	1.2 km
2	2.69 km/sec	1.2
3	3.65	0.2
4	4.96	5.3
5	7.15	7.4
6	8.15	H = 15.3

The 7.15 km/sec velocity observed for the basal layer of the crust is somewhat abnormal in that elsewhere in the area the velocity of the basal layer averages about 6.85 km/sec.

In the Hawaiian Trench area, where the depth of water is about 5.3 kilometres and the free-air gravity anomalies average about -100 mgal, the crustal section as shown below is somewhat thinner:

Layer	Velocity	Thickness
1	Water	5.3 km
2	2.7 km/sec	0.2
3	4.24	1.7
4	5.6	0.3
5	6.47	4.9
6	8.10	H = 12.4 km

The layer of superficial sediments with a velocity of 2.7 km/sec is remarkably thin for a trench area, and perhaps the 4.24 km/sec layer also represents sediments. This suggestion appears to be substantiated by reflection studies (Kroenke, 1965) which detected layering and structures in material of the trench down to a subbottom depth of 1.1 kilometres.

The crust continues to thin from the trench to the Hawaiian Rise where a minimum mantle depth and a minimum crustal thickness were obtained:

Layer	Velocity	Thickness
1	Water	4.2 km
2	2.7 km/sec	0.1
3	4.3	0.2
4	6.35	2.1
5	7.0	3.4
6	8.42	H = 10.0 km

In a composite crustal profile, constructed from the ridge across the trench to the rise, the changes in structure and gravity expression are as follows:

	Ridge	Trench	Rise
Surface elevation	-0.2 km	-5.3 km	-4.2 km
Thickness upper crustal layers[1]	9.0 km	2.2 km	2.4 km
Thickness basal crustal layer	12.0 km	4.9 km	3.4 km
Total thickness of crust	21.0 km	7.1 km	5.7 km
Ratio of thicknesses of upper crust to basal crust	1:1.33	1:2.23	1:1.42
Elevation of mantle	-21.2 km	-12.4 km	-10.0 km
Observed change in mantle depth below that on rise	+11.2 km	+2.4 km	0.0
Free-air anomaly	+200 mgal	-100 mgal	+30 mgal
Bouguer anomaly[2]	+205 mgal	+313 mgal	+357 mgal
Change in Bouguer anomaly relative to that on rise	-152 mgal	-44 mgal	0

[1]Includes sediments

[2]Mass deficiency of water column calculated using a mean crustal density of 2.9 gm/cc.

A graphic representation of the change in crustal structure is shown in Figure 4.

If we assume a mean density differential of 0.4 gm/cc between the crust and the mantle, the observed change in Bouguer anomaly values cannot be explained by the change in crustal thickness. In a first approximation using the gravity effect of a slab, the anticipated change in Bouguer anomaly would be as follows:

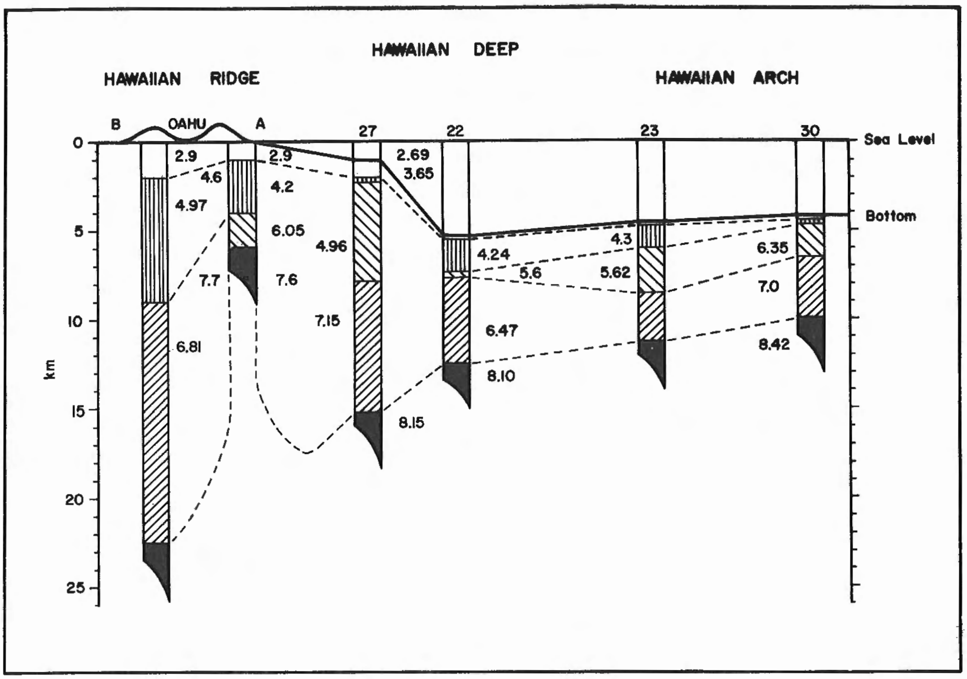

Figure 4. Composite crustal section from island of Oahu to Hawaiian Rise.

	Ridge	Trench	Rise
Observed change in crustal root	+11.2 km	+2.4 km	0.0
Calculated gravity effect[1]	187 mgal	40 mgal	0.0
Observed change in Bouguer anomaly	152 mgal	44 mgal	0.0

[1]Calculated using $\Delta g = 2\pi\gamma\Delta\sigma h$, where $\Delta\sigma = 0.4$ gm/cc and h = the observed crustal root increment.

There is thus about 35 mgal excess gravity associated with the ridge; this agrees in sign with the +75 mgal isostatic anomaly computed for the nearby Honolulu gravity base of the U.S. Coast and Geodetic Survey (See Duerksen, 1943).

Although the Honolulu isostatic anomaly value may be biased somewhat because it is close (17 miles) to the Wailaie and Koolau vent areas (each of which has a local Bouguer gravity anomaly effect of about +110 mgal relative to Honolulu), the ridge undoubtedly is characterized by excess gravity. That this positive gravity effect cannot be explained by the structure of the crust is indicated by the observed ratios of upper crustal material to basal material on and off the ridge. The lowest ratio (1:1.33), which can be assumed to have the higher density, is associated with the ridge, and the highest ratio (1:2.23) is associated with the trench. Yet the trench is marked by a slight deficiency in gravity, and the ridge by an excess in gravity. Neither can the velocity values associated with the crust explain the observed gravity relations if velocity values are assumed to be directly related to density. The upper part of the crust beneath the ridge consists of material with a velocity of 4.97 km/sec, whereas beneath the rise the velocity is 6.35 km/sec. The basal layer beneath the ridge has a velocity of 6.81 km/sec, and beneath the rise 7.0 km/sec.

It therefore appears that the positive gravity effect must be attributed to higher density mantle material underlying the ridge. The only clue supporting this conclusion is the high velocity value of 8.8 km/sec noted for the mantle between Oahu and Molokai. In an attempt to verify this value, recordings were made at five points on Oahu for one of the 500-ton HE detonations on Kahoolawe (Project Sailor Hat). The apparent velocities on different azimuths within a 20-degree spread at similar distances ranged from 7.4 to 11.4 km/sec. Although these observations proved that the underlying local crustal structure had a pronounced effect on arrival times in the Hawaiian area, they failed to give a clear-cut value for the velocity of the mantle. The average value of about 9.0 km/sec may be significant. Another experiment, just completed, may, hopefully, provide more definitive results, not available at the time of writing.

Magnetic Studies

To supplement the gravity and seismic studies, an aeromagnetic survey was made of the Hawaiian Islands, and a seamagnetic survey was carried out over the offshore area, in collaboration with the U.S. Coast and Geodetic Survey. These results, coupled with those for unpublished surveys by the Navy Oceanographic Office and the Scripps Institution of Oceanography in the area, provide rather comprehensive coverage.

Two striking features brought out by the magnetic studies are the pronounced dipole anomalies over each of the major vent areas, which incidentally are all characterized by local gravity highs, and the lenticular dipole anomalies over the Molokai fracture zone and rift areas beneath which a shallow depth to mantle-like material (7.7 km/sec velocity) was determined seismically. Not only was the latter situation noted off Oahu as discussed earlier, but it was also found to be associated with the shallow Moho depth (5.8 km) reported off Maui by Shor and Pollard (1964).

A noteworthy feature of the anomalies associated with the Molokai fracture zone is that the anomalies are aligned parallel with the fractures and are not offset along the fracture zone as has been observed off California. The anomalies can be traced beyond the point where the fracture system loses its bathymetric identity in the Hawaiian Trench, through the ridge area, and on westward across the Pacific Basin. Malahoff and Woollard (in press) have shown that all of the anomalies originate within the crust, and thus are due to intrusive material presumably derived from the mantle. As shown, the available seismic data appear to confirm this hypothesis of the origin.

If the aligned magnetic anomalies are interpreted as reflecting a crustal fracture pattern, the dominant fractures east of Molokai trend essentially westerly. West of Molokai, the fractures apparently trend northwesterly parallel with the Hawaiin Ridge. It appears that the more intensive vulcanism on Hawaii (five main vents) and on the Molokai-Maui-Lanai platform (six main vents) (as compared to two vents on the Oahu platform and one vent on the Kauai platform), is related to the intersection of the two crosscutting fracture systems. The abrupt termination of the ridge at Hawaii may also be explained by stress relief at this point, through vulcanism and possible movement on the Molokai fracture, such that the requisite strain for further propagation of the Hawaiian Ridge shear is lacking. Although the relative ages of the two fracture systems are not known, the Hawaiian Ridge, west of Layson Island (about one-fourth of the way southeasterly along the island chain from Midway), is undoubtedly offset to the south, and a crosscutting ridge (Necker Ridge) clearly formed south of the Hawaiian Ridge on the extension of the Murray fracture zone. Although these relations imply that the Hawaiian shear zone is older than some of the crosscutting fractures, they do not clarify the relations of the shear zone to the Molokai fracture zone which appears to cut across the southeastern end of the ridge without displacing any of it.

AGE RELATIONS AND SUBSIDENCE

Potassium-argon age determinations on volcanic rocks of the Hawaiian Islands indicate that the difference in age between the islands of Oahu and Hawaii averages 2.5 million years. Naughton and Barnes (1965), for example, give an age of 5.4 million years for the oldest rocks sampled on Oahu and 2.8 million years for the oldest rocks on Hawaii. The youngest rocks sampled on Oahu gave an age of 2.2 million years, while volcanoes are active on Hawaii. This difference in age might well explain the difference in mantle depth of about 5 to 8 kilometres (H = 21 km south of Oahu and

12-16 km on Hawaii) if it is assumed that crustal subsidence has gone on progressively since the islands were first formed. Although the amount of subsidence indicated beneath Oahu is 9 kilometres, if one relates the observed mantle elevation of -21 kilometres to the norm for the central Pacific area of -12 kilometres, most of this difference in values is related to thickening of the basal layer of the crust rather than to simple subsidence. A more reliable measure of subsidence might be obtained by considering the depth of the base of the upper crustal layer. If we compare the values for the ridge, trench, and rise to an average Pacific column as defined by Raitt (1956), the values are as follows:

	Ridge	Trench	Rise	Std. Col.
Elevation of base of upper crust	-9.0 km	-7.8 km	-6.6 km	-7.5 km
Difference	-1.5	-0.3	+0.9	0.0

As seen, these data suggest a subsidence of only 1.5 kilometres.

A direct measure of the subsidence is provided by comparing the elevations of terraces around the Hawaiian Islands if it can be assumed that they were developed at or near sea-level. Bathymetric data indicate that the Hawaiian platform is formed by a series of terraces, the deepest of which is about 600 fathoms (1,100 metres). If a normal shelf depth of 100 fathoms (190 metres) is assumed to be related to recent glacial-interglacial changes in sea-level, then approximately 900 metres of subsidence has occurred since the islands first emerged above sea-level. This appears reasonable in view of the well, recently completed at Ewa Beach, Oahu, which penetrated 1,150 feet (350 metres) of coral and lagoonal sediments overlying a weathered surface of a basalt flow, covered with rounded basalt stream gravels.

Another approach is to assume that the Hawaiian Trench was formed by the subsidence associated with the ridge. From the data considered earlier, the elevation of the base of the sediments in the trench is -7.2 kilometres, which is 2.7 kilometres deeper than on the rise. An exponential projection of this surface, as defined by intermediate seismic depth sections, to beneath the ridge would place this surface at -8.5 kilometres. This gives a differential subsidence of the ridge of 2.5 kilometres relative to a normal oceanic column (Raitt, 1956). A subsidence of about 2.0 kilometres therefore appears reasonable in the Oahu area. Presumably, the subsidence is greater in the Midway atoll area where recently completed drill-holes penetrated weathered basalt capped with coral at a depth of 550 feet (170 metres).

ORIGIN OF THE HAWAIIAN RISE

We can use the mean crustal model for the central Pacific as determined by Raitt (1956) as a standard for studying the Hawaiian Rise. The crustal structure based on Raitt's data is as follows:

Water	5.5 km
Sediment	0.5
Upper Crust	2.0
Basal Crust	4.0
Mantle	12.0 km

The total thickness of the crust including sediments is 6.5 kilometres. That observed beneath the rise is 5.8 kilometres. However, note that the water depth over the rise is only 4.2 kilometres, and the mantle is at a subnormal depth of 10.0 kilometres. Since crustal thickness generally increases with a decrease in water depth, all of the data support the idea of crustal uplift beneath the rise. It is not illogical to attribute this uplift to the migration of mantle material displaced by the thickened crust beneath the ridge. However, it is obvious that this thick crust was less a product of crustal subsidence than crustal growth, for, as shown earlier, the basal crustal layer beneath the ridge is 12 kilometres thick, or roughly 3.6 times the normal value. If we assume a transition from mantle material of 3.3 gm/cc to basal crustal material of 3.0 gm/cc, this transformation would require a volumetric increase of 10 per cent. If we assume a similar transformation of material up to the level of the base of the normal upper crust, this transformation for a crustal column about 15 kilometres deep would result in the displacement of about 75 cubic kilometres of mantle material for each kilometre along strike. That this crustal expansion was not accommodated by local uplift beneath the ridge is clearly evident, because there is positive evidence for subsidence in this area. It therefore appears probable that stress relief was accommodated by lateral movement of flanking mantle material. As the greatest stress would be exerted perpendicular to the sloping crust-mantle interface, the initial movement would have a marked downward component. However, as the direction of least opposing stress would be towards the surface, the path of movement would curve towards the surface and result in uplift. Since we are dealing with plastic flow and a mineralogical phase transformation, whose time constants are not known, the Hawaiian Rise probably did not develop at the same time as the Hawaiian Ridge, but developed considerably later. Such a process would explain both the absence of the rise off the island of Hawaii where there is now active vulcanism and the marked difference in crustal thickness beneath Hawaii and Oahu of 5 to 8 kilometres. Because the rise lacks a compensating root, it is obviously an unstable feature and can be expected to disappear in time by plastic flow, once the causative forces are removed. This conclusion appears to be verified in the Midway area where the rise is absent. Between Layson and Maui, where the rise is a conspicuous topographic feature, there should be an optimum depth for drilling to the mantle representing maximum uplift of the crust and minimum plastic flow eradicating the induced structure. So far, only the Maui end of the rise has been investigated seismically. Conceivably, between Layson and Maui, a site could be found at which the mantle is only 8 kilometres deep, and thus offer less technical problems for the Moho drilling program than might be encountered off Maui on the southern flank of the rise, where the mantle is a minimum of 9 kilometres deep.

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COMMENTS ON THE PACIFIC BASIN [1]

H.H. Hess
Princeton University

The fracture system and rises in the central Pacific Ocean basin, as shown in Menard's book "Marine Geology of the Pacific" (1964), are old, probably Mesozoic or early Tertiary. They are not active today. The Darwin Rise in the Central Pacific has subsided since Cretaceous time. The fractures crossing the rise fall more or less on great circles and are about perpendicular to its axis. At one time, a mid-ocean ridge existed along the axis of the rise, and crustal material moved away from the ridge axis for 100 or 200 million years. The fractures are related to that movement.

Much later, the East Pacific Rise was formed – perhaps in the last one to ten million years. Its young age south of the equator is indicated by the existence of sediments extending across the rise without change in thickness. Furthermore, if the rise does continue into the Colorado Plateau or Basin and Range Province, there the tectonic activity is also late Tertiary.[2]

The familiar linear magnetic pattern of the Pacific Ocean basin north of the Mendocino fracture zone extends over a large area of ocean. North of the Mendocino fracture zone, the anomalies extend at least 2,000 kilometres out into the Pacific. If the linear anomalies grew by westward migration of crustal material (like an unrolling window blind) at the rate of 1 centimetre per year, or even 2 or 3 centimetres per year, the growth of the belt requires something of the order of 100 million years. These are old anomalies and should not be correlated with the activity on shore.

The anomalies on a segment off California to Washington State on the north side of the Mendocino zone are probably young and may be forming today. It would be interesting to recontour the magnetics in the area while keeping in mind that the old anomalies trend north and the young anomalies trend east of north. Perhaps a discontinuity would appear between anomalies of the two ages.

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[1] Professor Hess considered the paper he presented at the Symposium unsuitable for complete publication. With his permission these comments have been extracted from the tape transcript by the editor.

[2] Note added in proof: Results in past year (1966) suggest that the East Pacific Rise is much older than 10 million years. H.H.H.

The older anomalies south of the Mendocino are about 70 kilometres apart and the younger north of the Mendocino are about 30 kilometres apart. The more widely spaced anomalies indicate a higher velocity of movement, roughly twice that of the closely spaced anomalies. If the successive positive and negative anomalies are the result of reversals in the earth's magnetic field and if the reversals occurred about every 1 million years, as calculated by Cox and Doell (1964), then the velocities of movement are 1 1/2 and 3 centimetres per year for the two sets of anomalies.

Vine and Matthew's (1963) hypothesis is very attractive; it may be right. We should drill some of the positive and negative anomalies to see if they consist of normally and reversely polarized basalt. We could date some of the basalts isotopically to determine how much time has lapsed between the formation of successive anomalies across the belt. From this, the velocity of movement could perhaps be calculated, and eventually the structure and growth in time of the entire ocean floor could be determined. I am anxious to see more well controlled magnetic surveys of the ocean areas.

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DISCUSSION

Prof. S.K. Runcorn (UK)

I have one suggestion to make. It seems that the number of complete reversals in the earth's magnetic field varies considerably throughout geological time. If, for example, we consider the anomalies in the Pacific as being Mesozoic, then it's almost certain that the reversals in the Mesozoic have not been as frequent as those in the Tertiary.

Prof. Hess

That's fine. We can sample and date the Mesozoic anomalies, too, as well as examine the magnetics. We should find areas of ocean floor of Permian age if any of the oceans are that old - reversals are not observed in Permian rocks – and we should find anomaly-free areas, if old ocean floors do exist and if Vine and Matthews are right.

Dr. M. Talwani (USA)

Menard has presented some very impressive arguments for the gentle slope of the East Pacific Rise north of the Mendocino escarpment and extending westward to about longitude 150°W. Using the magnetic patterns, he presented strong evidence for the offset across the Mendocino escarpment. Also the ocean is much deeper south of the escarpment; and the magnetic anomaly seems to follow the scarp. Do you have any thoughts on that?

Prof. Hess

I don't know. I haven't reviewed Menard's data with Wilson's hypothesis in mind. I'll do it for you though. Next time you ask, I'll have the answer.

Prof. J.T. Wilson (Canada)

I'd like to comment, if I may, that I'm glad that Professor Hess and I agree on the value and possible validity of the Vine and Matthews hypothesis and on its apparent usefulness.

In the first part of his talk, though, there were some points which I would like to question. The extreme youth of the East Pacific Rise and its lack of connection with these great scarps and fracture zones puzzle me, because it's so obvious that the fracture zones are offset and seem to be related to the East Pacific Rise in the South Pacific. And also there is all the palaeontological data which he did not mention. In a recent paper, Reidel and Funnel found only Pliocene fossils along the centre of the East Pacific Rise in the South Pacific, and progressively farther from the centre they found sediments of all the other ages in the Tertiary as old as Eocene. This suggests that the East Pacific Rise represents all of Tertiary time.

Prof. Hess

Well, I haven't seen that paper. They would have had to collect a great deal of information to do much with something as large as the Pacific Ocean. There are, I know, vast areas of Eocene southwest of Hawaii. I doubt if these are related to rises except, of course, the floor has to be older than Eocene in order to receive Eocene sediments.

Dr. K.L. Cook (USA)

I think that Menard's evidence plus other evidence given in several papers on the East Pacific Rise indicate that the rise continues into the Basin and Range province. One convincing characteristic that Menard emphasized was the gradual downward slope of the ocean floor from California to the Hawaiian Islands. Quite apart from the displacement along the San Andreas Fault, which Professor Wilson showed to extend north of the Mendocino fracture zone, this downward slope south of the Mendocino escarpment continues to the Hawaiian Islands. Other compelling evidence are the graben- and horst-like features found by George Shor of Scripps in 1963 off the coast of southern California southwest of Los Angeles (in the Continental Borderland province) that are apparently similar to the graben and horst features in the Basin and Range province. This similarity of structural features in these two regions indicates a common origin that is probably related to the East Pacific Rise.

For the time of formation of the great Pacific fracture zones off the coast of California, Dr. Hess has appealed to time as long ago as the Darwin Rise (perhaps 100 million years ago or more). According to Nolan, the faulting in the Basin and Range province as a whole has probably been in progress since early Oligocene time (about 36 million years ago); topographically expressed faults, however, probably date back only to late Pliocene (less than about 13 million years ago) or early Pleistocene. Because the block faulting in the Basin and Range province is probably related to processes that formed the East Pacific Rise, which apparently extends into this region, the East Pacific Rise in this region is therefore probably as old as early Oligocene time. So if we may appeal to the time only since Oligocene, the fault pattern and postulated convection currents within the upper mantle may have changed since this time. For example, in the Basin and Range province the postulated westward movement of the limb of a mantle convection cell (Cook, 1962) is in accord with the direction of left-lateral movement along the eastward-striking Garlock Fault in southern California that has an indicated horizontal displacement of about 40 miles since late Mesozoic or early Tertiary time (Smith, 1962). However, the Garlock Fault is terminated and (or) offset on the west and on the east by the right-lateral San Andreas and Death Valley Faults, respectively, in a pattern that suggests that these latter two faults have been displaced horizontally in Recent time by larger amounts than the Garlock Fault. Moreover, there is evidence suggested by Billings (1960) on the basis of recent earthquake activity in the Fairview Peak-Dixie Valley, Nevada earthquake area, that right-lateral strike-slip movements of the San Andreas type are invading an area characterized by Basin and Range normal-fault structure. Accordingly, the pattern of the mantle convection may have changed recently.

<u>Prof. Hess</u>

I did not mean to say that the East Pacific Rise might not extend into the Basin and Range province - it very well might, as far as I know. But I would not correlate the magnetic anomalies off California with the East Pacific Rise where it joins the Basin and Range province. I think there is a fairly reasonable argument that a branch of the East Pacific Rise or the whole thing might go off into that area. And there is another, smaller branch, that Professor Wilson mentioned, off the coast of Oregon and

Washington. But it is difficult to accept that the fracture zones of the Pacific cross the San Andreas Fault – they don't. So I'd make them older than most of the San Andreas.

Prof. Wilson

I'd just like to say that I agree with Dr. Cook that the East Pacific Rise did disappear under North America. But I think it disappeared under North America – when it went down, it just vanished – and I don't see much relation between the structure of the Nevada region and that of the mid-ocean ridges. If a connection through California was found, I think it would be very difficult to find a branch from Nevada to the vicinity of Vancouver Island. So I think that that's the argument from both sides and we'll probably not be able to resolve it today. But I think it's interesting that we've brought out these differences in point of view.

Dr. Cook

I have one final point. I think that the following mid-oceanic ridge areas and probably others – as more detailed data become available – will probably be found to have bottom topography and fault-block structure similar to the bedrock topography and fault-block structure of the Basin and Range province, that is, a series of trenches or grabens not in a straight line or continuous, but rather offset in en echelon pattern: 1) the southern part of the Mid-Atlantic Ridge, which Menard states has several central or "median" rifts; 2) the part of the Mid-Indian Ocean Ridge from the equator southwest to the Rodrigues Islands, described by Shepard; 3) the area on either side of the central rift valley along the northern part of the Mid-Atlantic Ridge designated by Heezen et al. (1959) as the "Rift-Mountains Province"; and 4) the areas of troughs and ridges in the East Pacific Rise. This striking similarity is a compelling reason, I believe, that the East Pacific Rise continues into the Basin and Range province.

Dr. D.H. Matthews (UK)

I hesitate to enter this arena. I am bothered about the permanent offsets of the axis of the Mid-Atlantic Ridge. One reason I hesitate to enter the arena is because I have to mention the word "convection". I feel that anybody who does not care to receive the mathematics of the upper mantle is not entitled to talk very much about convection. But it does seem to me that if the ridge has always had offsets of the order of hundreds of miles that the convection cell (let me define my term: I'm quite sure that everybody agrees that the ridge is a volcanic structure at the present time, and that heat flow on the average over it is higher than average. That's all I mean by convection, a source of heat.), this source of heat, must be very much wider than the area located under the crest of the ridge if the ridge has always had kinks in it. It must be really very wide, at least 500 miles across, because otherwise it has to be dislocated with two routes of escape, and that's rather hard to imagine. But if there's evidence that the source of high heat flow is that wide, then I don't think there's any difficulty in explaining the gradual tilt of the Pacific Ocean downwards away from the general vicinity of the presently active rise – the East Pacific Rise.

Dr. J. Healy (USA)

I'd like to make a comment which may apply to the problems concerning the upper mantle velocities across the United States. Marked differences have been revealed in the properties of the upper mantle between the east and west. In the Basin and Range province and over much of Western United States, we have measured mantle velocities of about 7.8 km/sec. The attenuation of the wave amplitudes is a function of about one over distance cubed. More recent measurements in the east from Lake Superior to the Rockies show mantle velocities of 8.2 km/sec to a depth of about 100 kilometres, and then they increase to 8.5 km/sec. The rate of fall-off with distance looks like one over distance, instead of one over distance cubed as in the west. These very marked differences both in attenuation and in measured velocities indicate fundamental differences in the properties of the mantle rock under these two different tectonic areas. It's difficult to say how deep these differences extend, but two lines of argument – 1) a normal refractive wave interpretation of this 8.5 km/sec arrival; and 2) arguments related to isostatic balance – suggest that the differences extend to a depth of at least an order of 100 kilometres. So I have two comments: 1) perhaps the low-velocity mantle in the west is associated with the East Pacific Rise; and 2) if the continents are drifting the zone of drifting must be at least 100 kilometres deep.

Prof. Hess

I agree with your last statement. It's obvious that the zone of drifting must be much deeper than this, perhaps several hundred kilometres. But, I feel that the differences in mantle velocities do not indicate compositional differences, but probably two things, temperature differences and seismic anisotropy, with temperature differences probably the more important.

Prof. Runcorn stated that the temperature difference required to produce a 5 to 10 per cent difference in mantle velocity is something like 1,000°C, which is too great to invoke.

Prof. Hess

I am looking for a 100-degree difference. It is true that the temperature difference for a 5 per cent difference in velocity is too large. But some scatter of velocities can be attributed to possible anisotropy as well. [Note added in proof: In hasty discussion without notes, I had forgotten the argument I used in previous papers, namely that the lower velocity was due to microfracturing and dilation with other effects being less important. This still is my considered opinion.]

F. SESSION ON PETROLOGY AND GEOPHYSICS OF CONTINENTAL MARGINS AND ISLAND ARCS

LATERAL VARIATION OF BASALT MAGMA ACROSS CONTINENTAL MARGINS AND ISLAND ARCS

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Abstract

Quaternary basalt magmas in the Circum-Pacific belt and island arcs, and also in Indonesia, change continuously from a less alkalic and more siliceous type (tholeiite) on the oceanic side to a more alkalic and less siliceous type (alkali olivine basalt) on the continental side. In the northeastern part of the Japanese Islands and in Kamchatka, zones of tholeiite, high-alumina basalt, and alkali olivine basalt occur in that order and aligned parallel with the Pacific Coast, whereas in the southwestern part of the Japanese Islands, the Aleutian Islands, the northwestern United States, New Zealand, and Indonesia, zones of only high-alumina basalt and alkali olivine basalt occur parallel with the coast. In the Izu-Mariana, South Sandwich, and Tonga Islands, where deep oceans are present on both sides of the island arcs, only a zone of tholeiite is represented. Thus a lateral variation of magma type is characteristic of the transitional zone between the oceanic and continental structures. Because the variation is continuous, the physico-chemical process attending basalt magma production should also change continuously from the oceanic to continental mantle. Three alternative suggestions explaining the lateral variation are presented (assuming a homogeneous mantle): 1) Close correspondence between depth of earthquake foci in the mantle and the basalt magma types in the Japanese Islands, indicates that tholeiite magma is produced where the earthquakes are generated by stress relief at depths of 100 kilometres, high-alumina basalt magma by the same mechanism at depths from 100 to 200 kilometres, and alkali olivine basalt magma at depths greater than 200 kilometres; 2) Inferred steep thermal gradient in the oceanic mantle and gentle gradient in the continental mantle suggest that the temperature of initial melting of mantle peridotite is reached at shallow depth on the oceanic side of the continental margins producing tholeiite magma, and at great depth on the continental side producing alkali olivine basalt magma, and that the two regions are linked by an intermediate depth of magma production (high-alumina basalt); and 3) Primary olivine tholeiite magma is produced at some depth in the mantle (100-150 kilometres), and then on the oceanic side of the continental

margin, the magma leaves the source region immediately after its production and forms a magma reservoir at shallow depth, perhaps in the crust where it undergoes fractionation to produce SiO_2-oversaturated tholeiite magma, whereas on the continental side, the primary magma forms a reservoir near the source region and stays there long enough for fractionation to produce alkali olivine basalt magma. In the intermediate zone, the primary olivine tholeiite magma forms a reservoir at intermediate depth where it fractionates to produce high-alumina basalt magma.

INTRODUCTION

Quaternary volcanoes along continental margins of the Pacific Ocean and island arcs comprise mainly basalt, andesite, dacite, and rhyolite. Within this series there is a definite variation in chemical composition with relation to the geographic position of the volcanoes. The alkali basalt-trachyte series also occurs within these regions. There are two general types of variation: one is a variation across the continental margin, and the other along the margin and island arc.

Island arc structure consists of three elements: from the ocean towards the continent, they are a deep trench at the margin of the ocean; next, a chain of uplifts lacking young volcanoes; and finally, a zone of active volcanoes. In some regions, one or two of the three elements may be lacking. A chain of uplifts and a zone of volcanoes may be a part of a continent such as in the northwestern United States. If volcanoes are scattered over a zone more than 50 kilometres wide, there is a systematic variation of basalt magma type from the oceanic to the continental sides.

LATERAL VARIATION OF MAGMA TYPE

Figure 1 shows the variation of basaltic rocks in the Japanese Islands in which three types of primary basalt magmas have been distinguished (Kuno, 1960). Tholeiite occurs in a zone near the Pacific Coast of northeastern Japan, and extends to the Izu Islands and the Marianas. To the west lies a zone of high-alumina basalt which is a little more alkalic than tholeiite. Still farther west, a zone of alkali olivine basalt covers a large area from the northwestern coast of Japan to Korea and Manchuria. Thus a continuous variation exists from tholeiite to alkali olivine basalt.

Associated with these three types of basalt, there are andesite, dacite, mugearite, trachyandesite, trachyte, and rhyolite. These more differentiated rocks have the same alkali-silica relations as their associated parent basalts. Figure 2 shows plots of basalt, andesite, dacite, and rhyolite occurring in the tholeiite and high-alumina basalt zones, and

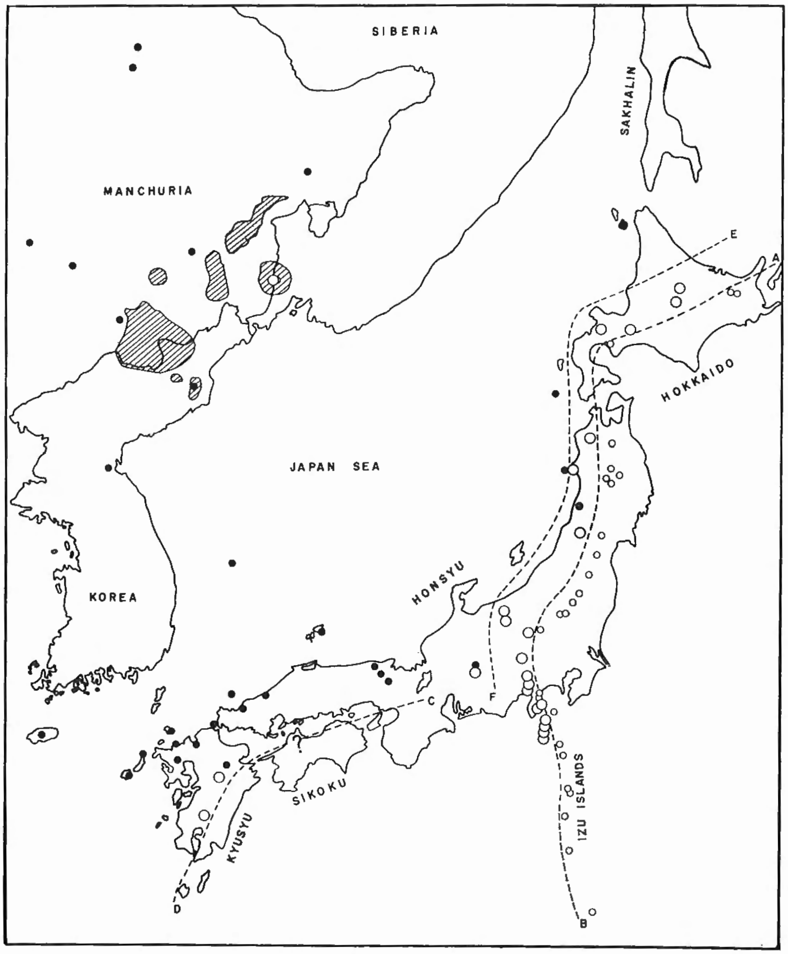

Figure 1. Distribution of tholeiite (small open circles), high-alumina basalt (large open circles), and alkali olivine basalt (solid circles) in Quaternary volcanoes of Japan, Korea, and Manchuria. The shaded areas in Manchuria consist of plateau basalt, mostly alkali olivine basalt of late Tertiary age. Lines AB and CD are the boundaries between the tholeiite and high-alumina basalt zones, and line EF is that between the high-alumina basalt and alkali olivine basalt zones.

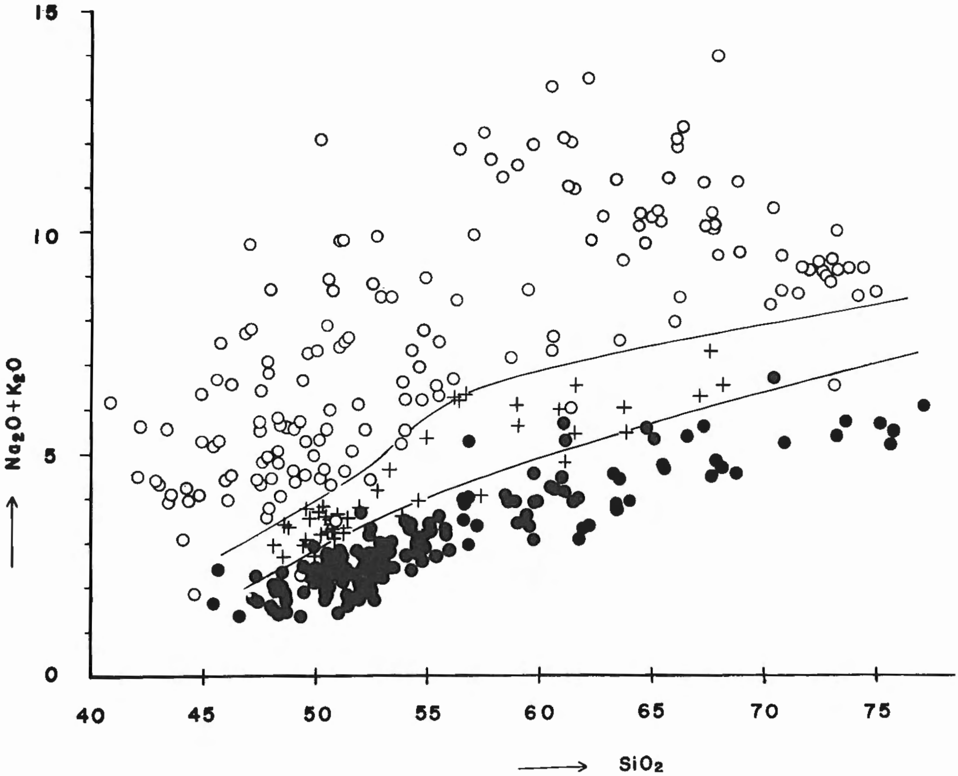

Figure 2. Total alkalies-SiO_2 relation in Miocene to Recent volcanic rocks of tholeiite series (pigeonitic rock series, solid circles), high-alumina basalt series (crosses), and alkali rock series (open circles) from the Izu Islands, central Honsyu, Japan Sea coast of southwestern Japan, Korea, and Manchuria. The two lines mark the general boundaries between the fields of the tholeiite series, high-alumina basalt series, and alkali rock series. These lines are reproduced in some of the following figures.

basalt, mugearite, trachyandesite, trachyte, and alkali rhyolite in the alkali olivine basalt zone. The rocks of the tholeiite zone are lowest in alkalies, those of the alkali olivine basalt zone are highest in alkalies, and those of the high-alumina basalt zone are intermediate. The two lines in the figure in general separate the three fields. They are used for reference in the following diagrams.

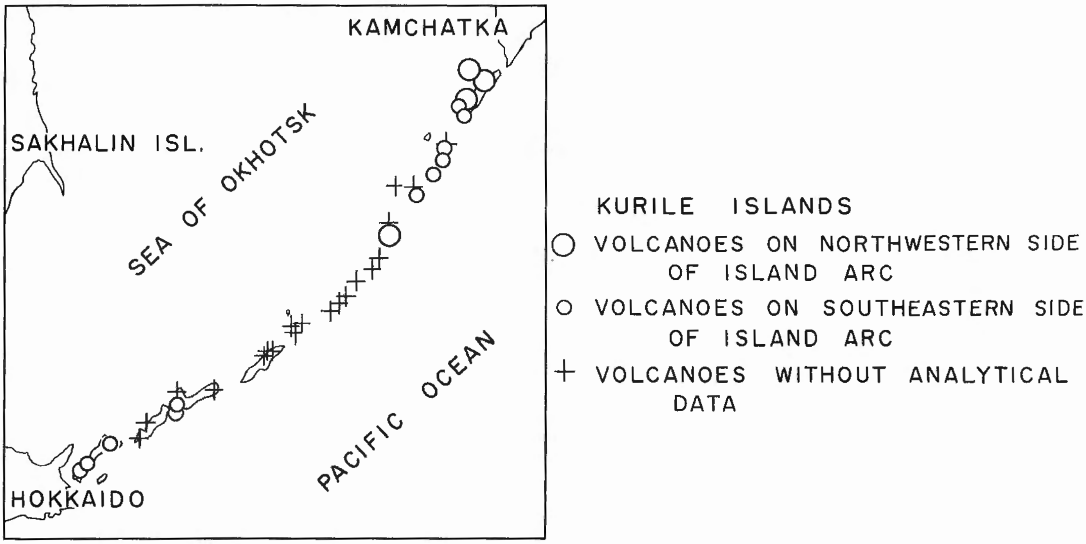

Figure 3. Distribution of active volcanoes in the Kurile Islands.

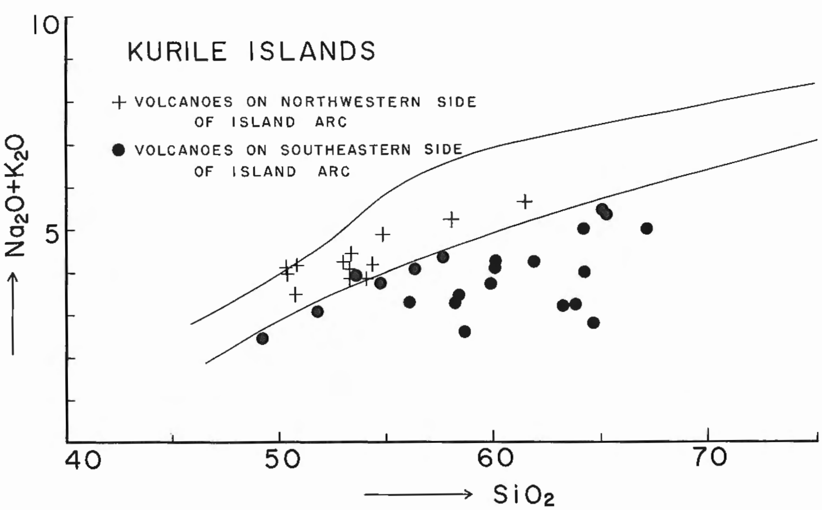

Figure 4. Total alkalies-SiO_2 relation in rocks of active volcanoes in the Kurile Islands.

The Kurile Islands (Fig. 3) are in general the extension of the tholeiite zone of northeastern Japan. However, in some volcanoes lying on the northwestern side of the central axis of the island arc (shown by large circles in Figure 3), high-alumina basalt and its variants occur (Fig. 4) (data from Gorshkov, 1958).

In Kamchatka, there are three zones of volcanoes – the eastern, central, and western zones (Fig. 5). As shown in Figure 6, the rocks of the eastern zone are least alkalic (tholeiite derivation) and those of the western zone are most alkalic (alkali olivine basalt derivation) if we compare rocks of the same silica percentage. The rocks of the middle zone are intermediate in alkali content (high-alumina basalt derivation) (data from Vlodavetz and Piip, 1959).

Figure 7 (Coats, 1962) shows distribution of Quaternary volcanoes in the Aleutian Islands and southwestern Alaska. As seen in the figure, Bogoslof and Katmai Volcanoes lie slightly towards the continental and oceanic sides, respectively, of the central axis of the volcanic zone. Pribilof and Nunivak Islands, both capped by young volcanoes, lie farther to the north of the zone.

Figure 8 shows that the rocks of the main part of the volcanic zone are of high-alumina basalt derivation, but the rocks of Katmai and Bogoslof are a little less and a little more alkalic, respectively, than the rocks of the main zone, a relation to be expected from their geographic positions. The rocks of Pribilof are markedly more alkalic (data from Barth, 1956; Byers, 1961; Coats, 1952, 1953, 1959; Coats et al., 1961; Fenner, 1926; Snyder, 1959), and the rocks of Nunivak are also alkalic (Hoare, oral communication, 1964).

Figure 9 shows the distribution of major volcanic cones in the northwestern United States. St. Helens and Shasta lie a little to the west of the central axis of the High Cascades, whereas Newberry and Modoc lie a little to the east. Craters of the Moon is situated farther to the east. The bulk of the High Cascades rocks appears to have been derived from high-alumina basalt magma, as shown in Figure 10. This is in harmony with the common occurrence of this type of basalt in this region, such as the Warner basalt. The rocks of St. Helens and Shasta are a little less alkalic than most of the rocks, whereas those of Newberry and Modoc are a little more alkalic. The rock of Craters of the Moon is decidedly more alkalic (data from Coombs and Howard, 1960; Powers, 1932; Williams, 1935, 1942).

Only a small number of analyses are available for the rocks of Central America. In Mexico, rocks of high-alumina basalt derivation occur in Paricutin Volcano and to the west, and more alkalic rocks occur east of Paricutin. Rocks of other Central American volcanoes are either of high-alumina basalt or tholeiite derivation (data from Wilcox, 1954; Mooser et al., 1958).

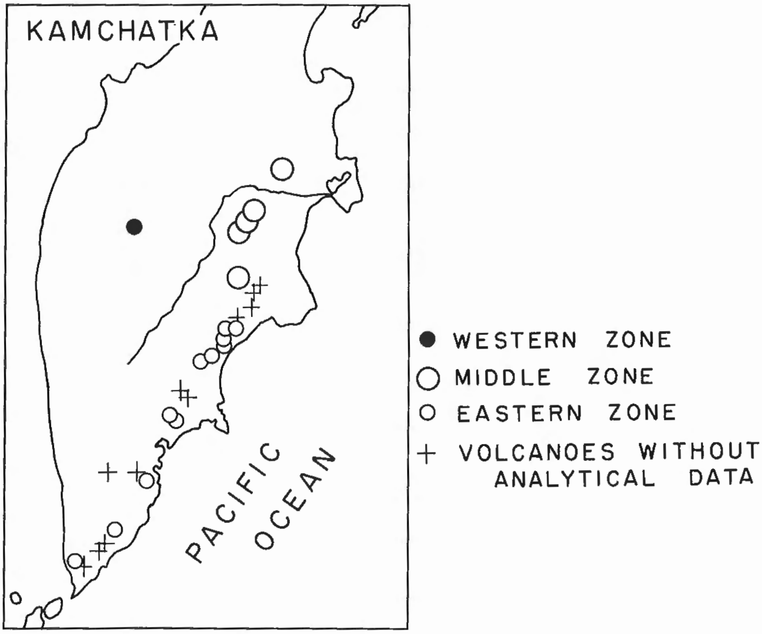

Figure 5. Distribution of active volcanoes in Kamchatka.

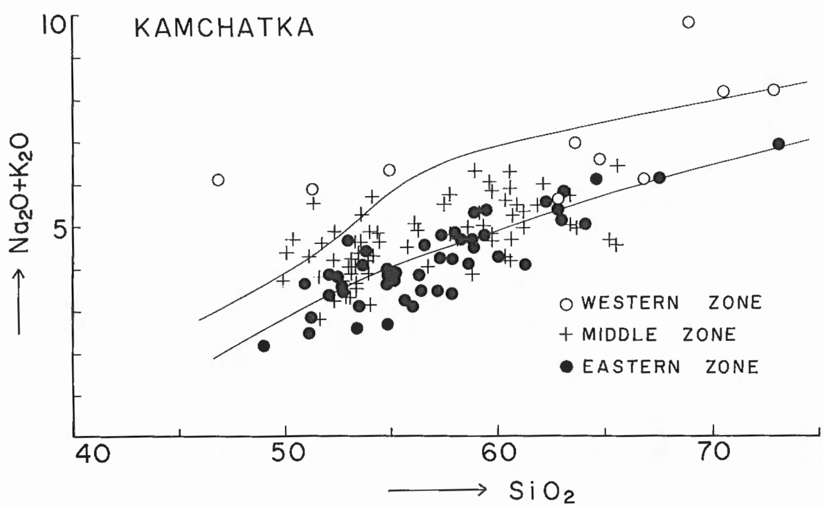

Figure 6. Total alkalies-SiO_2 relation in rocks of active volcanoes in Kamchatka.

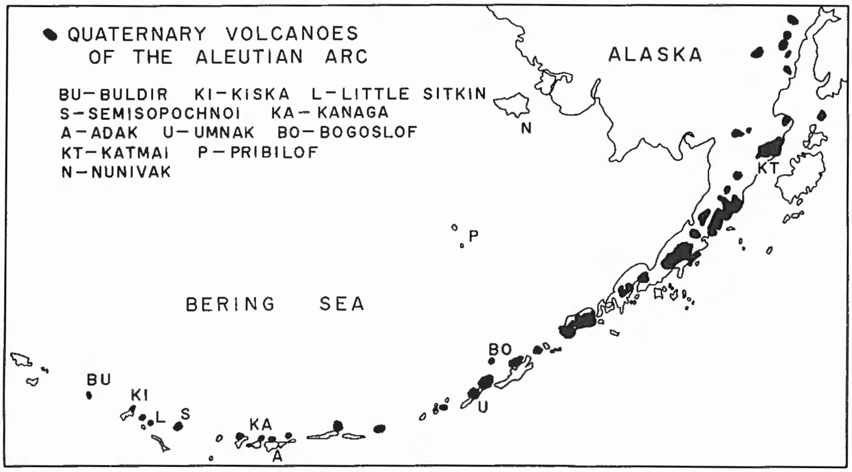

Figure 7. Distribution of Quaternary volcanoes in the Aleutian Islands and southwestern Alaska (Coats, 1962).

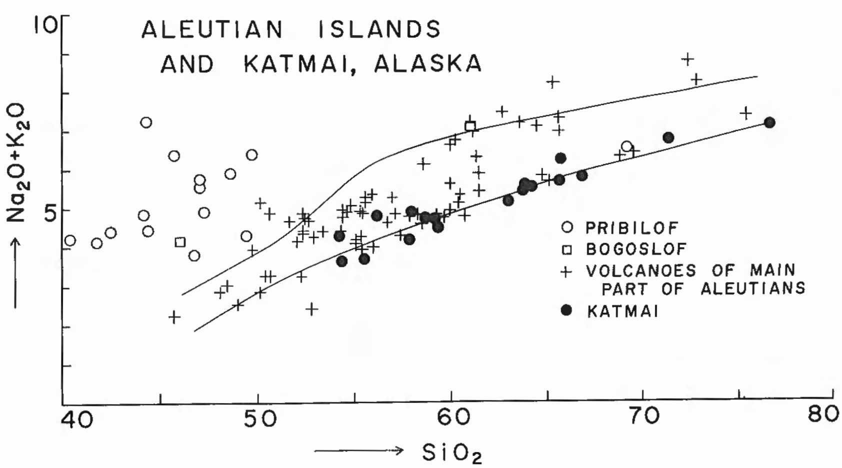

Figure 8. Total alkalies-SiO_2 relation in rocks of Quaternary volcanoes in the Aleutian Islands and southwestern Alaska.

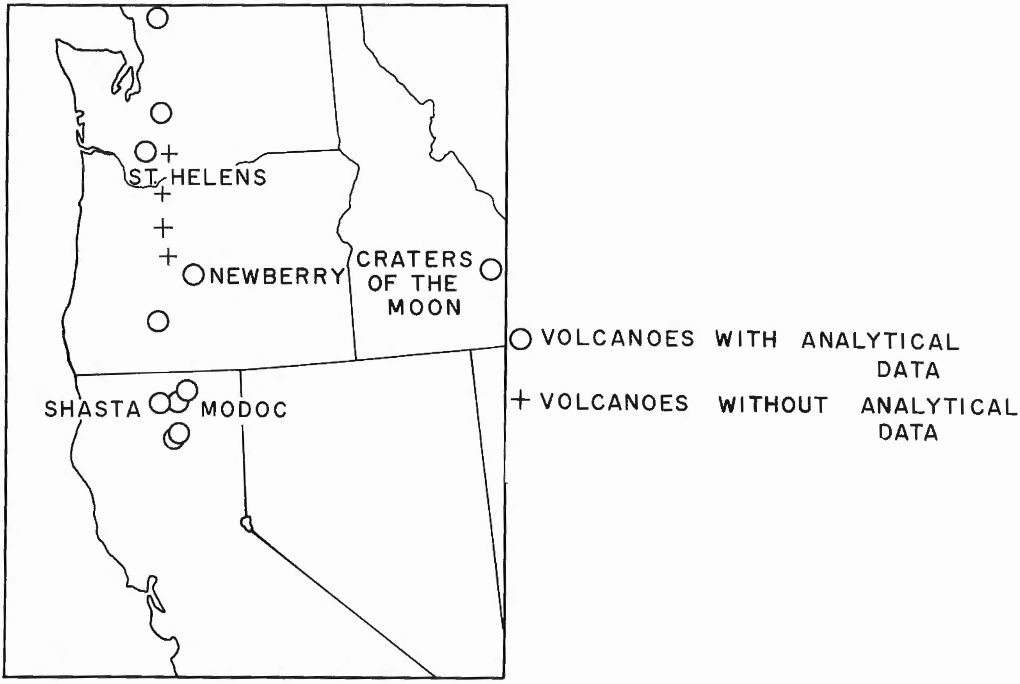

Figure 9. Distribution of Quaternary volcanoes in the northwestern United States.

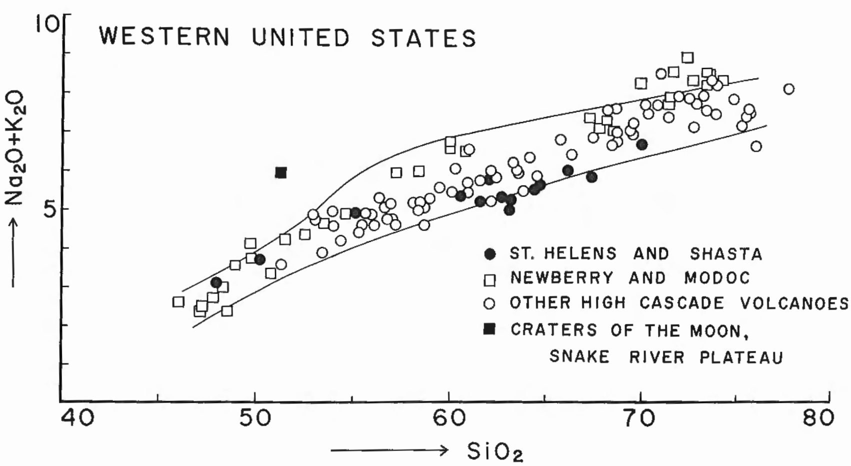

Figure 10. Total alkalies-SiO_2 relation in rocks of Quaternary volcanoes in the northwestern United States.

Rocks of Chilean volcanoes are mostly of tholeiite derivation (data from Casertano, 1963).

Although we have only a few analyses of rocks of the South Sandwich Islands, all are low in alkalies and are of tholeiite derivation (Tyrrell, 1945). In Antarctica, a lateral variation similar to that in the Aleutian Islands appears to exist, judging from scanty data (Tyrrell, 1945; Stewart, 1956).

On North Island of New Zealand, Cole (1965) found a variation of composition of volcanic rocks from less alkalic on the eastern side to more alkalic on the western side (near Auckland).

Rocks of the Tonga Islands (Richard, 1962) are all of tholeiite derivation and similar to the rocks of the Izu Islands (Fig. 11).

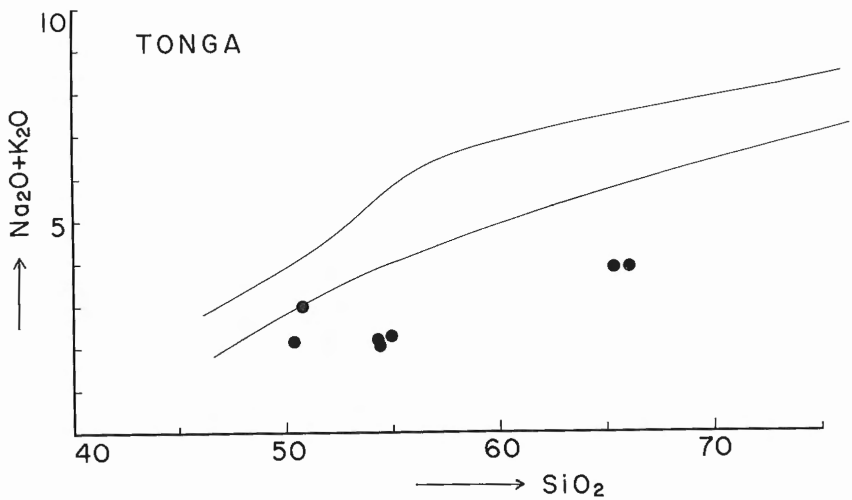

Figure 11. Total alkalies-SiO_2 relation in rocks of active volcanoes of the Tonga Islands.

Lateral variation of rock composition in Indonesian volcanoes has been pointed out by Rittmann (1953, 1958). The axis of the main volcanic zone passes from Sumatra to Flores and then northward to Halmahera (Fig. 12). Some volcanoes are located north of this axis in Java and Flores, and

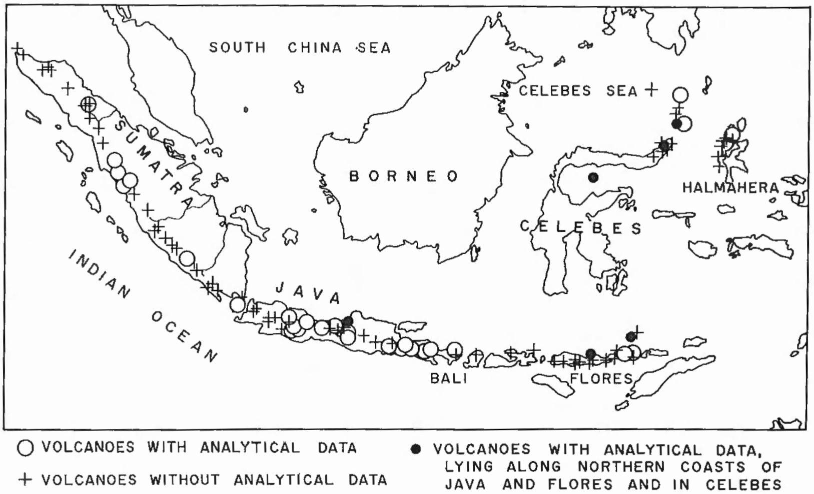

Figure 12. Distribution of active volcanoes in Indonesia.

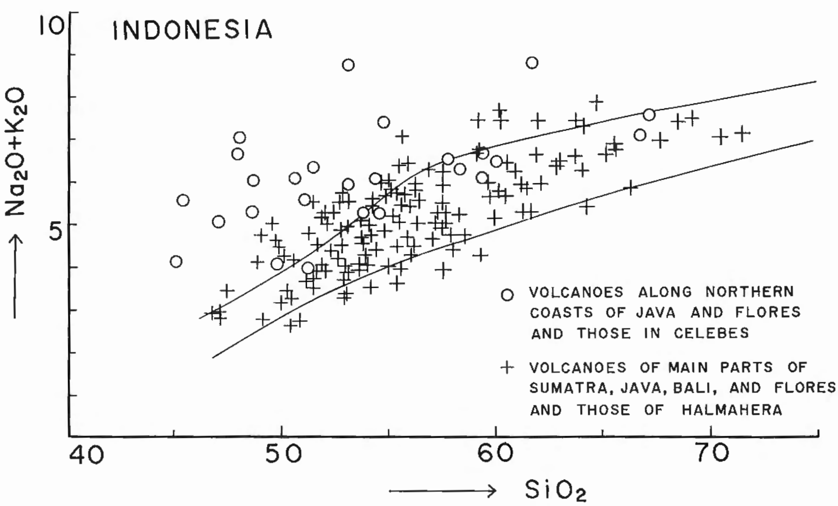

Figure 13. Total alkalies-SiO_2 relation in rocks of active volcanoes of Indonesia.

also in Celebes west of Halmahera. The rocks of the volcanoes in northern Java and Flores and in Celebes are strongly alkalic and sometimes contain leucite. But the rocks of the volcanoes of the main zone are mostly of high-alumina basalt derivation with intermediate alkali contents as shown in Figure 13 (data from Neumann van Padang, 1951). Little is known about the volcanic rocks of the Philippines.

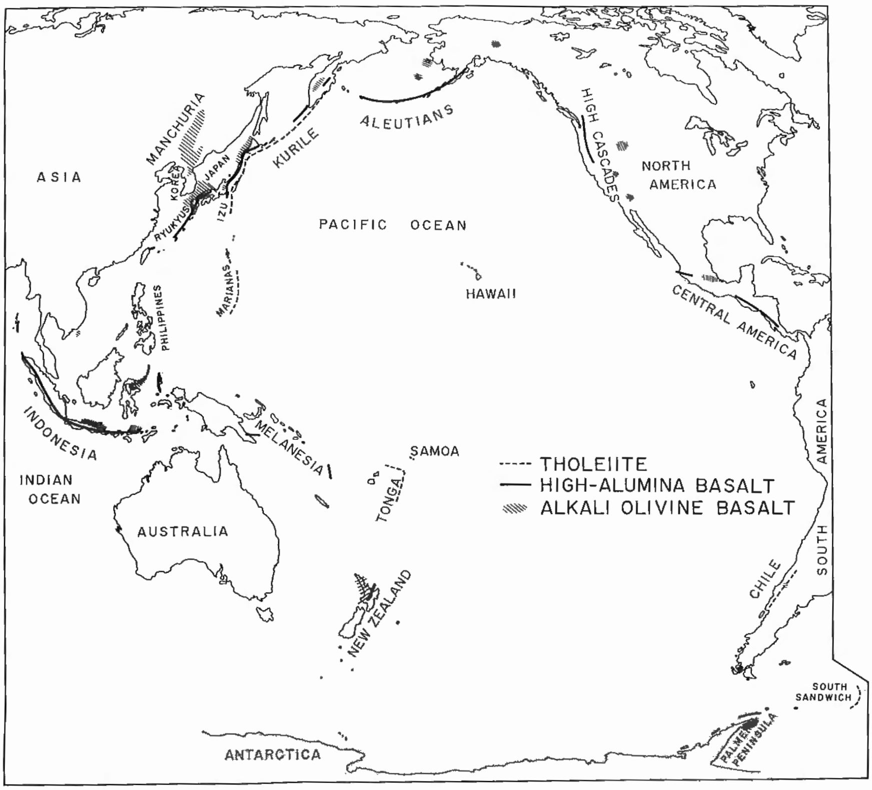

Figure 14. Regional distribution of the three basalt magma types in the Circum-Pacific belt and Indonesia.

Figure 14 summarizes the lateral variation throughout the Pacific Ocean and Indonesia. Two types of variation can be recognized: 1) in northeastern Japan and Kamchatka, zones of tholeiite, high-alumina basalt, and alkali olivine basalt are represented; and 2) in western Japan, the Aleutians, northwestern United States, Indonesia, and perhaps New Zealand, zones of only high-alumina basalt and alkali olivine basalt can be recognized. Tholeiite is the only magma available in the Izu-Mariana, Tonga, and South Sandwich Islands. These islands are bounded on both sides by deep oceans. It follows that the lateral variation of magma type is characteristic of the boundary between the oceanic and continental structures. The lateral variation probably originates from a lateral change of physical state from the oceanic to the continental mantle.

It should also be noted that the lateral variation is everywhere continuous, the zone of alkali olivine basalt being always in contact with that of high-alumina basalt and not with that of tholeiite. This implies that the process of basalt magma production changes continuously across the continental margin.

ORIGIN OF LATERAL VARIATION

Kuno et al. (1957), Kuno (1959), and Kushiro and Kuno (1963) suggested that partial melting of mantle peridotite produces tholeiite magma under low pressure, alkali olivine basalt magma under high pressure, and high-alumina basalt magma under intermediate pressure. Recent experiments by Yoder and Tilley (1962) and Kushiro (1964, 1965) also showed that tholeiite magma is produced under low pressure and alkali olivine basalt magma is produced under high pressure. However, the details of the process of producing the different basalt magma types are still uncertain.

According to Kuno and others, the different basalt magmas are produced independently and at different depths. This hypothesis was supported by a recent study of lead isotope ratios in these different basalt types (Masuda, 1964; Tatsumoto, oral communication 1964). The lead isotope ratios are different in these three types of basalt, and therefore they probably originated from different sources.

According to Yoder and Tilley (1962), on the other hand, olivine tholeiite, which is slightly more olivine-rich than SiO_2-oversaturated tholeiite, is produced by partial melting of garnet peridotite of the mantle at some depth, say, of 100 to 150 kilometres. If this magma undergoes fractional crystallization under low pressure, i.e. at shallow depth, it evolves to oversaturated tholeiite. But if the same magma undergoes fractional crystallization under high pressure, i.e. at great depth, it evolves to alkali olivine basalt.

Both hypotheses are consistent with experimental work by Kushiro (1965). Let us now examine how the two hypotheses explain the observed lateral variation.

Kuno (1959) drew attention to the relation between the distribution pattern of different basalt magma types and that of depth of earthquake foci in the Japanese Islands (Fig. 15). If Figures 1 and 15 are compared, it will be noticed that tholeiite occurs in a zone where earthquake foci are located at depths of about 100 kilometres, high-alumina basalt in zones of earthquake foci from 100 to 200 kilometres, and alkali olivine basalt in a zone of earthquake foci deeper than 200 kilometres. If the production of basalt magmas is genetically related to earthquake generation, this correspondence is in good agreement with the hypothesis of Kuno et al. (1959).

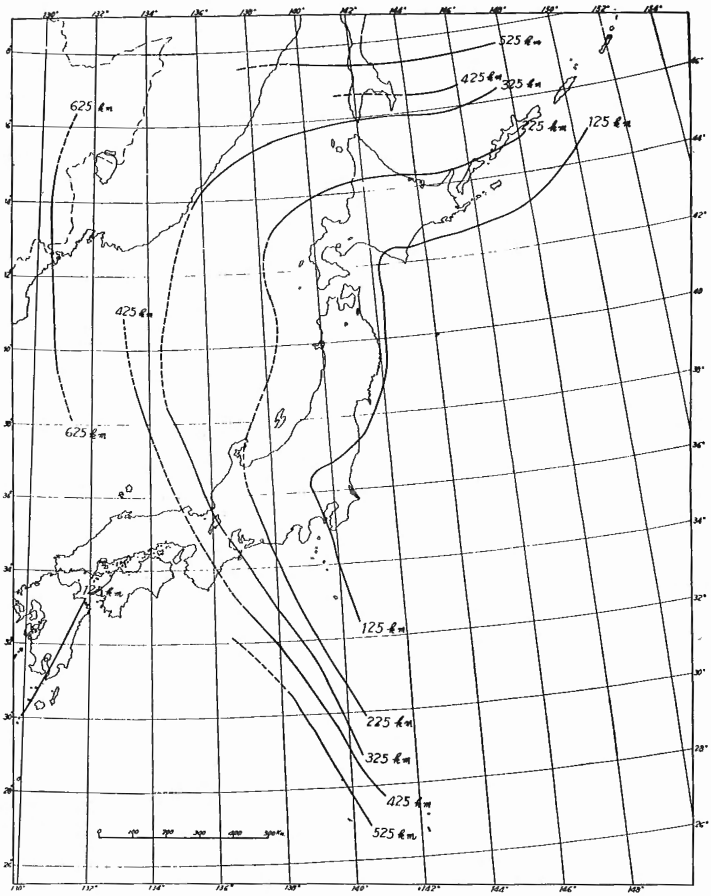

Figure 15. Average depths of earthquake foci in the mantle beneath the Japanese Islands (Sugimura, 1959).

Uffen (1959) discussed the relation between the mechanisms of earthquake generation and of magma production. He supposed that the rocks in the tabular zone of earthquake foci dipping toward the continent at its margin (as in Japan) are under compressive stress. Earthquakes are generated by stress relief due to compressive failure, which, in turn, causes partial melting of mantle peridotite to produce basalt magma. Thus basalt magma can be produced at the different levels where earthquakes are generated, resulting in different types of magmas depending on the pressure attending the partial melting. This idea is shown schematically in Figure 16.

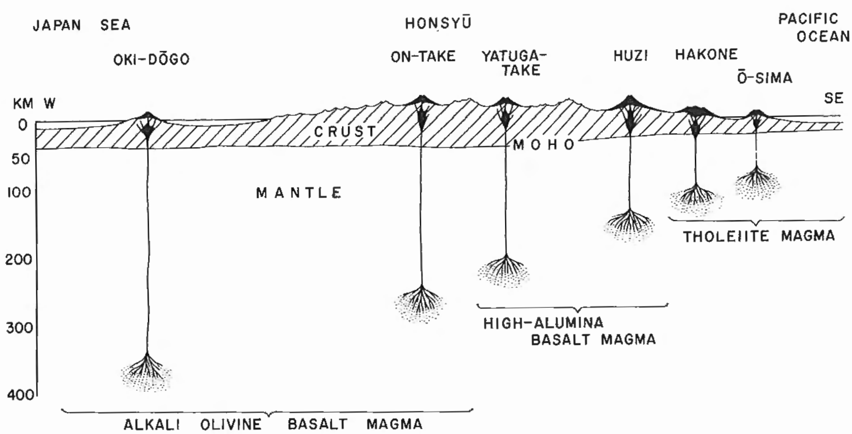

Figure 16. Schematic WNW - ESE cross-section through central Japan showing depths of magma production and of magma reservoirs, based on the hypothesis of Kuno et al. (1959).

An alternative suggestion is also offered. The temperature gradient in the upper mantle is supposed to be steeper under the ocean than under the continent (MacDonald, 1964). It follows that the temperature of initial melting of mantle peridotite would be reached at shallower depth under the ocean than under the continent. Thus the plane of initial melting would dip toward the continent, like the plane connecting the regions of basalt magma production illustrated in Figure 16.

If we accept Yoder and Tilley's (1962) hypothesis, the observed lateral variation may be attributed to different depths at which the primary olivine tholeiite magma undergoes fractionation. Thus, on the Pacific side of the Japanese Islands, the olivine tholeiite magma would rise to a shallow depth immediately after its production and there undergo fractionation in a reservoir to produce oversaturated tholeiite. On the continental side, however, the same olivine tholeiite magma would be stored in a reservoir close to its source region where it undergoes fractionation to evolve to alkali olivine basalt magma. High-alumina basalt magma would be produced in a reservoir at intermediate depth. This idea is illustrated schematically in Figure 17. No explanation can be offered at present as to why the olivine tholeiite magma should leave its source region immediately after its production on the Pacific side and why the same magma should be stored close to its source region on the continental side.

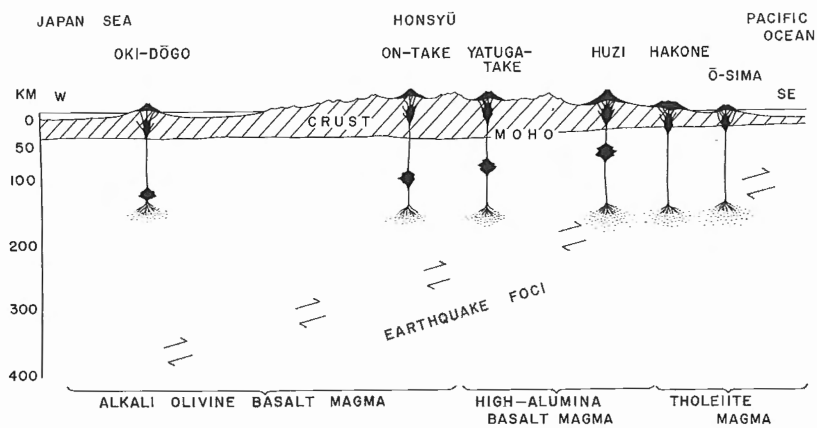

Figure 17. Schematic WNW - ESE cross-section through central Japan showing depths of magma production and of magma reservoirs, based on the hypothesis of Yoder and Tilley (1962).

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DISCUSSION

Dr. A.E. Ringwood (Australia)

I think Dr. Kuno has drawn attention to a very important relationship between the depth of earthquakes and the distribution of the different magma types at the earth's surface. However, I think that the causal relationship between these is very much more complex than he suggests. We have carried out a very large number of experiments on the generation of basalts under high temperature-pressure conditions. And we have been able to show fairly conclusively that the alkali olivine basalt magma can be generated only by fractionation processes taking place within a very limited depth-range. This process will not work at pressures less than 10 kilobars which is about 40 kilometres in depth, nor will it work at any pressure greater than about 21 or 22 kilobars which is somewhere around 80 or 90 kilometres. Thus, the process of generation of alkali basalts from an olivine tholeiite can only work in this very limited depth-range. Now, if you examine the distribution of earthquakes with depth, you see that the earthquakes where the alkali basalts are found occur at depths of about 300 kilometres. It is quite clear to us anyway, that the alkali basalts do not originate as deep as that. I am not saying that some sort of fundamental relationship does not exist, but the actual fractionation process, by which an alkali basalt forms, does not take place as deep as 300 kilometres.

Another point with regard to high-alumina basalt: it seems from our results that high-alumina basalt is formed in two very distinct depth ranges: 1) a very shallow type of fractionation occurs at pressures between 5 and 12 kilobars – that is about 20 to 40 kilometres deep; and 2) below 100 kilometres the equilibria are such that fractional melting processes again yield high-alumina basalt. Strangely enough you cannot make a high-alumina basalt by any process of fractionation between about 40 and 100 kilometres. Now I would suggest that Professor Kuno's high-alumina basalt indeed fractionates at a fairly shallow level but very much more shallow than the earthquake foci.

Also, I have a strong suspicion that the low-potassium, low-uranium tholeiites, which are becoming considerably important from a geochemical point of view and which are found on the mid-oceanic ridges, are nearly all high-alumina basalts. I believe that these are very deep and originate in the mantle – and indeed, may come from depths below 200 kilometres.

Prof. Kuno

High-alumina basalt is very common and very voluminous in the western part of the United States, as in western Washington and Oregon, and in northern California and Nevada. I do not know whether this high-alumina basalt, which is quite recent in age, was produced at very shallow depth, such as just at the Moho discontinuity, as Dr. Ringwood suggests, or at much deeper levels. This can be solved by studying the thermal structure of the crust and mantle of this region.

COMPOSITION OF PRIMARY MAGMAS AND SEISMICITY OF THE EARTH'S MANTLE IN THE ISLAND ARCS (A PRELIMINARY NOTE)[1]

Arata Sugimura
Geological Institute, University of Tokyo

Abstract

Chemical compositions of rocks of volcanoes fronting on oceanic trenches seem to be closely related to the seismicity of mantle earthquake zones. This relationship supports the hypothesis that primary magmas in the island arcs are generated at levels about 150 to 250 kilometres deep.

INTRODUCTION

It is well known that volcanic belts in island arcs are associated in space with mantle earthquake zones (Gutenberg and Richter, 1954). This association is assumed to indicate that they are genetically related. The main purpose of this paper is to provide additional material for the consideration of the nature of the genetic relation.

Island arcs and mountain arcs along continental margins are associated with a number of geophysical features. Both types of arcs form narrow belts in which geophysical characteristics are zoned relative to the arcs, that is, the arcs show a geophysical zonality. The geophysical features vary little along the arcs. Thus, zones of geophysical phenomena parallel the island arcs and can be depicted in a two-dimensional section across the arcs; and each of the phenomena is asymmetrically distributed with respect to the axes of the arcs (Sugimura, 1960). The "volcanic front" is defined as the border on the ocean side of a volcanic belt in an island arc; it falls along the axis of the arc. Along these fronts are the densest population of volcanoes. Towards the continental side of the fronts, the volcanoes become more and more sparse. On the oceanic side of the fronts not a single volcano is to be found.

SETTING OF THE PROBLEM

Primary magma of the volcanoes on the oceanic side of an island arc is rich in silica and poor in alkalies, and is usually called

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[1] Read by Prof. H. Kuno.

tholeiitic magma. In contrast, the primary magma of the volcanoes on the continental side of the arc is poor in silica and rich in alkalies, and is usually called alkali-basaltic magma.

Furthermore, the depth to the seismic plane below the volcanoes derived from tholeiitic primary magma is about 150 kilometres, whereas that below the volcanoes derived from alkali-basaltic primary magma is from 200 to 250 kilometres. This relationship supports the hypotheses, first, that the generation of primary magmas and the occurrence of intermediate (70 km $\leqq$ depth $<$ 300 km) earthquakes have a common source of energy and, second, that the primary magmas are generated in the mantle earthquake zone.

Temperatures within the upper mantle at depths of about 130 to 250 kilometres may be close to the melting points of mantle material at the corresponding levels (Shimozuru, 1964). The island arcs are not an exception to this universal charcteristic. Thus, deeper than 130 kilometres (horizontal dashed line in Fig. 1) in the mantle, the temperature being very near the melting point, even a relatively small amount of energy generated along the seismic plane will produce magma. At shallower depths, much greater increases in temperature are necessary to bring about the formation of magma. It would seem that where the required energy supply associated with the seismic plane does not occur down to the 130-kilometre level, no parent magma will be produced. In the cross-section of Figure 1, the point representing the intersection of the inclined line marking the maximum depth of the earthquake foci and the 130-kilometre depth line lies directly beneath the volcanic front.

From the preceding discussion, one may make the following predictions. First, it is assumed that the amount of energy required for the local temperature increases and for the occurrence of intermediate earthquakes differ from one island arc to another. If the energy supplied to the mantle earthquake zone in island arc "A" is more than that in island arc "B", then the increase in temperature along the seismic plane will be larger in "A" than in "B". It follows that the range of depth in which the magma is generated will be greater in "A" than in "B". The shallowest depth of the magma-generation zone, just under the volcanic front, will be closer to the surface under island arc "A" than under "B".

It is suggested that a tholeiitic basalt magma will be produced at shallower depths or lower pressures, and an alkali-basaltic magma at greater depths or higher pressures (Kushiro and Kuno, 1963). In other words, the shallower the locus of magma-generation, the more siliceous and the less alkaline is the resulting primary magma.

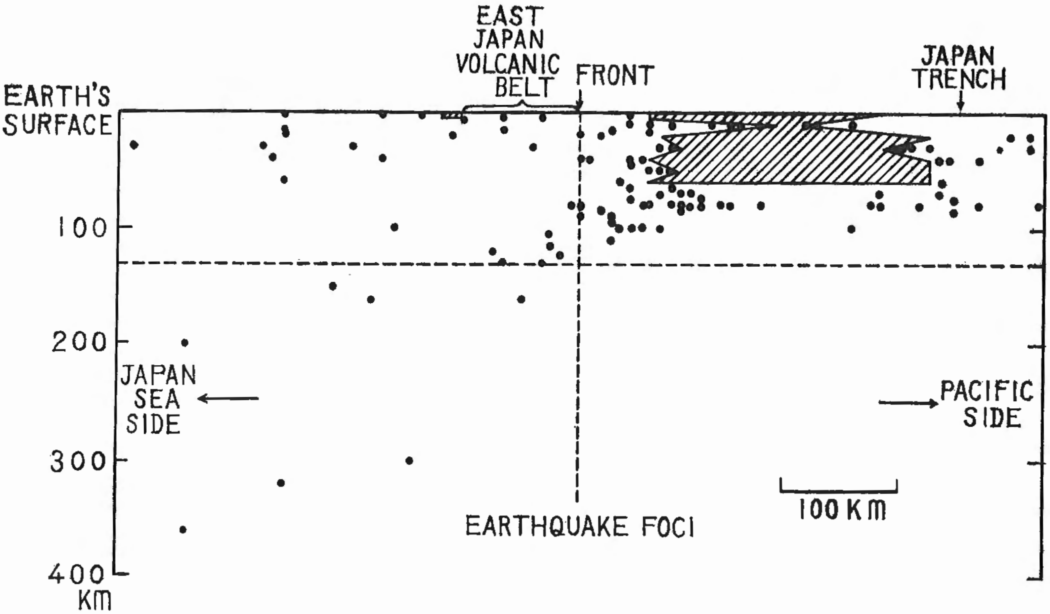

Figure 1. Cross-section through eastern Japan showing distribution of earthquake foci at latitudes 38° to 41°N with no vertical exaggeration. The black dots represent earthquake foci and the hatching their region of concentration.

Thus, the most siliceous primary magma for each arc will be more siliceous in island arc "A" than in island arc "B". We may expect that the primary magma of the volcanic front of "A", where the larger amount of heat energy is supplied, is more siliceous than that of the front of "B".

DATA

If one accepts that fractional differentiation and (or) contamination of basaltic magma leads to an increase in the molecular ratio $(Na_2O + K_2O)/Al_2O_3$, a plot of the weight percentages of oxides against this ratio provides a method of estimating the chemical nature of the primary magma. As in the variation diagrams in which albite ratios are plotted against SiO_2 weight percentage on the ordinate (Wager, 1956, p. 234), a better chemical discrimination between tholeiitic basalt magmas and alkali-basaltic magmas was obtained (Sugimura, 1960).

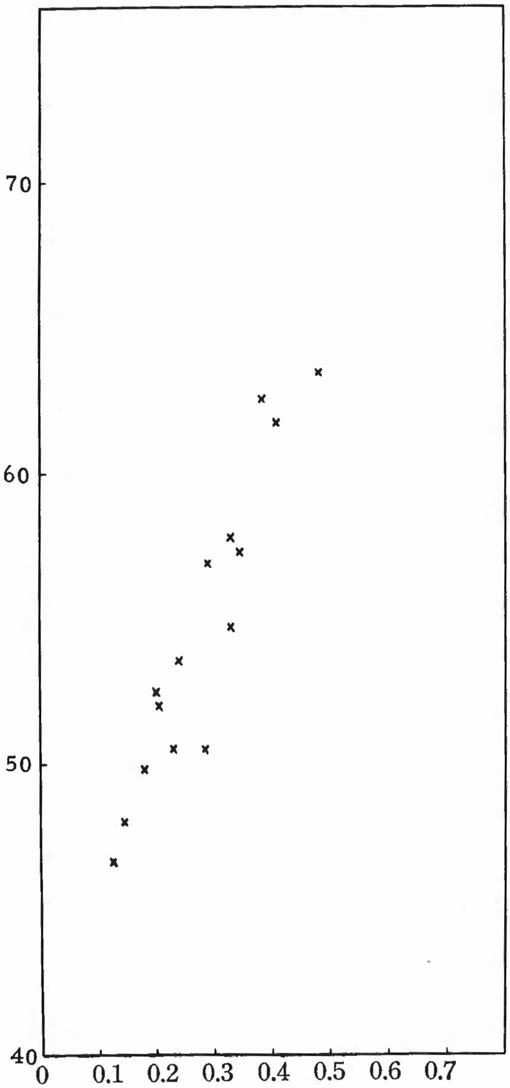

Figure 2. Graph of SiO_2 in weight per cent against the ratio $(Na_2O + K_2O)/Al_2O_3$ in molecular proportions, for Hatizyô volcano. Data are derived mostly from Isshiki (1959), and partly from N. Isshiki (pers. comm., 1957).

Such diagrams were drawn for a score of volcanoes in Japan; that for one is shown in Figure 2. A linear relation was revealed for many of the volcanoes. The data, therefore, were treated statistically. The regression lines $SiO_2 = \underline{a} + \underline{b}\,(Na_2 + K_2O)/Al_2O_3$ have been fitted to the data from each of these volcanoes. A common value of $\underline{b} = 47$, within the limits of the standard errors of estimate, was obtained for all volcanoes. It indicates that the trend lines for these volcanoes have a common slope; they are nearly parallel.

On the other hand, the values of a become progressively and significantly larger as the rocks become more siliceous. Thus, the value of a can be used as an index of how siliceous the primary magma was. The writer has named the value a the θ index, in which the symbol θ stands for the word "tholeiite". θ is therefore computed according to the formula:

$$\theta = SiO_2 - 47\,(Na_2O + K_2O)/Al_2O_3$$

where SiO_2 is in weight per cent and the other oxides in molecular proportion.

Recently Yen (1963) prepared a map of the θ index values for Quaternary volcanoes along the arcs from Indonesia through to Taiwan, Japan, and the Kurile Islands (Fig. 3). It represents one method that indicates the petrological trend in which volcanic rocks on the continental side of island arcs are shown to have originated from alkali-basaltic magmas and those on the oceanic side to have originated from more siliceous magmas. The θ index for the volcanic front is the highest for the rocks of a particular island arc and is almost constant along the front (Fig. 4).

It follows from the discussion in the preceding section that the θ index of primary magma at a volcanic front would indicate where magma is generated at the shallowest depth, and at the same time the relative amount of energy delivered along the seismic plane in the island arc. The table shows a positive correlation between θ index for the front and seismicity of the mantle for island arcs.

CONCLUSIONS

The positive correlation shown in the table is consistent with the hypothesis given in the preceding section. Thus, the locus of magma generation would be at the same level as that of a part of the mantle earthquake zone, and the source of energy of magma generation is probably genetically related to the mantle earthquake occurrence.

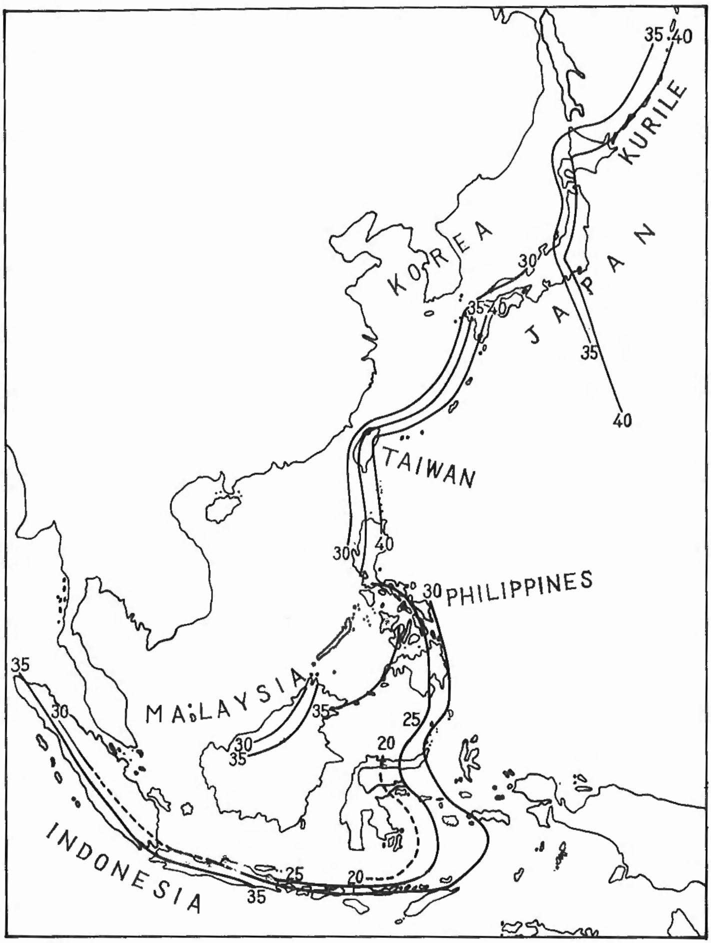

Figure 3. East Asia showing contoured values of petrochemical index θ of Quaternary volcanoes. After Yen (1963)

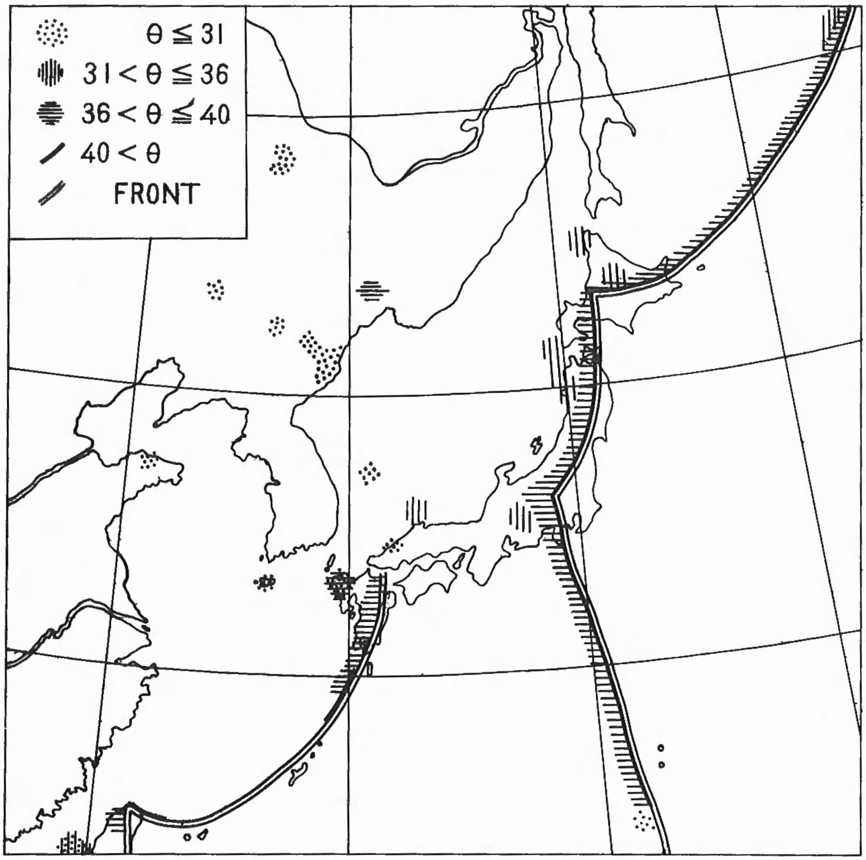

Figure 4. Volcanic rocks of Japan divided into petrographic provinces defined by θ index. Revised from Sugimura et al. (1963).

Table

θ Index and Seismicity of the Mantle

Region	$\bar{\theta}$ for the Front[1]	Frequency of Mantle Earthquakes[2]
1. Tonga	42.0	0.19
2. Kurile and Kamchatka	41.6	0.17
3. Marianas and East Japan	41.8	0.09
4. Central America	38.1	0.08
5. Indonesia	36.0	0.06
6. Taiwan and West Japan	38.9	0.05
7. Aleutian and Alaska	37.5	0.05

[1] $\bar{\theta}$ is the average of θ's for frontal volcanoes; and the θ for each volcano is in turn the average value of θ's for rocks having $(Na_2O + K_2O)/Al_2O_3 < 0.40$. Analyses from 1. Richards (1962); 2. Gorshkov (1958) and Vlodavetz and Piip (1959); 3. and 6. Sugimura (1963); 4. Mooser et al. (1958); 5. van Padang (1951); and 7. Byers (1961), Coats (1952, 1959), Coats et al. (1961), Drews et al. (1961), and Snyder (1959).

[2] The numbers indicate the annual number of deep and intermediate earthquakes with the magnitude $\geqq 7.0$, per 1,000 kilometres of the volcanic front for the period 1919 to 1952. Based on a table by Gutenberg and Richter (1954).

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DISCUSSION

Someone asked what Dr. Sugimura thought is the thickness of the layer where the magma is produced.

Prof. Kuno

I do not know his ideas. He appears to suppose that generally the low-velocity layer is fairly thin. But he doesn't mention anything about the thickness.

Dr. A.E. Ringwood (Australia)

If I could just comment once more on this relationship between the depth of an earthquake focus and the depth at which a magma is generated. To a petrologist, the depth at which a magma is generated essentially refers to the depth at which a large body of liquid molten material segregates from its crystals. To an experimentalist this is also the depth at which we would say a particular magma cooled by crystal liquid fractional processes which we can study in the laboratory. Now, this is one definition of the depth of origin of a magma. But I do not believe that this is simply related again to the earthquake foci. I think that this depends on the way in which we believe magmas are formed. I would suggest that an alternative way to look at this is to regard the earthquake foci as indicating a region of instability in the mantle, which marks a place at which a large volume or blob, something like a salt dome, which is completely solid, starts to move upwards in the mantle where, of course, the adiabatic gradient is much smaller than the melting point gradient. This means that at some higher level above the earthquake foci in the mantle, this blob is going to start fractionally melting. And then, depending on its degree of superheat, there will be some critical level at which the crystals start to separate from the magma and we get a magma as we realize it. So, I do not think there is necessarily an inconsistency. I think the relationship that you showed us between the depth of the foci and the chemistry of the lavas is important, but I think it is important also to define what we mean by the depth of origin of a lava, because there are two distinct processes occurring here.

Prof. Kuno

I think that Dr. Ringwood has pointed out a very important matter. However, I have two points which should be considered first. One is the chemical and mineralgoical composition of the upper mantle material – whether it is a peridotite or garnet peridotite – and also what is the chemical composition of the rock. I know that Dr. Ringwood postulates a certain kind of peridotite which he named pyrolite, which is a mixture of three parts dunite and one part ordinary basalt. If this kind of peridotite is subjected to partial melting, it produces basaltic magma.

The second point which we should consider is what is a primary magma? Or what is the chemical composition of the magma which is generated by partial melting of the peridotites? I think there are two schools of thought. I postulate that some primary magma is fairly olivine-poor, such as the chilled margin of the Muskox Intrusion, the chilled margin of the Palisade diabase, and the most basic basalt of the Japanese Islands. Such tholeiite is just saturated if we calculate the C.I.P.W. norm. Another school appears to postulate a slightly different kind of basaltic magma. For instance, Yoder and Tilley sometimes say that the primary magma has a composition of olivine tholeiite, containing about 5 per cent normative olivine, such as the olivine tholeiite of the Kilauea volcano. But in some other parts of their paper they appear to postulate picrite basalt magma which is very rich in olivine. So the discussion regarding the genesis of basaltic magma solely depends on what kind of chemical composition we postulate for the primary magma.

ORIGIN OF THE VOLCANIC ROCKS OF EUGEOSYNCLINES AND ISLAND ARCS[1]

Warren Hamilton
U.S. Geological Survey

Abstract

The volcanic rocks which characterize eugeosynclines now parts of the continents are dominantly tholeiitic basalts in some instances, and andesite, dacite, and high-alumina basalt in others. Either type can occur upon crust previously either oceanic or continental. The modern analogue of the oceanic tholeiitic eugeosyncline is the floor of the ocean along a continental margin, whereas the analogue of the oceanic andesitic eugeosyncline is the island arc.

High-pressure laboratory data demonstrate that at pressures less than that of the transformation of gabbro to eclogite, most of the plagioclase of mantle rock melts before pyroxene, and that the complete melting of both minerals occurs over a broad temperature range. At pressures greater than that of the eclogite transformation, pyroxene and garnet melt together over a narrow range. As high-alumina basalt differs from tholeiite primarily in its greater content of plagioclase, it is probable that high-alumina magma was equilibrated with crystals at depths shallower than that of the eclogite transformation, whereas tholeiite was equilibrated deeper than the transformation. The andesitic suite of magmas may represent widely varying degrees of partial melting of the basaltic component of mantle rock at levels shallower than the eclogite boundary, whereas the tholeiitic magmas may be produced by more complete melting of the basaltic component beneath that boundary. Alternatively, if the erupted magmas are products of the differentiation of more basic magma at depth, then the andesitic suite must differentiate at depths shallower than the eclogite transformation. Assimilation by zone refining may have profoundly modified initially basaltic magmas to produce the more silicic magmas.

TECTONIC SETTING

Eugeosynclines characteristically contain volcanic rocks, and can be separated into at least two major types on the basis of the kinds of igneous rocks present. Many eugeosynclinal terranes contain andesite,

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[1] Publication authorized by the Director, U.S. Geological Survey.

dacite, and high-alumina basalt, spilitized to varying degrees. The upper Palaeozoic and lower Mesozoic eugeosynclinal assemblage of western Idaho and northeastern Oregon exemplifies this type (Hamilton, 1963, Fig. 43). Many other eugeosynclinal suites contain tholeiitic basalt as their sole or dominant igneous rock; high-alumina basalt may be present also, but more silicic rocks are scarce or lacking. The Jurassic and Cretaceous Franciscan Formation of coastal California (Bailey et al., 1964, Table 4) is an example of such an assemblage.

Andesite, dacite, and high-alumina basalt also characterize modern island arcs where subaerial rocks show little alteration, but older, uplifted submarine rocks have been variably spilitized and are compositionally indistinguishable from the andesitic eugeosynclinal assemblages now parts of the continents. The submarine volcanic rocks of the Aleutian Islands (Hamilton, 1963, Fig. 66), for example, appear identical in compositional and distributional parameters to the much older eugeosynlinal suite of western Idaho. Island arcs form across oceanic crust; it follows that the mantle beneath oceans can yield these aluminous and relatively silicic rocks under the localized tectonic conditions which produce the arcs. As many writers have suggested, it is highly probable that oceanic, island-arc vulcanism produces much eugeosynclinal material which can be incorporated tectonically into the continents.

The tectonic nature of island arcs and associated trenches has been the subject of an extensive literature which will not be reviewed here. Conflicting hypotheses variously invoke tension, compression, strike-slip faulting, motion toward or away from nearby continents, and stability in geographic position. The writer prefers the explanation that the existing island arcs of the Pacific Basin are moving oceanward, away from nearby continents which are also moving oceanward but at a slower speed.

Tholeiite is generally only a minor component of the volcanic products of modern island arcs, and hence eugeosynlines characterized by tholeiite have no analogue in island arcs; some other tectonic environment must be sought. The apparent modern analogue for some tholeiitic eugeosynclines is the floor of the present ocean along continental margins where neither island arcs nor trenches are present. Modern ocean-floor volcanic rocks are dominated by tholeiite, and high-alumina basalt is much subordinate (Engel and Engel, 1963; Nicholls, 1965). The Franciscan terrane of California contains such volcanic rocks and consists mostly of greywackes derived from metamorphic source-rocks and deposited by turbidity currents in water of fully oceanic, but not trench, depths (Bailey et al., 1964, p. 36, 67, 77); a probable analogue is in the turbidite fans extending oceanward from the base of the present continental slope along the western United States. Such ocean-floor eugeosynclinal materials, like island-arc products, can become welded tectonically to the continents.

Some eugeosynclines, such as the Appalachian one, contain both tholeiitic and andesitic volcanic suites in different regions, or even at different stratigraphic levels in one region. Some eugeosynclines of both tholeiitic and andesitic types form upon continental crust, although such a base cannot be a prerequisite for either type of vulcanism. Batholithic intrusions are widespread in andesitic eugeosynclinal terranes, and occur also in miogeosynclinal and unstable-platform settings, but perhaps are lacking in tholeiitic eugeosynclinal terranes except where they long postdate the tholeiitic vulcanism.

COMPOSITION

The rocks of the andesite-dacite-basalt suite are typically high in alumina. Plagioclase phenocrysts and orthopyroxene are common. Compositions of the volcanic rocks in most provinces show a broad frequency distribution, with a mode and an average composition in the andesite range; some show a secondary mode in the rhyodacite range (Peck et al., 1964, Fig. 31). Tholeiite suites, by contrast, show a narrow frequency distribution. High-alumina basalt differs from tholeiite in being markedly lower in magnesium, iron, and titanium, and markedly higher in sodium and aluminum (Table, cols. 1 and 2)[1]. Bulk composition of the high-alumina suites of island arcs and analogous eugeosynclines is approximately that of basaltic andesite (col. 3). The composition of high-alumina basalt (col. 2) is equivalent to a combination of tholeiite plus calcic plagioclase (col. 5), and that of basaltic andesite (col. 3) is approximately equivalent to tholeiite plus sodic plagioclase (col. 6).

Eugeosynclinal basalt in many suites has been converted in varying degrees to spilite, and andesite and dacite to keratophyre. The fact that the clinopyroxenes in such sodic rocks are normal augites and pigeonites, and are not sodic, demonstrates that the rocks crystallized from calc-alkaline magmas, and that the process of spilitization is not a magmatic process (Wilcox, 1959); therefore, spilitization need not be considered with the problems of the origin of the magmas.

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[1]See Macdonald and Katsura (1964) for examples of ocean-island tholeiites, and Engel et al. (1965) for examples of ocean-floor tholeiites, differing from the average tholeiite cited in the Table. Engel et al., however, designate as "tholeiite" those basalts containing as much as 19 to 22 per cent Al_2O_3; these rocks are better classed as high-alumina basalt.

Table – Chemical composition, in weight per cent, of average tholeiite (Nockolds, 1954, p. 1021), high-alumina rocks of the Aleutian Islands (scaled at SiO_2 values specified from Hamilton, 1963, Fig. 65), and of calculated combinations of average tholeiite plus plagioclase.

	Tholeiite	High-alumina association			Calculated combinations	
		Basalt	Basaltic andesite	Dacitic andesite	75% tholeiite + 25% An_{65}	65% tholeiite + 35% An_{25}
	1	2	3	4	5	6
SiO_2	50.8	51	56	61	51	55
Al_2O_3	14.1	18	17	16.5	18.1	17.4
Iron as FeO	11.7	9	8	6	8.8	7.6
MgO	6.3	5	3.5	2.5	4.7	4.1
CaO	10.4	11	8	6	11.0	8.3
Na_2O	2.2	3	3.5	4	2.7	4.4
K_2O	.8	.7	1	1.5	.6	.5
TiO_2	2.0	1	1	<1	1.5	1.3

MAGMAGENESIS

Both the tholeiitic and andesitic magma assemblages are obviously generated in the upper mantle rather than in the crust, at least in the ocean-floor and island-arc environments. Evidence from converging lines of research suggests that the upper mantle consists largely of rock having the composition of basalt plus magnesian olivine, and that the basaltic portion of this material takes the form of diverse mineral assemblages controlled by temperature and pressure conditions and volatile content, whereas the olivine is generally stable. Laboratory studies (Yoder and Tilley, 1962; Cohen et al., 1965; and others) of mafic rock systems under pressures and temperatures appropriate to those of the upper mantle provide a basis for inferences regarding the origin of different magmas from source rocks of probably much more uniform bulk composition.

The behaviour at high pressures of rocks and liquids of basaltic composition is illustrated by the Figure. At pressures less than that of the transformation to eclogite, gabbro melts or crystallizes over a wide temperature range and, except at very low pressures, plagioclase is a markedly lower temperature mineral than is clinopyroxene. At pressures greater

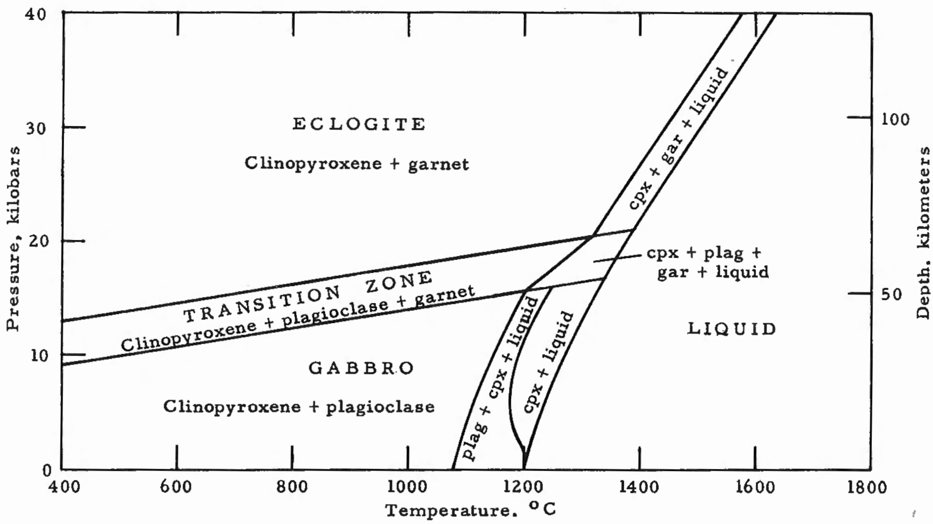

Figure Pressure-temperature phase relationships in material of anhydrous basaltic composition. The data plotted are those of Cohen et al. (1965), with additions consistent with the data of Yoder and Tilley (1962). Olivine or orthopyroxene or both would be present in rocks of appropriate compositions (the liquidus and solidus curves are in fact those of olivine tholeiite), but are not illustrated here. Abbreviations: cpx, clinopyroxene; gar, garnet; plag, plagioclase.

than that of conversion to eclogite, garnet and clinopyroxene melt or crystallize more or less together, and over a much narrower temperature range. (As olivine is more refractory than these other minerals, it will be little affected by partial melting in either pressure environment.)

It follows from these relationships that high-alumina magmas are equilibrated with crystals at depths shallower than that of the eclogite transformation, whereas tholeiite magmas are equilibrated at depths greater than that of the transformation. This equilibration might represent any combination of partial melting, partial crystallization, or assimilation.

The contrast in the melting behaviour of gabbro and eclogite at pressures comparable to those of the upper mantle led the writer (Hamilton, 1964) to suggest that narrow-spectrum tholeiite is the product of nearly complete melting of the garnet and pyroxene of mantle rock at depths below that of the eclogite transformation, whereas the broad-spectrum andesitic suite is the product of widely differing degrees of partial melting of plagioclase and pyroxene above the eclogite boundary. The more complete the melting of plagioclase and pyroxene, the more calcic and basaltic will be the resulting liquid. For either the tholeiitic or the high-alumina assemblages, the resulting magmas represent melting over only a few tens of degrees centigrade (Figure). Similar explanations have been presented by Lidiak (1965) and Nicholls (1965).

The character of the final erupted magma depends upon both the depth of melting and the depths of fractional crystallization during ascent, as O'Hara (1965) emphasized. The composition of the liquid erupted is controlled by the pressure at which the liquid was last in equilibrium with crystals, and this pressure need not be that of initial melting. The course of crystallization, like that of melting, is a function of depth, so differentiation follows different trends at different depths, and the residual magma at each level represents a low-temperature liquid at that depth.[1] If the aluminous magmas are produced by differentiation, then that differentiation must occur at depths shallower than that of the eclogite transformation. Further complications must be produced by variations in such factors as the partial pressures of water and oxygen.

Tholeiites erupted above sea-level, whether on oceanic islands or on continents, differ from ocean-floor tholeiites in generally having, for example, more potassium. Such contrast may be due to factors such as the rising of potassic fluids in high-standing magma columns under the influence of pressure and temperature gradients. The importance of such processes in basaltic differentiation was discussed elsewhere (Hamilton, 1965, p. 63-68).

Assimilation of crustal material through which mantle-generated basaltic magma rises may profoundly affect the composition of the final erupted magma. Dickson's (1958) zone-melting mechanism must operate to modify magma composition and may be the most important process

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[1]O'Hara explains high-alumina basalt as a product of progressive differentiation at decreasing depth of initially picritic magma generated deep in the mantle; but he explains andesite as a product of wet melting high in the mantle, and dacite as a differentiate of andesite. Perhaps his explanation for high-alumina basalt is applicable to the ocean-floor rocks, where such basalt is less common than olivine tholeiite and where more silicic rocks are virtually lacking. To postulate unrelated origins for high-alumina basalt and for andesite closely associated with it in island arcs and eugeosynclines, however, does not appear reasonable.

producing silicic magmas in island arcs and eugeosynclines. Any magma chamber must be vertically graded in composition in response to pressure differentials, with water and the most-volatile components being concentrated high in the chamber. This must result in raising the freezing temperature and in crystallization of refractory minerals low in the chamber, and in lowering the melting temperature and in assimilation of the roof rocks of the chamber. As a magma rises this process will result in progressive change in composition of the liquid toward the components with the lowest melting temperatures for the pressure involved. The final result could be a magma whose material had been derived almost wholly from assimilated crustal rocks through which the constantly changing magma rose; only the energy packet and some of the more volatile components of the original magma need make the entire trip from mantle to surface. The liquid-solid equilibration by assimilation, as by either partial melting or fractional crystallization, must occur shallower than the eclogite transformation. The granitic magmas of batholiths also might form by zone-refining assimilation of crustal rocks in mantle-generated magmas of initially basic compositions.

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DISCUSSION

Prof. H. Kuno (Japan)

Would you explain your interpretation of the relationship between the structure linking the North American and South American continents, and the origin of high-alumina basalt and tholeiite?

Dr. Hamilton

Laboratory data permit the explanation that high-alumina andesite, basalt, and dacite magmas form from mantle material. Tectonic and geophysical arguments suggest that these magmas are erupted across segments of oceanic crust as well as continental crust, and that high-alumina magmatism can form bridges of new continental crust across regions of prior ocean. Such a bridge apparently connects North and South America by way of Costa Rica and Panama, and similar bridges are perhaps being formed along the island arcs of the Lesser Antilles and the South Sandwich Islands.

Prof. H. Kuno

I would like to point out that the most important difference between tholeiite magma and high-alumina basalt magma is the higher percentage of normative olivine in high-alumina basalt. High-alumina basalt, such as the Warner basalt of California, and similar rocks in western Oregon and Japan, and the chilled margin of Skaergaard, all contain about 3 per cent normative olivine. But ordinary tholeiites usually contain less than 5 per cent normative olivine, and many are over-saturated. According to my understanding, you propose that high-alumina basalt magma is produced at shallower depths than tholeiite magma. If the pressure is lower for the production of high-alumina basalt, then we expect the existence of incongruent melting of enstatite. But if the pressure increases, the incongruent melting of the enstatite disappears. By this means, we should have oversaturated liquid under lower pressure but undersaturated basaltic magma containing normative olivine under higher pressure. But high-alumina basalt, according to your interpretation, is produced at shallower depths than tholeiite. This is just the reverse of the indications of the content of normative olivine.

Dr. Hamilton

High-alumina basalt occurs primarily as the low-silica member of a rock suite dominated by andesite and containing abundant dacite. The most mafic high-alumina basalts do contain normative olivine, but the more silicic high-alumina basalts contain normative quartz instead, as of course do all of the andesites and dacites. Dr. Kuno's hypothesis that incongruent melting of enstatite produces high-alumina rocks thus cannot apply to the abundant andesitic rocks. Even the most mafic high-alumina basalts have compositions that cannot be explained in terms of the addition of the components of olivine to tholeiite: such a combination would have lower calcium and aluminum than does tholeiite, rather than the reverse as is actually the case, for example.

STRUCTURE OF CONTINENTAL MARGINS AND DEVELOPMENT OF OCEAN TRENCHES[1]

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Abstract

The transition from continent or island ridge to ocean basin occurs in a distance of about 100 to 150 kilometres. The crustal thickness beneath continents and island ridges is normally about 20 to 30 kilometres and thins to oceanic crustal thicknesses of 5 to 7 kilometres with the most abrupt change occurring beneath the 2,000-metre contour.

Trenches normally form in this transition zone along the coast of continents and island ridges, although there are many coastal margins where no trench has formed. The thinning of the crust on the seaward side of many trenches indicates extensional forces are involved with moderate extensions of only a few kilometres. The trench is formed either by graben faulting, or by normal faulting on the landward side and a flexure on the seaward side. Downdropping the trench block by 2 to 4 kilometres produces the topographic and gravitational features of the trench. The shape of the trench is controlled by the shape of the coastal margin along which this process occurs.

The formation of a trench can be contemporaneous with the development of the nearby coastal margin, but in many cases it is probably a much later development. It is believed that such a feature is now forming along the northeasterly margin of the Hawaiian Islands.

INTRODUCTION

The generally accepted concepts of ocean deeps and island arcs are not valid. Rather than dwell on what is wrong with these concepts, I will describe the definitive characteristics.

Probably the most important fact is that each trench is located at or near the margin of an island ridge or a continent. Some trenches are markedly arcuate (Marianas, Aleutian, Puerto Rico, South Sandwich).

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[1]Lamont Geological Observatory Contribution No. 860. A more comprehensive discussion of this subject can be found in Worzel (1965a).

Others are much less arcuate (Java, Ryukyu, Kuril-Kamchatka, Middle America). Others are nearly linear (Tonga, Philippines, Chile, Peru). And there are others that are markedly angular (New Britain-Solomon, Yap-Marianas, Banda Sea). Usually one side of a trench is adjacent to an ocean basin, but this is not always true (Banda Sea, New Britain-Solomon, the Celebes). On one side of most trenches there is an island ridge or continental margin. There are many continental margins without nearby trenches (east coast of the United States, east coast of South America, the southern coast of Asia, etc.). There are also many island ridges which do not have an associated trench (Tuamotu Archipelago, Hawaiian Islands, Marshall Islands, etc.). These facts support the conclusion that deep trenches have formed along the margins of continents or island chains, that their shape is determined by the nearby coastal region, and that deep trenches do not form at the margin of every continent or island ridge.

CONTINENTAL MARGINS

Figures 1 to 9 show representative structure sections of coastal margins deduced from seismic refraction and gravity measurements, for a number of continental margins and for the islands of Hawaii, Bahamas, and Puerto Rico (Worzel, 1965b). This survey of continental margins and island margins shows that the similarities are much greater than the differences. Continental platform crustal thicknesses of 20 to 30 kilometres thin to oceanic thicknesses of 5 to 7 kilometres in a distance of 100 to 150 kilometres. In most cases the greatest change in thickness occurs beneath the 2,000-metre contour and from 30 to 50 kilometres to each side. Less abrupt changes in thickness occur beyond these distances.

Since deep trenches normally form in the transition region between continent or island ridges and the nearby ocean basin, and in the part where the crustal thinning is taking place, it is suggested that this process involves a combination of faulting and crustal warping, or graben faulting.

MODELS OF CONTINENTAL MARGIN STRUCTURE

Figure 10 shows several models of continental margins and the associated gravity curves. In model 1, a continental-type block changes discontinuously to an oceanic-type block. Both blocks are in isostatic equilibrium. A gravity anomaly curve would be observed with peaks of 100 mgal. In model 2 a coastal margin gradationally varying to an oceanic model in a distance of 100 kilometres, all in perfect isostatic equilibrium, shows a positive peak of about 50 mgal at the termination of the continental-type block with a minimum of about 20 mgal at the termination of the oceanic type block.

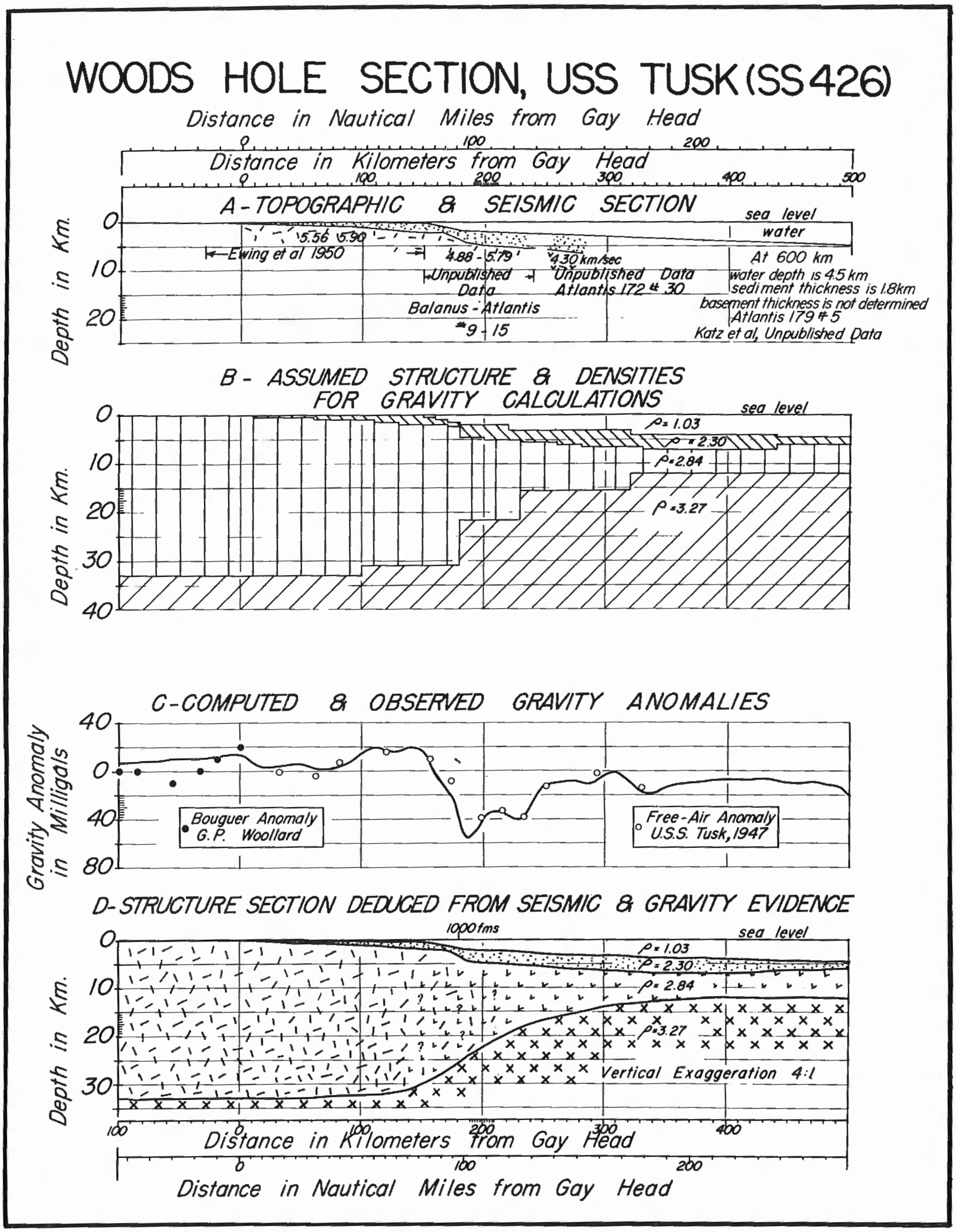

Figure 1. Structure section south of Woods Hole deduced from seismic refraction and gravity data. (After Worzel and Shurbet, 1955)

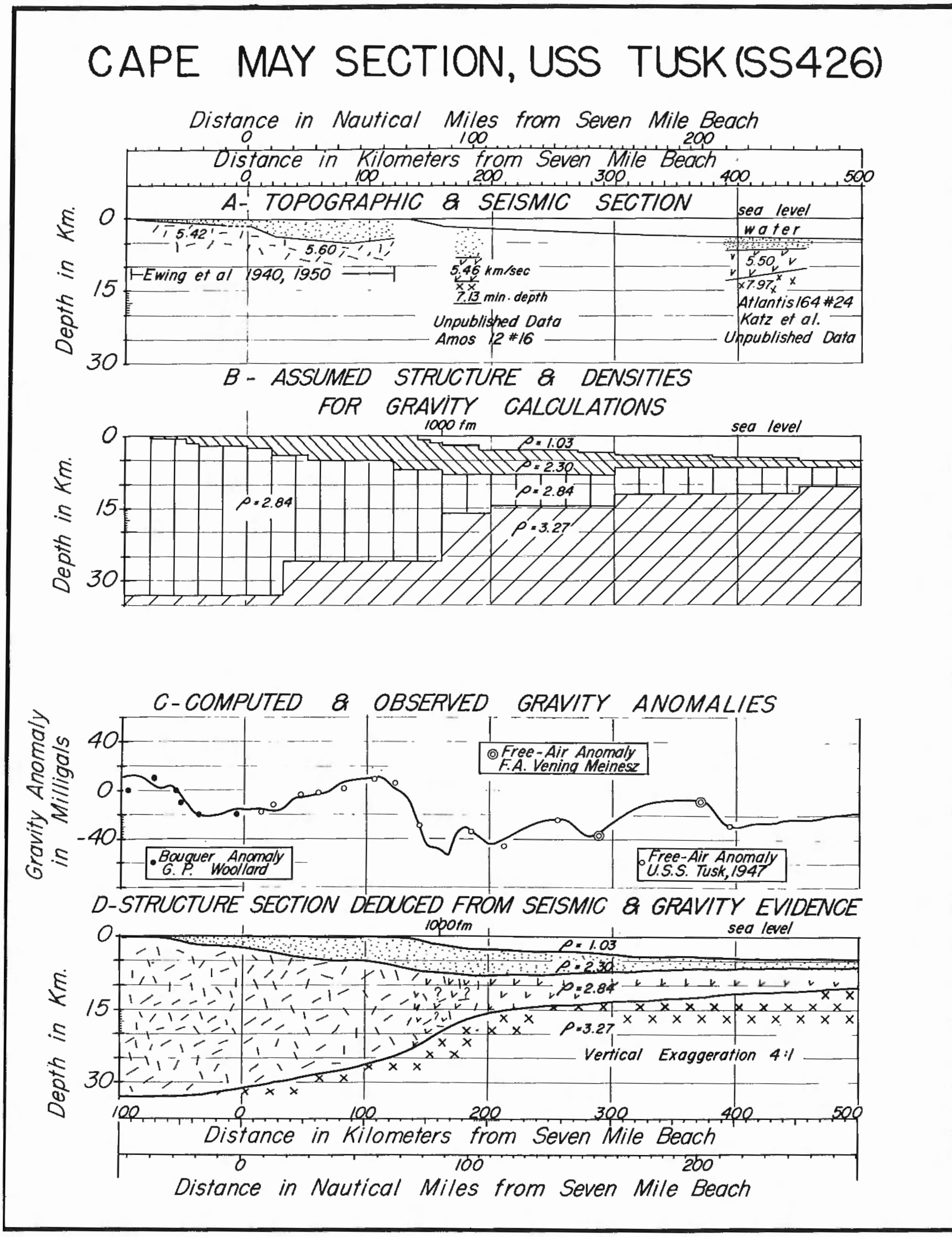

Figure 2. Structure section off Cape May deduced from seismic refraction and gravity data. (After Worzel and Shurbet, 1955)

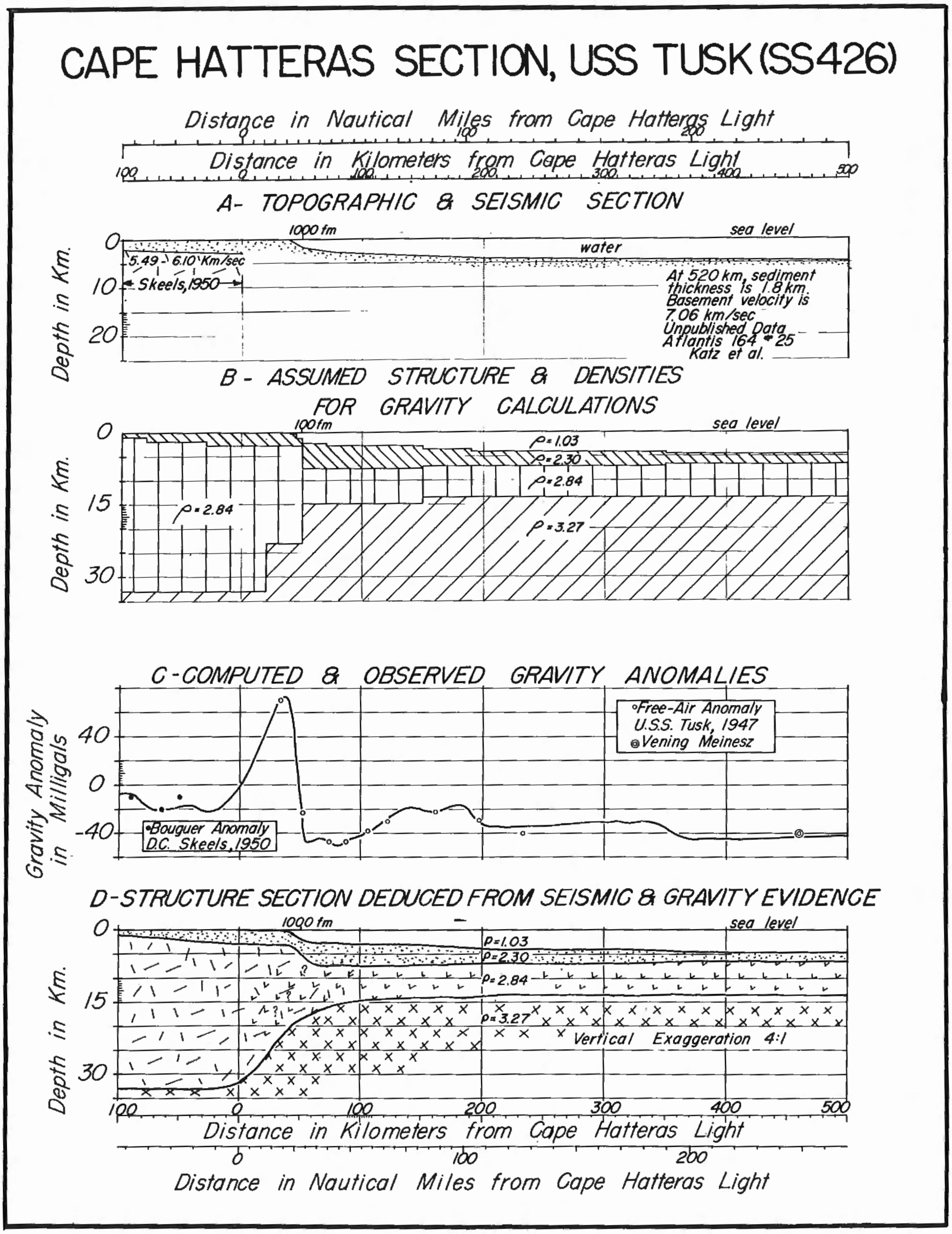

Figure 3. Structure section off Cape Hatteras deduced from seismic refraction and gravity data. (After Worzel and Shurbet, 1955)

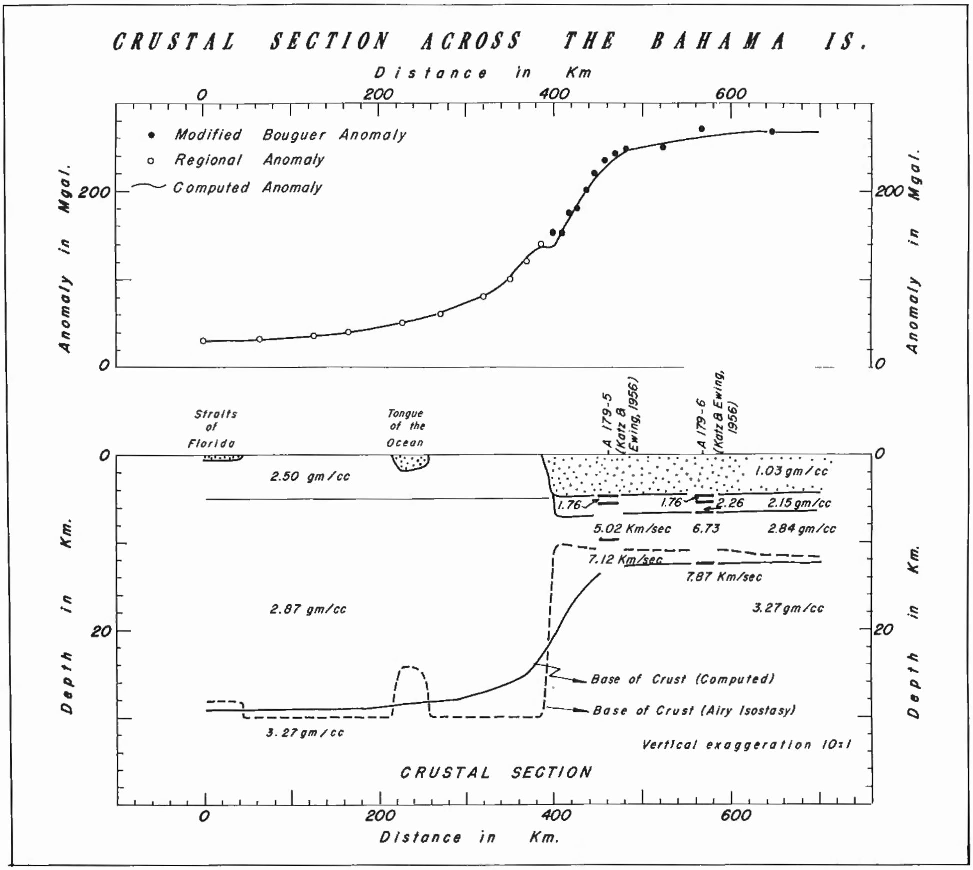

Figure 4. Structure section of the Bahama Islands deduced from gravity data. (After Talwani et al., 1957)

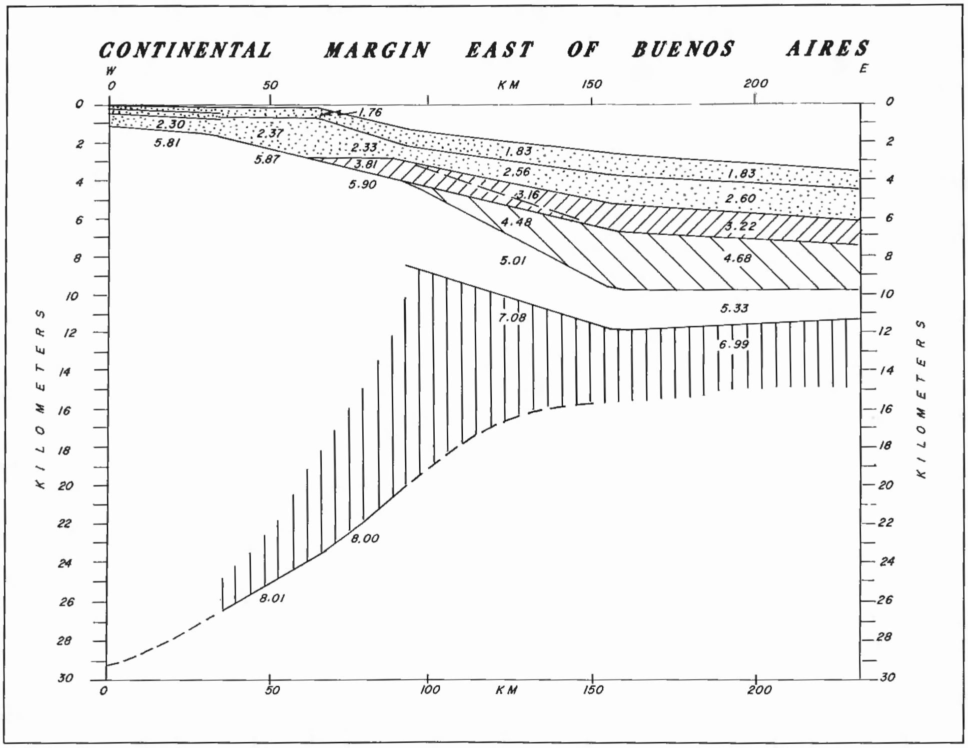

Figure 5. Structure section east of Buenos Aires, Argentina, deduced from seismic refraction data. (After Ewing et al., 1963)

In model 3, the isostatic compensation is not perfect beneath the transition block since the base has been moved about 20 kilometres to the right (seawards) without isostatic adjustment. This modifies the gravity curve by reducing the positive peak to about 25 mgal and broadening the negative trough with a minimum of about -60 mgal. This latter model is quite similar to the observed structure and gravity anomaly curves along the east coast of the United States.

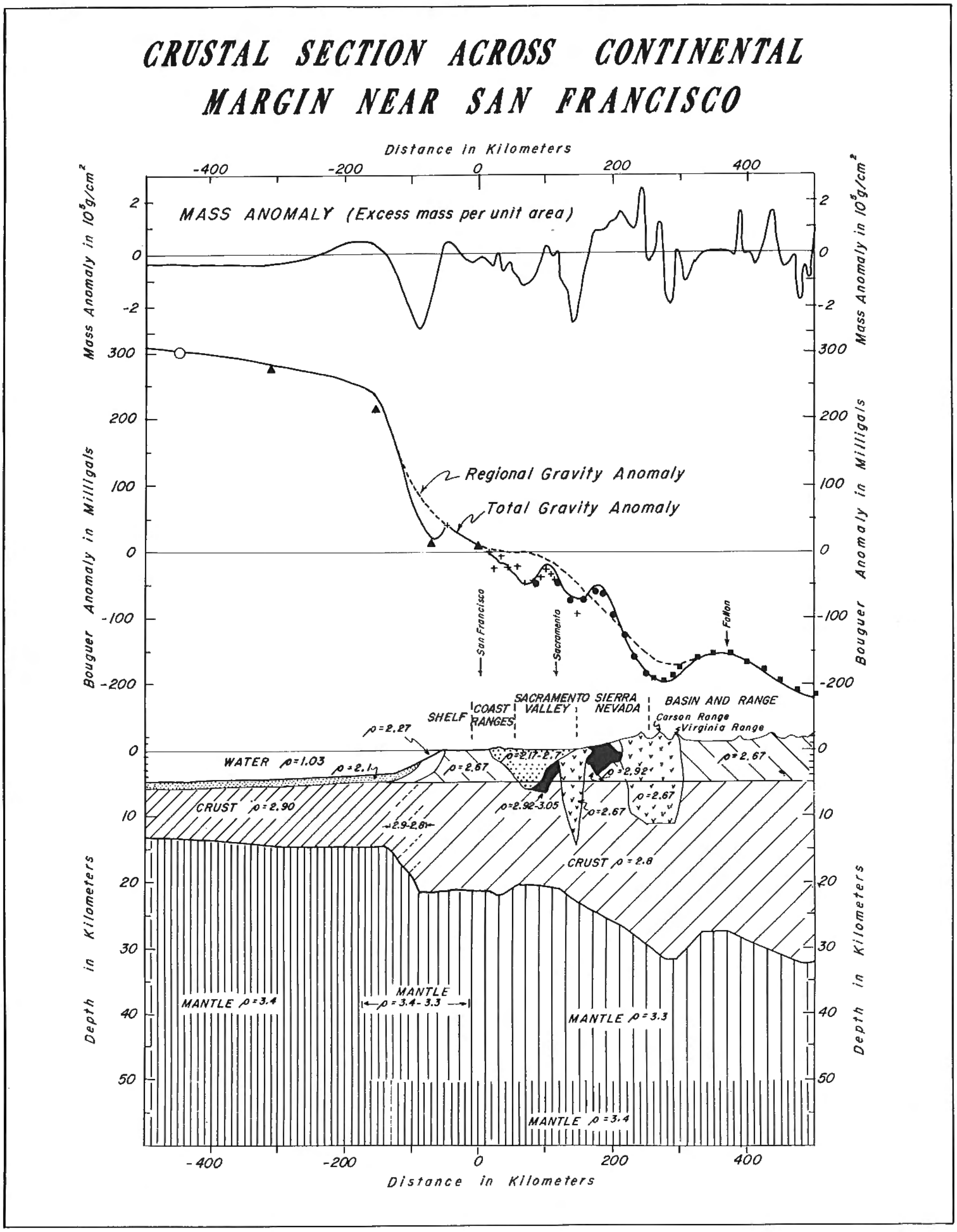

Figure 6. Structure section west of San Francisco deduced from known geology and gravity data. (After Thompson and Talwani, 1964)

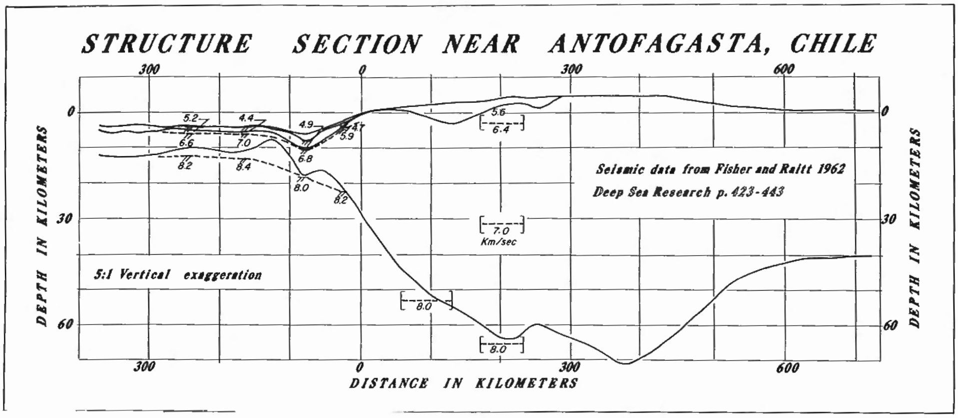

Figure 7. Structure section west of Antofogasta, Chile, deduced from gravity data after Wuenschell (unpublished thesis), and compared to seismic data after Fisher and Raitt, 1962.

MODELS OF TRENCH STRUCTURE

Figure 11 shows three models of "trenches" developed in and about the transition region of model 2 in Figure 10. Model 6 shows a downthrow of about 2 kilometres at the edge of the "continental" block and a flexure about 250 kilometres farther "offshore". The positive peak is slightly less than that of model 2, but the negative trough is broadened and a minimum value of about -150 mgal results. In model 5, a "graben" with a 2-kilometre drop is located at the transitional region of model 2. Again the positive peak of the gravity anomaly is slightly reduced from that of model 2, but the negative trough is deepened and has a minimum value of almost -200 mgal near the "seaward" side of the "graben". In model 4, a "graben" with a 2-kilometre drop is located in the outer part of the transition region and in part of the "oceanic" crust. The positive peak in the gravity anomaly is substantially the same as in model 2 while the minimum is broadened and has a minimum value of about -200 mgal. The great similarity of these three models to the trenches formed at the coastal margins is striking both in the similarity of the topography and the gravity curves. A modest extension of about 2 kilometres would provide the space needed for the downdropped block in each case.

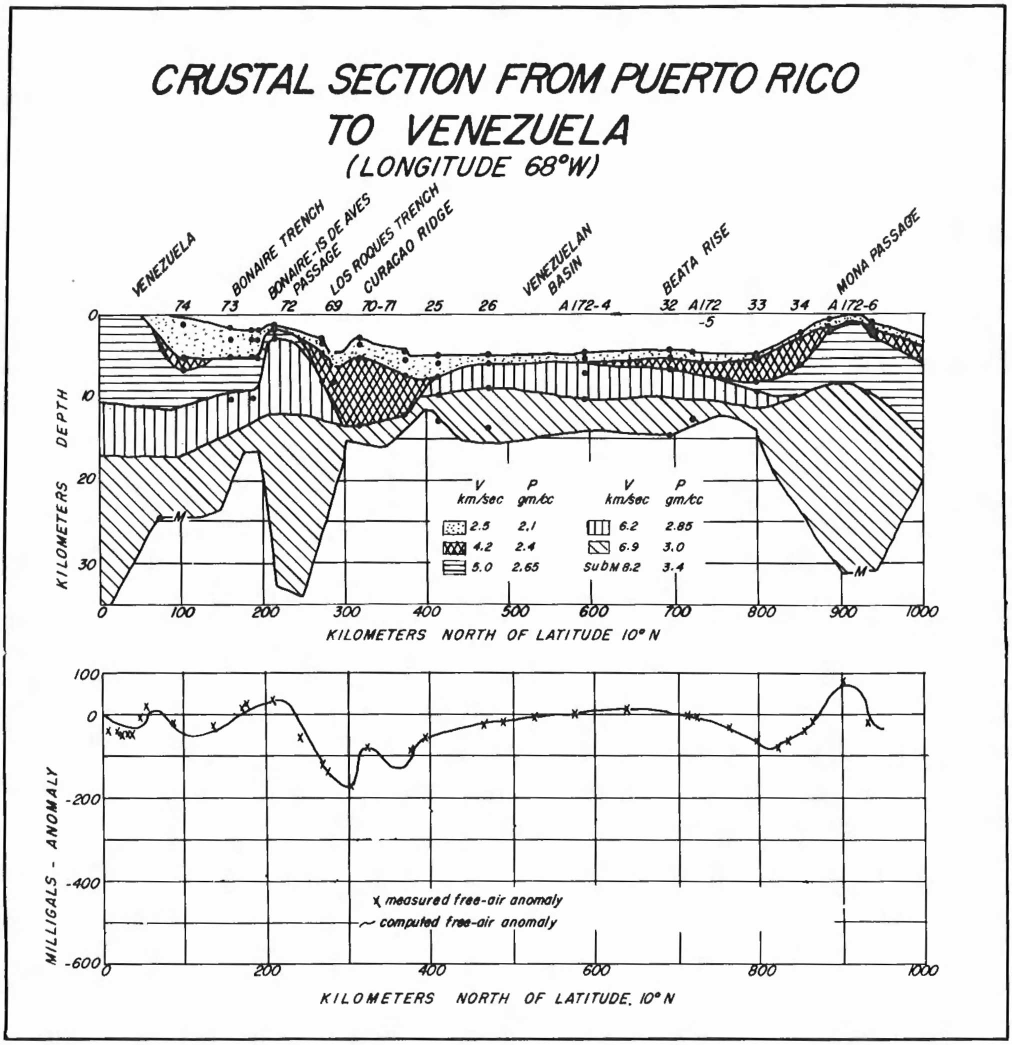

Figure 8. Structure section from Puerto Rico to Venezuela deduced from seismic and gravity data after Hambleton (unpublished manuscript).

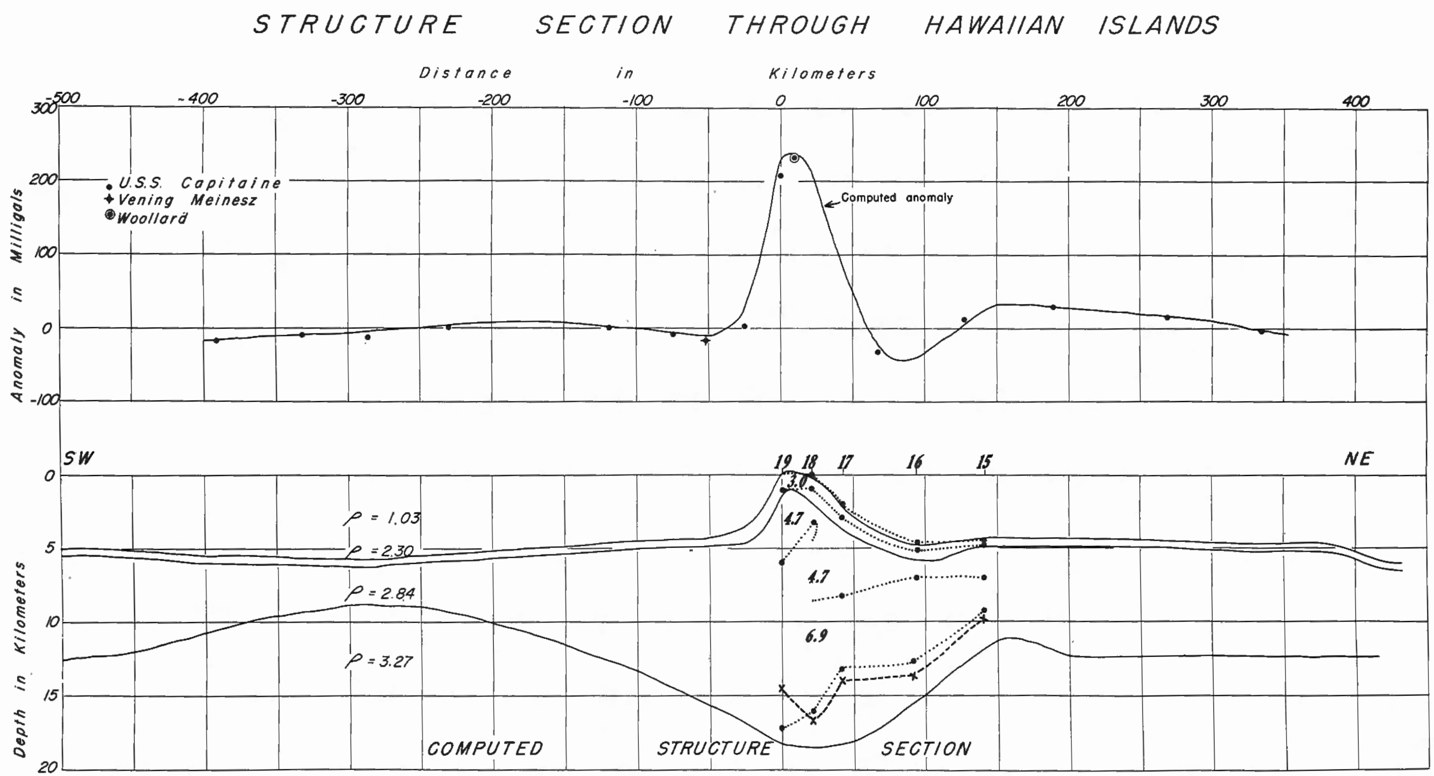

Figure 9. Structure section through Hawaiian Islands deduced from gravity data after Worzel (1965b), and compared with seismic data after Shor, 1960.

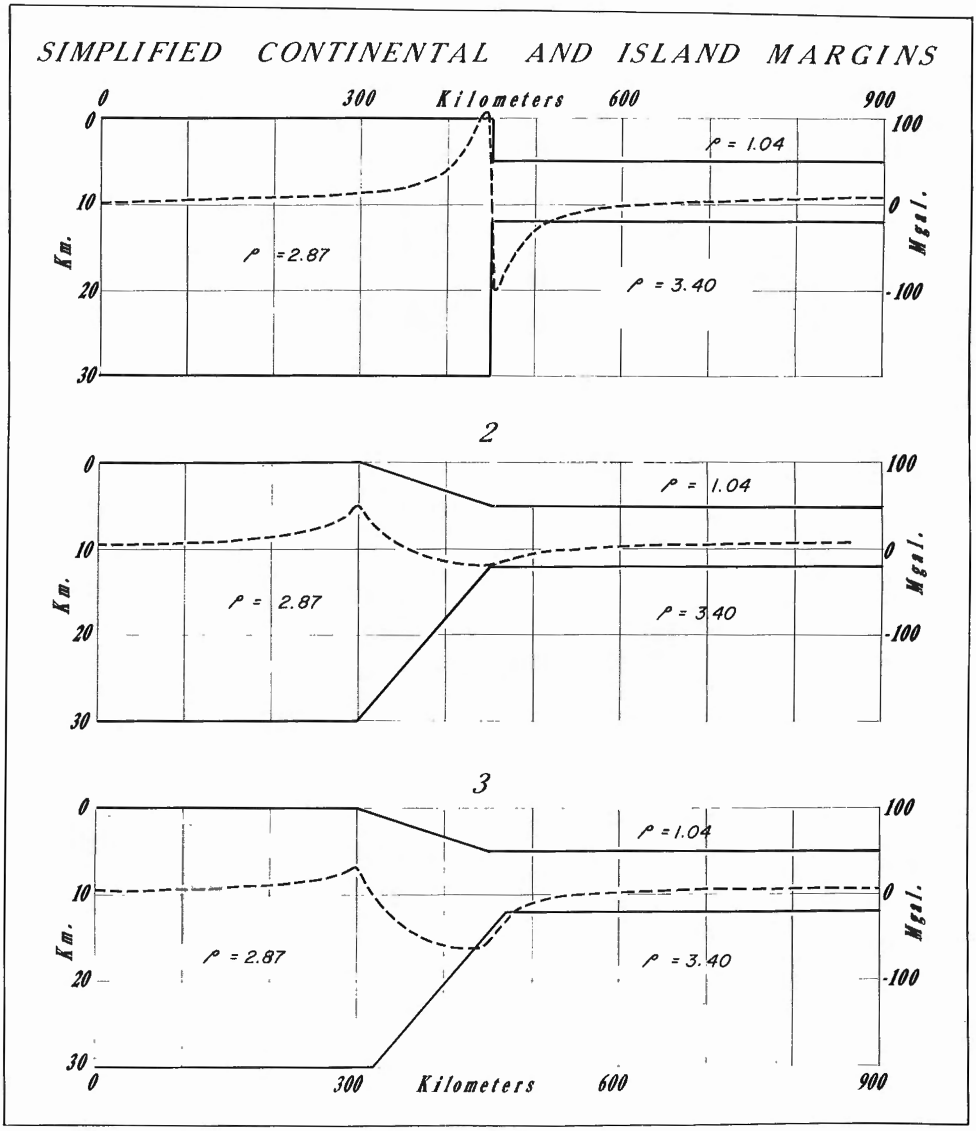

Figure 10. Models of simplified continental and island margins.

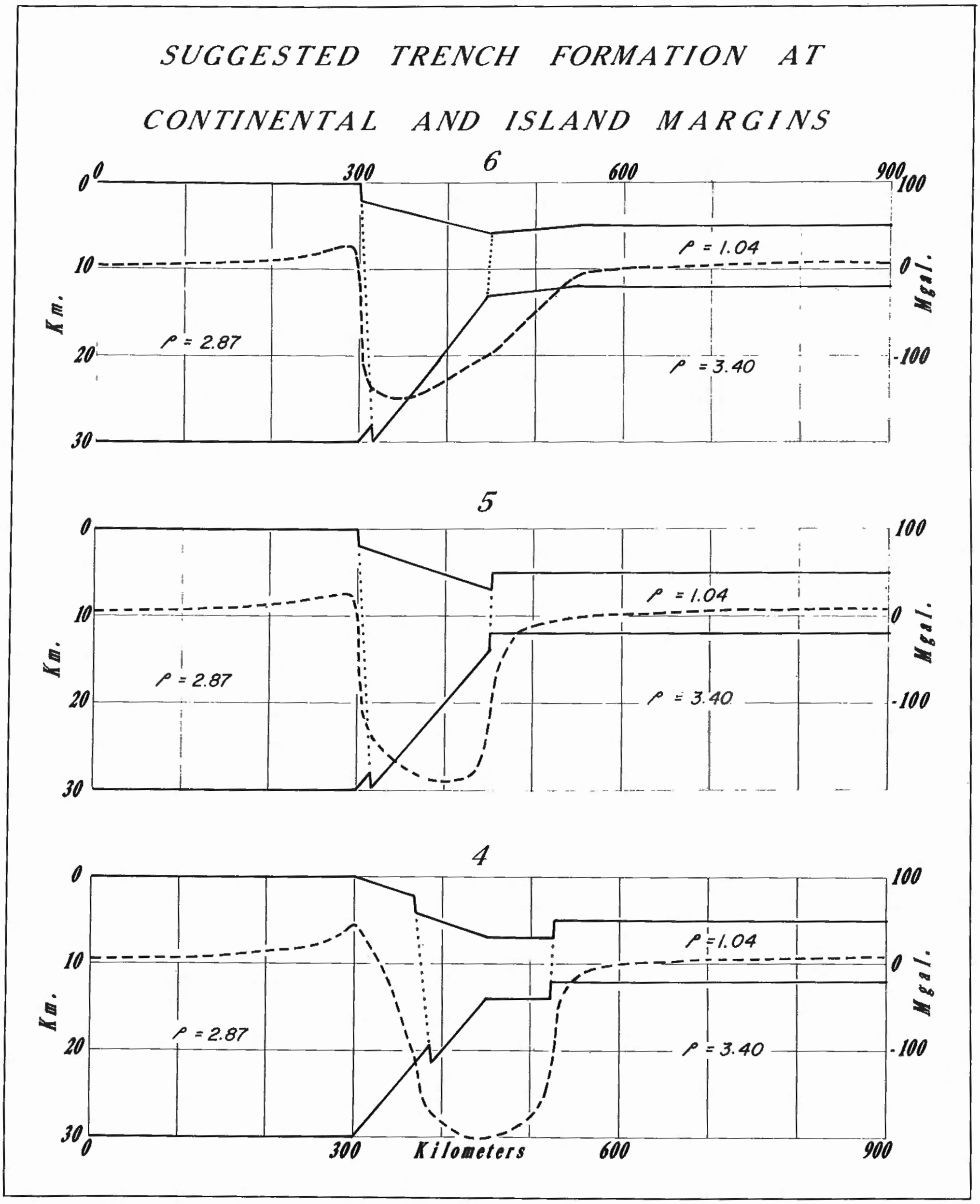

Figure 11. Models of suggested trench formation at continental and island margins.

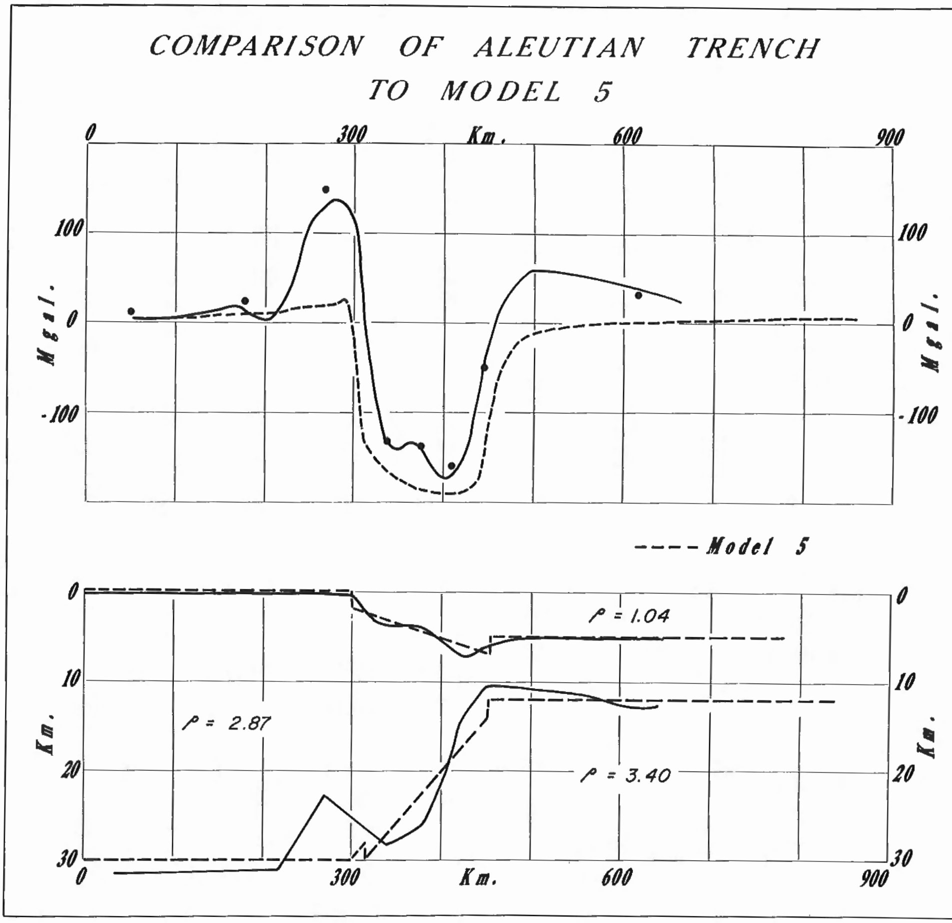

Figure 12. Comparison of Aleutian Trench to model 5.

Aleutian Trench

Figure 12 compares model 5 in Figure 11 to the Aleutian Trench. The solid line in the top part of the figure is the computed gravity curve (using a mean crustal density) for the structure determined for the Aleutians from the topography and gravity data as indicated by the solid lines in the lower part of the diagram. The dots are the observed gravity pendulum data. The overall agreement of the negative anomaly region is quite satisfactory. The increased positive in the observed section requires the introduction of an excess of mass of the order indicated at about 260 kilometres in the section. The thinning of the crustal section beneath the outer ridge is required to fit the data and is similar to the observed thinning of the Puerto Rico Trench (Talwani et al., 1959; Bunce and Fahlquist, 1962).

Tonga Trench

Figure 13 shows a comparison of the Tonga Trench to model 7, a variant of model 5, in which the "graben" is much narrower and the vertical drop is 4 kilometres instead of 2 kilometres. The solid lines are those devised by Talwani et al. (1961) to fit the seismic and gravity data. The dashed lines are those of model 7. The negative anomaly of the section agrees quite well with that of model 7. An allowance for intrusion of higher density volcanic rocks into the "island ridge crust" of the model could make a better match of the positive anomaly.

Puerto Rico Trench

Figure 14 shows a comparison of the Puerto Rico Trench to model 4B, a variant of model 4, in which a "graben", 100 kilometres across instead of 150 kilometres, is considered with a vertical drop of 3 kilometres instead of 2 kilometres. The solid lines in the bottom diagram show the structure determined by Talwani et al. (1959) from a combination of seismic and gravity data. The fit to the gravity data is considered excellent. Again the introduction of high-density volcanics in the region of the positive anomaly would make the fit in this region more reasonable. Thinning of the crust beneath the outer ridge is required to explain both the seismic and gravity data.

CONCLUSIONS

Thus, it is concluded that there is a transition region 100 to 150 kilometres wide between a continental crust or an island ridge crust of 20 to 30 kilometres thickness and an oceanic crust of 5 to 7 kilometres thickness. It has been demonstrated that oceanic trench topography and the associated negative gravity anomaly curve result if a block 50 to 100 kilometres wide in this transition region is lowered by 2 to 4 kilometres by faulting or a combination of faulting and flexure. Comparisons of such details with presently existing trenches demonstrate the striking similarities.

This type of structure could develop contemporaneously with nearby coastal margins, but it is more probable that it develops later. The large number of coastal margins in which such a development has not occurred lend support to the above statement.

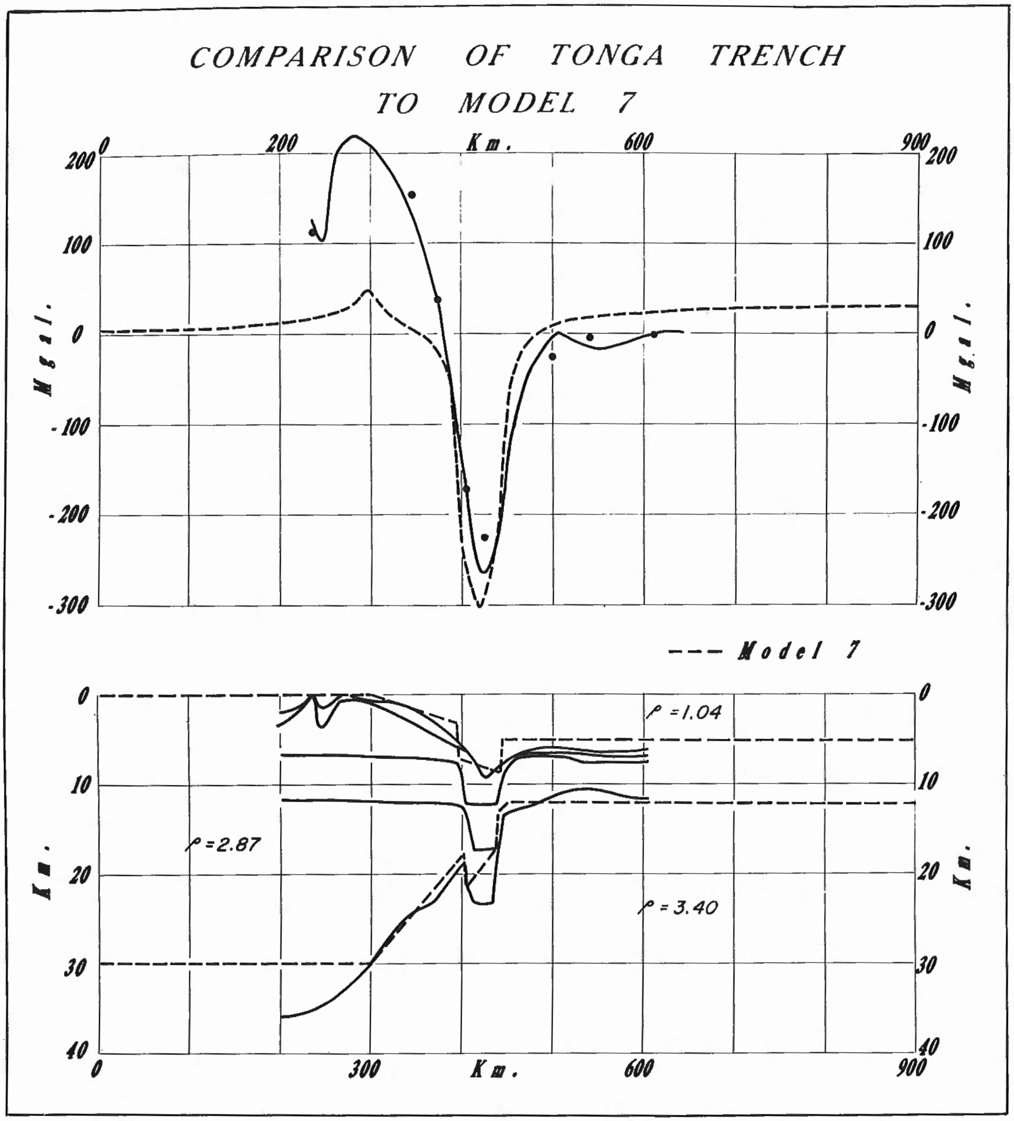

Figure 13. Comparison of Tonga Trench to model 7, a variant of model 5.

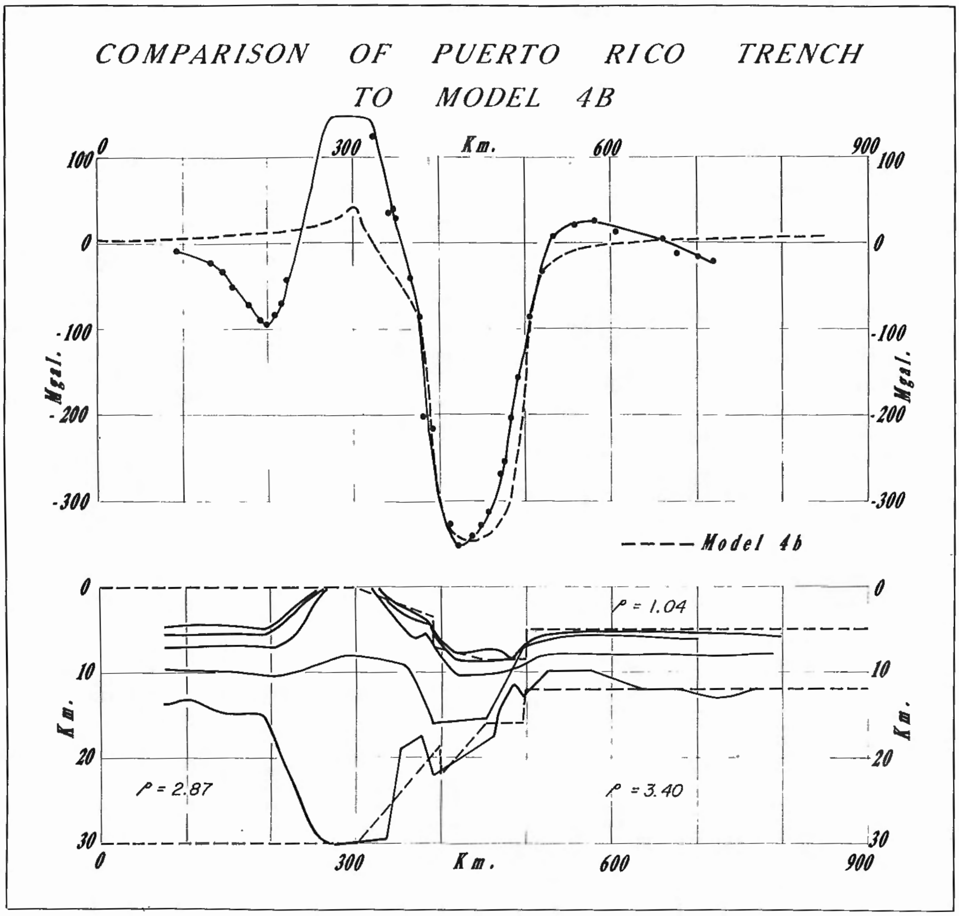

Figure 14. Comparison of Puerto Rico Trench to model 4B, a variant of model 4.

Extensional forces are required to make space for the down-dropped block. The thinned crustal section of the outer ridge is convincing evidence in support of such forces. It is strongly suggestive that such a trench is forming along the northerly margin of the Hawaiian Island chain. Already a minor trench has developed and the crust has thinned beneath the outer ridge. As is well known, this site has been chosen for the drilling of the Mohole because of the thin crust. It is clear that extension would produce thinning of the crust and upper mantle, and fracturing would cause blocks of the crust and upper mantle to adjust their position. Initially this adjustment would be downwards and a negative imbalance of the region would be created just as has been observed at Puerto Rico by Talwani et al. (1959). Later isostatic adjustment should gradually remove the regional imbalance.

If compressional forces caused trench formations, a thinned crustal section could not be explained, and upwarping, fracture, and initial uplift of fracture blocks would be expected, because only in this way can space for the blocks be made available. This would create a positive isostatic imbalance of the region. Such an imbalance has not yet been discovered.

It is, therefore, concluded that extension forces have been operative in a region where a trench has formed.

ACKNOWLEDGMENTS

Mrs. E. Skinner and Miss J. Hastings helped with the computations while Miss A. Trefzer made the drawings. This work was carried out with the support of the Office of Naval Research of the United States Navy under contract Nonr 266(48).

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ISLAND ARCS AND THEIR SIZE-SHAPE SIGNIFICANCE

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Abstract

The degree of curvature of an island arc can be matched by other arcuate structures whose shapes are clearly controlled by the size of the elliptical or polygonal cratonic blocks which they bound.

Linear island groups without visible curvature are taken to be the shared polygonal side of two contiguous and nearly identical rigid plates. On this basis a plausible subdivision of the Pacific floor is suggested.

The size-shape groups of the rigid plates of which the island arcs are partial sutures, each belong to a specific structural mosaic. Usually any mosaic can be subdivided into finer mosaics in the manner of a hierarchy. Island arcs and island chains are but one manifestation of this characteristic. The broad classification of tectonic features into only two shape-categories, the linear and the equidimensional, is thought not to be an oversimplification as it has led directly to the concept of a hierarchy of mosaics. The size-classification then constitutes a refinement on the shape-classification, and the two together permit a degree of prognostication, which would otherwise be difficult or impossible.

INTRODUCTION

So extraordinarily little has been written about the size-shape significance of island arcs, both length and radius, that it is apparent that little is known of their origin. If their origin were known, one could write knowledgeably about the reason for their size and shape. I propose here to investigate the size and shape of island arcs for clues to their origin.

The investigation considers pure form, about which no precise laws have ever been formulated on a scale larger than crystallographic.

CRUSTAL BLOCKS AND LINEAR BELTS

Let us begin with the proposition that all tectonic forms can be divided into two broad classes: 1) the rigid blocks of the crust, i.e. the cratons, characterized by being roughly equidimensional in area; and 2) the linear belts, i.e. the mobile belts of Bucher or the hinge zones of Hans

Cloos. The linear belts include bisectors, or fracture zones, that make two cratons out of one. They would also include island arcs.

The mosaic concept holds that in any given mosaic the polygonal units adjoin their neighbours in linear belts or lineaments (Fig. 1) (Brock, 1956, 1957). The polygonal shape owes its existence to the interaction of neighbouring plates; indeed no polygon can stand alone. Within any unit, structures approach concentric arrangement.

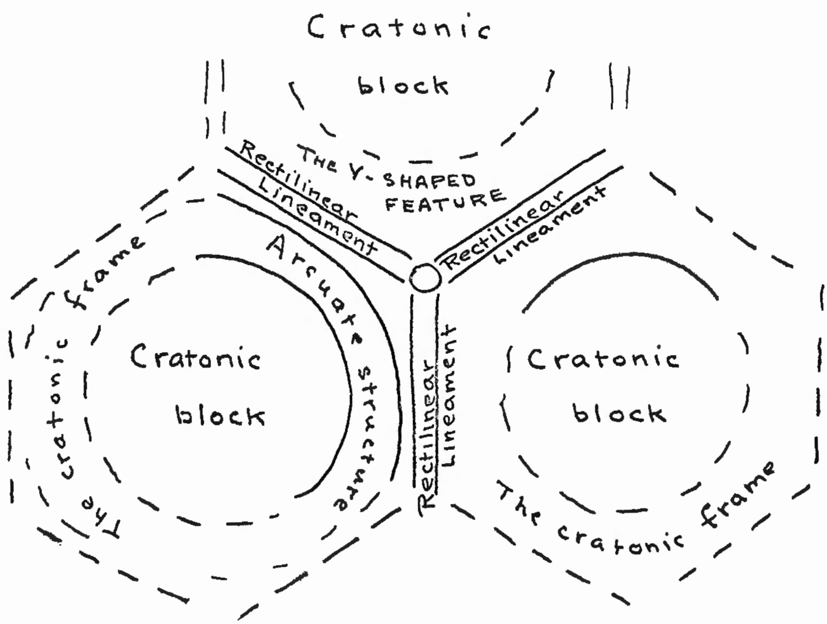

Figure 1. The Y-shaped feature and the reconciliation of radial and concentric structures.

STRAIGHT BELTS

The straight island chains could represent the actual suture shared by equal units. Three such sutures shown in Figure 1 meet to form a "Y". The curvilinear island chains or island arcs could represent part of a cratonic mass. In this model we reconcile concentric patterns and radiating patterns.

The Y-shaped junction is now becoming quite familiar in bathymetric work, such as, for instance, the one in the Indian Ocean of which Rodriguez forms the junction, and the one in the southeast Pacific near Easter Island. The Y-shaped feature is a manifestation of the universal tendency for three and not more than three lineaments to form a junction, hence leading to the overwhelming prevalence of 120 degrees as a structural angle in regions of stability.

When four or more lineaments converge, Nature's subterfuge to ensure that no more than three lines meet is a polygonal hub of as many sides as there are converging lineaments. The resulting polygon has a close analogy in the hub of a spoked wheel, in which any two spokes and the intervening segment of the rim form a rigid triangle. The triangular motif, like the wheel itself, is the very essence of lateral rigidity.

Southern Africa, with its spoke-like ridges linking it to the median ridges of the South Atlantic and the Indian Oceans, can also be considered as the hub of a stable wheel-like ensemble.

ARCUATE BELTS

I propose now to test the model of Figure 1 as applied to island arcs and rectilinear island chains.

The well-ordered curvature is one of the most constant things about an island arc. The aligned volcanic peaks mark the curvature, as well as associated seismic activity, gravity anomalies, parallel ocean trenches, and even mountain arcs as in Japan, Java, and Sumatra. Island arcs are in fact sufficiently varied that a close relationship with other world features suggests itself: mountain arcs of fold mountains, oceanic median ridges, spur ridges, isthmuses, and certain peninsulas. It is considered that all these things are variations on a theme, and that essential form, that is, size and shape, may be an important link.

By putting all kinds of arcuate features into their respective size-groups (Table), the relationship becomes clear. Island arcs share a common form with: 1) mountain arcs, 2) coastal bulges of Precambrian continents, 3) arcuate rifts, and 4) structurally-controlled river valleys (Fig. 2). All these form-analogues are tectonically better understood than island arcs. If the analogy is legitimate, the island arc helps to frame a craton now sunk below the sea. In the case of the East Asian chain of arcs, each arc partly bounds an inland sea.

Table – Island arcs and comparable features on a size-shape basis

ISLAND ARC	RADIUS	CHORD	RELATED SEA	DIMEN-SION	MOUNTAIN ARC	CRATON	BULGE	CRATON	BIGHT	RIDGE	CRATON (subsided)	RIFT VALLEY OR RELATED STRUCTURE	CRATON
Sundu	22	40	(Indonesian seismic closure)	40 x 30	Cordillera (Mexican and U.S.A. coast)	Body of N. America	Antarctica Australian sector	Antarctic shield	Siberian coast	Mid-Atlan. Ridge (equatorial stretch to Tropic of Cancer	Cape Verde & Canary Basins	Western Rift	Rift Block
							North Africa	W. African shield					
Aleutian	12	22	Bering Sea	22 x 12	Himalayas	Tibet	C. Verde to Tunis		Gulf of Guinea	S. Atlantic Ridge Tristan da Cunha to Bouvet (not enough detail to distinguish smaller areas)	Cape Basin	Eastern Rift	
Ryukyu	9	12	East China & Yellow Seas	15 x 7	Zagros Mountains	Persian Block	West Africa Liberia to Sp. W. Africa	W. African shield				Zambezi depressions 1. Lower Zambezi arc	Rhodesian craton
Japan	6	12	Sea of Japan	12 x 6	Alaskan Range	Alaska	Wilkes-Victorialand coast	Antarctic shield				2. Upper Zambezi arc	Zambian craton
					Taurus	Anatolia							
South Sandwich	3	6	Scotia	22 x 6 Com-posite craton?	Alps		E. Australian coast	continent of Australia	Coast of NW Australia				
							E. China coast Tonkin to Dairen	E. China shield	Great Australian Bight (minor portion)				
Antillian	3	4	Caribbean	22 x 7 Com-posite craton?	Carpathians								
							Wilkesland coast	Antartic shield	Gulf of Tonkin				
							Somali coast	Somali block					
							Hadhramaut coast	Arabian peninsula					
							W. coast Kamchatka						
							French Indochina coast	Thailand Plateau					

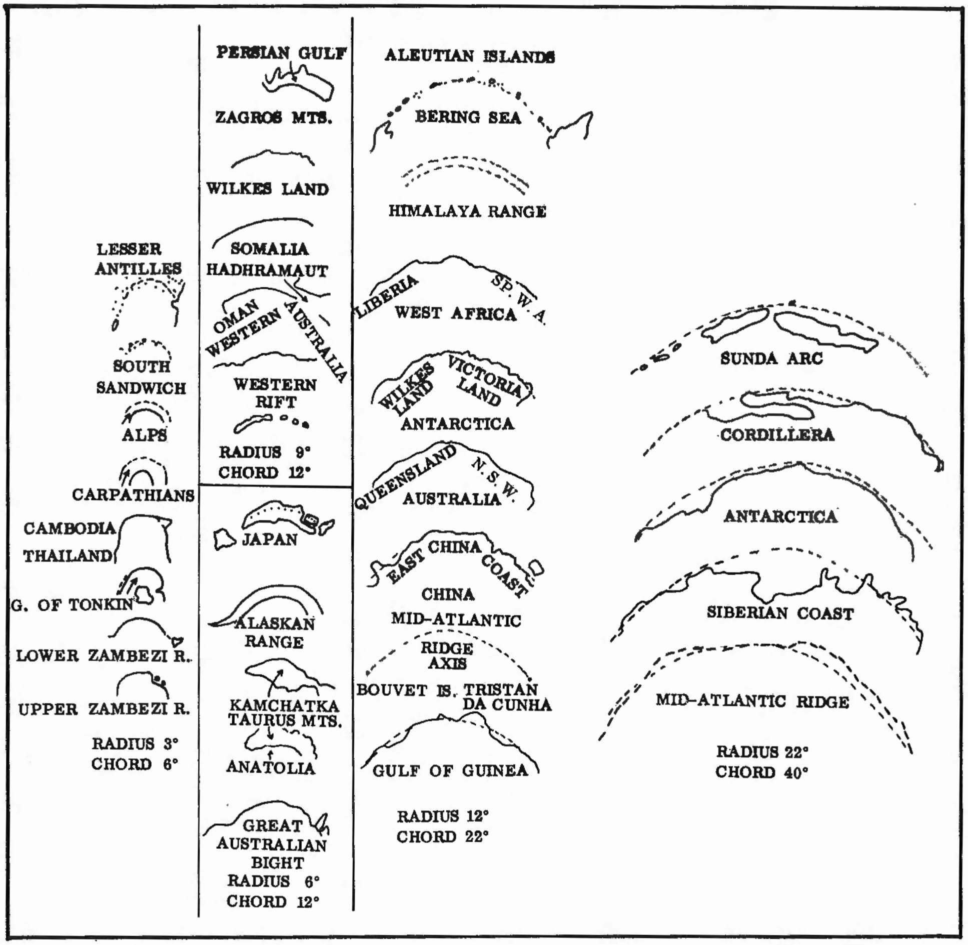

Figure 2. Size-shape groups of island arcs and their continental equivalents.

If the sediments forming Japan's mountains were derived from the presumed craton of the Sea of Japan, the minimum amount of subsidence of the craton must equal the 1,000 fathoms depth of water.

LENGTH OF ARCUATE BELTS

Let us examine the relation between the length of the arc and the dimensions of the sea that the arc partly bounds (Fig. 3). In most cases the length of arc approximates the mean of the axes of the sea, as shown in the following:

	Length of Arc	Dimensions of Related Sea
Aleutian	22°	22° x 13°
Kuril	19 (overall)	16 x 11
	10 (islands alone)	
Japan	12	12 x 8
Ryukyu	13	15 x 8
Philippines	23	26 x 16

Thus, the arc in terms of polygonal sides would be the equivalent of two sides of a hexagon. Many areas can in fact be broken down into two distinct segments, each approximating one side of a hexagon.

The East Asian chain of arcs, in terms of a mosaic hierarchy, reflects a much finer pattern than that of the ocean which it bounds. A model continental craton is the Plateau of Tibet, embraced by fold mountains including the arc of the Himalayas.

In the same manner that the circumpacific seismic zone makes the most useful and practical boundary of the Pacific, so other seismic closures on a smaller scale can outline rigid blocks whose adjustments with neighbouring blocks have resulted in seismically active belts. Examples are the Philippine Sea and the Banda Sea, both of which have cratonic counterparts recognizable over the face of the earth.

LENGTH OF STRAIGHT BELTS

Now let us turn to the rectilinear island chains which may be regarded as bisectors, round which symmetry might be sought.

The linear island groups of the Pacific show a marked preference for 21- to 23-degree lengths (Fig. 4); something of the significance of such a length is observable in the Philippine Sea boundaries. If the parallelogram is not accepted as the normal shape of a craton and the hexagon is considered much more representative of an average shape, the 22-degree side would result in a cratonic polygon roughly the size and shape of Australia.

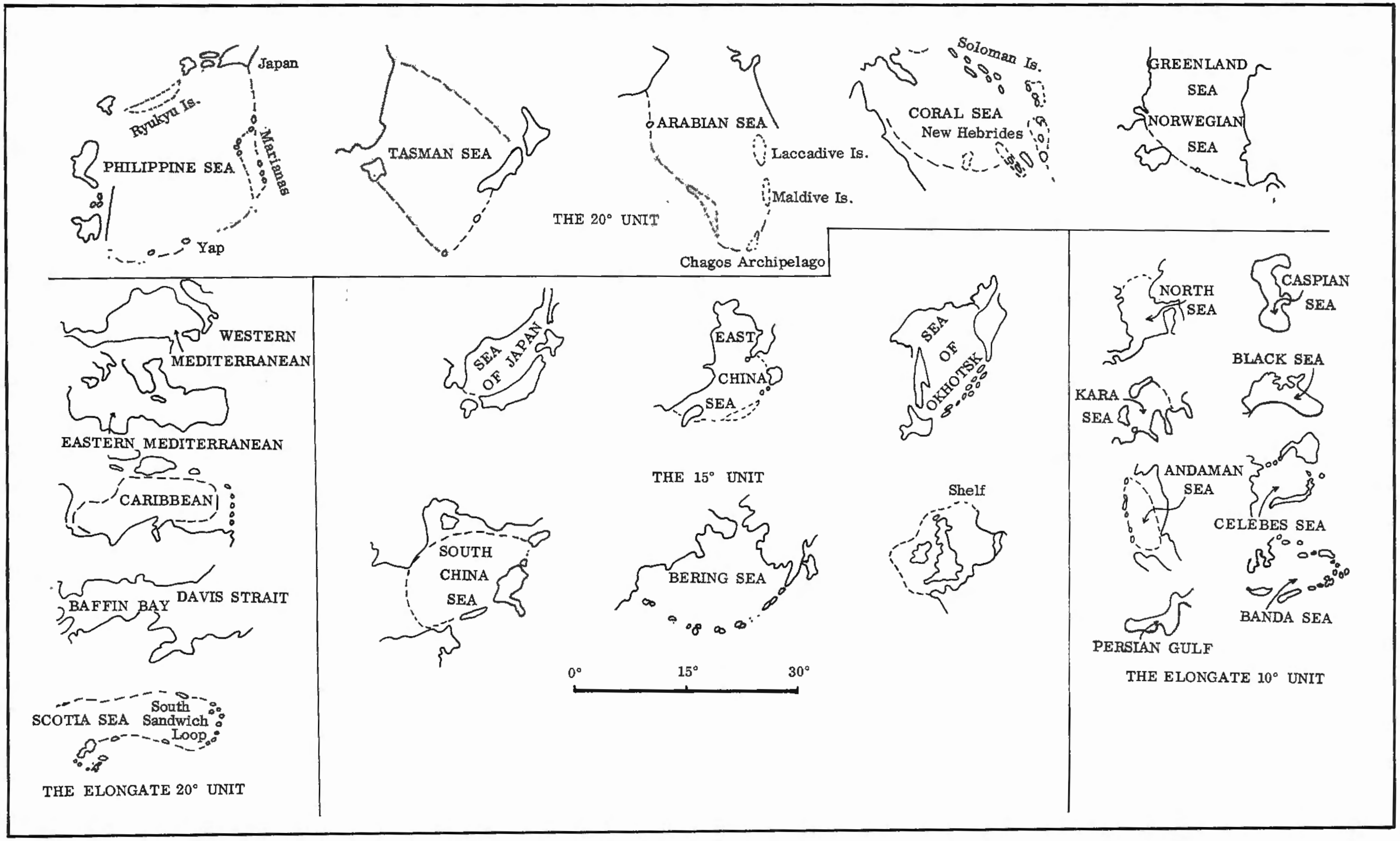

Figure 3. Inland and coastal seas in size groups.

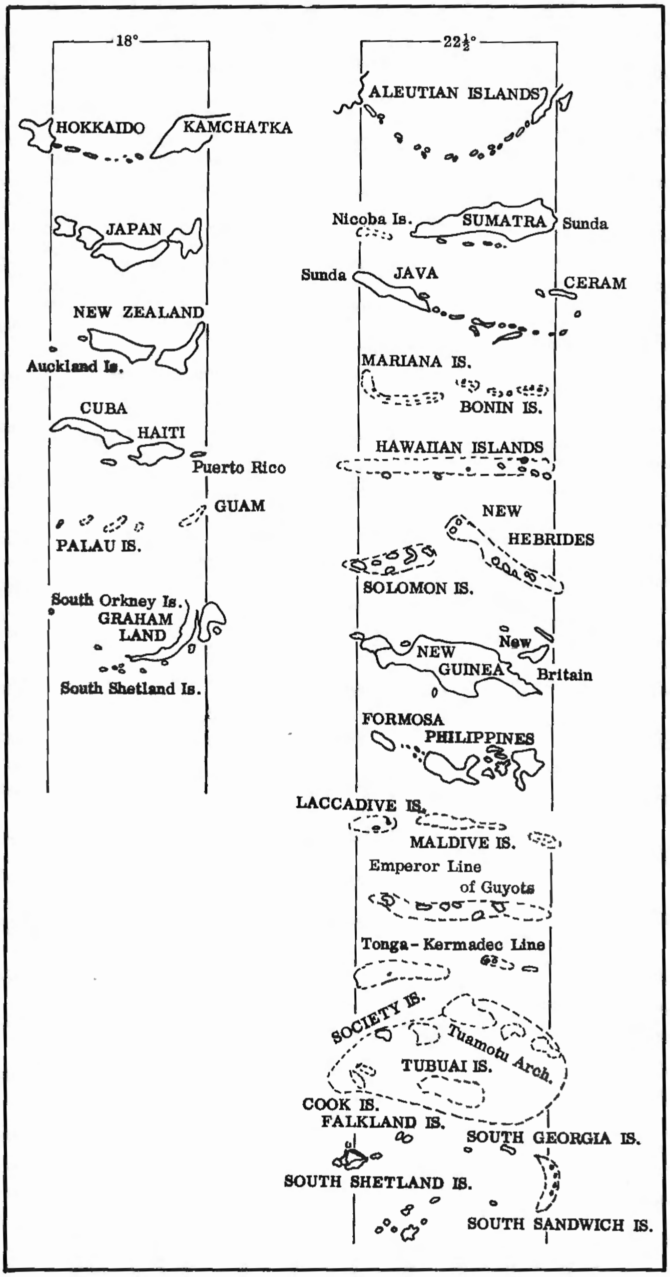

Figure 4. Island arcs and chains of the 18- and 22 1/2-degree groups.

MOSAIC MODEL OF PACIFIC BASIN

If the island chains of the Pacific are presumed to be in fact sutures, the Pacific can be divided into approximately equidimensional plates.

Analysis of equidimensional basins on land suggest that if a basin has a polygonal centrepiece which has behaved as a structural entity, this centrepiece is the size of plate to expect and the apices of that polygonal plate provide a further clue as to how the rim is fragmented.

The centrepiece of the Pacific would be regarded as the polygon bounded by the Line Islands, part of the Hawaiian line, part of the Marcus-Neckar Ridge, the Gilbert-Ellice line, and the Samoa-Society Island groups (Fig. 5).

The encircling sub-units fall into place with the help of 22-degree island chains. Only two conjectural lines were necessary to complete the picture; one of these, between the north central and the northeast sub-units, clearly separates two distinctive types of bathymetric pattern. The net result is a mosaic with eight crustal plates of homogeneous size and design. The Coral-Tasman seas would be a ninth plate, but is excluded by the Tonga seismic salient. The southeast Pacific basin, likewise with continental affinities, is excluded by the East Pacific Rise.

CONCLUSION

The size and degree of curvature of island arcs relate them to other arcuate features throughout the world which are clearly related to the edges of crustal cratonic plates. In a relatively stable landmass, the cratonic boundaries are marked by arcuate coastal bulges. In tectonically active zones the boundaries may be mountain arcs, rift valley arcs, or oceanic ridges. All arcuate structures would appear to be variations on a theme. The island arc with its associated unfilled trench lacks a source of sediment to fill the trench. Thus fold-mountain arcs which constitute part of an island arc imply that the crustal blocks from which the sediments were derived have subsided beneath the sea.

The festoon-like arcuate island chains separate two mosaics of different scale. On the other hand, straight or sinuous alignments separate similar crustal fragments. The 22-degree rectilinear alignments of islands in the Pacific permit a subdivision of the Pacific into eight roughly equal units.

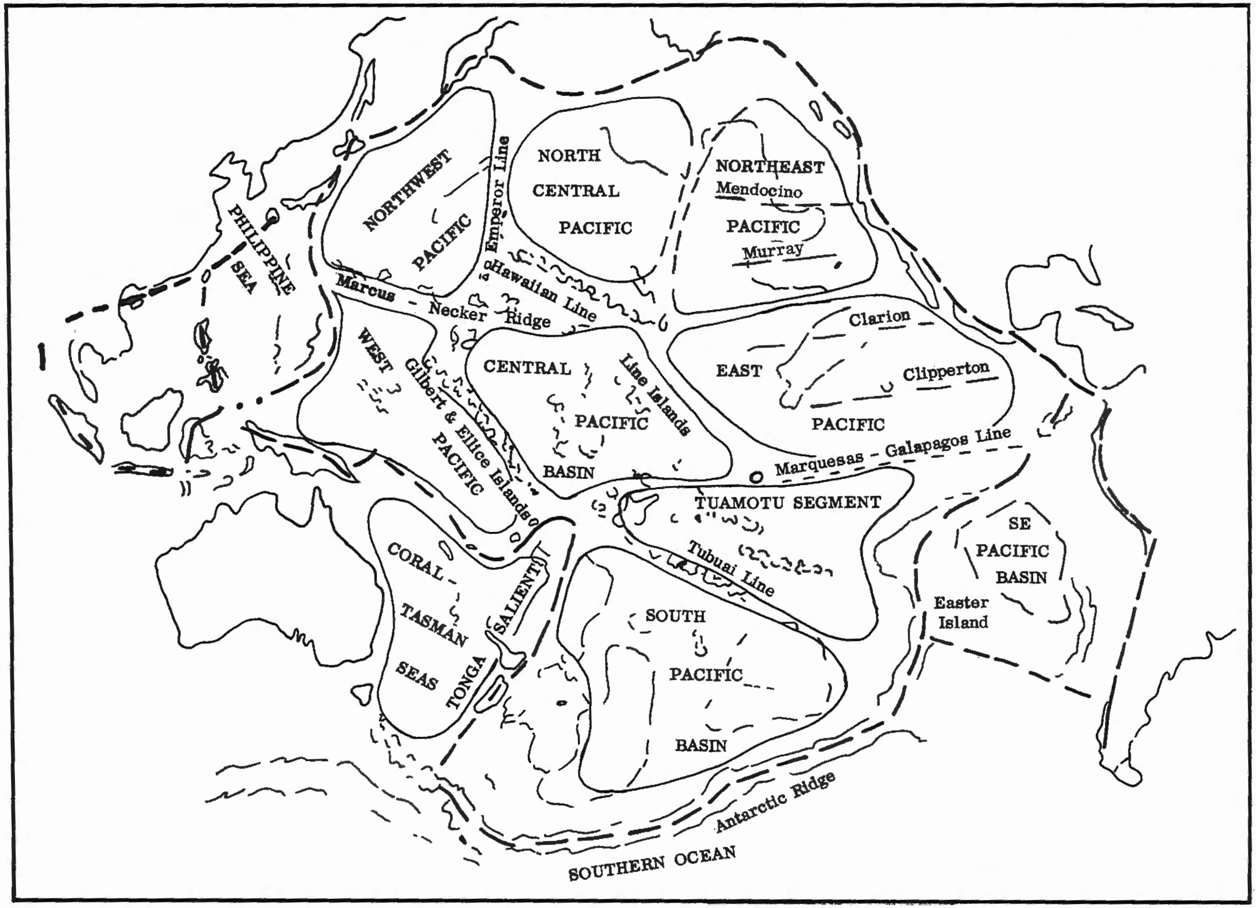

Figure 5. A mosaic analysis of the Pacific Ocean floor.

For such alignments, whether arcuate or rectilinear, the term "lineament" seems appropriate, particularly considering the great variety of features marking the edge of a cratonic unit: lines of volcanic or coral islands, guyots, oceanic trenches, coastal trenches, arcuate coastlines, mountain chains, etc. All are believed to represent sutures of one mosaic pattern or another. The degree of curvature and also the length of the lineament is some indication of which mosaic pattern is concerned.

Using a prevalent length of lineament of 22 degrees, a plausible subdivision of the Pacific Ocean floor was obtained - an indication of the prognostication value of the method. At the very least, it points out oceanic areas where further data are required to complete the picture.

It is apparent that the mosaic concept upon which the above arguments have been based suggests the relative permanence of continents. Further arguments against continental drift are derived from the triangular patterns of lateral rigidity, as well as from widespread repetitive patterns of a fundamental nature (that is, not repetitive as a result of having pulled apart).

In a word, the evidence of island arcs and island chains speaks of order as opposed to the chaos which the concept of drifting continents must imply.

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DISCUSSION

Prof. S.K. Runcorn (UK)

I think almost everyone will agree that there is some order about the distribution of oceans and continents. It is, of course as Dr. Brock said, most easily demonstrated by noticing the antipodal relation of oceans and continents. The figure of 5 per cent is given for the amounts of land which is antipodal to land. Geologists have always been interested in the explanation of this. It think it is extremely dangerous to argue that any pattern is immutable, that it can't change. I think most of us that favour the possibility of continental drift merely say that any system of convection pattern will impose some kind of order on the distribution of oceans and continents because the continents will ultimately become positioned over the downgoing streams. But if the convection pattern is altered, then obviously the positions of the continents and oceans must change. And yet before and after this has happened, there is some symmetry about the distribution.

Dr. Brock

I see your point entirely. But the mosaic concept demands an evolutionary change throughout the ages in the convection currents from very fine and turbulent to just a limited number of cells.

PATTERNS OF GROWTH OF OCEAN BASINS AND CONTINENTS

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Abstract

The geology of ocean floors differs greatly from that of continents in age, petrology, types of faulting, ore deposits, seismicity, and in the associated systems of mountains and ridges. These differences resemble those between the surface of a fluid convecting in a cauldron which is renewed like the ocean floors, and the islands of froth or slag that collect like continents. The tectonic pattern of continents is due to marginal growth distributed by the periodic breaking up and reassembly of continental blocks. The pattern on the ocean floor reveals the flow in the upper mantle which seems to take the form of a single complex cell.

Increasing knowledge of ocean floors and oceanic islands is showing how different these regions are from continents, especially when all are suitably defined.

The differences in elevations and morphology are obvious, although it was only in 1956 that Ewing and Heezen (1956) pointed out the continuity of the greatest mountain system on earth, the mid-ocean ridges (Menard, 1964). In age, no true oceanic islands or any cores from ocean floors are older than Late Jurassic, which is only a twentieth of the age of the oldest rocks on the continents (Wilson, 1965a). The common rocks of continental crust, gneisses and schists, are wholly lacking in ocean floors and oceanic islands. Recent examinations of many dredge hauls, especially by Engel et al. (1965), show that the ocean floors consist of tholeiitic basalt. This basalt is exposed at the surface of only the largest islands on submarine ridges and in a few areas on continents, but the conical peaks of all oceanic islands consist of alkali basalt, often highly differentiated. It has been suggested that the chief fracture zones of ocean basins are not the faults found on continents, but a new class of transform faults only possible where crust is being created and reabsorbed (Wilson, 1965b). No ore deposits or even traces of gold or base metal sulphides have been reported from oceanic islands.

From the available surveys, the patterns of magnetic anomalies appear complex over continents, but appear arranged in simple parallel strips over oceans as Mason and Raff have shown (Vacquier, 1965).

Continents grow along island and mountain arcs with one pattern of fracturing and seismicity, whereas ocean floors grow along mid-ocean ridges with another. The different modes of growth produce different lavas, different crust, and apparently different layers in the upper mantle.

It is becoming apparent from developments by Hess (1962), Elsasser (1963), Tozer (1965), and Orowan (1965) of the original convection hypothesis of Holmes (1931) that there is probably a shallow convecting layer in the mantle at a depth of from one hundred to a few hundred kilometres, and that it is likely to be convecting in rolls of great lateral extent with motions of a few centimetres per year.

Analogy with the surfaces of other convecting fluids, such as crucibles of iron and slag, cauldrons of soup, and froth or eddies of water and foam, suggest that the ocean floors correspond to the freshly risen surfaces of clear iron, soup, or water, and the continents correspond to the islands of slag, froth, or foam which have accumulated over a much longer period of time and in complex fashion. Thus it is on the ocean floors and not on the continents that one must expect to find the answer to the fundamental flow pattern and mode of behaviour of the earth.

The general pattern appears to be a single cell rising under the mid-ocean ridges and sinking under the active island and mountain arcs (Wilson, 1965b). The nature of the loop in the ridge through the Southern Ocean suggests that the loop is expanding northwards and that the pattern is a self-altering one – which offers an explanation of the periodicity of mountain building independent of the behaviour of the core (Wilson, 1965c).

In the southern hemisphere, northward spreading of the Gondwanaland continents has produced about a dozen major rifts and shears striking northerly, which are not matched in the northern hemisphere; this results in dislocations along the equator. Carey (1963) drew attention to them and attributed them to torroidal shear. But the newly suggested origin is considered to fit recent observations better and also to provide an explanation for the origin of regions of intermediate-type crust and of ridges in the Caribbean, Scotia, and Tasman Seas.

Thus the pattern of flow deduced from the ocean floors, the implied spreading of the upwelled parts of the ocean floors, and reabsorption of other parts along trenches, suggests a unified explanation of the recent movement of continents and the varied behaviour of mountain belts. This will serve as a first approximation until complete magnetic surveys of the oceans enable the detailed history of the spreading to be analyzed (Vine and Wilson, 1965; Wilson, 1965d). The notion that the history of spreading of the ocean floors can be established depends upon the hypothesis advanced by Vine and Matthews (1963) that periodic reversals of the earth's main magnetic field every 10^5 or 10^6 years are recorded in the strips of positive and negative magnetic anomalies.

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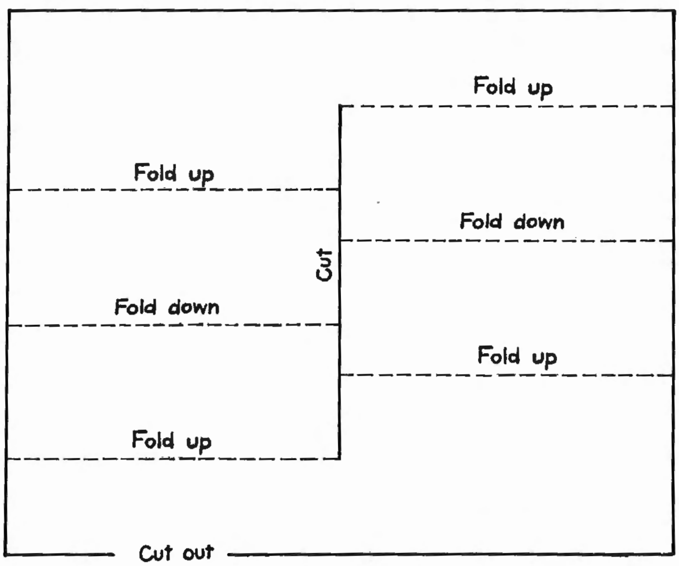
Editor's Note

The discussion below followed Professor Wilson's paper presented at the Symposium on a new type of faults which he called Transform Faults. He illustrated twelve varieties and showed examples which occur throughout the world. His thoughts on this subject are fully explained in two papers published in "Nature", vol. 207, pp. 343-347 and 907-911, 1965 and in two papers published in "Science", vol. 150, pp. 482-485 and 485-489, 1965.

The accompanying figure to be cut out and used to illustrate one of the types in three dimensions, was prepared by Dr. Charles H. Smith in jest, but is perhaps worthy of enclosure herein.



Do-it-yourself transform fault kit, or "ocean expander".

DISCUSSION

Dr. G.B. Udintsev (USSR)

Are there any data which do not fit your theory?

Dr. M. Talwani (USA)

Have you any explanation of why the ridges are ridges? In other words, why is the whole ridge, not just the crest, higher than the surrounding ocean basin?

Prof. Wilson

This has nothing to do with the geometry of transform faults and I think that the question should be directed to Professor Hess, who has contributed more to this problem than I have. I can only suppose that the crest may be uplifted over an expanded rising column.

Dr. D.C. Krause (USA)

I would like to compliment Dr. Wilson on another tour de force. I think it is striking how the conclusions are converging at this meeting towards this type of faulting. From conversations between him and myself, I know that we obviously have the same feeling. The proposal to offset the ocean floor along older zones of weakness, which certainly do exist, is, I think, very nice indeed. The fault in the North Atlantic where the scarp off West Africa goes out at sea, and then connects with the offset in the Mid-Atlantic Ridge, I think, solves what we know of these scarps very well indeed.

Dr. H.P. Laubscher (Switzerland)

I just wanted to point out that this new type of fault, called a transform fault, is not so very new. I think it was over 50 years or so ago that a German described certain so-called tear faults along which blocks moving on thrust planes are displaced one relative to another.

Prof. Wilson

I am glad you mentioned that. Let me say that I didn't take the point of view that transform faults are wholly new, but I think that in recent literature, and certainly in textbooks on structural geology, tear faults are not discussed or clearly defined as a new and different type of fault. I think that these faults deserve clearer and more definite recognition. I may say that my views on them have been published in "Nature", 24 July 1965, and 28 August 1965, and in "Science", with F.J. Vine, on 22 October 1965.

Dr. B.C. Heezen (USA)

The idea of these transform faults, I think, is very clearly a fresh one, but if you examine the rift graben in the South Atlantic you can see that the idea wasn't exactly unknown to us. The seismic belt does go through these offsets and it has occurred to us that the Pacific anomalies could be explained in the same way. In fact, this is in press in a volume that should be out in the next few weeks from the Symposium on Continental Drift held a year ago in London. In the Indian Ocean we have been able to extend this idea a little more. The same concepts have been expressed not only by us but also by Matthews and others in regard to the Murray Fault in the Indian Ocean. It is quite clear that the active belts have these offsets built into them. If a rift valley is growing now, it is growing with built-in offsets, and therefore, why couldn't we explain these big offsets in the past in the same way? However, I don't believe that I would say that there is precisely the same amount of movement north and south of the fault. It seems to me that the evidence suggests that the amount of growth on different sections of the ridge is different. This is shown by the fact that ridges form with different widths. So I would expect that the magnetic patterns on either side of the fault should be similar but not exactly the same. This is similar to the suggestion I made in regard to Dr. Talwani's paper. I think that the distance from the present axis out to any particular anomaly will differ in each sector of the ridge as the total width of the ridge varies.

Dr. A.S. Laughton (UK)

I would like to comment on a slightly smaller example of these transform faults in the Gulf of Aden and northwest Indian Ocean. Crossing the Gulf of Aden, as I described the other day, are diagonal faults which have displaced the central rift zone. One of these in particular extends from one side to the other and offsets the central zone by 15 or 20 miles. And it is precisely on this offset zone that the major concentration of earthquakes occurs. In this region the difficulty has always been that if the fault is a transcurrent one, then why don't offsets occur on the continents on either side? The theory of transform faults makes it clear why no offsets should occur, and there are no signs of young faults extending this feature onto the continents. It is evident that there are old lines of weakness considerably predating the formation of the Gulf of Aden. This proposal answers the difficulty which we had in this region, that is, that the only fracture zone, the Kossack Trench, is a left-lateral fault, while it is apparent, according to ideas of transcurrent faults that it should be a right-lateral fault. There doesn't seem to be any particular reason why there should be a reversal in the sense of these two faults. If, however, they are both transform faults, then such a reversal is not necessary, and the transform faults are a consequence of the original lines of weakness.

Dr. G.A. Thompson (USA)

It is evident from the many comments that this hypothesis has a great deal to offer. I hesitate, therefore, to raise a question of detail. According to your proposal, the East Pacific Rise terminates at the San Andreas Fault. Does not this overlook the rather overwhelming evidence that the East Pacific Rise extends into western North America through the Basin and Range system? Can you explain that?

Prof. Wilson

I am not very clear about that evidence, I am afraid.

Dr. Thompson

It includes high heat flow, low velocities in the upper mantle, the topographical rise, the great extent of normal faulting, and seismic activity along the extension of the same crest.

Prof. Wilson

Well, there certainly is an unusual situation in the Basin and Range province, but I don't know that it very closely resembles a mid-ocean ridge.

Dr. Thompson

I think that Menard postulated that the mid-ocean ridge did extend into the Basin and Range province.

Prof. Wilson

Yes, I recall Menard's idea that the East Pacific Rise passed under California and Nevada and emerged from Oregon striking in a northwesterly direction, but I think that the topography suggests that the ridge off Vancouver Island is running at right angles to that and in a northeasterly direction. Benioff's seismic data also suggest this as do the magnetic anomalies. I am just wondering whether formerly, during the early Tertiary, a mid-ocean ridge did not go into the Gulf of California, pass through the Basin and Range province as far as the Rocky Mountain Trench and not come out. In that case the San Andreas Fault and the ridge off Vancouver Island are younger Pliocene or Miocene additions, and the Rocky Mountain Trench might be an early Tertiary forerunner of the San Andreas Fault.

Dr. G.G. Shor (USA)

We have been studying the ridge off the State of Washington. There is a high heat flow determination off Cape Mendocino. Many high heat flow values have been determined northwest of there, as well as a low velocity zone off Cape Mendocino. Last spring we worked just off this ridge west of the Alaskan abyssal plain and found a low velocity mantle. As far as I can see, all the trends, except possibly the magnetics, are northwesterly. So I would much prefer to take the ridge system that way.

Prof. Wilson

You mentioned the fact that the direction of the magnetic anomalies does not agree with your interpretation.

Dr. Shor

Everything else does, except some of the magnetics.

Prof. Wilson

But the topography as it is shown on Professor Menard's map agrees with the northeast strike of the magnetics.

Dr. Shor

You can interpret all the topography in the other direction too.

Dr. J. Healy (USA)

I haven't quite followed your whole idea, but I am a little disturbed about this failure to conserve mass. Do I understand correctly that you propose that the whole Atlantic crust has come up through the Mid-Atlantic Ridge?

Prof. Wilson

Yes, precisely.

Dr. Healy

Where does it come from?

Prof. Wilson

The mantle. And it goes back into the mantle in trenches farther on. That is the whole idea of a convective system. The total mass of the earth is conserved, but upwelling currents under mid-ocean ridges bring up lava from the mantle to create new crust and downward currents under the trenches take ocean crust back into the mantle.

Dr. Healy

Does the crust in the Pacific coast of the United States go back to the mantle and come up in the Mid-Atlantic Ridge?

Prof. Wilson

Well, I don't think I would discuss it in those terms, but at the present time new crust comes up in the Atlantic, while North America and the Pacific Ocean move west, and older ocean crust goes down under Japan.

Dr. Healy

Wouldn't you admit that there is a pretty difficult chemical problem here, a composition problem?

Prof. Wilson

No, I don't think so. There is a mechanical problem, yes, but not a chemical problem. We know from the work of Eaton and Murata in Hawaii that basalt lava comes from the upper mantle. This fresh lava comes up from below, pushes the crust apart (there is no chemical problem there), and later at some other place, in an ocean trench, the lava on the ocean floor is carried down and reabsorbed as R.R. Coats has suggested in Alaska. It is not a difficult chemical problem. There is, if you like, a mechanical problem as to what carries it round.

Prof. S.K. Runcorn (UK)

There are, of course, one or two points on which Professor Wilson and I agree. Perhaps, to make our position clear, I should say that I agree that he has demonstrated very clearly why the convection current in the Atlantic follows so well the coastline of South America and Africa. But it seems to me he is saying, in a way, that he is pulling himself up by his own bootstraps in talking about changes in the convection pattern. During their movements, the continental blocks have lots of time to reach equilibrium. The question that the classical theory is actually asking is why the cracks develop in such places. For example, why have the convection currents parted North America and Europe, and South America and Africa, along this more or less north-trending line. Professor Wilson claims that the theory of convection is not relevant to this question. One of his reasons is that he feels it is undue simplification to talk about the mantle as if it were uniform. I am rather doubtful about this criticism, because I am sure we both agree that there is an upper layer of material which acts like a solid, the typical mixed phase, and below it is a deep zone, which is essentially fluid on a plot against time. One can show that even the smallest amount of inhomogeneity, even corresponding to density differences of, say, one part per million, would produce motion by buoyancy. And so a mantle of this kind would flow and become uniform even if it wasn't in the first instance. In other words, it would be in isostatic equilibrium. And we know from gravity data, of course, that it isn't very far from it. So I believe that the theory of convection can be reasonably applied to this problem and I think that Professor Wilson is a little misleading when he talks of an enormous, single convection cell wrapped around the earth. When you analyze this by spherical harmonics, it breaks up into a set of smaller cells. The theory of convection goes on to explain why the pattern changes and why the pattern has this rather large scale, and what sort of patterns exist in, say, millions of cells. Such patterns we know are the cause of break-up of the continental masses. From the size of the fragments we can find the mode of the cells, which increase in number as the core grows and the mantle gets thinner.

Prof. Wilson

Professor Runcorn and I don't agree about the growth of the core. He considers that the whole mantle is convecting and that as the core grows slowly throughout geological time the number of cells increases and the pattern of mountain building changes, about five times. I follow Elsasser and Tozer in thinking that the lower mantle is rigid and that the growth of the core - which probably happened quickly - has had no effect on mountain-building.

I have examined the geology and I think the pattern I get from it is a good suggestion of what that pattern of flow is in the earth, but, on the other hand, the regular little cells which Runcorn plots from a simple interpretation of the mathematics with no reference to the geology do not look at all like the real earth to me.

GEOTHERMAL STUDIES OF CONTINENTAL MARGINS AND ISLAND ARCS[1]

W.H.K. Lee[2], S. Uyeda[3], and P.T. Taylor[4]

Abstract

The thermal regime in continental margins and island arcs was investigated by analyzing the existing heat flow results and other pertinent data. Heat flow patterns across the continental margins were found to be correlatable with geological features. Time series analysis of ocean water temperature records indicated that annual and semidiurnal temperature variations are dominant in the oceans. These suggest that oceanic heat flow measurements can be carried out in shallow water, provided that the probe penetrates beyond a depth of about 3 metres.

INTRODUCTION

The purpose of this paper is to investigate the thermal regime in continental margins and island arcs. Results of existing heat flow measurements and other pertinent data will be reviewed. Water temperature records have been analyzed and show that oceanic heat flow measurements could be carried out in shallow waters.

CONTINENTAL MARGINS

Definition. Continental margin has been defined by Heezen et al. (1959) to include those provinces of the continents and oceans which are associated with the boundary between these first-order features of the earth.

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[3]Geophysical Institute, Tokyo University.

[4]Lamont Geological Observatory.

Crustal Structure. Lee and Taylor (in press) have recently analyzed the results of seismic refraction measurements. The average crustal thickness for the continents was found to be about 35 kilometres and that for ocean basins 7 kilometres. A plot of crustal thickness versus elevation shows that the transition zones between continental and oceanic crusts occur in approximately 0 to 2 kilometres depth of water around the edge of the continents. Taking this as a simple working definition, the continental margins comprise about 15 per cent of the earth's surface.

Geological Features. Figure 1 shows the major geological features of the earth. Three main types of continental margins are readily recognized: 1) stable margins – areas bordering stable continents and ocean basins (e.g., east coast of the United States); 2) ridge margins – areas bordering young orogenic belts and oceanic ridges (e.g., Southern and Baja California, and the Gulf of Aden); and 3) island arcs and trenches (e.g., Japan and Indonesia island arc areas). In the next section, we will show that heat flow patterns in these three types of continental margins are different.

HEAT FLOW

The most direct observation of the thermal regime of the earth is the measurement of terrestrial heat flow. Surface heat flow from the earth's interior is the rate of heat transferred across the earth's surface per unit area per unit time. Near the earth's surface heat is transported mainly by thermal conduction and hence heat flow is determined as the product of thermal conductivity and vertical temperature gradient.

Techniques of oceanic heat flow measurements are based on the fact that the bottom temperature in deep oceans is remarkably constant in space and time. The ocean floor sediment therefore should reach steady thermal state with the deeper crustal materials. Because of the difficulty in recording temperature for more than half an hour in the ocean floor, the above assumption has never been seriously tested except when Von Herzen and Maxwell (1964) measured heat flow at a preliminary Mohole site off Mexico to a depth of 154 metres and found that the heat flow was constant with depth and agreed well with surface measurements by the Bullard-type probe.

Because of possible thermal instability in continental margins (see later section), heat flow measurements have seldom been made under shallow ocean water (e.g., Figure 2, where heat flow values are plotted against station elevation or depth, shows the lack of data points at 0 to -2 kilometres). Figures 3 and 4 show the average heat flow values in a 5-degree grid. A close examination of these figures reveals that heat flow falls into three main patterns according to the types of continental margins. In stable

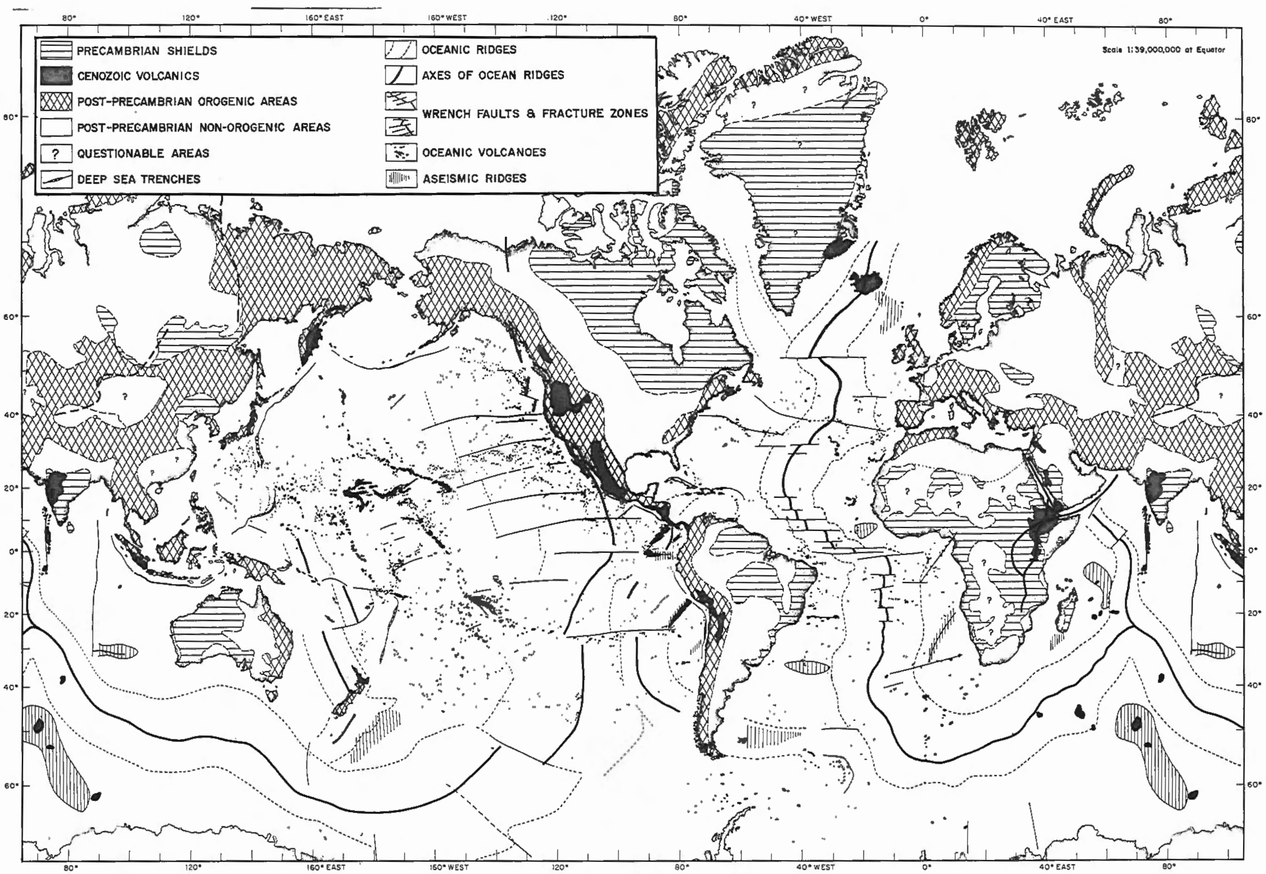

Figure 1. Major geological features of the earth. Most oceanic features have been taken from Menard (1965) with additional data from Fisher and Hess (1963), Heezen (1962), and Heezen and Ewing (1963). Geological features on land have been compiled from various geological maps.

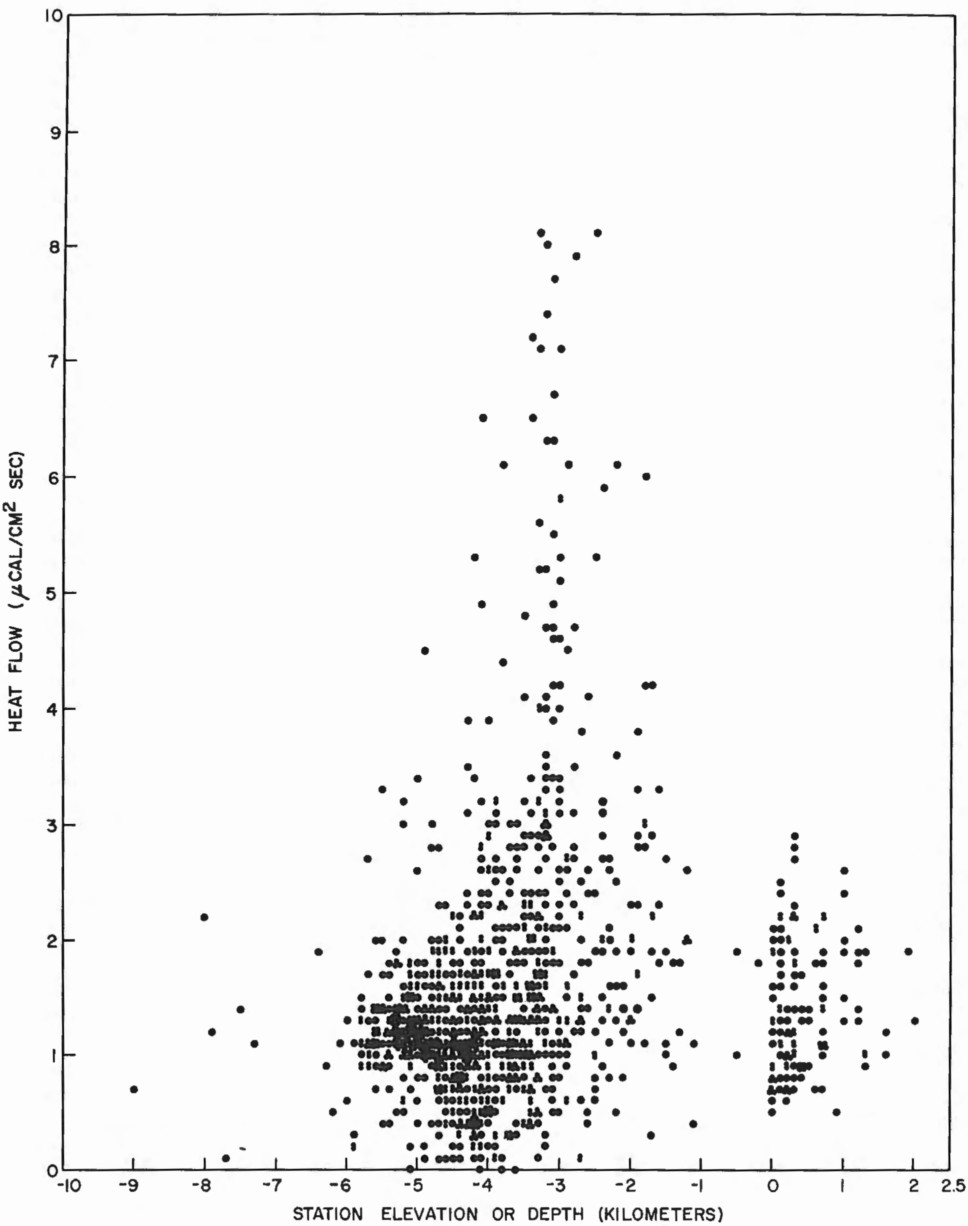

Figure 2. Distribution of heat flow values with station elevation or depth. Each dot, regardless of its size, represents one data point. (From Lee and Uyeda, 1965, Figure 47)

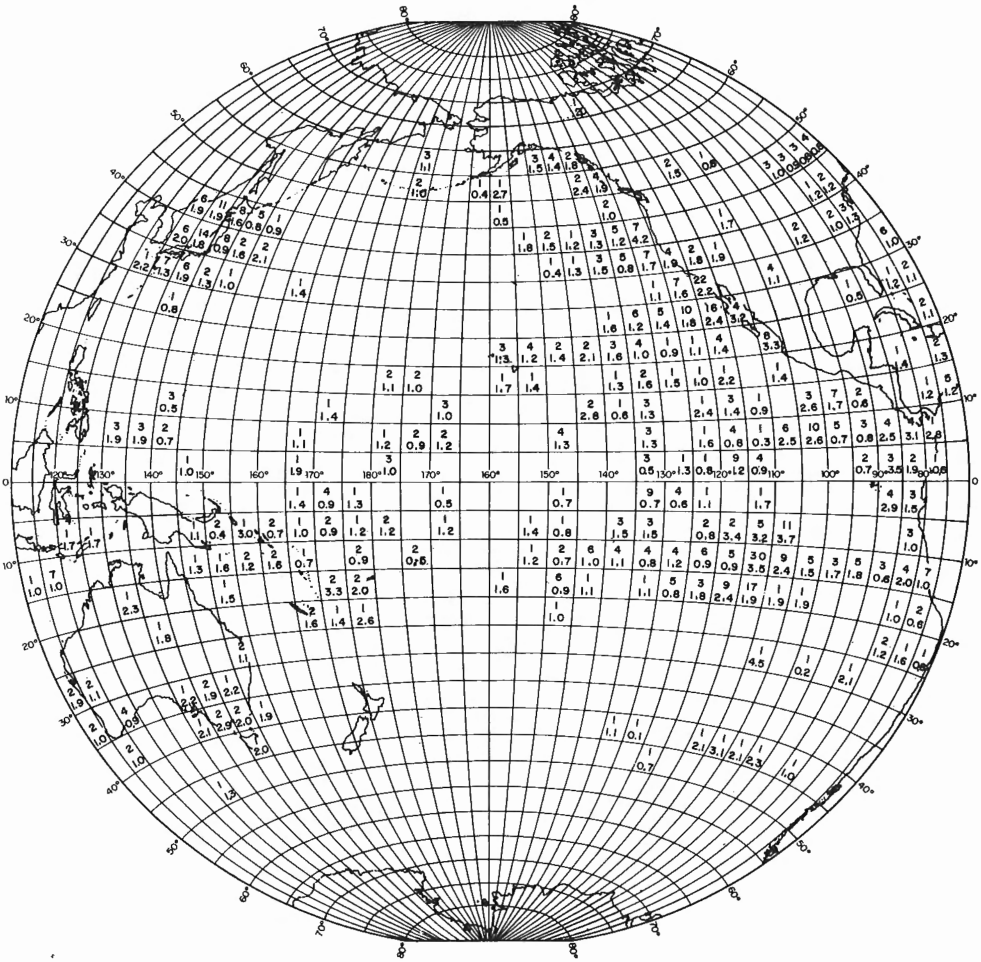

Figure 3. Number and arithmetic mean of analyzed heat flow data in 5° by 5° grid. (From Lee and Uyeda, 1965, Figure 1a)

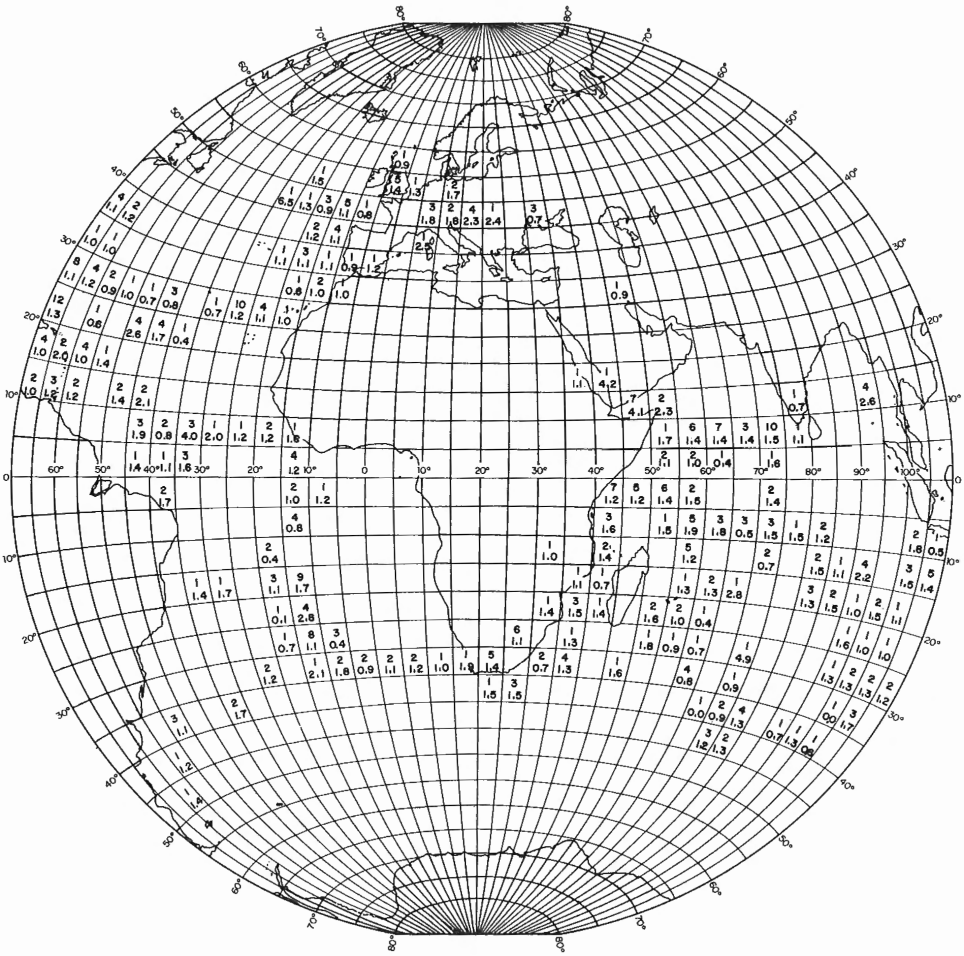

Figure 4. Number and arithmetic mean of analyzed heat flow data in 5° by 5° grid. (From Lee and Uyeda, 1965, Figure 1b)

margins, heat flow appears to be uniform and has an average value of 1 μcal/cm^2 sec, whereas in ridge margins, heat flow seems to be high, and averages about 2 μcal/cm^2 sec. Finally, in island arcs and trench complexes, heat flow appears to be very complicated, and has high, low, and high values across the continental margins (e.g., Figure 5 shows a heat flow profile across Japan together with crustal structure and gravity anomaly profiles).

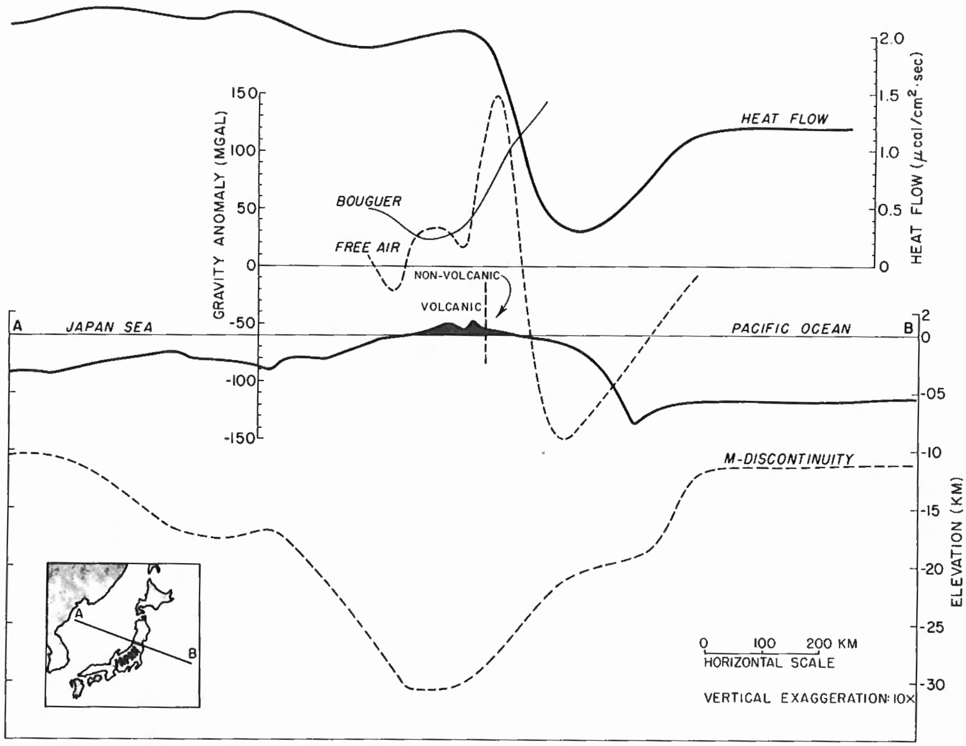

Figure 5. Cross-sections showing heat flow, elevation, gravity anomalies, and crustal structure across Japan.

These three different types of heat flow patterns are obviously related to the different tectonic activities in the continental margins. In stable margins, there are few active tectonic processes and consequently low and uniform heat flow values are found. The ridge margins are closely related to the crestal zones of the mid-oceanic ridges, where vulcanism and shallow earthquakes are common, and hence heat flow is high. The complicated heat flow patterns in island arc and trench areas simply reflect the complexity of tectonic activities (such as trench formation, vulcanism, deep and shallow earthquakes, and metamorphism) occurring beneath.

THERMAL CONDITIONS OF OCEAN FLOOR

As mentioned previously, oceanic heat flow measurement is based on the assumption that the bottom water temperature in deep oceans is constant with time so that the ocean floor sediment is in a steady thermal state with the deeper crustal materials. Variations of water temperature in deep oceans at the same location have been observed to be within the instrumental errors (± 0.02°C), although there are small geographical variations (Wooster and Volkmann, 1960; Knauss, 1962). The number of such observations is few and they are usually not repeated at the same place more than once. Lubimova et al. (1965) have observed super-adiabatic temperature gradients near the ocean bottom due to heat flowing from the earth's interior. However, such gradients have not been observed by other research groups (M.G. Langseth and A.H. Lachenbruch, private communications). Reid and Lynn (1965) have analyzed the temperature, salinity, and oxygen data obtained from 123 deep hydrographic stations off California from January 1960 to December 1963. They found that beneath the depth of the temperature minimum (3 to 4 kilometres deep), the water appears to be vertically homogeneous in potential temperature, salinity, and oxygen. They concluded that such homogeneity is a consequence of heat conducted from the earth's interior causing convective overturn and mixing upward from the bottom to the depth of the temperature minimum.

Rossby (1937, 1938) has demonstrated from theoretical grounds that a great deal of thermal unrest should exist in the deep ocean, because internal inertial gravity wave motions are induced in the deep stratified layers of the sea in response to transient wind-stresses. Defant (1932, 1950) has suggested that internal tidal waves are widespread in the oceans and has presented many analyses of rather short series of observations as evidence. Recently, Haurwitz et al. (1959) have analyzed their temperature observations from depths of 50 metres and 500 metres, offshore from Castle Harbor, Bermuda Islands. Their data extending from December 1954 to October 1955 is not only the longest nearly continuous time series of ocean temperature data, but also is from a locality which is well situated to represent thermal conditions far from the effects of continental borders. They have carried out time series analyses on their data and found that at low frequencies, the spectra possibly show small peaks near the semidiurnal tidal frequency and (at 500 metres) near the inertial or diurnal tidal frequency. Aside from these peaks and a very broad maximum of the 500 metres spectra centred at 0.5 cycles/hour, the spectra decrease monotonically with increasing frequency.

Very recently, Lee and Cox (1966) have analyzed four sets of time series of water temperature records, two of which are at almost the same location (Fig. 6). For short period variations, the temperature data are based on that of Cox et al. (1965) who measured the temperature at 15

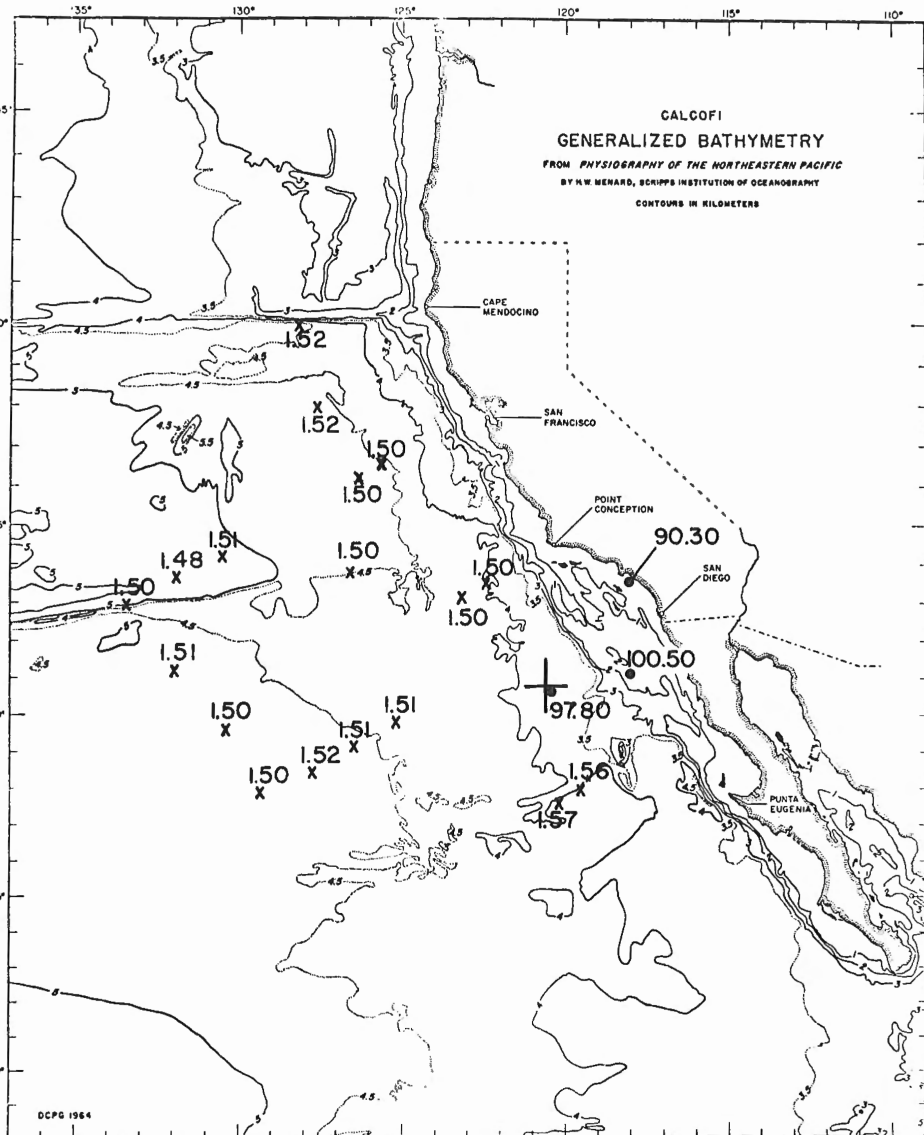

Figure 6. Station locations for time series analysis of ocean water temperatures. Station of Cox et al. (1965) is marked by ┼, and hydrographic stations by ●. In addition, temperatures at 4 kilometres depth are indicated by x. (After Reid and Lynn, 1965)

depths, every 5 minutes, for 14 days, off California. Time series analysis has been carried out for all these 15 series and the results are shown in Figure 7, where the spectral density is plotted in the logarithmic scale. Since the temperature fluctuations seem to be related to ocean tides, the principal tidal line spectra are also given with heights proportional to their equilibrium values in an arbitrary relative scale. The temperature spectra show a large peak at semidiurnal frequency for all series except perhaps the last. These semidiurnal peaks are several times greater than the backgrounds and become less dominant only near the ocean bottom; their amplitudes are summarized in Table I. Series 15 is recorded at 3,802 metres, almost at the ocean floor (3,836 metres), and its spectrum shows two small peaks. This series probably represents the noise of the instruments, and the temperature fluctuation there is perhaps no greater than the noise level. Secondary peaks near the inertial and/or diurnal tidal frequencies can also be seen in most of the temperature spectra. We therefore conclude that part of the temperature fluctuation of ocean water is probably due to motions induced by internal waves caused by tidal attractions. Moreover, there is also a continuum in the spectra due to various unknown interactions.

For long period variations, the temperature data are based on three hydrographic stations, located in Figure 6, at which approximately monthly observations were taken between 1950 and 1960 and extending to depths of 500 and 1,000 metres. The temperature spectra of these data are shown in Figure 8, where the spectral density is plotted in the logarithmic scale. At the surface, all three stations clearly show a large peak at the annual frequency as expected from the annual variation of solar radiation. The annual peak is fairly well preserved to 400 or 500 metres depth at Station 90.30 (near the coast). It disappears at about 400 metres at Station 100.50 (farther away from land), and perhaps is not recognizable at Station 97.80 (in the open ocean). Since the incoming solar radiation is rapidly absorbed in the first few metres of sea water in the oceans, the annual temperature oscillation is therefore expected to diminish at greater depths, as is indeed indicated in Figure 8. The amplitudes of the annual peaks are summarized in Table II.

The effects of the short and long period temperature fluctuations on the heat flow can be estimated from their amplitude and frequency. (Tables I and II summarize the amplitudes at dominant frequencies of the time series studied.) The temperature at depth z due to a sinusoidal oscillation, $T_o \cos(\omega t)$ at $z = 0$ is

$$T_z = T_o \exp(-kz) \cos(\omega t - kz) \qquad (1)$$

Here, $\omega = 2\pi/P$, where P is the period, $k = (\omega/2\kappa)^{\frac{1}{2}}$, and the wavelength λ is

$$\lambda = 2\pi/k = (4\pi\kappa P)^{\frac{1}{2}} \qquad (2)$$

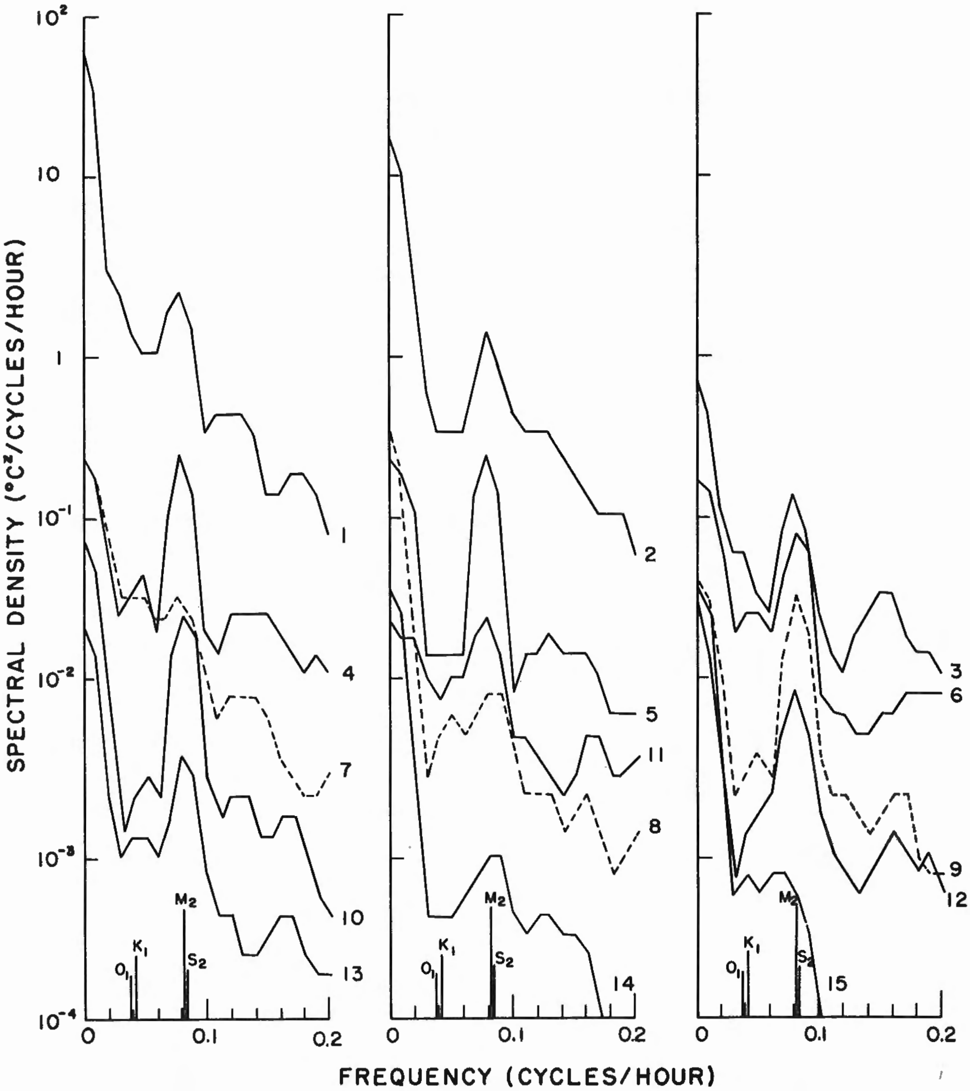

Figure 7. Spectra of temperature data of Cox et al. (1965). Series numbers indicated on the right correspond to depths given in Table I.

TABLE I

Statistics of temperature data of Cox et al. (1965)[1].

Series	Depth (Metres)	N[2]	Mean Temperature (°C)	Standard Deviation (°C)	Amplitude at Semidiurnal Frequency (°C)
1	85	320	12.0	0.91	0.20
2	128	314	9.8	0.56	0.14
3	175	316	8.7	0.13	0.05
4	230	313	7.7	0.11	0.06
5	320	315	6.8	0.11	0.07
6	432	313	6.15	0.08	0.04
7	565	319	5.25	0.08	0.02
8	720	320	4.65	0.07	0.01
9	890	312	4.10	0.04	0.02
10	1080	311		0.04	0.02
11	1330	317	3.10	0.05	0.02
12	1610	311	2.60	0.03	0.01
13	1990	307	2.05	0.02	0.01
14	2500	306	1.80	0.02	0.005
15	3803	308	1.55	0.02	0.0005

[1] Station located at latitude 30°44.0'N, longitude 120°40.8'W; 3,836 metres water depth.

[2] N is the number of hourly averages available for the analysis. If no data are missing, N = 325.

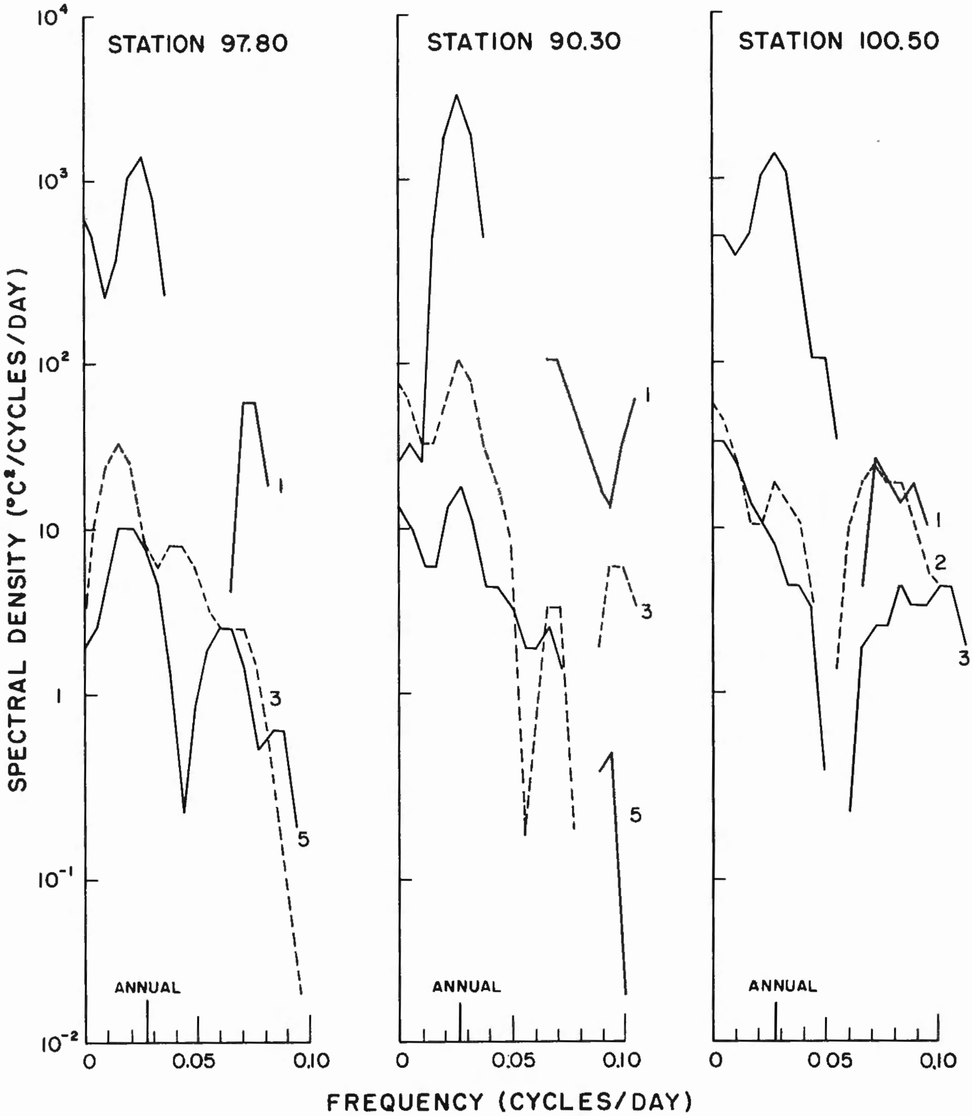

Figure 8. Spectra of hydrographic station temperature data. Series numbers indicated on the right correspond to depths given in Table II.

TABLE II

Statistics of hydrographic station data

Station	Series	Depth (Metres)	N[1]	Mean Temperature (°C)	Standard Deviation (°C)	Amplitude at Annual Frequency (°C)[2]
	1	0	55	16.97	1.65	1.27
97.80	2	100	55	12.80	1.53	
(30°35'N	3	200	54	8.72	0.29	
120°30'W	4	300	54	7.30	0.20	
3843 m	5	400	51	6.41	0.18	
water depth)	6	500	51	5.82	0.15	
	1	0	58	16.43	2.13	2.10
90.30	2	100	58	10.05	0.98	0.58
(33°25'N	3	200	57	8.87	0.51	0.18
117°55'W	4	300	57	8.03	0.36	0.11
600 m	5	400	57	7.17	0.23	0.11
water depth)	6	500	45	6.45	0.17	0.05
	1	0	76	16.55	1.78	1.38
100.50	2	200	75	8.56	0.39	0.12
(31°00'N	3	400	74	6.75	0.29	
118°08'W	4	600	54	5.51	0.18	
1740 m	5	800	35	4.64	0.09	
water depth)	6	1000	33	3.99	0.08	

[1]N is the number of monthly averages available for the analysis. If no data are missing, N = 125 for Station 97.80, N = 112 for Station 90.30, and N = 119 for Station 100.50.

[2]Where annual peak in the spectra is not pronounced, the amplitude has not been estimated.

Taking $\kappa = 0.002\ cm^2/sec$ for ocean sediments, the wavelength of semi-diurnal oscillation is about 35 cm, and that of the annual oscillation is about 9 metres. At a depth of one wavelength, the amplitude of the oscillations is reduced by a factor of $\exp(-2\pi) = 0.002$ and so is negligible for temperature variations of 1°C or less.

From Tables I and II it is seen that the temperature fluctuations are larger from long period data than from short period data. If the present data are typical for the continental margins (off the continental shelf, and water depth greater than 200 metres), then the expected annual amplitude of temperature fluctuations there is about 0.1°C. Since the temperature is usually measured to 0.002°C in heat flow measurements, the required depth beyond detectable temperature disturbance is about 3.5 metres. Short period fluctuations have long been damped out at this depth. Therefore, it is possible to obtain heat flow measurements in shallow waters if the probe penetrates beyond 3.5 metres, which is feasible using an existing Ewing-type probe. However, other thermal disturbances such as rapid sedimentation, turbidity current, etc., in the coastal areas may greatly hinder the measurement. Furthermore, there is the problem of penetrating coarse sediments offshore; and local hydrographic conditions must also be taken into account.

FUTURE WORK

From Figures 3 and 4, it is obvious that there are several geologically important areas where little or no heat flow measurements have been made, such as margins neighbouring the Phillipines, Antarctica, South America, and the New Zealand-Tonga Trench area. We wish to emphasize that designed surveys will greatly aid in analyzing results using statistical methods. Station sites should be carefully selected so as to be representative of investigated areas. Deeper penetration of the heat flow probe should be made wherever possible to reduce possible thermal disturbances. Furthermore, other measurements such as seismic, gravity, magnetic, geochemical, and geological should be made simultaneously, so that a more complete picture of continental margins may be obtained.

ACKNOWLEDGMENTS

We wish to thank J.L. Reid for helping us locate water temperature records, and R.S. Arthur for lending us a set of Oceanic Observations in the Pacific. This work was supported by a grant from the National Aeronautics and Space Administration (NsG 216-62).

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DISCUSSION

Dr. A.S. Laughton (UK)

I think it is very important in heat flow measurements to make careful observations of the temperature variations in bottom water, and I think what Dr. Lee has just shown us is an important analysis. But it is dangerous to generalize too much and assume that these results can apply to all parts of ocean basins. First, we must understand the horizontal movements of the various water masses which have been identified, I think, mainly by the physical oceanographers. We should study the boundaries between these different water masses. The continuous measurement of vertical temperatures, being made these days by oceanographers, indicates temperature fluctuations with depth rather greater than have been supposed. These fluctuations are presumably accompanied by variations in density and salinity and give rise to stratification.

If a layer with temperature variations intersects a region of high topography, like the mid-ocean ridge, then it may produce fluctuations in the locally bottom temperatures. Perhaps these fluctuations could give rise to some of the erratic results on the mid-ocean ridges and in other shallow areas. For instance, cold water from the Norwegian Sea flowing through the Faroe Channel, comes through in great globules of water called "boluses" by Cooper. They form quickly and irregularly and surely disturb the temperature gradients along their paths. We should understand these moving water masses and not rely too much on a time series analysis taken at one or two places in the world.

Dr. Lee

I agree that we should make more measurements of water temperature. However we now know the order of magnitude to expect. The results we have agree very well with those of the Atlantic Ocean. The Scripps people plan to make more measurements off California. And the Lamont people plan to make some there, too. So we will have a good check against each other.

Dr. A.E. Beck (Canada)

To be quite sure of heat flow measurements in ocean basins, one of the problems is measuring the gradient of conductivity in mud and in bottom water. If the water is stable, surely the heat flow is the same across the boundary.

Dr. Lee

There is a mechanical difficulty. The adiabatic temperature gradient in the sediment is of the order of 10^{-4} cgs units whereas in the water it is of the order of 10^{-6}. The change of scale is a factor of 100 at the interface.

However, the vertical tidal motion of the water is of the order of 10 metres. The oxygen content at the bottom is very much like that at the surface. Mixing of the water by tidal motion prevents the oxygen at the bottom from being depleted. Actually, the temperature measurements were originally made to study the vertical motion of water. We can readily calculate the vertical velocity. This has been done by Cox, who found the vertical movement to be about 10 metres.

Dr. G.B. Udintsev (USSR)

What do you mean when you say that the influence of tide on the temperature extends down for approximately 3 metres? Must not you take the measurements below 3 metres?

Dr. Lee

Yes, this is true, in shallow water. Unless the upper sensitive element of the probe is at least 3 metres below the surface, it will be affected by the tidal motion. The Bullard-type probe which is about 2 metres long is not suitable for shallow waters. However, in water deeper than 4 kilometres, the tidal effects are negligible.

Dr. R.W. Girdler (UK)

I wish to appeal for more attention and care to be applied to spherical harmonic analyses of heat flow data. One of the most impressive features in the world heat flow map is the positive thermal anomaly plotted over Africa, where there are no observations and which is presumably due to high heat flow measurements in the Red Sea and Gulf of Aden. We need two kinds of analyses: a broad analysis of all the data and an analysis of local heat flow values. For a picture of the overall heat flow pattern, we should filter out the local values from the mid-oceanic rift, Red Sea, and others.

Dr. Lee

In the paper, Lee and MacDonald (1963), we carried out analyses by discarding data with greater than one standard deviation from the mean. So, in this way, we cut out all the high and low values. But the results still indicated a high over the East Pacific Rise and a low over the Central and North Pacific Ocean.

Dr. Girdler

Yes, but this is not the same. One should find some criteria - geological, physiographic, or such, but not purely mathematical - for excluding local observations that may have an abnormal effect on the broad analysis.

Dr. Lee

Yes, we tried to do that by using geological criteria. As you have seen, we divided the world into 5° by 5° areas, and estimated within each area what portions are ocean basin, ridges, and so on. However, the analyses have not been completed yet.

Dr. A.H. Lachenbruch (USA)

Are the places where you took the temperatures in the water far from land?

Dr. Lee

About 80 nautical miles offshore.

Dr. Lachenbruch

Was not one place in water of full oceanic depth?

Dr. Lee

That one is off Bermuda by Haurwitz and others. But they took measurements in no deeper than 500 metres of water.

Dr. Lachenbruch

There are so many sources of transient disturbance of the temperature gradient that the best approach to oceanic heat flow is to make the penetration deep enough and to have enough thermal elements, so that at least two independent determinations of heat flow can be made at each station. Consistency between determinations precludes any transient condition.

One more point: in your discussion of the bias of heat flow measurements on the oceanic ridges, you pointed out that where the probe failed to penetrate is potentially a place of higher heat flow. But where the penetration is successful, there is frequently a topographic low, locally a small basin, and the results are not representative of a local topographic high.

Dr. Lee

Yes, allowances for topography have never been made on the oceanic heat flow data, as far as I know. We do not know the topography that well. One individual heat flow value has very little meaning, but the average of ten or twenty measurements over a small area may be significant and reliable.

A REVIEW OF RECENT STUDIES ON CONDUCTIVITY ANOMALIES ALONG CONTINENTAL MARGINS

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Abstract

The disturbance vector of geomagnetic variation of a duration from several minutes to several hours along some continental margins (e.g. the Australia, Antarctica, and California coasts and Japanese Islands) has an anomalous behaviour referred to as the coastal effect. The coastal effect is attributed to a difference in electric conductivity of the upper mantle under the oceans and under the continents; either the thickness of the non-conductive uppermost part of the mantle is much thinner under the oceans than under the continents, or the conductivity of the upper mantle is much higher under the oceans than under the continents.

In connection with the Upper Mantle Program (UMP), the working group of magnetism of the Upper Mantle Committee (UMC) took up the problem of anomalous electrical conductivity of the earth's interior, often found near continental margins, as one of its geomagnetic research projects.

An international symposium on this special problem was held at Berkeley on August 24, 1963, as one session of the International Union of Geodesy and Geophysics (IUGG) and 13 papers were presented (Ref. 1). The same problem was discussed at Pittsburgh on November 20, 1964, in an "International Symposium on Magnetism of the Earth's Interior", co-sponsored by the International Association of Geomagnetism and Aeronomy (IAGA) and UMC, and 11 papers were presented (Ref. 2).

This short note will deal with the writer's present view on this special problem based on summaries of those two symposia.

The problem of conductivity anomalies is connected with anomalously large values of the vertical component of geomagnetic variations of comparatively short periods of one minute to three hours. In 1951, the writer questioned the downward displacement of all SSC's (Sudden Storm Commencement) observed at Kakioka, Japan, because the vertical component of SSC's are upward in most stations in the Northern Hemisphere. It has been well established that the SSC magnetic field is approximately northward along the geomagnetic axis so that the vertical component of SSC's in the Northern Hemisphere should be upward.

Electric currents induced by the geomagnetic variation into the electrically conductive earth's interior intensifies the northward horizontal component (ΔH) and reduces the upward vertical component (ΔZ). However, the downward magnetic field produced by the induced current can never exceed the upward component of the primary field, in so far as there is no lateral change in the distribution of electrical conductivity within the earth. Therefore, the downward displacement of SSC's observed at Kakioka must be considered anomalous.

Similar anomalies in the vertical component of geomagnetic variation for geomagnetic bays of one- to three-hour duration have been found in this area (Rikitake et al., 1952). Extensive observational and analytical studies were made chiefly by Rikitake and his co-workers (1952, 1953) to study this problem in Japan. Since the beginning of the UMP, five magnetic stations have been built to fill the gap in the existing Japanese network, and a research group on the conductivity anomaly problem was established to study the problem in as much detail as possible using all data obtained from these coordinated stations.

Figure 1 shows the UMP network of geomagnetic stations in Japan and an example of the distribution of a geomagnetic bay (March 20, 1964) at these stations.

Figure 2 illustrates the distribution of vertical component ΔZ for the geomagnetic bay of March 20, 1964. Negative values are normal and positive values are anomalous. The anomalous zone extends approximately along the Pacific coast of the Japanese Islands. At the locality where the anomaly is at its maximum, the ratio $\Delta Z / \Delta H$ reaches a high of 1.2. This anomaly has been called the "Japan anomaly". The maximum value of the ratio $\Delta Z / \Delta H$ in the Japan anomaly increases to 1.5 for shorter period variations.

Maeda et al. (1965) have recently studied eight examples of SSC fields obtained at 126 magnetic stations distributed throughout the world. They confirmed: 1) that the SSC field at continental stations (52 in number) is approximated by the sum of an external field (E) and an internal field (I) induced in a model earth having a uniform spherical core of 10^{-12} emu in electric conductivity and of (Re-400) kilometres in radius where Re denotes the earth's radius; and 2) that the SSC fields observed at some stations near continental coasts (i.e. coastal stations of 57 in number) definitely do not follow the general rule of the relationship between E and I found for the continental regions.

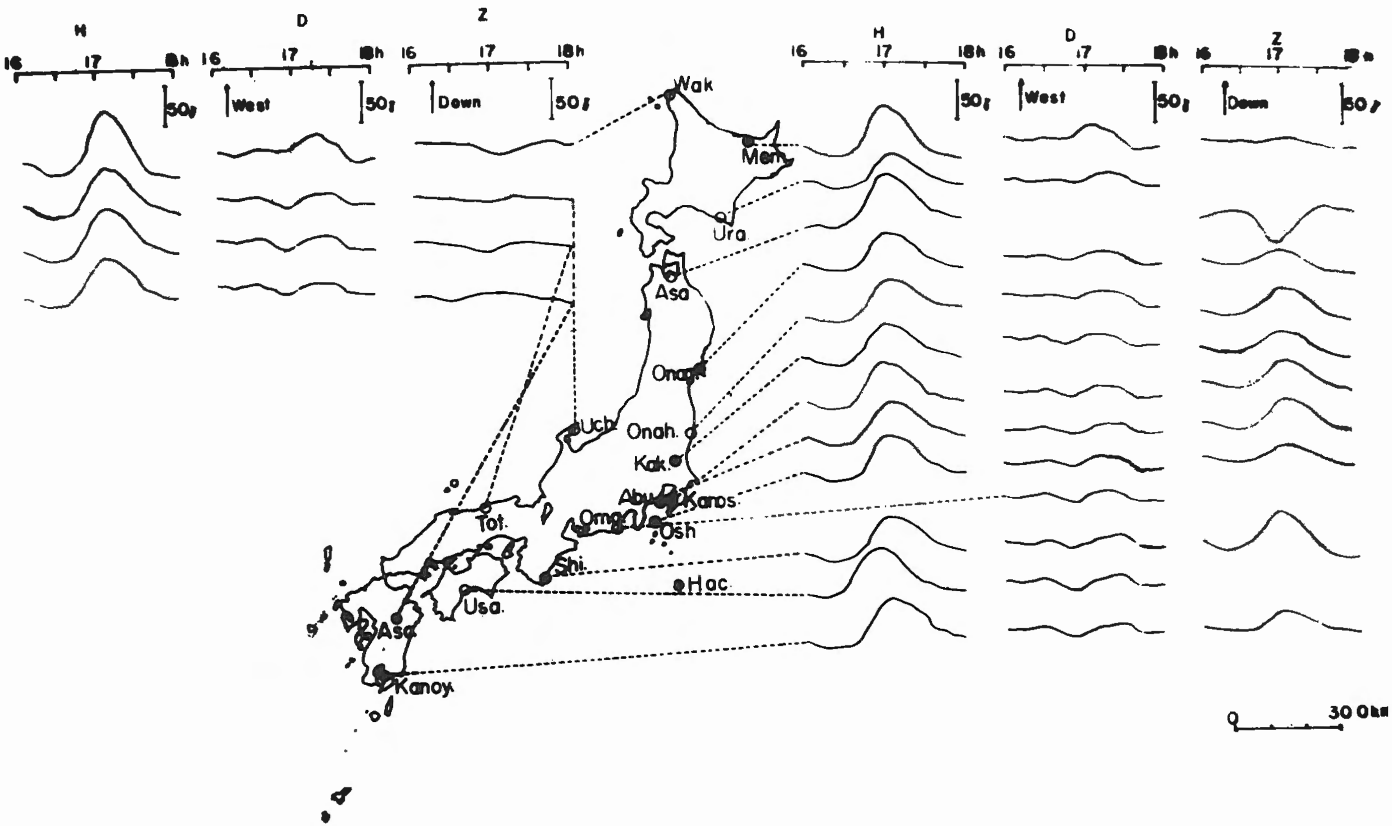

Figure 1. UMP network for geomagnetic observations in Japan and an example of an observed geomagnetic bay. (March 20, 1964)

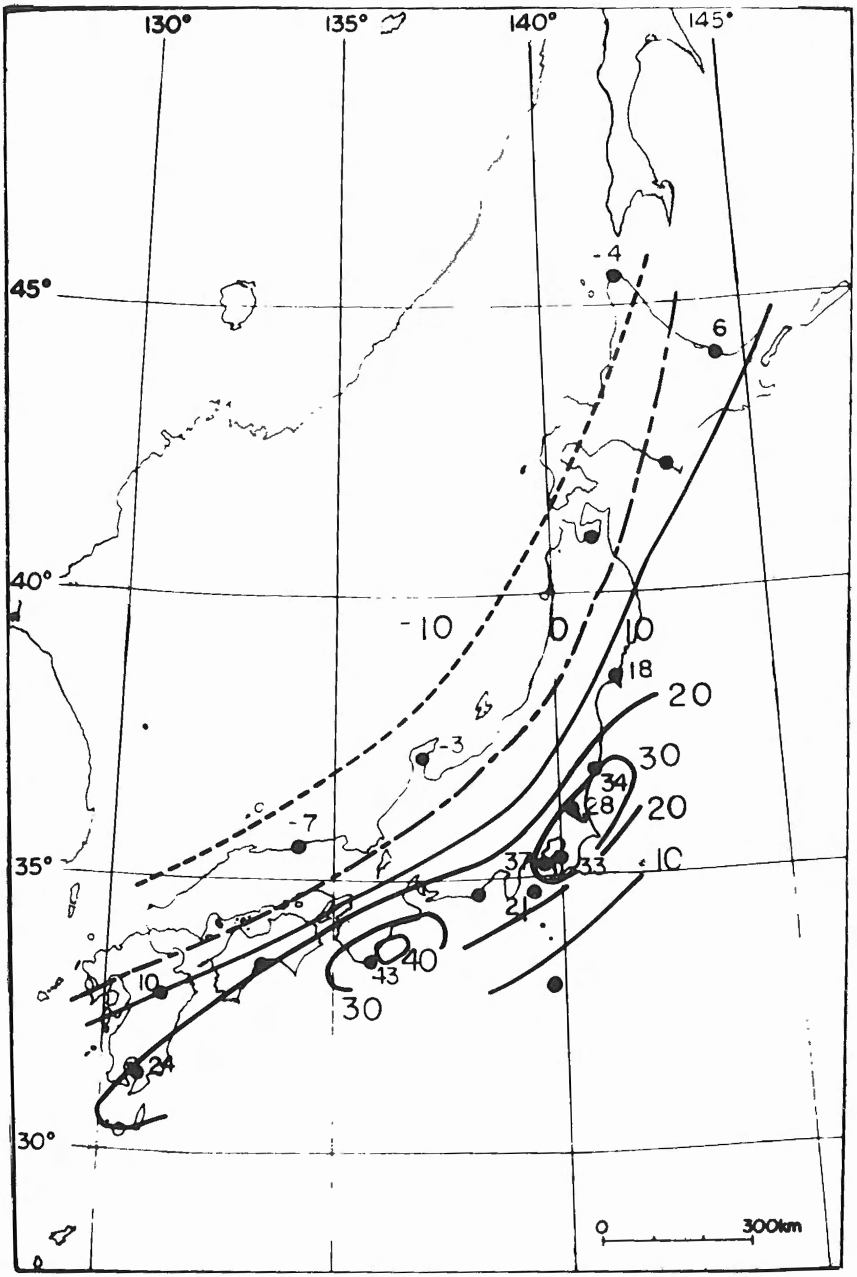

Figure 2. Distribution of Δ Z of a geomagnetic bay in gammas on March 20, 1964, over the Japanese Islands. Positive values of Δ Z are anomalous.

It had been pointed out earlier by Rikitake and Yokoyama (1953) that the disturbance vectors, $\Delta F = (\Delta X, \Delta Y, \Delta Z)$, of transient geomagnetic variations at any one of the Japanese coastal stations are contained approximately within a plane, such that $\Delta Z = a\Delta X + b\Delta Y$.

Parkinson (1959) found a similar relationship for geomagnetic transient variations observed at coastal stations in Australia, and proposed to express the plane, to which the geomagnetic disturbance vectors are confined, by a horizontal vector whose direction is coincident with the horizontal projection of a down-pointing pole normal to the characteristic plane and whose length is proportional to $\Delta Z/\Delta H = \Delta Z/\sqrt{(\Delta X)^2+(\Delta Y)^2}$. This vector has been called Parkinson's vector.

Figure 3 illustrates the distribution of Parkinson's vectors for the average SSC field obtained by Maeda et al. (1965). There are a number of stations, at which the disturbance vectors cannot be plotted on a plane. Figure 3 shows vectors only for those stations where the vectors are determinable. The vectors can be determined at most coastal stations and most of these have particularly large values of which the majority point towards the ocean side. In particular, the Parkinson's vectors are markedly large along the Japanese Islands and the Antarctic coast.

Maeda et al. (1965) have further examined similar characteristics of geomagnetic bays of one- to three-hour duration. Figure 4 shows an approximately linear relationship between $\Delta Z/\Delta H$ of the geomagnetic bays and $\Delta Z/\Delta H$ of the SSC field for the world. It may be concluded, therefore, that the remarkable characteristics of transient geomagnetic variation, $\Delta F(t)$, at coastal stations described for the SSC field are applicable on longer period geomagnetic variations up to several hours duration.

Detailed studies in the same field have been carried out not only in the Japanese Islands but in many other areas, particularly along the coast surrounding Australia by Parkinson (1959, 1962, and 1964) and in the neighbourhood of the California coast and the Peru coast by Schmucker (1964). They have found that the Parkinson's vectors along the coast of continents point toward the ocean and are aligned approximately perpendicular to the coastlines.

Figure 5 shows the distribution of the Parkinson's vectors along the Australian coasts obtained by Parkinson (1964) and Figure 6 shows the distribution of similar vectors[1] in the neighbourhood of the California coast obtained by Schmucker (1964).

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[1]Schmucker has defined the length of vector to be proportional to $\Delta Z/\Delta Ho$ where ΔHo denotes ΔH at an inland station where the coastal effect can be considered negligible.

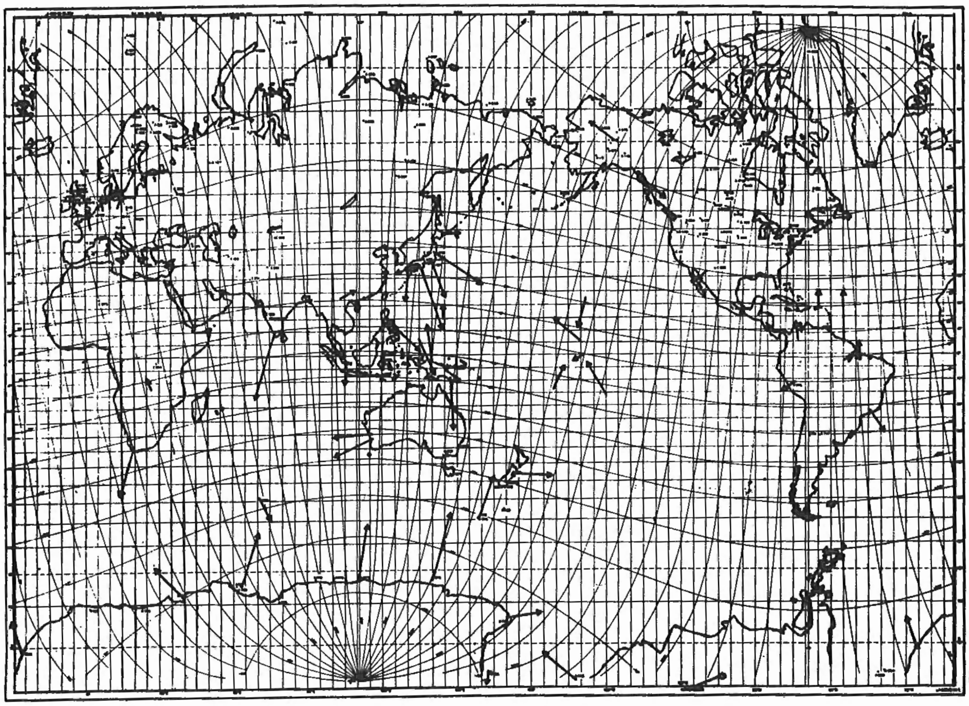

Figure 3. Distribution of the Parkinson's vectors. (After Maeda et al. 1965)

It will be clearly seen in Figure 6 that the ΔZ anomaly is stronger near the ocean coast. In Figures 5 and 6, the Parkinson's vectors, or Schmucker's modified Parkinson's vectors, point toward the ocean, and are perpendicular to the coastline. Thus, the ΔZ anomaly along the ocean coast has been called the "coastal effect".

It seems likely that the coastal effect can be attributed directly to the effect of the conductive ocean itself. It has been established that the distribution of average electric conductivity with depth within the earth increases almost discontinuously from about 10^{-15}emu to 10^{-12}emu at a depth of about 400 kilometres. Thus, we may consider that the conductive ocean of about 10^{-11}emu in electric conductivity is an electromagnetic screen blanketing the spherical conductor within the earth.

This idea, first proposed by Cox (1960), probably explains the observed coastal effect. Theoretical studies (e.g. Cox, 1960; Rikitake, 1961; Schmucker, 1964) and experimental model studies (e.g. Nagata et al., 1955; Parkinson 1964) on the coastal effect have tested Cox's proposal. It is

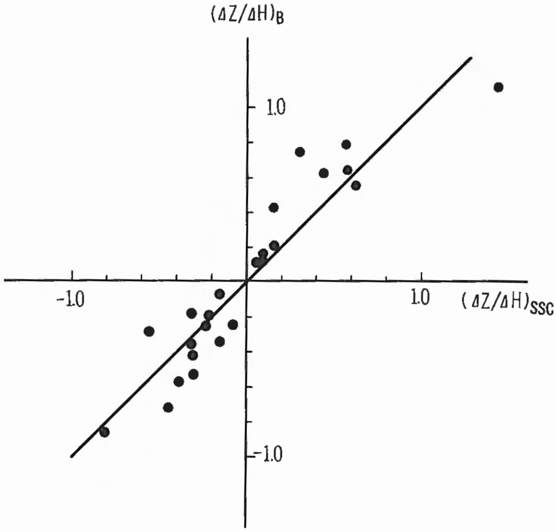

Figure 4. A linear correlation between $\Delta Z/\Delta H$ of SSC's and $\Delta Z/\Delta H$ of geomagnetic bays at different stations for the world. (After Maeda et al., 1965)

intuitively obvious that magnetic lines of force in a changing field, which are inhibited from penetrating the ocean because of its extremely high conductivity, are oriented more downward on the much less conductive continental area and that the curvature of the lines of force reaches a maximum at about the edge of the ocean (Fig. 7). Thus, in the neighbourhood of a coastline, the geomagnetic variation force directed toward the ocean points upward, and the force toward the continent points downward, whereas the force parallel to the coastline has no anomaly in the vertical direction. This result is consistent with the characteristics of Parkinson's vector in the neighbourhood of the coast. However, the numerical result of actual calculations has shown that the screening effect of the ocean is not large enough to screen geomagnetic variations of a period larger than 10^3 seconds. Parkingson (1964) also concluded from the results of his model experiment that, although the screening effect of model oceans results in slight modification of magnetic variation similar to the observed coastal effect, the magnitude of the effect for even an exaggerated model ocean is far too small compared with the observed coastal effect. Filloux and Cox (1964) have recently proved experimentally that the observed induced current in the sea off the California coast is far too small to explain the observed California coastal effect.

It seems, we must assume that another characteristic of the ocean area produces the coastal effect. One possible interpretation is as

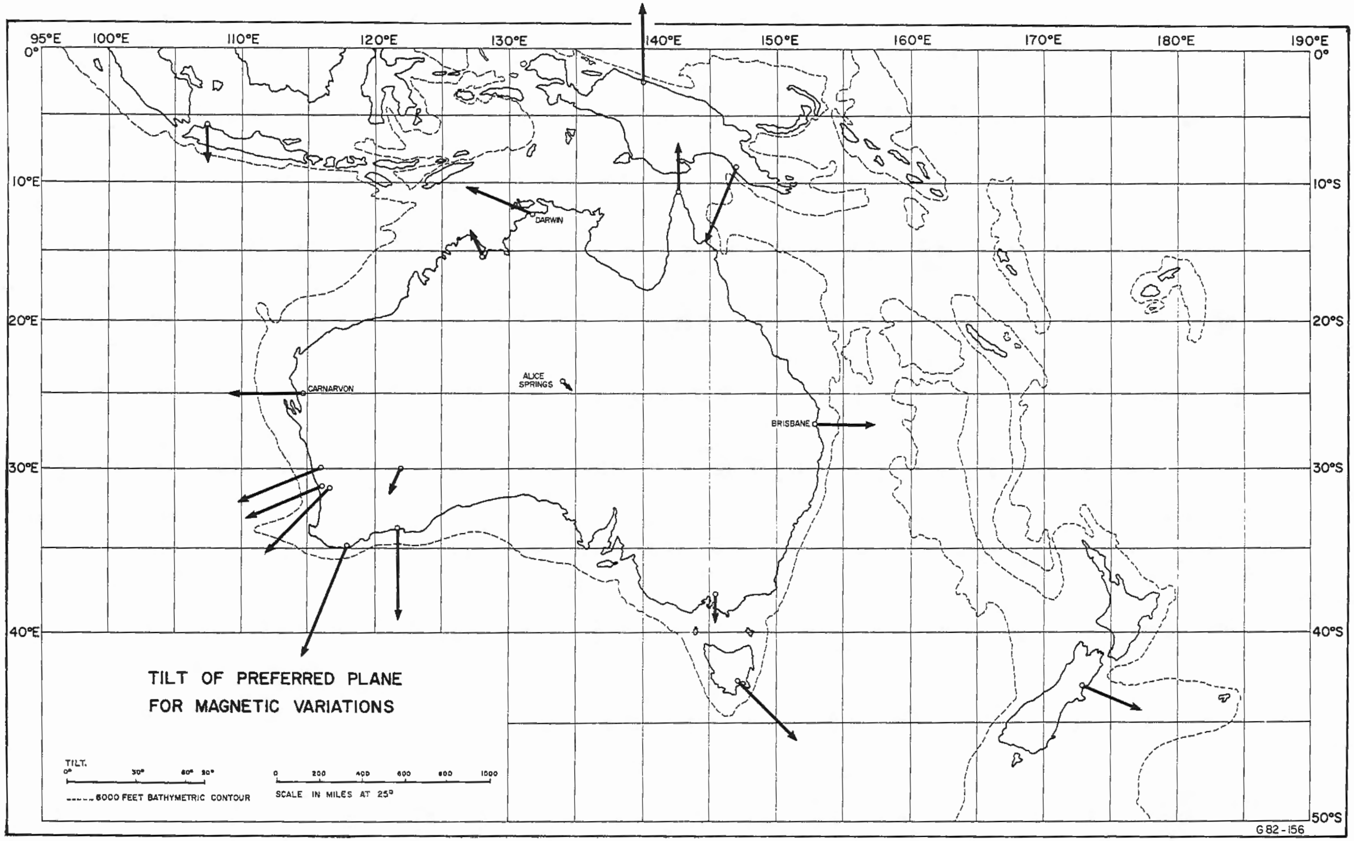

Figure 5. Distribution of the Parkinson's vectors along the coast of Australia. (After Parkinson, 1964)

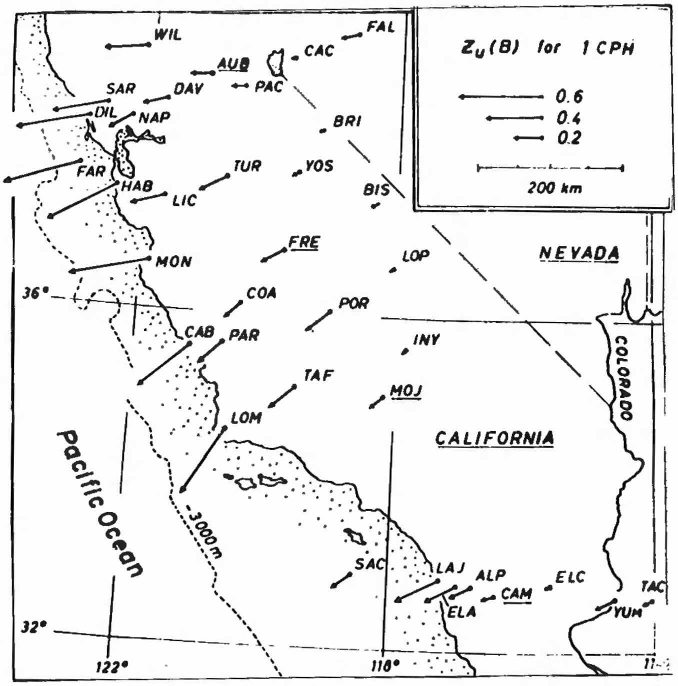

Figure 6. Distribution of the modified Parkinson's vectors along and near the coast of California. (After Schmucker, 1964)

follows: The boundary surface of the extremely high conductive upper mantle may be much shallower under the ocean than under the continent where the depth to the discontinuity is about 400 kilometres. As shown in Figure 8, this assumption produces an effect like the coastal effect. The coastal effects observed in Australia and in California can be satisfactorily explained if we assume that the depth to the surface of the conductive mantle under the ocean is about 100 kilometres. However, no direct evidence to justify the above assumption has been yet observed. The Japan anomaly and the Antarctic anomaly are too large to be ascribed even to this model. Therefore, a more marked lateral change of the subterranean mantle electric conductivity between oceanic areas and continental areas must be considered for these particular cases. It follows that either the non-conductive, uppermost part of the mantle is much thinner under the ocean than under the continent, or the conductivity of the upper mantle is much higher under the ocean than under the continent at least along the Californian, Australian, and Antarctic continental margins and along the Pacific side of the Japanese island arc.

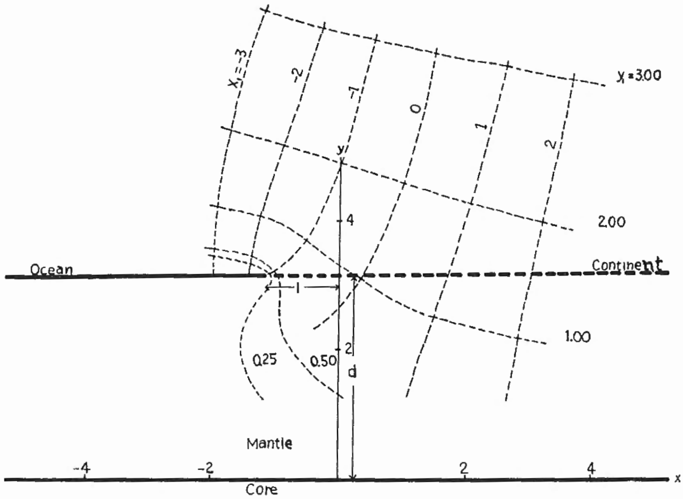

Figure 7. Screening effect of an infinitely conductive shallow ocean for rapid geomagnetic variation. x = equipotential line; y = line of force. (After Cox, 1960)

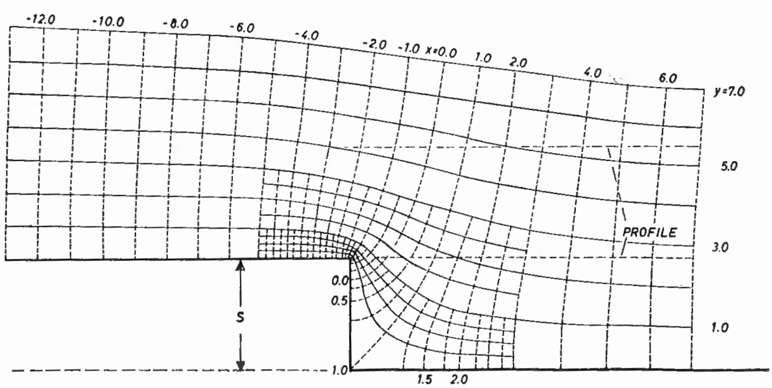

Figure 8. Change of lines of force for sharp geomagnetic variation caused by a step in the top surface of an infinitely conductive, subterranean mass. y = lines of equal force. (After Schmucker, 1964)

However, the coastal effect does not seem to exist along every continental margin. For example, Schmucker (personal communication, 1965) found no coastal effect along the Peruvian coast, and Horton (1964) reported that geomagnetic variations at USSR stations along the Arctic coast do not show such a regular characteristic as represented by Parkinson's vectors. These observations indicate that the coastal effect is not due only to the direct effect of ocean water but mostly to the electric structure of the earth's upper mantle. No satisfactory interpretation has yet been suggested.

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DISCUSSION

Dr. S.P. Srivastava (Canada)

Would Dr. Nagata comment on an experimental demonstration of the possibility of explaining the coastal effect as an effect of an ocean, which has recently been published by Dr. Roden (Geophys. J. 8, 375-388, 1964)?

Dr. Nagata

Dr. Roden demonstrated by his model experiment that the effect of the seas surrounding the Japanese Islands can produce the anomalous behaviour of geomagnetic daily variation near the Pacific coast of Japan, which is charcterized by a phase shift of one to two hours. This anomalous behaviour of geomagnetic daily variation in Japan is quite different, in nature, from the so-called coastal effect for shorter duration phenomena, which we are now discussing. Anyway, the observed coastal effect for rapid geomagnetic variations is too large to be attributed to the direct effect of ocean water, even if Dr. Roden's result is taken into consideration.

GRAVITY OVER TRENCHES AND RIFTS[1]

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Abstract

Mid-ocean ridges and the deep trenches are the most prominent features of the ocean basins, and both have been explained by investigators as resulting from convection in the mantle. Some aspects of these interpretations are examined. The ridges are in nearly isostatic equilibrium (free-air anomaly values are generally less than 50 mgal), but the trenches have very large negative free-air anomaly values and are considerably out of isostatic equilibrium. The Puerto Rico Trench has the largest free-air anomaly so far measured on the earth's surface (-380 mgal). A comparison of the Gulf of Aqaba, the East African Rifts, the Red Sea, the Gulf of California, and the Cayman Trough is made. Assuming a tensional origin for these features, it is concluded that between 40 and 100 kilometres of separation appear to be necessary before dense substratum begins to rise upward beneath the trough or rift.

INTRODUCTION

Ten to fifteen years ago the deep trenches associated with island arcs were cited as the most dramatic surface expression of convection currents taking place in the mantle of the earth. These trenches, the deepest portions of the world's oceans, and the associated large negative gravity anomalies, were attributed to the effect of compressive forces and the downward pull of the descending part of a convection cell. As parts of the crust were pulled deeper into the earth, they became metamorphosed as a result of the higher temperatures. Isostatic adjustments and erosion after the convection current had ceased, resulted in exposure of a core of metamorphosed rocks.

Investigators pondered what the configuration of these convection cells would be in three dimensions, confined as they are to a rotating spherical shell, and wondered how the arcuate structure of the island arcs and trenches is produced. They further wondered where were the extensional areas which must be associated with the rising limb of the convection cell. Satisfactory answers were not forthcoming and generally only the downward portions of a convection cell were related with a two-dimensional profile to surface geology.

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The developing field of oceanography had a great impact on our geological concepts. With the discovery of the gigantic mid-ocean mountain ranges and their central rift valleys, a spectacular tensional feature was located. Soon the crestal portion of the ridge was found to have the highest values of heat flow on earth (excluding possible localized thermal areas associated with hot springs on land), and confirmation that the ridge was indeed the site of the rising limb of a convection cell seemed assured.

Although both depressed (compressional) and tensional areas were then identified, the relating of these two regions to a single convection cell was generally bypassed by the introduction of the concepts of the youthful age of the ocean floor and of sea-floor spreading (Hess, 1962; Dietz, 1962) which appeared to explain the similarity of shape of the South American and African coastlines and the existence of mountain ridges midway between two continental masses. These hypotheses hold that the crust rides passively on top of the horizontal limbs of convection cells and is carried away from the site of upwelling. Thus South America and Africa were originally joined at the present location of the Mid-Atlantic Ridge and were slowly separated by horizontal motion of the underlying limb of the convection cell at a rate of about 1 centimetre per year. To account for the lack of Tertiary and Quaternary deformation along the eastern seaboards of North and South America, these entire continents were assumed to be riding on the back of the Atlantic convection cell. The downward limb of the convection cell was first located on the Pacific coasts of these continents where the present tectonic activity occurs. However, it now appears that the East Pacific Rise and its associated high heat flow impinges on the west coast of North America at the Gulf of California and may continue northward beneath California. Thus this potential site of the downward portion of the Atlantic cell seems eliminated. Where, then, is the downward limb? And where is it on the European and African side of the Atlantic? Apparently it is as difficult to locate as were the tensional areas for the early proponents of the tectogene hypotheses.

Deep trenches and mid-ocean ridges are the most prominent features of the ocean basins. Are their origins related, and are they produced by convection cells? If indeed they are related and produced by the same convection cell, the cell must have a severely contorted shape, confined within a spherical zone of a rotating, gravitating earth. If they are formed by separate convection cells, where are the tensional areas for the "trench cells", and where are the compressional areas for the "rift cells"? Must we choose between these two prominent types of structures, as to which feature may be produced by such cells and attempt to determine a different origin for the other, or should a non-convection origin be sought for both trenches and rifts?

Girdler (1963) concluded that a fifth degree spherical harmonic convection pattern best explains the location of the world rift system. Wilson (1965) has attempted to relate both mid-ocean ridges and mountain ranges to a single world-wide convection cell. Although Wilson's construction seems unsatisfactory in several localities, it is a useful approach. More efforts should be made in this direction, especially to bring into better focus the possible relation of convergent and divergent flow to local intensity of tectonism. Both geological and theoretical approaches should be advanced as, hopefully, they will antagonize each other and eventually converge on the truth.

TRENCHES

The deep-ocean trenches of the world are characterized by very large negative free-air gravity anomalies as first noted by Vening Meinesz for the Java and Puerto Rico Trenches. Over the Puerto Rico Trench the value obtained was -328 mgal. The maximum negative free-air values obtained in the East Indies are as follows: Java Trench, -165 mgal; the deep north of Tanimber Island, -255 mgal; the deep north of western Ceram, -162 mgal; the deep north of Soela Island, -216 mgal; and in the passage northwest of Halmahera, -179 mgal. A gravity survey of the Puerto Rico Trench conducted from R/V CHAIN of the Woods Hole Oceanographic Institution in 1962 located two minima (-330 and -380 mgal) along the axis of the trench. The latter -380 magal value is centred approximately on longitude 66°30'W and is the largest known negative free-air anomaly on the earth's surface (Bowin, in preparation).

In 1947, Lamont Geological Observatory initiated a program of gravity measurements at sea. The locations of several thousand pendulum measurements conducted in submarines during the period 1947 to 1953 is given by Worzel et al. (1955). From these measurements (Worzel, personal communication, 1965), the following maximum negative free-air anomaly values have been determined: Chile-Peru Trench, -223 mgal; Middle America Trench, -102 mgal; Aleutian Trench, -190 mgal; Japan Trench, -311 mgal; Marianas Trench, -250 mgal; North Solomons Trench, -248 mgal; and North New Hebrides Trench, -278 mgal. Submarine pendulum measurements aboard H.M.S. TELEMACHUS in the Tonga-Kermadec area (Talwani et al., 1961) obtained maximum negative free-air anomaly values of -224 mgal over the Tonga Trench and -210 mgal over the Kermadec Trench.

That the deep-sea trenches are not in local isostatic gravity equilibrium is obvious. Isostatic gravity computations (both local and regional for T = 30 km, R = 0 to 232.4 km) show anomalies in the East Indies region greater than -100 mgal (Vening Meinesz, 1948, Plates 1-3). Hayford-Bowie isostatic anomalies (T = 113.7 km) computed for the Puerto Rico

Trench show values of over -200 mgal (de Bruyn, 1951). A contour map of a portion of the Japan Trench (Hayford isostatic anomalies, d = 40 km) was presented by Hess (1948, Fig. 9) from values computed by Heiskanen on data obtained by Matuyama. Anomalies greater than -150 mgal occur over the trench.

The extent to which the trench areas of the world may be in regional adjustment is still to be decided. Talwani (1964) pointed out that the positive gravity anomalies over ridges adjacent to the trenches have been largely ignored in tectonic analyses, and he emphasized that since it is generally accepted that isostatic equilibrium takes place on a regional rather than a local basis, the mass deficit should probably be computed over an area including the trench and the island arc. The only area for which this appears to have been done is the Puerto Rico Trench.

Talwani (1964, Fig. 10) presented a crustal section along longitude 66°30'W across the island arc and trench, and a profile of mass deficiency per unit area for the crustal section. The mass deficit over the trench and a much smaller mass excess over the island clearly demonstrate that there is an over-all mass deficiency in this area.

The free-air anomaly profile across the Aleutian Trench presented by Peter et al. (1965, Fig. 9) at first appeared to indicate that the integrated free-air anomaly across the trench would have a positive value. However, to the south of their profile, positive free-air anomalies of 30 to 40 mgal continue for about 360 kilometres (Peter, personal communication, 1965). This suggests that the observed anomalies should be compared to a regional value of +30 to +40 mgal rather than to zero; if this is done, a negative integrated free-air anomaly value across the trench becomes apparent.

A somewhat similar relationship characterizes the Java Trench. Integration (using a planimeter) along the five regional isostatic anomaly profiles of the Java Trench and across Java and Sumatra presented by Collette (1954, Figs. 4-8) yields positive values (18, 12, 20, 20, and 14 mgal) for all profiles, using zero mgal as a datum. With +20 mgal as a regional datum, as given in Collette's profiles, integration yields a negative value for three of the profiles and positive values for the remaining two (-2, -0.4, +0.4, +8, and -8 mgal, respectively). Free-air anomaly profiles are not presented by Collette, but a similar integration of the free-air anomalies of that region would be interesting for comparison.

It is important to ascertain whether all trench-island arc systems have an over-all average mass deficit, or whether some have an average mass excess. Clearly, if some have a total mass excess, then the convection hypothesis has major difficulties. In any event, knowledge of the total gravity field of trench-island arc systems is needed to study the total mass balance of these features, and thereby to better interpret their origin.

WORLD RIFT SYSTEM

A world encircling system of mid-ocean ridges was inferred by Ewing and Heezen (1956) from bathymetry and from the coincidence of earthquake epicentres with the crest of the ridge. Menard (1958) pointed out how closely the mid-ocean ridges are located at median distances from continents. Important exceptions are the East Pacific Rise where it impinges on the North American continent near Lower California, and the Carlsberg Ridge where it trends into the Gulf of Aden.

From the gravity measurements of Vening Meinesz (1948) in the North Atlantic, it was determined that the Mid-Atlantic Ridge is characterized by small free-air anomalies of generally less than ±50 mgal. Talwani et al. (1965) showed the results of continuous gravity profiles across the Mid-Atlantic Ridge and the East Pacific Rise. These profiles confirm that the free-air anomalies are close to zero mgal (within ±50 mgal) over the ridges. The Mid-Atlantic Ridge profile (near latitude 32°N) indicates that an integrated free-air anomaly over the ridge would be positive, as also suggested by the data of Vening Meinesz for the area north of about latitude 20°N, but the East Pacific Rise profile suggests that it would integrate to a small negative value. In both cases the mid-ocean ridges appear to have positive anomalies with respect to the surrounding ocean basins.

The small free-air anomaly values over the ridge indicate that the ridge is nearly in isostatic equilibrium, for were the mass composing the ridge not compensated, it would produce a free-air anomaly of over +250 mgal at the crest. Seismic refraction studies (Menard, 1960; Le Pichon et al., 1965) have shown that the crust does not thicken beneath the mid-ocean ridges, and Talwani et al. (1965) have suggested that the isostatic compensation may be achieved by the existence in the ridge area of anomalous low-density mantle material.

As noted previously, the mid-ocean ridge system impinges on a continental mass in two locations: the Gulf of Aden and the Gulf of California. Earthquake epicentres and magnetic anomalies suggest a continuity of structure from the crest of the Carlsberg Ridge into the Gulf of Aden (Matthews, 1963; Sykes and Landisman, 1964). At the west end of the Gulf of Aden the trend of epicentre locations bifurcates, one branch trending northwest along the Red Sea, and the other continuing along the trends of the African Rift valley structures. Structural trends appear again to bifurcate at the north end of the Red Sea, the Gulf of Suez constituting one branch, and the Gulf of Aqaba-Dead Sea-Jordan Valley trend the other branch. On the basis of structural, gravity, and seismic information, current investigators have generally considered these features to be tensional in origin.

Hamilton (1961) concluded that the Gulf of California was a pull-apart feature and that subcontinental materials had welled up into the rift gap. Heat flow measurements (Menard, 1964, Fig. 6.10; Lee and Uyeda, 1965, Fig. 4) suggest that the Pacific Rise structure continues into the Gulf of California and perhaps northward under California. Thus at both locations where mid-ocean ridges impinge upon continental masses, rift structures occur inland from the continental margin.

Table – Gravity Anomalies and Dimension of Rifts and Possible Rifts

	Maximum Free-Air Anomaly	Maximum Bouguer Anomaly (crustal density = 2.67)	Width km
Gulf of Aqaba (Allan et al., 1964, Fig. 5)	-180	-100	26
East African Rift, Lake Albert (Bullard, 1936, p. 508)	-100	-190 (-50 to -80)	42
Red Sea, at latitude 16°N (Drake and Girdler, 1964)	0 to -40	+120	100
Gulf of California (Harrison and Spiess, 1961; Harrison and Mathur, 1964)	-70	+140	150
Cayman Trough (Data from R/V CHAIN Cruise 46)	-150	+330	220

A summary of gravity anomalies and dimensions of the rifts referred to above are presented in the Table. All are characterized by negative free-air gravity anomalies although the values for the Red Sea do not depart greatly from zero mgal. The Bouguer gravity anomalies, on the other hand, are negative over the Gulf of Aqaba and Lake Albert Rift, and positive over the others. The local Bouguer anomaly (difference between values for the centre and side of the rift) for the Lake Albert Rift was given as -50 mgal by Girdler (1964). A Bouguer gravity map published by the Department of

Mines and Surveys, Uganda, shows an anomaly of about -80 mgal over the Albert Rift, i.e. -210 mgal over the centre and -130 mgal on the Uganda side (Girdler, personal communication, 1965). The negative Bouguer anomalies suggest a mass deficiency beneath the Gulf of Aqaba and East African Rifts, whereas positive Bouguer anomalies and seismic refraction investigations (Drake and Girdler, 1964; Phillips, 1964) show that there is dense material beneath the Red Sea and the Gulf of California. The Bouguer anomaly values are close to zero at the margins of both the Gulf of California and the Red Sea.

From the Table it is clear that as the width of the rift increases, the Bouguer anomalies become increasingly positive. This relationship suggests a common process of development, but interpretation is complicated because these features may be in different stages of development, the intensity of tectonism may be different, and the original crustal thicknesses were probably different. These relations are interpreted to suggest that a certain amount of extension of the crust must take place before denser subcrustal material is able to rise up beneath the centre of the rift. From the information collected in the Table, it appears that when about 40 to 100 kilometres of separation of the earth's crust has occurred subcrustal material has an opportunity to rise to a shallower level and thereby change the gravity characteristics of the central trough.

The Cayman Trough is included in the Table not because it is considered to be part of the world rift system, but to emphasize that its gravity values and dimensions suggest that it may be the result of a tectonic process similar to that producing the other rift features. Bouguer anomalies at the margin of the Cayman Trough are about +95 mgal. Seismic refraction measurements in the Cayman Trough indicate that the mantle rises to about 11 kilometres below sea-level (Ewing et al., 1960) and thus the trough is similar to the Red Sea and Gulf of California in that the increase in positive Bouguer anomaly values over the centre of the trough presumably results from dense crustal or subcrustal material at a shallow level.

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DISCUSSION

Prof. S.K. Runcorn (UK)

I think it is very interesting that all the trenches that you have described, which at the earth's surface have strong negative anomalies, are associated with regions of high gravity in maps of the geoid obtained from satellite observations. The latter anomalies are based on the lower harmonics, and the comparatively small-scale anomalies over the trenches do not appear. But these high gravity anomalies are caused by denser material deep in the mantle and one concludes that this is causally related to the mechanism by which the trenches are produced. On the convection hypothesis, uprising and descending flow will cause tension and compression, respectively, in the crust. These flow columns will also be different in density and therefore give rise to gravity anomalies.

Dr. Bowin

I would like to look more closely at the map of the lower harmonics of the satellite observations. It seemed to me that it was only about a 50:50 correlation.

Prof. Runcorn

Yes, but the chief discrepancy in the correlation was the Mid-Atlantic Ridge. The trenches are very positive and closely associated with gravity anomalies, for example, in the Japan-Philippine Trench, the Tonga Trench, the Java Trench, and the one off South America.

Dr. M. Talwani (USA)

Why do the mid-oceanic rift anomalies not fit this pattern?

Dr. Bowin

The rift anomaly is about 30 kilometres wide in some places where I examined it. The profile made by R/V CHAIN has a positive Bouguer anomaly right over the trench. But our computations were made with an assumed density of 2.83 gm/cc. Studies of the changes in the anomaly if slightly different densities were used have not yet been made. However, the formation of the Mid-Atlantic Ridge has many characteristics quite different from breaking apart of a sialic continental crust, so it does not surprise me that it is not obvious where the mid-ocean rift anomaly fits into the pattern shown in the Table.

Dr. G.B. Udintsev (USSR)

It is well known that there is a relation between ocean trenches and marginal swells on the margin of the ocean floor. Are there also regular relations between the marginal swells and the Bouguer anomalies?

Dr. Bowin

Are you referring to the island arcs or to the outer ridges?

Dr. Udintsev

The outer ridges.

Dr. Bowin

These appear to have very small gravity anomalies. For example, in the Puerto Rico Trench area the outer ridge has a Bouguer anomaly of +20 mgal (+420 mgal at centre and +400 mgal on flanks).

Dr. Udintsev

In the case of other trenches, what is your observation?

Dr. Bowin

I have not had a chance to look at the gravity of very many trenches except for the information that's shown here. The information from Lamont I believe will be published soon.

REGIONAL VARIATIONS IN THE STRUCTURE OF THE UPPER MANTLE AND THE PROPAGATION OF THE Sa PHASE[1]

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Abstract

Regional variations in the velocity of Sa indicate high velocities in the upper mantle under shield areas. This result is in agreement with results from fundamental mode Rayleigh and Love waves and with results from P-wave delay time studies.

INTRODUCTION

The Sa phase observed on seismograms represents elastic wave propagation in modes which are very sensitive to the shear velocity structure of the upper mantle. This may be demonstrated by theoretical particle motion diagrams for modes which make up the Sa phase (Kovach and Anderson, 1964). Large amplitudes which persist to depths of several hundred kilometres show that these waves are sensitive to the structure of the upper few hundred kilometres of the mantle. Thus, if large regional variations in the velocity of the upper mantle occur, they should drastically affect the propagation of the Sa phase.

Regional variations in the velocity of the upper mantle have already appeared in studies of fundamental mode waves. This was observed by Brune (1961), who measured mantle Rayleigh wave phase velocities over several great wide paths around the earth and found that phase velocities over the great circle paths including the epicentre of the southeast Alaska earthquake and the seismograph stations at Perth and Ottawa were significantly higher than phase velocities over the other great circle paths used in the study. These differences were as great as 0.02 km/sec out to periods as great as 200 seconds. It was tentatively suggested that this result might be due to the large amount of oceanic regions covered by these paths, but the true explanation was discovered later by Brune and Dorman (1963) in their

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[1] Contribution No. 1391, Division of the Geological Sciences, California Institute of Technology.

study of the structure of the Canadian Shield. The shear velocity of the upper mantle under the Canadian Shield was found to be considerably higher than had been previously determined for other regions of the earth, and the difference was enough such that if it was assumed that if other shield areas, in particular the Australian Shield, had similar high velocities, then the entire 0.02 km/sec range in velocity could be explained by variation in the amount of propagation through shield areas. Recently Chander and Brune (1965) found additional evidence of lateral variation of the velocity of mantle Rayleigh waves. In a detailed study of the radiation pattern of mantle Rayleigh waves from a Hindu Kush earthquake, the pattern of observed phases of mantle Rayleigh waves of 150-second period as a function of azimuth, determined at 30 stations, indicated high velocities under shield areas and low velocities under the eastern Pacific.

Recently regional variations in the structure of the upper mantle have also been indicated by studies of variations in the velocity of propagation of mantle Love waves. For mantle Love waves the effect of lateral variation in shear velocity structure of the upper mantle is much greater. Toksoz and Anderson (1966) found regional variations in mantle Love wave phase velocities of as much as 0.05 km/sec for different paths at a period of 200 seconds and significant differences extended to periods as great as 350 seconds. Smith (1966) obtained similar variations in phase velocities between the Alaska-Kipapa and Alaska-Isabella great circle paths by analyzing the data in terms of free oscillations.

REGIONAL VARIATIONS IN THE VELOCITY OF Sa

Press and Ewing (1955), in an early study of Sa, found velocities for Sa over certain paths as high as 4.57-4.63 km/sec, much higher than those found by Caloi (1953). An average velocity reported by Caloi was 4.43 km/sec. A study of the table given by Press and Ewing shows that the high velocities reported for Sa correspond to paths across the Canadian Shield.

Båth and Arroyo (1963) have made a comprehensive study of velocities of first arrival for Sa arriving at Uppsala from numerous regions of the earth. They conclude that although there is a great deal of scatter, the Sa phase travels faster across continents than across oceans. This could be partly the effect of high velocities in shield areas since a large portion of most of their continental paths crosses shield areas.

Recently a comprehensive study of the propagation of the Sa phase from a Hindu Kush earthquake across North America was carried out by Brune (1965). It was concluded that the Sa phase represented a complicated type of wave propagation in a range of period and phase velocity where neither a simple isolated mode nor a simple ray representation was adequate. Nevertheless it was possible, by using Fourier analysis, to establish a definite regional variation in group velocity for different paths across North America. The Sa phase group arrival time study indicated that in the period range 30-60 seconds, the energy travelled more than 0.1 km/sec faster across shield areas than across regions of more recent tectonic activity. Similar results were obtained when the velocity of first arrival was picked, although this method introduced uncertainty because it was not possible to establish an unambiguous time of first arrival.

Very recently, evidence from P-wave travel time station corrections has also suggested high velocities in the upper mantle under shield areas. For example, Gordon, Carder, and Jordan (1965) recently presented a paper in a symposium on seismic travel times which explained early P-wave arrivals in shield areas as resulting from relatively high velocities in the upper mantle.

In summary, several different studies have indicated that the shear velocity in the upper mantle is higher under stable shield areas than under continental areas with more recent tectonic activity. These studies include mantle Rayleigh wave phase velocity studies, mantle Love wave phase velocity studies, Sa phase group velocity studies, and P-wave delay time studies.

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CRUSTAL STUDY ALONG A TRANSCONTINENTAL GREAT CIRCLE FROM WASHINGTON, D.C., TO SAN FRANCISCO, CALIF.[1]

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Abstract

The North American continent has been spanned by a strip of twenty continuous aeromagnetic profiles spaced 5 miles apart which not only reflect gross lithology and structural trends in the magnetic rocks of the crystalline basement, but also indicate a fundamental difference between the crust to the east of the Rocky Mountains and the crust to the west. This crustal contrast is supported by the results of recent seismic refraction studies and shows a good correlation with the available heat-flow data, particularly when the magnetic data are filtered to remove the short wavelength anomalies caused by inhomogeneities in the upper part of the crust.

AEROMAGNETIC STRIP SURVEY

An investigation into the nature of the continental crust by aeromagnetic techniques has been made along the arc of a great circle passing through Washington, D.C., Denver, Colo., and San Francisco, Calif. The data for this study were obtained in a joint project of the U.S. Geological Survey and the U.S. Naval Oceanographic Office. The survey consists of twenty parallel profiles, spaced 5 miles apart; they cover a strip 100 miles wide across the entire continent and continental shelves on both sides. The flight altitude was approximately 5,000 feet above sea-level except for the area between the Rocky Mountains and the Sierra Nevada, where it was approximately 16,000 feet.

MAGNETIC CHARACTER OF THE CRUST

The magnetic data reveal a fundamental contrast in the properties of the crust to the west of the Rocky Mountains and the crust to the east. This is illustrated by the magnetic profile (Fig. 1) from Point Reyes, Calif., to the Illinois-Indiana border at latitude 40°N. This profile shows numerous

[1] Publication authorized by the Director, U.S. Geological Survey.

[2] Speaker.

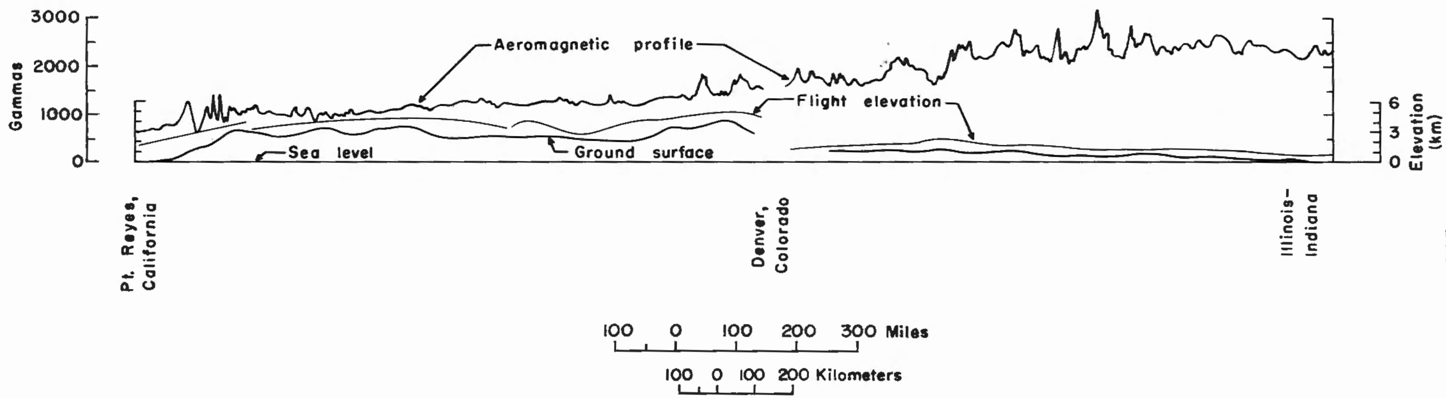

Figure 1. Aeromagnetic profile from Point Reyes, California, to the Illinois-Indiana border. (After Pakiser and Zietz, in press)

large anomalies across central United States to a point about 100 miles west of Denver, where the profile becomes nearly flat with only minor anomalies as far west as California. The great abundance of magnetic material in the rocks of the eastern sector indicates that the crust contains much mafic rock, whereas in the region west of the Rocky Mountains the crust is apparently predominantly silicic to considerable depths.

The magnetic data are consistent with the data from seismic studies of the crust both east and west of the Rocky Mountains (Pakiser and Steinhart, 1964). The seismic data indicate that the United States can be divided into two superprovinces on the basis of crustal and upper-mantle characteristics. In the western superprovince, except for a narrow zone along the Pacific coast, the mean velocity in the crust is generally less than 6.4 km/sec, the compressional velocity in the upper mantle is less than 8 km/sec, and the crust is generally thinner than 40 kilometres. In the eastern superprovince the mean velocities for both crust and upper mantle are generally greater than these values, and the crust is thicker than 40 kilometres (Pakiser and Zietz, in press). This is illustrated by a cross-section along one of the aeromagnetic profiles (Fig. 2). The distribution of the mafic material is shown only schematically but the section indicates that a much greater percentage of the crust is mafic east of the intermontain plateaux than in the western area. In the western area the crust is thin and most of it is silicic except for a distinct layer of higher velocity at the base of the crust.

Gross lithology and structural patterns of the crystalline basement rocks can be clearly recognized from the magnetic data. The largest anomalies in the west are those recorded along the axis of the Sacramento Valley of California (Grantz and Zietz, 1960) where the mafic rocks causing the anomalies are concealed by a thick sedimentary sequence. The most prominent magnetic anomalies associated with the Sierra Nevada are south of the profiles shown in Figures 1 and 2; these anomalies indicate a more mafic and denser crust at depth than would be expected from an analysis of the gravity data. This confirms seismic refraction data which indicate that there is a thicker, more mafic crust under the Sierra Nevada than in the regions on either side (Eaton, 1963).

The Uinta Mountains are associated with a linear, east-west magnetic anomaly which can be traced for more than 400 miles across northern Utah and northwestern Colorado. The anomaly lines up with the inferred location of a possible rift system linking the Cape Mendocino fracture system in the Pacific Ocean off the coast of California with the wrench-fault system proposed by Drake and Woodward (1963) in eastern United States.

The aeromagnetic data east of Denver, Colo., are shown in Figure 3 in contour form. As nearly all this area is covered by a thick

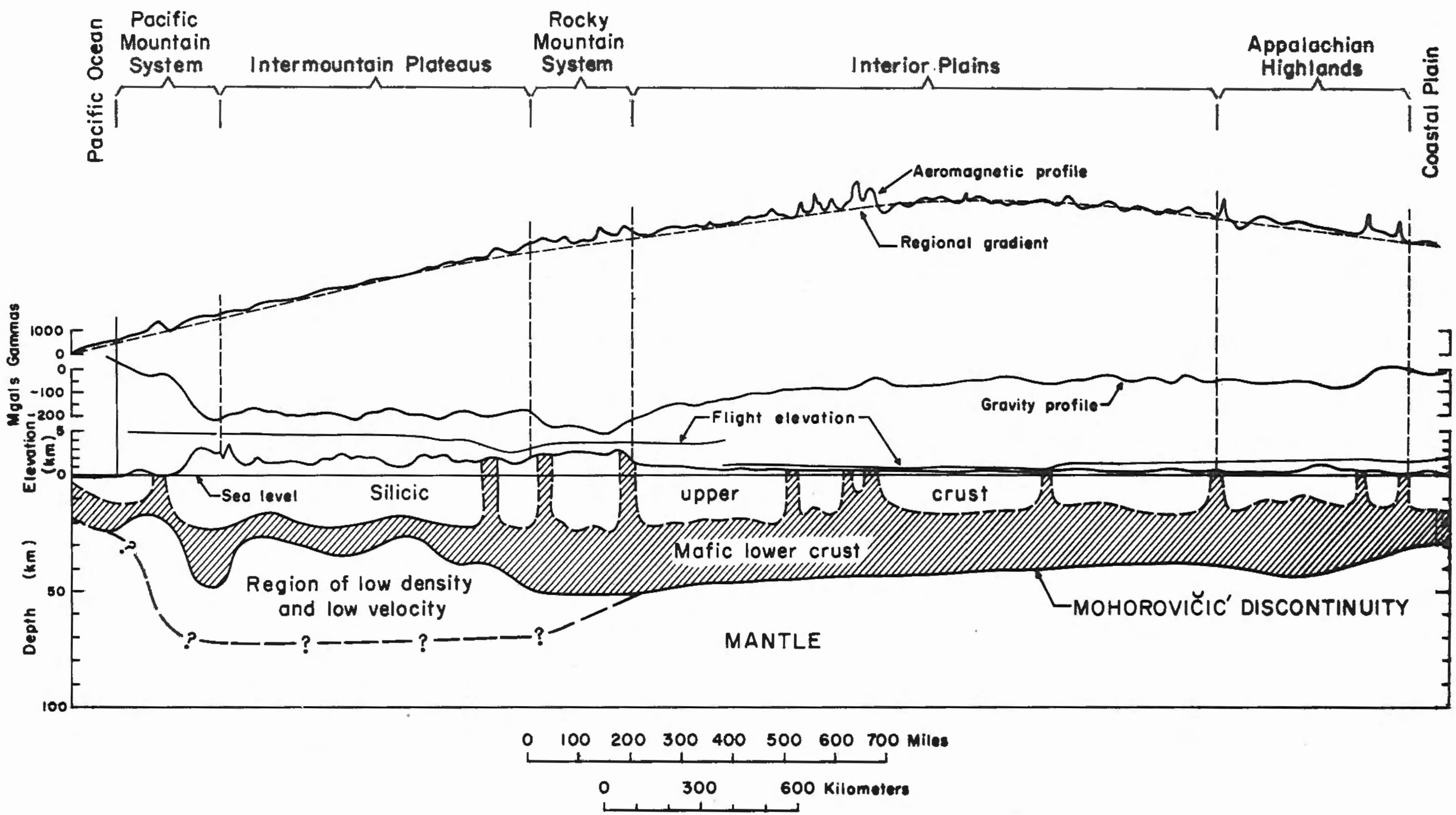

Figure 2. Representative aeromagnetic profile along the transcontinental great circle from Washington, D.C., to San Francisco, California. Gravity profile derived from Bouguer gravity anomaly map of the United States (A.G.U. and U.S.G.S., 1964). Crustal section from Pakiser and Zietz (in press)

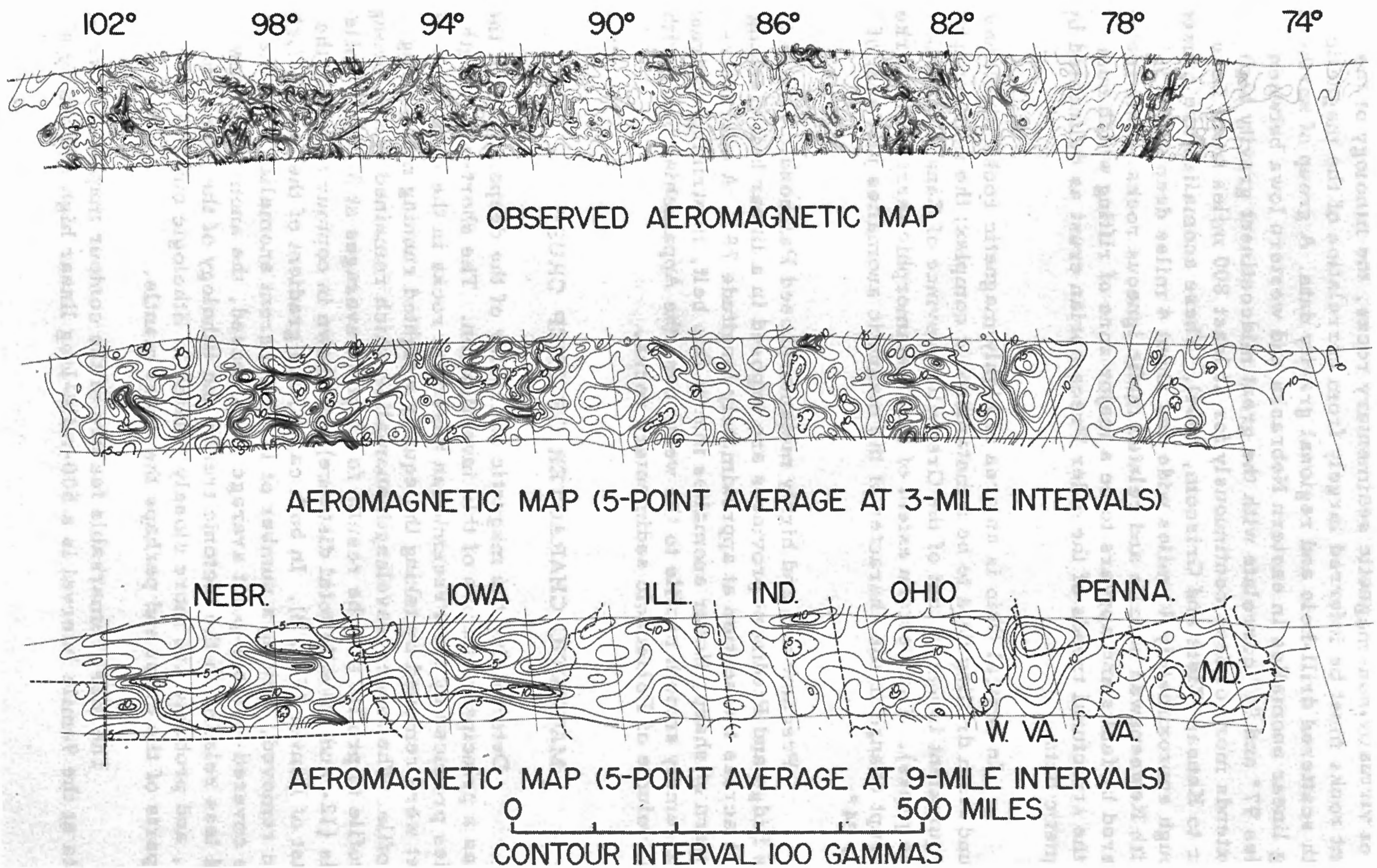

Figure 3. Contoured magnetic data along the section of the transcontinental great circle east of Denver, Colorado.

blanket of virtually non-magnetic sedimentary rocks, the lithology of the basement rocks must be inferred largely from correlation of the magnetic data with scattered drill-hole and regional gravity data. A group of northeast-trending linear anomalies in eastern Nebraska and western Iowa between longitudes 97° and 94° correlate with the great midcontinent gravity high which extends more or less continuously for at least 800 miles from Lake Superior to Kansas (Zietz and Griscom, 1964). These anomalies are caused by a trough approximately 40 miles wide and about 4 miles deep which is filled with Keweenawan basalts and related mafic igneous rocks. This feature is bordered by faults and appears to be a major zone of rifting which cuts across the structural trends of the older Precambrian crust as delineated by the magnetic data.

In central Ohio is an area of highly magnetic rocks which have been found from drilling data to be a metamorphic complex; the metamorphism is equivalent in age to that of the Grenville province of Canada (Lidiak et al., in press). The western extent of this metamorphic terrane is marked by an abrupt change in the character of the magnetic anomalies just east of longitude 84°.

Precambrian and highly metamorphosed Palaeozoic rocks of the Blue Ridge and Piedmont provinces are exposed in a linear belt trending northeast across the section at approximately longitude 78°. A characteristic pattern of sharp, linear anomalies marks this belt, in striking contrast to the extremely smooth profile to the west, over the Appalachian basin with its great volume of Palaeozoic sedimentary rocks.

MAGNETIC CHARACTER OF DEEP CRUST

Determining the magnetic character of the deeper parts of the crust was a principal objective of this investigation. The short-wavelength anomalies produced by the Precambrian basement rocks in the upper part of the crust were removed by taking the equally weighted running mean along each profile. The longer wavelength anomalies which remained carry through from profile to profile and the results for 5-point averages at 3- and 9-mile intervals (12- and 36-mile total distance) are shown in contour form for the strip east of Denver (Fig. 3). In both cases, the gradient of the earth's field has been removed, leaving a number of large coherent anomalies. As the distance covered by the 5-point average is increased, the anomalies show less and less relation to the tectonic trends and lithology of the basement surface, and probably are more closely related to lithologic units in the deeper parts of the crust and perhaps the upper mantle.

The most remarkable feature of the contour map of the averaged data at the 9-mile interval is a 500-mile-long linear high flanked by a low on the north. This feature extends east-southeast from longitude 99° in northern central Nebraska longitude 91° just east of the Iowa-Illinois state line. Its relatively narrow width indicates that the depth to its source does not exceed 40 kilometres, which is near the base of the crust in this area. The high is on line with the proposed transcurrent rift system to which the previously mentioned Uinta Mountain structure and its associated magnetic anomaly may belong, and could be caused by mafic material emplaced along such a rift. Along the westerly projection of this linear feature is a marked shift in the structural trends of the Rocky Mountain system. Seismic studies by Jackson and Pakiser (in press) indicate an abrupt thinning of the crust under the Rocky Mountains from 50 to about 40 kilometres or less north of the easterly projection of the Uinta arch.

The map at the 9-mile spacing shows a definite contrast between broader and less numerous anomalies of more or less north-south trends east of longitude 87° and the more numerous anomalies of dominant east-west trends west of longitude 87°. West of the Rocky Mountains these long-wavelength anomalies are conspicuously absent, except in the far west over the Sierra Nevada and Sacramento Valley.

CORRELATION WITH HEAT-FLOW DATA

Correlation of these magnetic data with measurements of heat flow in the continental United States is significant. Preliminary studies of heat flow in Iowa indicate values on the order of 1.0 microcal/cm^{2}sec, in contrast to values of more than 2 microcal/cm^{2}sec in Nevada, Utah, and California (Gene Simmons, personal communication, 1965). Where heat flow is lowest, the geotherms may reasonably be assumed to be depressed, with a greater thickness of rock at less than the Curie point, the temperature which establishes a lower limit for the magnetization of rocks. In the region of most intense magnetic anomalies in Nebraska and Iowa, the Curie point geotherm may be deep enough to include some upper mantle material, but in the west, particularly in the Basin and Range province, it may be at a much shallower depth, so that much or all of the mafic lower crust is non-magnetic. The Basin and Range province is a region of great interest in crustal studies, because it has been postulated to be the landward extension of the East Pacific Rise.

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DISCUSSION

Dr. R.W. Girdler (UK)

What was the flight spacing, the height, and the maximum amplitude that you observed?

Dr. Zietz

The spacing was approximately 5 miles; the flight elevation east of the Rockies was about 5,000 feet above sea-level. West of the Rockies it was 16,000 feet so we could, of course, get above the peaks. And west of the Sierras it was about 4,000 or 5,000 feet so we could get closer to the source of the anomalies. Many of the anomalies in the midcontinental area were well over 1,000 gammas in amplitude. Some of those anomalies were 1,500 gammas, but that is about the maximum.

Prof. S.K. Runcorn (UK)

The directions of the intensity of magnetization of the Keweenawan have been measured. Do these directions of intensities match the anomaly on the midcontinent gravity high?

Dr. Zietz

Well yes. As you said they have been measured up north in the Lake Superior district. And they have a magnetization which is different from the earth's field. The magnetization has an azimuth of about 270° and it is pointing down about 70 some degrees. And if you make a calculation, which is difficult to do because we know it only from way up north, but if you do that, you get the general magnetic effect of the whole series. But the very interesting thing that has come to our attention so far is the fact that in making calculations you have got to use something like 40,000 feet of flows to satisfy the gravity anomaly. To satisfy the magnetic anomalies, we are almost certain from the character of the anomaly and from looking at the details that we are only seeing the uppermost mile. So that means we have about 20,000 to 30,000 feet of flows unaccounted for. One of the possibilities is that maybe you have a stack of flows which have reversals in magnetization and they compensate. I do not know if they are doing this, but I really do not know how to account for it otherwise.

Prof. Runcorn

But they are up on edge, aren't they?

Dr. Zietz

The flows dip inwards toward the centre. They are steeply dipping and vertical only at the edges; but in between they are approximately horizontal.

Dr. E.H.S. Gaucher (Canada)

I was wondering about the depths of the anomalies. Wouldn't an anomaly with a body 100 miles wide by 10 miles thick give an anomaly 100 miles wide?

Dr. Zietz

Well, not entirely. What you get are sharp anomalies at the edges, and the field is relatively low in between. Now that's a good point. It is possible to get a distribution of magnetism, if it is shallow, so that you can get a broad anomaly. But as I pointed out we have two such areas, the Piedmont and the midcontinent gravity high. In both cases the anomaly does disappear for the broader averages. Now that is important. It does disappear, but that doesn't mean it will always disappear. This is an ambiguity that we cannot resolve.

G. GENERAL SESSION – RECOMMENDATIONS AND RESOLUTIONS

Chairman: A.E. Ringwood (Australia)

Dr. A.E. Ringwood

This is the final session, and the meeting is now open for proposals and discussion on future investigations of continental margins and island arcs. The resolutions and recommendations will be submitted to the Upper Mantle Committee meeting tomorrow.

Dr. P.H. Mattson (USA)

I was associated with the project in which the National Academy of Sciences drilled in Puerto Rico to study serpentinite. We obtained a great deal of data and made many interesting conclusions from this hole. I believe much valuable information would result from drill-holes in other island arcs and in different locations in the West Indies arc.

One of the greatest gaps in knowledge about island arcs is the lack of concrete data on the ages and chemical compositions of the plutonic, volcanic, and even the sedimentary rocks exposed in the land areas of the arcs. I recommend that holes be drilled for the scientific study of land areas in island arcs, preferably in areas where the surface geology is well known and where the holes can be located at geologically significant spots. These drill-holes, which should be cored to depths of 500 to 3,000 metres, would extend our geological knowledge to greater depths, and perhaps permit more accurate correlation and lithologic identification of seismic velocity layers described by nearby seismic profiles. In-hole measurements of physical properties such as heat flow should be carried out. Core from the holes should provide material for petrologic studies, chemical analyses, isotopic dating, and other studies.

Dr. C.A. Burk (USA)

I have two proposals that I would like to make. First, I believe it is important to emphasize that studies of island arcs and continental margins not be terminated at the shoreline. I have been impressed at this Symposium by the close relationship between offshore and onshore geological and geophysical studies. We saw the other day, for instance, that continental margins or island arc systems in many localities have great gravity minima over their trenches and gravity maxima over the adjacent arcs. If you can look at them from far enough away, these two gravity anomalies seem to average out. We see a great deal of downbowing in the trenches and uplifting in the adjacent arcs. You see tensional features in the trenches but if you look carefully you see many things that indicate strong compression in the arcs themselves. There was a suggestion the other day, for instance, that trenches are a result of loading and downbowing by the adjacent arc. But if you look on the arc you see little evidence of downbowing; you see evidence of uplifting. Consequently I think that it is important that we integrate what we are finding out about these areas in the oceans with what we already know about them and that we initiate further studies on land. I would therefore propose that we reaffirm the value of integrating both marine and non-marine data in planning and reporting on existing and future studies of island arcs and continental margins. An important corollary of this, of course, is the need for broad palaeogeographic studies that give us some idea of the location of past ocean basins, where continental blocks existed, and where continental margins and island arcs were once located. Certainly this work should be continued and emphasized.

Second, there has been a great deal of valuable work in the study of continental margins and island arcs. And all of this has certainly improved our knowledge of both arcs and continental margins. However, most of the work has been done in local areas for specific purposes to suit the desires of a particular investigator or to solve a particular local problem. It seems that we certainly learned a great deal this way. But it also seems that we have reached an appropriate time in our stage of learning where we can devote a concerted effort to a broad examination of areas of particular interest or significance. I therefore propose that we emphasize the need for continued studies of island arcs and continental margins throughout the world, and that we specifically endorse a cooperative or coordinated international program to study in detail the structure and the history of the Bering Sea and its adjacent arcs, continental margins, and trenches. The results of such a specific program could serve as a basis for more profitable planning and interpretation of local surveys of similar areas to be carried out in the future. We have in the Bering Sea a relatively small area which contains most of the features which we now associate with island arcs and perhaps continental margins as well. Arcs, trenches, and margins can probably be related to each other, and to variations in the mantle, more easily here than in many other areas. The seismicity is very recent and fossil vulcanism is abundant. Magnetic anomalies terminate at the trench. There are abundant deep-focus earthquakes, and perhaps the tectonic structures of margins and arcs can be more closely related and the times of deformation more easily determined than in many other areas. In addition, there are aseismic ridges that we can study during the course of the program and perhaps there are even fossil trenches that we can study. This seems to me to be an area of special importance, one that can be easily studied, and perhaps one that should be examined in a more systematic manner.

It would seem reasonable also to select for broad, careful study a continental margin which is not associated with trenches or volcanic arcs such as the Atlantic coasts of South America, Africa, Australia, or perhaps even the coast of Africa bordering the Indian Ocean where work is already underway.

Prof. H. Kuno (Japan)

Following my paper, Dr. Ringwood provided some very interesting discussion. I know that Dr. Ringwood and his colleagues at the Australian National University in Canberra are now approaching the problem of the origin of basaltic magmas by high-temperature, high-pressure experiments. There are many people working on the same approach in the Geophysical Laboratory of the Carnegie Institute at Washington, and also some people in the United Kingdom, and in Japan. Probably in a few years we will have a fairly clear picture of the origin of basaltic magmas, and what kind of basaltic magma is generated under certain sets of temperature and pressure. However, experimental results should be checked by observation of natural rocks and also by geophysical observations. So I would strongly suggest that combined petrological and geophysical studies be carried out in the zones of active volcanoes. With that preamble, I will read the summary of my recommendation. "Three different types of variation in the chemical composition of lavas from young volcanoes along continental margins and island arcs can be distinguished as we pass from the oceanic to the continental side: 1) tholeiite passing through high-alumina basalt to alkali basalt, as exemplified by northeastern Japan and Kamchatka; 2) high-alumina basalt to alkali basalt, as exemplified by the Aleutian Islands, High Cascades, and Indonesia; and 3) tholeiite alone as in the Izu-Mariana, South Sandwich, and Tonga Islands. Such variation probably originates from a difference of the depth of basalt magma generation which depends in turn on physical environments in the upper mantle, such as the thermal gradient, rate of heat transfer, stress condition, and pattern of convection current.

"It is strongly recommended therefore that petrological study of volcanoes combined with heat flow, magnetic, gravimetric, and seismic observations be carried out along a few selected traverses across each of the above three groups of regions. Study of seismicity in these regions is especially important, carefully discriminating between volcanic and tectonic earthquakes by determining the locations of foci of even the smallest earthquakes. Petrological study of volcanoes should also be encouraged for regions where the variation in chemistry of lavas is not yet known."

Dr. A.S. Laughton (UK)

During the past three days we have heard a great deal about those continental margins, firstly, where there are trenches and island arc systems and, secondly, where there are lineaments that are not parallel with the continental margins themselves. We have not heard very much about those parts of the continental margins where the structures extend across the margin or towards the margin. And it seems to me that this is a great lack in some of our knowledge. We do not have as good observational data on this type of margin as we do on the island arc and trench margin. And I think it might be appropriate for the Upper Mantle Committee to recommend that more effort be made to study those particular parts of the margin which lack island arc systems, trenches, and paralleling mountain ranges. We might learn a lot about continental drift theories in terms of matching up structures which appear to cross the continental margin. Examples of such critical areas are the margins of Australia, and Antarctica, and those of the North Atlantic.

Dr. Ringwood

Thank you, Dr. Laughton. If I might comment on one aspect of Dr. Laughton's suggestion, there is an additional interest in studying continental margins in situations where the Precambrian shields abut directly against deep oceanic basins. I think we know from geothermal arguments that the temperatures beneath the crust of the Precambrian shields are perhaps 200 to 300 degrees cooler at depths of 15 to 20 kilometres than they are at the same depths beneath the adjoining ocean basins. There should be quite wide variations in physical properties in the mantle beneath the Precambrian shields and that beneath deep ocean basins. These margins provide perhaps one of the best major contrasts that we can hope to find. One notices, of course, that the seismic velocity profiles beneath shields and oceans are very different. I would suggest, in support of Dr. Laughton's proposal, that these regions are particularly well suited for geophysical investigations of many types.

Dr. C.V.G. Phipps (Australia)

A great deal of the work that has been brought forward in this Symposium has been of a somewhat general nature on the broad ocean basins and the margins thereof, resulting probably from the fact that the areas as a whole are extremely large. To cover the ocean basins and arrive at the relationship of the continental margins to the basins, the area that must be covered is physically difficult to encompass in sufficient detail in reasonable time to get the data, particularly geophysical data, that give you the answers in sufficient detail to be irrefutable. What I would like to propose is that a detailed study be made of some of the small ocean basins - the three that come to my mind at present are the Mediterranean, the Tasman Sea, and the South China Sea. In the Mediterranean, for example, there is a relatively small area with oceanic crust. In terms of continental drift, possibly this is an area where there are two continents coming together. In contrast to this, the Tasman Sea is an area that suggests the opposite; the continental areas of Australia and New Zealand may have become separated. In this area there is true oceanic crust bounded on either side by continental areas. A possible extension of the mid-ocean ridge passes through New Zealand and the centre of the Tasman Sea. No rift has developed, which may suggest that it is in the early stages of development. Island arcs border the sea on the east and an essentially stable continent borders it on the west. The area is small enough and accessible enough that you can carry out a detailed study of the whole region without having to go more than 600 miles from any port. This is a distinct advantage when using ships. I feel that the knowledge gained from these small areas could be applied to the larger ocean basins, such as the Indian Ocean, the Atlantic, and the Pacific, and we could interpret their features on a more regional scale far more accurately.

Dr. T.K. Gaskell (UK)

I favour the suggestion of Dr. Phipps. But, please, do not think that you are going to learn something about the Pacific Ocean by studying the Tasman Sea or the Mediterranean Sea. In my view, they are quite different, and while you are going to learn more about oceanography and the structure of the earth, do not fool yourself by believing that by going 600 miles out in the Tasman Sea or the Mediterranean that you are going to get the same structure that you got in the Pacific. All the results that have been done to date indicate that the Tasman Sea and sea northeast of New Zealand have a different crustal structure. True, it's very interesting to do it, but you must not confuse the issue by saying you are studying the Pacific Ocean at the same time.

Dr. Phipps

The point I want to emphasize here is not that they may be directly applicable but, as far as the Tasman is concerned, we have very little data on it.

Mr. G. Peter (USA)

I would like to repeat the recommendations I made after my paper:

1) That the International Upper Mantle Committee recognize the parallel magnetic lineations in oceanic areas as a major crustal phenomenon, and encourage the organization of systematic surveys to determine the global distribution of these lineations.

2) Since the understanding of these lineations is closely related to major hypotheses about the development of the oceanic crust, special geological and geophysical investigations should be carried out to determine the geological cause of these lineations.

3) If these proposals are accepted, then Dr. D.H. Matthews, whose work is the best known in connection with these lineations, should be the coordinator or reporter of studies involving magnetic lineations of the ocean floor.

Dr. D.H. Matthews (UK)

I support Mr. Peter's suggestion and would act as coordinator if wanted.

I also support Professor Kuno's proposal for investigation of the petrology of the crystalline rocks of the deep ocean floor (as distinct from those of large seamounts and oceanic islands). Such a study is significant for at least two reasons:

1) Their chemistry can tell us about the upper mantle.

2) We may be able to map zones of active hydrothermal alteration. Transfer of volatiles from depth, as well as transfer of lava from depth, is a possible explanation of high heat flow values.

Moreover, we should commend the study of areas on land where it is possible that we have samples of the oceanic crust brought up in thrust blocks. Such areas include parts of Cuba and Puerto Rico, the Troodos massif in Cyprus, and outcrops in Greece and Turkey. They can be studied relatively cheaply.

It is surprisingly important from the viewpoint of interpretation of anomalies to prepare maps of regional fields – magnetic, gravity, and heat flow. The determination of just what we mean by regional field is not merely a question of semantics and should be seriously considered, although there may be no solution. In any case it would be a good thing for everyone to use the same regional fields.

Dr. B.D. Loncarevic (Canada)

I would like to present a recommendation which parallels one that was presented three days ago at the Rift Symposium, and which is linked very closely to Mr. Peter's suggestions. Namely, in order to promote cooperation between specialists working in different disciplines, and in order to encourage the exchange of information, it is recommended that a project group be established to study continental margins and island arcs and to coordinate, collect, and disseminate information.

Dr. G.B. Udintsev (USSR)

I would like to support some ideas which were proposed by Dr. B.C. Heezen at the Rift Symposium and some which were discussed by Dr. Burk for the investigation of continental margins.

And I would also like to recommend that all modern methods of work be included in the investigations of continental margins, such as:

1) Palaeogeographical investigations of land areas to study the distributions of land and sea in the geological past.

2) Detailed bottom topography surveys.

3) Seismic refraction studies.

4) Continuous seismic reflection profiling.

5) Magnetic surveys.

6) Gravity surveys.
7) Heat flow measurements.
8) Bottom sediments.
9) Bedrock of the sea bottom.

Dr. W.J. Ludwig (USA)

I support Dr. Burk's proposals for a cooperative study in the Bering Sea. We have learned from Dr. Shor that this area appears to be a normal oceanic section which has been depressed by a great weight of sediment, 3,000 to 4,000 metres thick. Lamont has run a few seismic reflection profiles in this region and from the results of one track alone we find that at least the upper 1,000 metres of this 3,000- to 4,000-metre sedimentary section consists of a succession of opaque and transparent sedimentary layers which are presumably turbidites. I also recommend that the results of the program be published in a single volume rather than scattered throughout the literature.

Dr. G.G. Shor, Jr. (USA) submitted the following recommendation: "It is recommended that systematic geophysical studies be made in the major trenches and island arcs of the world to determine their structure and to provide evidence bearing on the nature of faulting in trenches. The use of reflection, refraction, and geothermal studies is particularly desirable. In addition, investigations should be made in areas where trenches may be concealed by sediments to elucidate the distribution of trenches on the globe."

Dr. B.C. Heezen (USA)

I have two recommendations that were given to me by members who have left. One is by Dr. C.L. Drake; I will read it: "The margins of the continents are among the most promising areas of the earth's surface for study at the present time. They represent the major discontinuities in the crust and upper mantle and many important orogenic events have taken place along these in the past. It may be expected that other such events will take place in the future.

"The structure of the margins is poorly understood in all but a few areas. Surprisingly little data is being collected at the present time. A great deal of additional geophysical and geological work is required, both offshore and onshore, to determine the character of the margins, their history and development; and it is essential that data from all lines of investigation be integrated into the final analysis. In particular, investigations should be directed towards such problems as the permanence or growth of the margins, the continuation of continental structures into the oceanic areas, the nature of the margins on opposite sides of the oceans which are presumed to have been joined prior to continental drift, and the terminations of geosynclinal belts. Efforts should be made to find features of the margins which can be used to help in determining the age of the ocean basins."

Mr. W.H. Geddes of the Naval Oceanographic Office has given me a recommendation to read. "An investigation of world-wide magnetic data is recommended to determine whether a characteristic anomaly exists at the transition between oceanic to continental crust. It is also recommended that magnetic measurements be made on all geophysical surveys whenever possible."

I think that these recommendations and others cover my views on the subject. We all realize that both the continental margins and island arcs are important features to study.

I think the idea of international collaboration in these surveys is not only fruitful in providing greater resources to solve problems but is also fruitful in providing people of different background and different training so that these problems can be attacked with a less one-sided view. I think that the recommendations presented should go far towards this end.

Dr. Ringwood

Ladies and gentlemen, our conference is nearly at an end, and I would like to call on Prof. Beloussov to make a few remarks.

Prof. V.V. Beloussov (USSR)

I do not think that it is necessary to add to the proposals which have already been made. They are all very sound and very interesting. But, I should like to stress some of them without adding anything different.

First, I would like to stress the importance of the connection between onshore and offshore investigations. Of very great importance are palaeogeographic studies which might reveal former land areas in some regions which are now covered by water.

I think that we need to prepare a synopsis of our knowledge about the margins of oceans, and in such a synopsis it seems to me that it would be very important to make a thorough comparison of the different types of margins. There are two – the most important types, Pacific and Atlantic – but maybe the classification is more complicated. I think the proposal to draw our attention to such places where the continental structures are cut by the margins of oceans is quite sound. And it seems to me that the margins of the Indian Ocean are of very great interest.

Regarding the Mediterranean Sea, I share completely the idea that the Mediterranean might give us important data about processes and structures which are now beneath the water in other parts of the world. The structures in different parts of the Mediterranean are very different. The Mediterranean is very accessible and not large. But I agree with Dr. Gaskell; we cannot solve all the problems we face by studying only the Mediterranean Sea.

And finally I think that the proposal to set up a project group, like we have for other problems, is sound. It is quite necessary to coordinate our work and if we decide, for instance, to prepare such a synopsis, as I have mentioned, it would be quite necessary to have some organization which would deal with it.

And finally, there is the symposium. We have decided to hold a symposium on the rift system at the next General Assembly of the International Union of Geology and Geophysics. And I think we might decide to recommend that the Union organize at the same time a symposium on continental margins.

Dr. Ringwood

Thank you Prof. Beloussov. And now I would like to call on Dr. Gaskell to make some closing remarks.

Dr. Gaskell

The remarks I would like to make include first of all thanking the Canadian Department of Mines and Technical Surveys and especially Dr. Charles H. Smith for arranging what, to my mind, has been one of the most successful and useful meetings on this earth sciences subject that I have ever attended.

I would like to thank in detail some of the workhorses that have been doing all the odd jobs around the place. There are about eight unsigned and hard working chaps who are recording the session. I can speak from bitter experience as a geophysical secretary myself of what a miserable job this is. I think they have done a very good job from the bits I have seen so far and I wish them luck and sympathy with the rest of their job. I would like to thank very much our two projectionists John Emslie and John Kemp who as far as I can recall have not, in fact, put one slide in upside down during the entire meeting. I would like to thank very much indeed, and I am sure you will all join me, the young ladies who have been assisting us right from the time we arrived at the airport with all our little worries and troubles. And, in fact, we have little mementos for them. These are for Frances Aitkens, Lynda Styler, Cathy Hunt, and, finally, Betty Thomas who coordinates the office. If these young ladies would like to come up here we will present these little gifts to them.

I am sure that all of you felt the same way as I have in this awkward business of getting to and fro between the hotel and the lecture hall and being made to get to the lectures on time. This has all been arranged by those kind gentlemen who have been meeting us in those rather smart limosines outside the hotel every morning. I would like to thank the drivers of those cars for doing what must be a dreary chore indeed - to go back and forth, up and down that road eight times a day for a whole week or more must have been extremely uninteresting.

Now I would like to thank Alex MacLaren and Bob Gait for making all the room arrangements. I can only speak for myself - my room arrangements were perfectly adequate and very comfortable, and of those whom I visited at late hours, their arrangements seemed to be good too.

I would like to thank Angus Hamilton for doing all the meal organizing. This is a pretty difficult job because as you know we worked over the weekend, all against trade union rules of course, and we worked on Labour Day. And it has been extremely tricky to try to feed us all over this holiday period.

And last but not least, I would like to thank the typists. I presume there must have been some typists around here, because one hands in a scruffy bit of paper with an abstract on it, and somehow it appears in several hundred copies, enough to satisfy us all. And so I would like to thank those typists who have managed to read everybody's writing and to provide a semicoherent account of what we are all trying to say. So by and large I would like to embrace all those people, and thank you all, and thank the Canadian Government and everybody who has helped to support what I am sure you will all agree, has been a most excellent meeting.

Dr. Ringwood

There is another person that I feel we should all thank and that is Dr. Bruce Heezen for the organization of the talks and speakers. With the enormous amount of work which he has put into it, I think we all realize what a resounding success it has been.

And now, ladies and gentlemen, thank you very much for your attendance. The Symposium is now over.

APPENDIX I

PROGRAM

SYMPOSIUM ON CONTINENTAL MARGINS AND ISLAND ARCS

Organized by B.C. Heezen

6 September a.m.

ATLANTIC CONTINENTAL MARGINS

Chairman: B.D. LONCAREVIC   Reporter: W.H. POOLE

J.M. HARRISON:
V.V. BELOUSSOV: Opening Remarks.

M.J. KEEN and J.E. BLANCHARD* (Canada): The Continental Margin of Eastern Canada.

P.J. HOOD (Canada): Magnetic Surveys of the Continental Shelves of Eastern Canada.

W.H. GEDDES (USA): Atlantic Shelf Magnetic Anomaly.

J. TUZO WILSON (Canada): New Kind of Faulting.

J.B. HERSEY (USA): Geophysical Investigations in the Eastern Caribbean Sea Area.

J.I. EWING, M. EWING and R. LEYDEN* (USA): Seismic Profiler Survey of the Blake Plateau.

R.M. DEMENITSKAYA and V.D. DIBNER (USSR): Morphological Structure and Earth's Crust of the North Atlantic Region (by title).

6 September p.m.

ATLANTIC AND ARCTIC CONTINENTAL MARGINS

Chairman: J.B. HERSEY   Reporter: T.N. IRVINE

J.B. HERSEY (USA): Opening Remarks.

C.L. DRAKE (USA): Recent Investigations on the Continental Margin of Eastern North America.

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*Speaker

J.B. HERSEY (USA) and W.F. WHITTARD* (UK): The Continental Margin Under the South Celtic Sea.
H. BERCKHEMER* (Germany) and J.B. HERSEY* (USA): Some Features of the Alpine-Mediterranean Orogen.
W.D. NESTEROFF (France): Deux exemples de bordure continentale française: le gouf de Cap Breton et le Cap Cartaya.
W.J. LUDWIG (USA): Argentine Continental Margin.
H. HUNKINS (USA): The Continental Margin of Alaska.
E.F. ROOTS (Canada): The Northern Margin of North America: A Progress Report.
C.V.G. PHIPPS (Australia): Some Structural Features of the Outer Continental Shelf of Eastern Australia
R.M. DEMENITSKAYA and A.M. KARASIK (USSR): Magnetic Diagnostics Confirm that the Nansen-Amundsen Basin is of "Normal" Oceanic Type (by title).

7 September a.m.

ATLANTIC ISLAND ARCS

Chairman: J. TUZO WILSON — Reporter: A. LAROCHELLE

J.T. WILSON (Canada): Opening Remarks.
E.T. BUNCE (USA): The Puerto Rico Trench.
P.H. MATTSON (USA): Geological Characteristics of Puerto Rico.
R.J. HURLEY (USA): Geological Studies of the West Indies.
C. BOWIN (USA): Gravity Over Trenches and Rifts.
M. TALWANI (USA): Gravity Anomaly Belts in the Caribbean.
W. HAMILTON (USA): Origin of the Caribbean and Scotia Arcs. Origin of the Igneous Rocks of Island Arcs and Eugeosynclines.
H.H. HESS (USA): The Caribbean.

7 September p.m.

PACIFIC ISLAND ARCS

Chairman: T. NAGATA — Reporter: T.N. IRVINE

T. NAGATA (Japan): Opening Remarks
I. ZIETZ (USA): Crustal Study Along a Transcontinental Great Circle from Washington, D.C., to San Francisco.

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*Speaker

G.G. SHOR (USA): Continental Margins and Island Arcs of Western North America.
D.E. HAYES (USA): The Peru-Chile Trench (Presented by J.L. WORZEL).
C.A. BURK (USA): The Aleutian Arc and Alaska Continental Margin.
G. PETER (USA): Preliminary Results of a Systematic Geophysical Survey South of the Alaska Peninsula.
P.S. WEIZMAN (USSR): On the Deep Structure of the Kuril-Kamchatka Region (Presented by V.A. MAGNITSKY)
W.J. LUDWIG* (USA) and S. MURAUCHI (Japan): Sediments and Structure of the Japan Trench.

8 September a.m.

PACIFIC AND INDIAN OCEAN ISLAND ARCS

Chairman: S.K. RUNCORN — Reporter: E.F. ROOTS

S.K. RUNCORN (UK): Opening Remarks.
L.R. SYKES (USA): Seismicity of the Tonga-Fiji Region (Presented by J. DORMAN).
D. TOCHER (USA): Seismicity of the Pacific Margin.
J.N. BRUNE (USA): Propagation of the Sa Phase through the Upper Mantle.
V. VACQUIER and P.T. TAYLOR* (USA): Geothermal and Magnetic Survey off the Coast of Sumatra.
B.B. BROCK (South Africa): Island Arcs and Their Size-Shape Significance.
W.H.K. LEE*, S. UYEDA and P.T. TAYLOR (USA): Geothermal Studies of Continental Margins and Island Arcs.
J.C. GROVER (Solomon Is.): Gravity Surveys in the British Solomon Islands (by title).

8 September p.m.

PETROLOGY AND GEOPHYSICS OF ISLAND ARCS

Chairman: V.A. MAGNITSKY — Reporter: W.H. POOLE

V.A. MAGNITSKY (USSR): Opening Remarks.
H. KUNO (Japan): Lateral Variation of Magma Types in Volcanoes of Island Arcs and Continental Margins.
A. SUGIMURA (Japan): Compositions of Parental Magmas and Seismicity of the Earth's Mantle in Island Arcs (Presented by H. KUNO).

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*Speaker

T. NAGATA (Japan): A Review of Recent Works on Conductivity Anomalies along Continental Margins.

J.L. WORZEL (USA): Structure of Continental Margins and Development of Ocean Trenches.

DISCUSSION OF RECOMMENDATIONS

Chairman: A.E. RINGWOOD

Reporter: W.H. POOLE

Recommendations were submitted and read by:

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H. KUNO (Japan)
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G.G. SHOR (USA)
C.L. DRAKE (USA)
D.H. MATTHEWS (UK)
C.V.G. PHIPPS (Australia)
B.C. HEEZEN (USA)
V.V. BELOUSSOV (USSR)
B.D. LONCAREVIC (Canada)
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