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The Suffield Craters as Analogues of Impact Structures

BY

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Prepared for:

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THE SUFFIELD CRATERS
as
ANALOGUES OF IMPACT STRUCTURES

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G.H.S. JONES

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Scientific Authority, DRES/MES, J.E. Slater
Department of National Defence
CANADA
1995

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FOREWORD

Several hundred high explosive trials have been held at the then Suffield Experimental Station, now the Defence Research Establishment, Suffield, near Medicine Hat, Alberta, Canada. The majority of the trials were fairly small in scale, from a few pounds to a few tons of TNT. There was, however, a variety of trials at larger scale, ranging from 20 tons TNT to 500 tons TNT. All the trials were designed primarily for specific military purposes. To that end, the results have been published in many hundreds of agency reports, many of which remain classified, and virtually all of which report on single trials, or the progression of some single effect.

It is with the shorter series of relatively large scale trials that this present publication is concerned, a series which while still designed primarily to meet military needs has excited wider interest. The craters produced by these larger trials were strikingly similar to features on the surface of the earth and with lunar features. At the time of the trials no comparable features had been found elsewhere, but with the advent of the interplanetary space probes it has since become evident that the features are common to all planetary bodies with solid surfaces. Although some of the data from Suffield has indeed appeared in open scientific publications and books, as well as in limited distribution reports, attention has in the main been concentrated on single trials.

It has therefore appeared desirable to prepare a unified text, giving comparable data where available on the series of craters produced at Suffield which were analogous to the planetary features. In addition, it seemed necessary to locate, annotate and collate archival material not hitherto published in any form.

The present publication is intended to serve that purpose, and place the material in the public domain. It is probable that the Suffield craters in the sense of a graduated series of excavated, well studied structures on a single type of terrain will remain unique, if only due to the high cost of replication. Each major trial at Suffield cost several million dollars, in mid-century dollars.

Herein, effort is concentrated upon those craters which demonstrated a morphology essentially analogous to the terrestrial structures previously called crypto-explosive, but now generally accepted as the scars of meteorite impact. In the past they have been denied such an origin in part because experimental craters did not normally exhibit the complex morphology of the typical crypto-explosive structures. This morphology normally included central uplift structures, overturned ejecta blankets, and systems of circumferential synclines, anticlines and fractures, radial fractures and associated volcanic type features such as dykes and extrusive flows of liquid material.

High Explosive surface detonations at Suffield produced craters which exhibited all the above features, and provided precise information on the pattern of displacement and fractures associated with them. Thus the data become a significant element in the present identification of such planetary features as being the result of impact.

It should be noted that this publication deals only with the specific series of crater-forming blast trials at Suffield. As such, it is a time capsule, viewed some three decades after the event. It is therefore appropriate that the Bibliography reflects primarily the events described, together with those other publications which were directly influential in the interpretation made in the immediate aftermath of the trials, and a few later publications which actually made significant use of the Suffield data.

Since the end of the Suffield program, there has been a vast increase in the knowledge relating to impact structures within the planetary system, a virtually unknown field at the time of the Suffield trials. Obviously, there have been hundreds, probably thousands of publications both in this new field and relating to other, large scale, explosive trials. No attempt would be proper to include these later publications. It is understood that the U.S.A. DNA maintain an unclassified, computer based bibliography covering the entire field of crater studies. Recourse may be made to that bibliography by serious workers in the field.

ACKNOWLEDGEMENTS

The debt owed by the author to his erstwhile staff at Suffield is reflected in the joint authorship of reports, and this will be clear from the bibliography. Nevertheless, special mention must be made of Messrs Diehl, Pinnel, Cyganik, Briosi and Winfield, without whose efforts there would be little to discuss. More widely, the support of the field staff under Norman Spackman, the photographic staff under Frank Trafford and Morley Fach, and of Norman Bonin is recognized. While it is invidious to name a few and leave many un-named, with the passage of decades this is inevitable. Many indeed are the contributions recalled, but the association with individual names is often regrettably lost.

The author is indebted to Prof N.J. Price for decades of illuminating discussions and support, and to David Roddy for his long and active participation.

The particular, and personal debt to Dr. C.S. Beals, the doyen of believers in impact cratering on earth, is remembered with pride. In the last two years of his life he was excited by the Suffield craters, and gave endless moral support to the author. (In passing, Dr. Beals was the last holder of the honourable title of Dominion Astronomer for Canada. The author regrets, as he did, the passing of such inexpensive but valuable honorifics. Perhaps Britains Astronomer Royal will yet be Chief/Anon X).

The willing, and most valuable, unofficial support given to the author in the field by members of the British and American teams is gratefully recognized, as is the financial support from DASA, now DNA, without which the excavations of the later craters could not have been undertaken.

The present staff at Suffield, in particular Dr. John Slater and Mr. David Ritzel, have been directly instrumental in the production of this latest result of our work back in the joyous days of the Blast Program at Suffield.

Finally, without the staunch and unfailing support of the late B.J. (Joe) Perry, then Director of Research, the program of research, as opposed to testing, would not have existed. His support was, indeed, like the shadow of a rock in a barren land.

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CHAPTER ONE
THE SUFFIELD CRATERS

1.1 INTRODUCTION

During the decade 1960 to 1970 the various test sites located on the thousand square mile Suffield reserve in Alberta, Canada, hosted a series of international trials based upon the detonations of high explosive charges of cast TNT, culminating in several trials using 500 ton (10^6 lb) charges (see Table 1/1). These trials, under the auspices of The Technical Cooperation Programme, were intended to provide technical information relatable to the detonation of Nuclear Weapons. Teams of scientists from Canada, the U.S.A., Great Britain, New Zealand and Australia participated in the trials and carried out many thousands of experiments, some of which remain "classified" to a greater or lesser degree.

Fortuitously, circumstances were such that an unexpected development was recognized as being important in a much wider context than the avowed military purpose of the trials. It was observed that detonations on this test site, with charges greater than 20 tons, produced craters quite different from any known earlier detonations, even at the nuclear scale. The craters, however, proved to be quite close models of naturally occurring geological features, both terrestrial and lunar. Later planetary probes have indicated that such features are common to most, if not all, heavenly bodies with solid surfaces, within the solar system. On earth, such features were commonly known as "crypto-explosive structures" and were almost universally interpreted as being of volcanic origin.

A small minority of geologists, astronomers and geophysicists held a contrary view, and interpreted such structures as being the residual scars of meteoritic impact. A few such structures on earth, which were essentially bowl shaped, and which had traces of metallic debris, such as the Barringer Meteor Crater in Arizona, were accepted as being of meteoritic impact origin. The majority of the terrestrial (and lunar) structures were, however, termed crypto-explosive, and probably volcanic by most the

Table 1/1

LIST OF TRIALS AND COMPARISON OF CRATER DIMENSIONS

Trial/ Crater	Charge* (Ton)	Date D/M/Y	Apparent Diameter (ft)	Lip Diameter (ft)	Overall Diameter (ft)	Apparent Depth (ft)	Apparent Rim Height (ft)	Visable Ejecta (ft)
FE535	20 H/S	- /8/60	74.8	87.2	180	18.4	4.32	476
FE556	20 H/S	4/7/63	73.5	80	-	15	5	-
LT314	20 H/S	15/8/63	81	89.5	140.8	-	-	-
DP3	20 ½B	28/7/66	72.6	83	-	17	-	-
DP5	20 ½B	9/2/67	67.5	75.5	-	15.5	-	-
ANFO1	20 H/S	- /8/69	72.5	80	-	16.5	-	324
ANFO2	20 H/S	21/8/69	63.2	77.8	-	18	-	402
ANFO3	100 H/S	28/8/69	116	154	-	28	-	602
1961	100 H/S	3/8/61	154	182	-	20	-	Central Uplift Crater
DP6	100 T/S	26/7/67	88	112	-	16	-	Central Uplift Crater
SNOWBALL	500 H/S	17/7/64	286	322	-	-	-	Depressed Rim, Central Uplift
PRAIRIE FLAT	500 T/S	9/8/68	210	270	-	12	3	Depressed Rim, Central Uplift, Ringed Crater
DIAL PACK	500 T/S	23/7/70	200	280	-	12	4	Depressed Rim, Central Uplift Ringed Crater

*** Change Geometry: H/S = Hemisphere ½B = Half Buried Sphere T/S = Tangent Sphere on Ground**

scientific community. Despite a small and enthusiastic group supporting the impact hypothesis, these "astroblemes", as they were dubbed by Dietz (1961), were denied an impact origin on the seemingly realistic grounds that impacts, essentially surface explosions, simply did not produce the complex structures such as central uplifts, ring synclines, and coherently overturned rims, which were commonly found in the suspect structures.

The Suffield Craters, in the range 100 tons to 500 tons, showed, feature by feature, correspondence with the terrestrial and lunar structures, and thus became a significant factor leading towards the wide spread acceptance of the impact hypothesis today, thirty years after the Suffield experiments.

The present author and field team recognized the probable significance and alerted the scientific community to the new experimental evidence, relating surface explosions to complex astrobleme type structures. Consequently, for many of the later trials, cooperation was obtained with many agencies not originally concerned with the military orientated trials. The volume of data recorded became vast, far too great to allow full interpretation, let alone publication, during the trials period. Naturally enough, friends and opponents of the impact hypothesis have over the years demanded access to the original material, and this was certainly desired by the present author and collaborators. It is to that end that the present publication is being written, more than twenty years after the last Suffield trial.

1.2 EXPLOSION RESEARCH AT SUFFIELD BEFORE 1960

No large scale experimental programme develops without a long background of related studies, and this was certainly the case at Suffield. Quite major explosive trials were held just after WW2 for severely practical ends. In particular, the British "Wall Blast Trials", designed to investigate the use of Berms to protect ammunition dumps, was an early example of international cooperation in explosive research. Later a team from Suffield, under Dr. Ross Harvey, participated in the British nuclear trials in Australia, developing a technique of measuring the blast wave by optical methods. However, by 1957 explosive research at Suffield was almost non-existent, but considered desirable. A small team of three young scientists, Trevor Groves, John M. Dewey and the present author were recruited to work under Dr. Harvey to develop a viable programme.

The group was afforded a remarkable degree of freedom to undertake whatever studies most appealed to them, with initial freedom to use ¼ lb charges of TNT, a few BD10 pressure gauges, and one or two cameras. Groves and Dewey concentrated upon the study of the airblast itself, while the present author with a background in engineering and geophysics, felt inclined to undertake studies of the effect of the blast upon structures, and, in particular, the seismic effects of explosions on and above the test surface. No team could have had better support from their masters. In particular, B.J.(Joe) Perry, The Director of Research, was prepared to support the team well beyond the realms of obviously practical studies. Also, from the earliest days the team was pushed by the senior members of the Defence Research Board into participating in the deliberations of the international community as represented by the various committees of The Technical Cooperation Programme (TTCP), a joint venture by Canada, the U.S.A., Great Britain, Australia and New Zealand.

At the time, there was a growing need to investigate the effects of nuclear weapons, but without the political (and scientific) hazards associated with actual nuclear detonations in or venting to the atmosphere - the realm of actual military interest.

The Suffield team experimented briefly with the use of alternative explosives - based, for example, on Fertilizer Grade Ammonium Nitrate, known initially as FGAN but later more widely termed ANFO (Ammonium Nitrate-Fuel Oil). However, it became clear that international interest was closely tied to TNT, partly because TNT was used as the base explosive for measuring nuclear yield, and partly because large stocks of TNT could be made available from military stores, particularly American. The explosive section at Suffield therefore developed a form of experimental charge based upon blocks of cast TNT, built into hemispherical charges. All the initial large scale trials at Suffield were based upon these hemispherical charges, but at a later stage the same technique was used to build spherical charges, ranging as high as 500 tons (10^6 lb) of TNT.

Under the auspices of TTCP, Suffield was promoted as a suitable test site for international trials, and a search was made of the 1,000 square mile area for suitable sites which could be used for increasingly large trials. In consultation with the Field Staff, a final choice was made by Perry and the present author of two sites, to be known as Drowning Ford and Watching Hill (see diagrams in Appendix A). On these sites, facilities were installed and the first large scale trials were held on the Drowning Ford test site. This series was restricted to 5 ton charges of hemispherical form with the interest mainly in the airblast effects on Bell Telephone Company hardened communication and radar systems. Despite the primary significance of the airblast, wide use was made of the trials for other experiments, ranging from the simple measurement of crater size to ejecta distribution and seismological effects.

As the Drowning Ford site is essentially an alluvial plain, much re-worked by the adjacent South Saskatchewan River it was anticipated that sub-surface effects would be less consistent than the airblast, but this was not of serious concern even to the present author as the craters were small, and the seismic effects were related to Air Coupled surface waves.

However, pressure was increasing for trials of larger scale, with much greater international participation, and in 1960 work commenced on the Watching Hill test site. The site consists essentially of horizontally layered lacustrine sediments. It was anticipated that by using fresh sites for each trial even the sub-surface effects would be consistent. After a 20 ton trial in 1960, the first large international trial was held in 1961, the charge being a 100 ton hemisphere of TNT. It is with the results of trials in the decade 1960 to 1970 that this publication is primarily concerned (see Table 1/1).

The topography and some detail of the surficial geology are shown in Figures A and B, (back cover pocket) after Hobson et al (1970), of the Geological

Survey of Canada. Their work is discussed in the next section, but these maps may be taken as a general introduction to the remainder of this text and are suitably located as "separates" at the end of this publication.

1.3 THE WATCHING HILL TEST SITE

Despite the name, deriving from an adjacent feature, the Watching Hill Test Site was an essentially flat plain underlain by a remarkably consistent series of horizontally layered lacustrine deposits, mainly sands and silts over thicker beds of blue clay. Over the years hundreds of shallow bore holds were drilled and monitored, some in considerable detail. Much detail is preserved in the reports written in connection with each trial, and these reports are listed in the Bibliography. Generally speaking, these reports, while of limited circulation, are unclassified and available for study. In this section a sample of typical data relating to the site is given. It should be noted that the major series of 100 ton and 500 ton trials were all carried out on this site, but in each case on previously undisturbed ground. In no case was a re-consolidated previously cratered area used, and the Ground Zero of each trial was sufficiently far removed from that of earlier trials to ensure that there was no overlapping of the craters from one to another, even though structures relating to an individual crater extended far beyond the obvious rim of the crater, usually to many diameters from GZ.

The underlying bedrock, which was not usually breached, also consisted of horizontally stratified deposits of Cretaceous age (Oldman Formation) of mainly softly indurated sandstones. The lacustrine deposits, constituting the working area, will in the main have been derived from similar previously eroded rocks higher in the formation, incorporated in glacial Till, redeposited by water in a small melt-water lake which occupied the site for, presumably, some centuries. The general geology of Southern Alberta is well described by Williams & Dyer (1930) and Russell and Landes (1940). However, the most detailed study available relating directly to the Watching hill and Drowning Ford test sites is that prepared by Hobson, Hunter & Scott (1970). Obviously, this only became available towards the end of the series, but it incorporates earlier studies by the present author and by the Century Geophysical Company of Calgary, Alberta. While the 1970 study is far more detailed than the earlier studies, there is general agreement among them. The 1970 study is in the public domain and need not, therefore, be quoted extensively. The information may be summarized briefly in so far as it is relevant to the present purpose.

The upper layers are certainly lacustrine, but these are underlain by clays and gravels which are probably glacial till. The velocity of the layers very close to the surface is as low as 1,100 fps, but the mean velocity of the lacustrine deposit, which varies between 45 ft and 60 ft in total thickness, is 2,200 fps. These are the velocity layers which allow for the generation of Air Coupled surface waves, as discussed later. This section is underlain by a sequence of beds, both Till and pure clay, interleaved with thin sand and gravel beds, the upper sections of which show a velocity of about 2,600 fps increasing to 6,000 fps and possibly one thin stratum of 7,200 fps. The 6,000 fps layer ranges between 80 ft and 180 ft thick, as it overlies the bedrock, which may be as shallow as 140 ft or as deep as 230 ft to the contact. This bedrock has a velocity of approximately 7,700 fps. Immediately beneath the explosion sites, there is considerably less relief in the bedrock. Thus, although there is detailed variation between the areas cratered by the explosions, all the trials were on essentially similar ground in terms of both the velocity profiles and the sequence of flat lying lucustrine sands, silts and clays. In the hundreds of drill holes scattered through the test sites, water frequently appeared at depths of 26 to 28 ft, but below this one passes into an impervious blue clay and then into water bearing gravel at depths of about 45 ft. The blue-grey clay is dry to the touch and will not yield water to wells but has considerable connate water and some fracture permeability. The upper aquifer may be regarded as a "perched" water table, with small flow potential.

It will however be appreciated that the above is a rather subjective averaging of conditions over a wide area, and the various trials over the decade were in widely separated locations. Not only could the specific details for the stratigraphy vary, but so also could the degree of saturation of individual strata. By the middle of the decade several major trials had been held, and the craters excavated in detail. As the craters tended not to be of the classical, bowl-shaped pattern, there was controversy regarding the reasons for the "anomalous" crater patterns, some participants suggesting changing the charge construction and height of burst, others relating the effects entirely to the height of the water table, and yet others, including the present author, maintaining that it was essentially a scale effect, so that the detonations at up to 1 kT equivalent on this soft ground simulated the effect of multi-megaton or impact effects. As further large detonations were planned, these varying opinions resulted in much additional work. In particular, a more detailed "preliminary" soil survey was undertaken by the Suffield Geophysics group, as an aid to future planning. This resulted in a limited circulation report Jones & Diehl (1966) on a preliminary soil survey for 1967 DISTANT PLAIN 6 and the 1968 PRAIRIE FLAT trials. As this represents the best information available at the time, and is essentially unpublished, it is given here in abstract form.

Seven holes were drilled in the pattern, as shown in Figure 1/1, across the areas tentatively scheduled for future trials. An attempt was made to undertake full core sampling, but it was found that with the equipment available, and the very dry and free running nature of many of the strata, this could not be completed in a satisfactory way. Recourse was therefore made to specially designed bucket augers, and this, while theoretically less refined than core sampling, proved quite satisfactory, but would tend to miss some of the fine layering in the sand strata.

Copies of the field records obtained from the seven bore holes are included here as Figures 1/2 to 1/9 at the same scale.

As the top and bottom hole elevations are given, the location of a given layer may be read off with all the precision justifiable for the sampling method. It is noted that some layers are indicated as "very wet", but caution is needed as the sampling method allowed for water contamination from higher levels, and the in-situ strata may not, in fact, be palpably wet, a fact well confirmed by post-trial excavation, as will be seen later.

These bore holes results may be compared with several seismic profiles, which are given herein as Figures 1/10 to 1/13 which are in general agreement with the bore hole data for the upper layers. These seismic profiles are discussed further in the next section, which deals with seismic effects relating to the explosive trials. Figure 1/14 shows graphically the layout of the seismic lines.

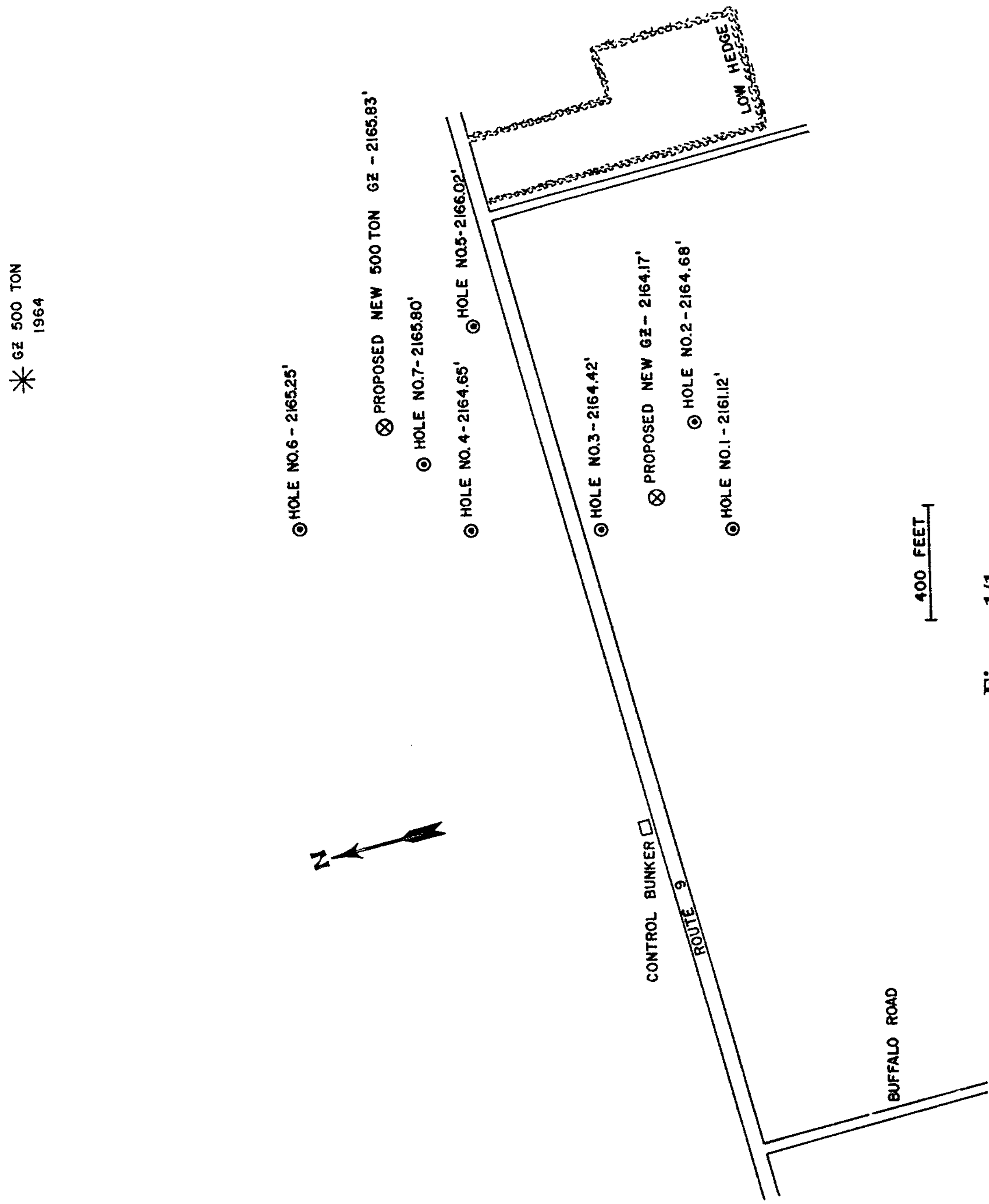

Figure 1/1
Layout of Soil Sample Holes on WATCHING HILL Site 1967.

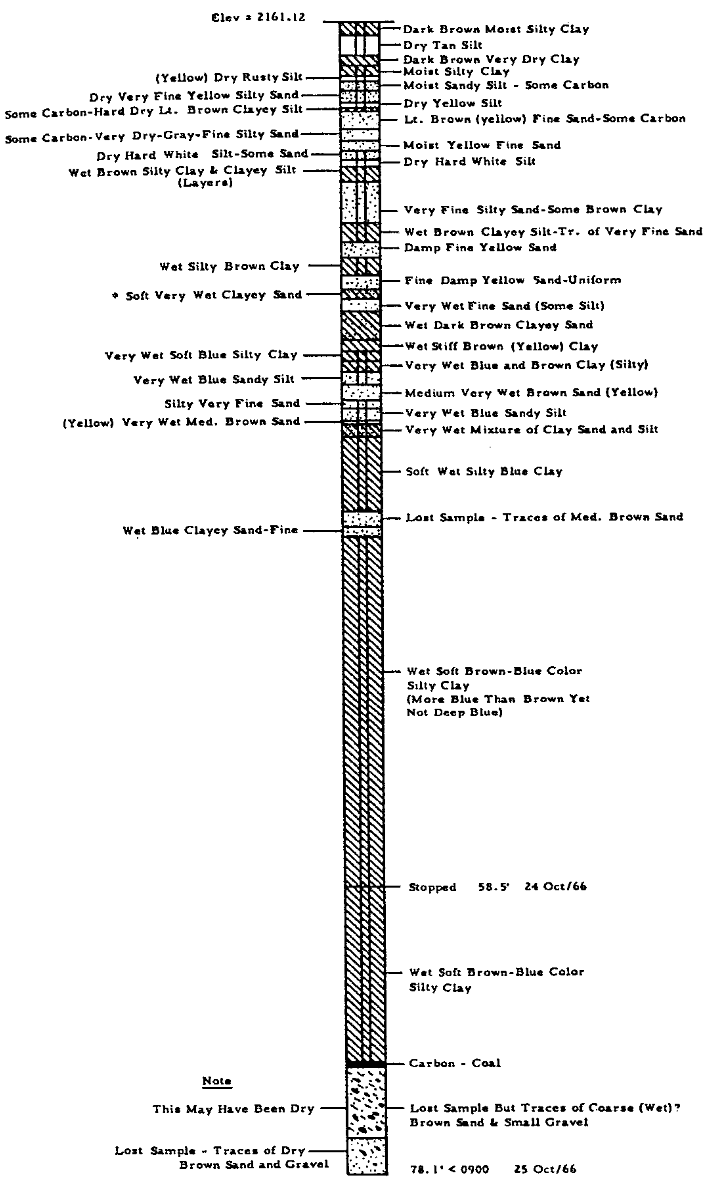

Figure 1/2

Hole No. 1

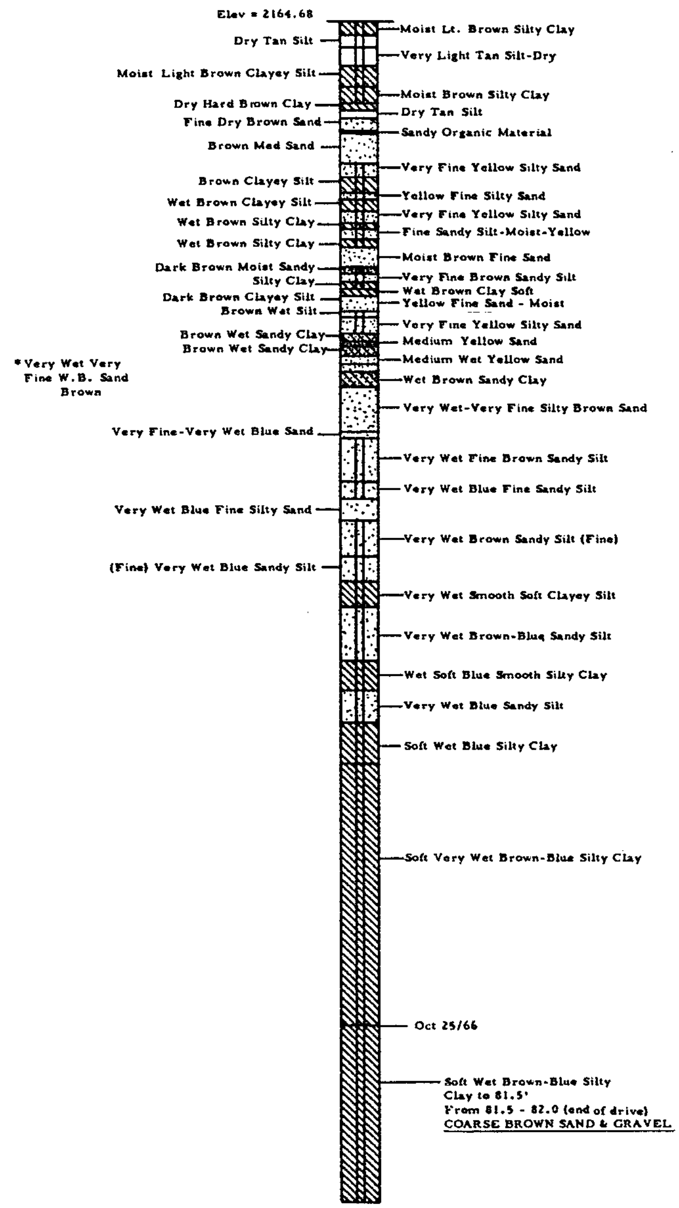

Figure 1/3

Hole No. 2

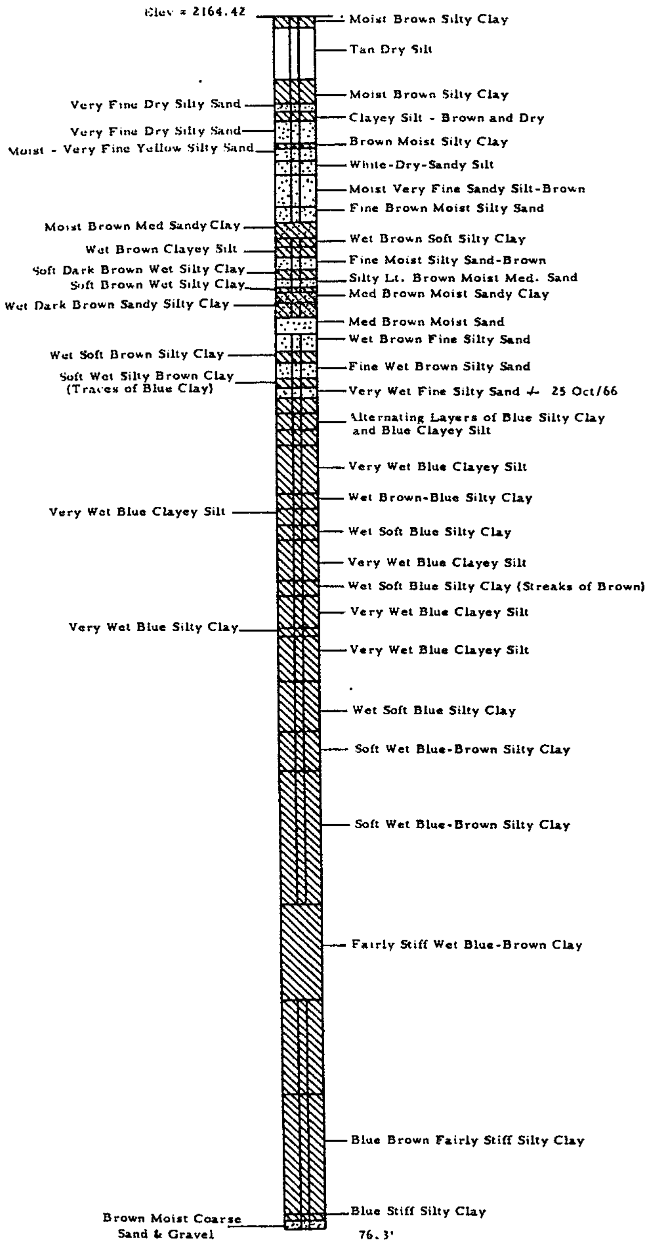

Figure 1/4
Hole No. 3

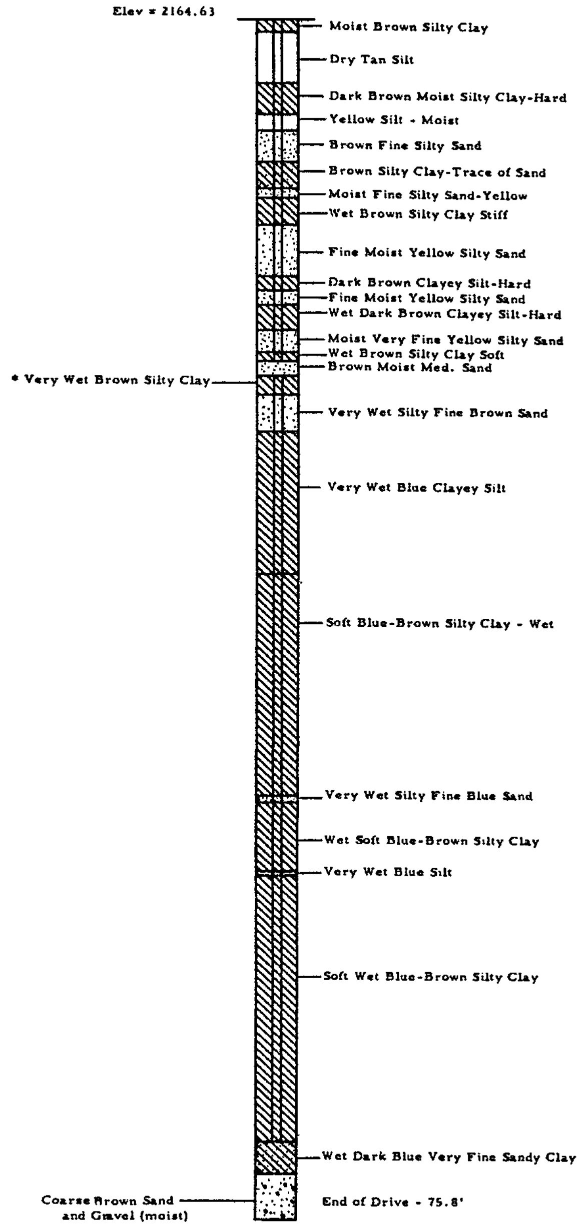

Figure 1/5
Hole No. 4

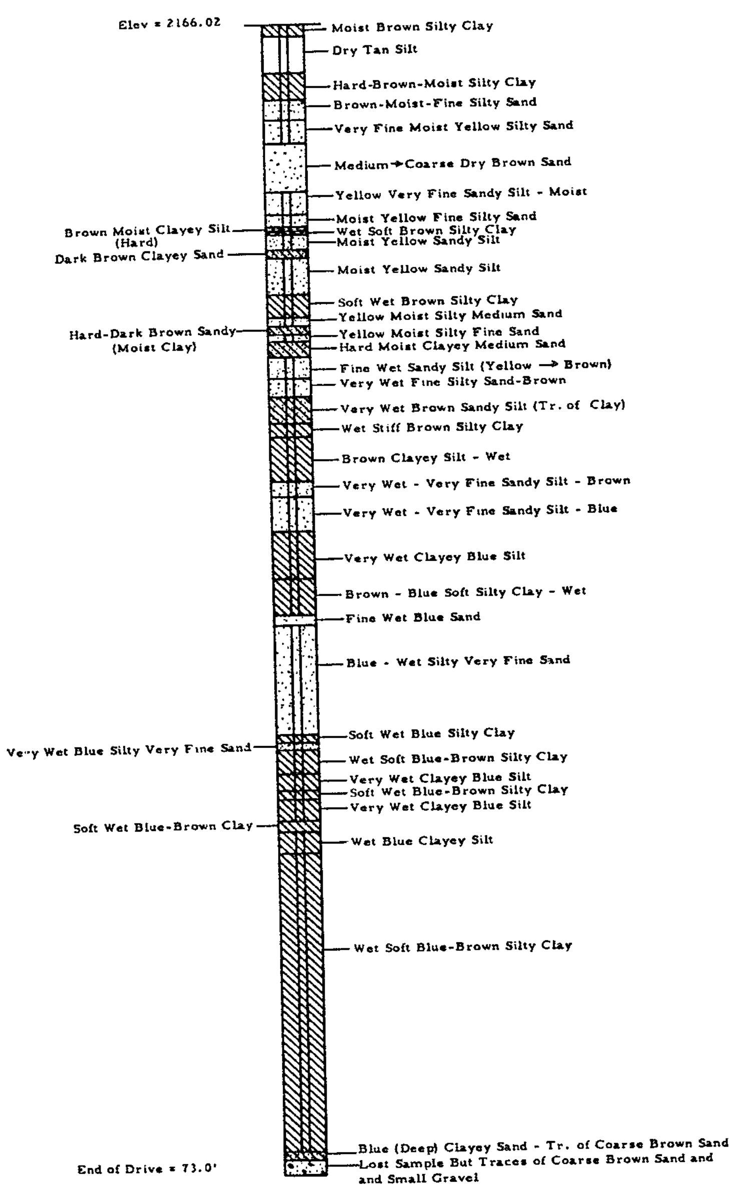

Figure 1/6
Hole No. 5

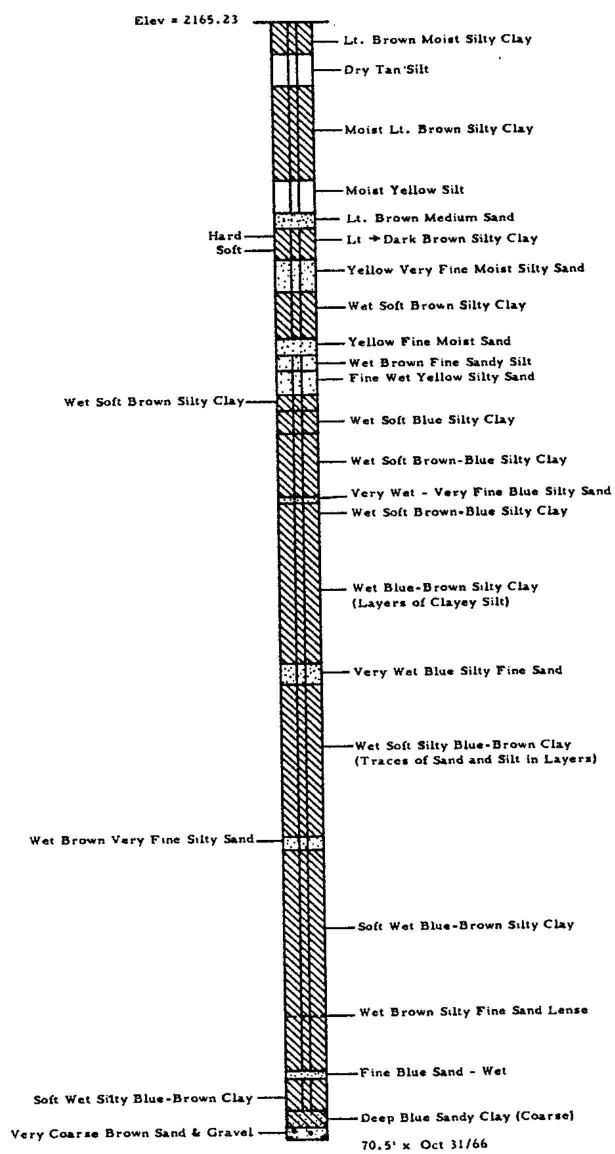

Figure 1/7
Hole No. 6

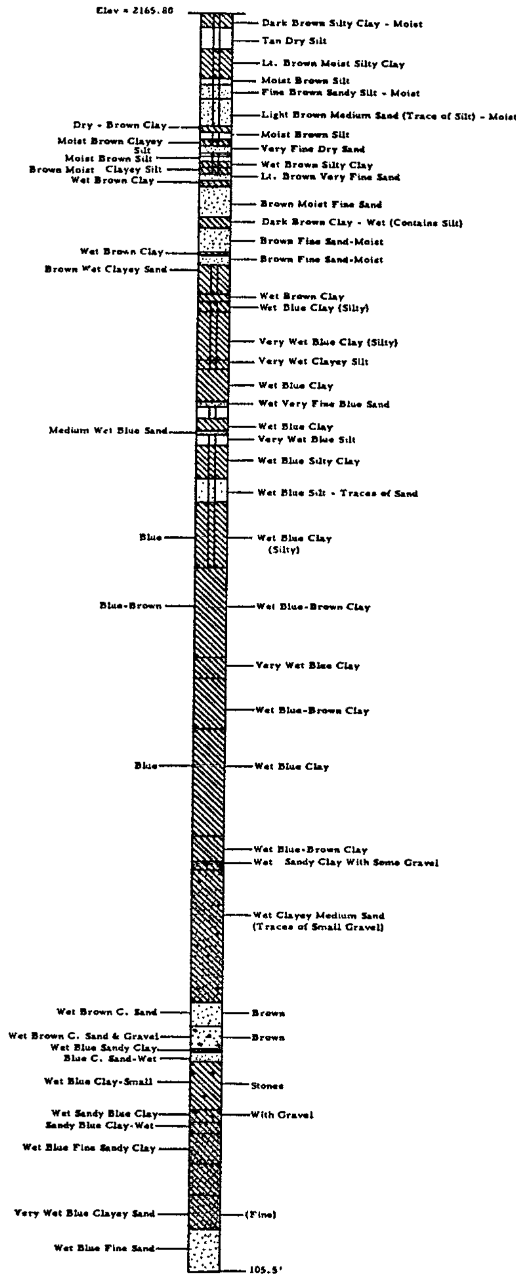

Figure 1/8
Hole No. 7

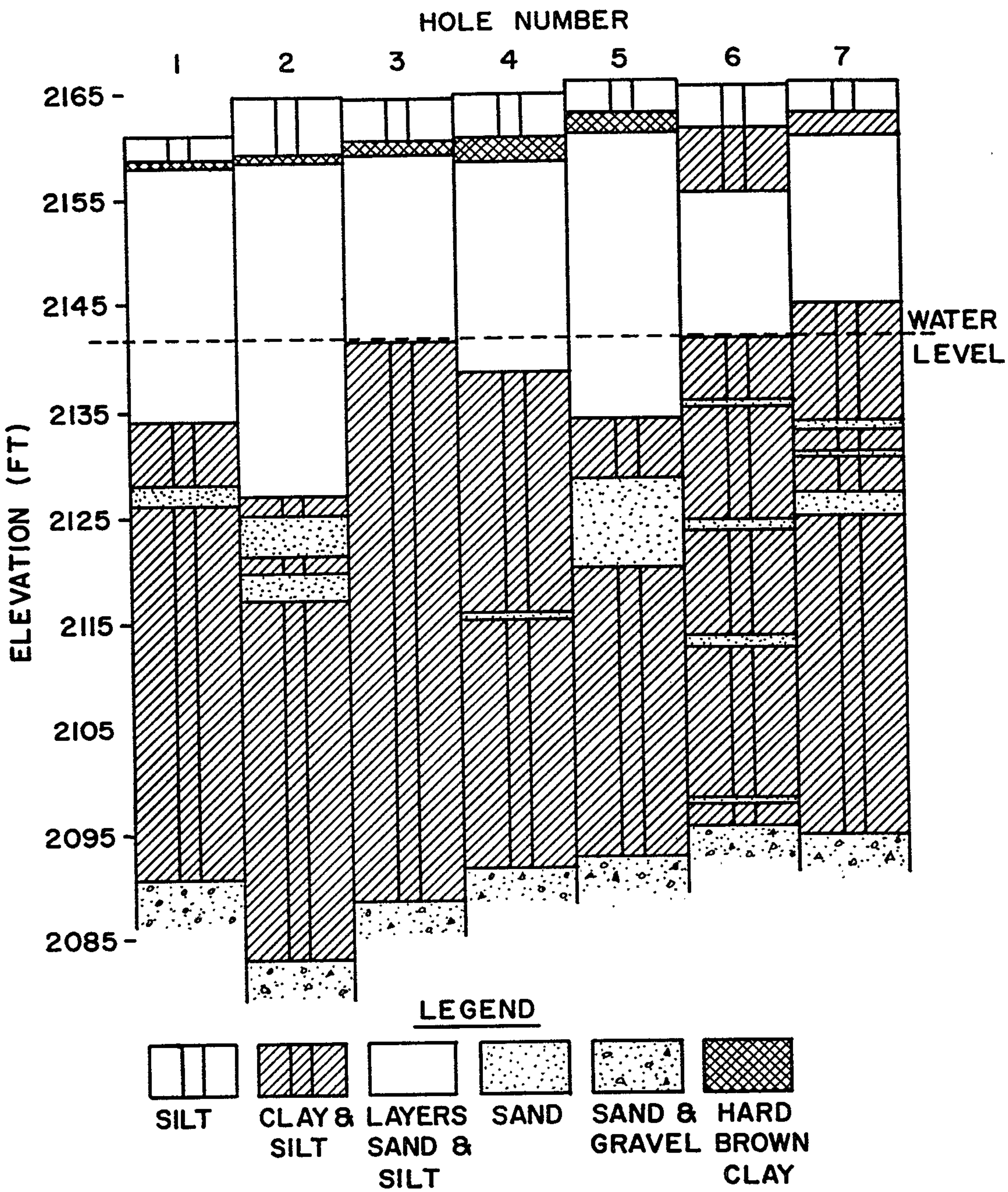

Figure 1/9
Consolidated Plot of Field Data

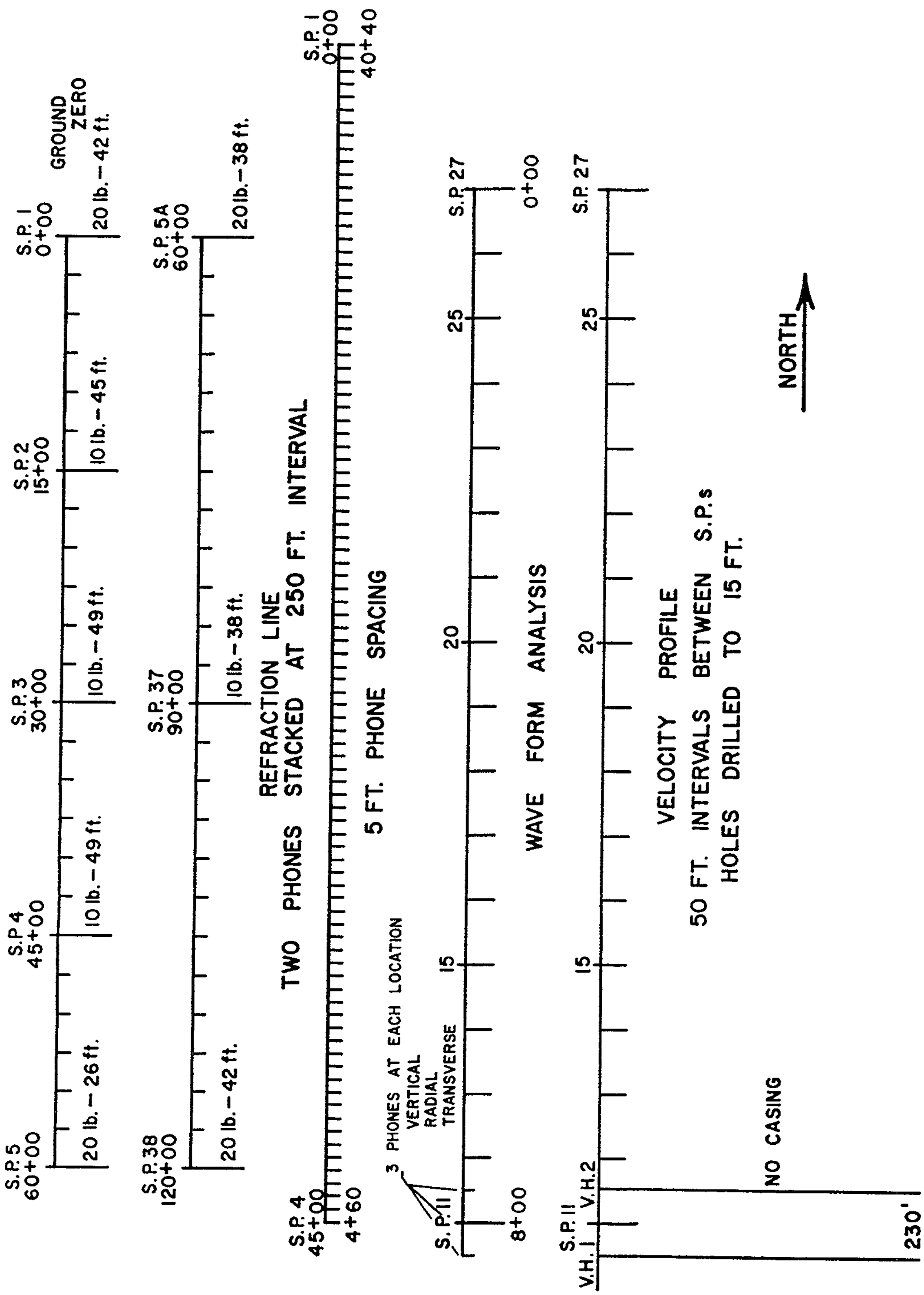

Figure 1/10
Refraction and Velocity Layout - WATCHING HILL Site

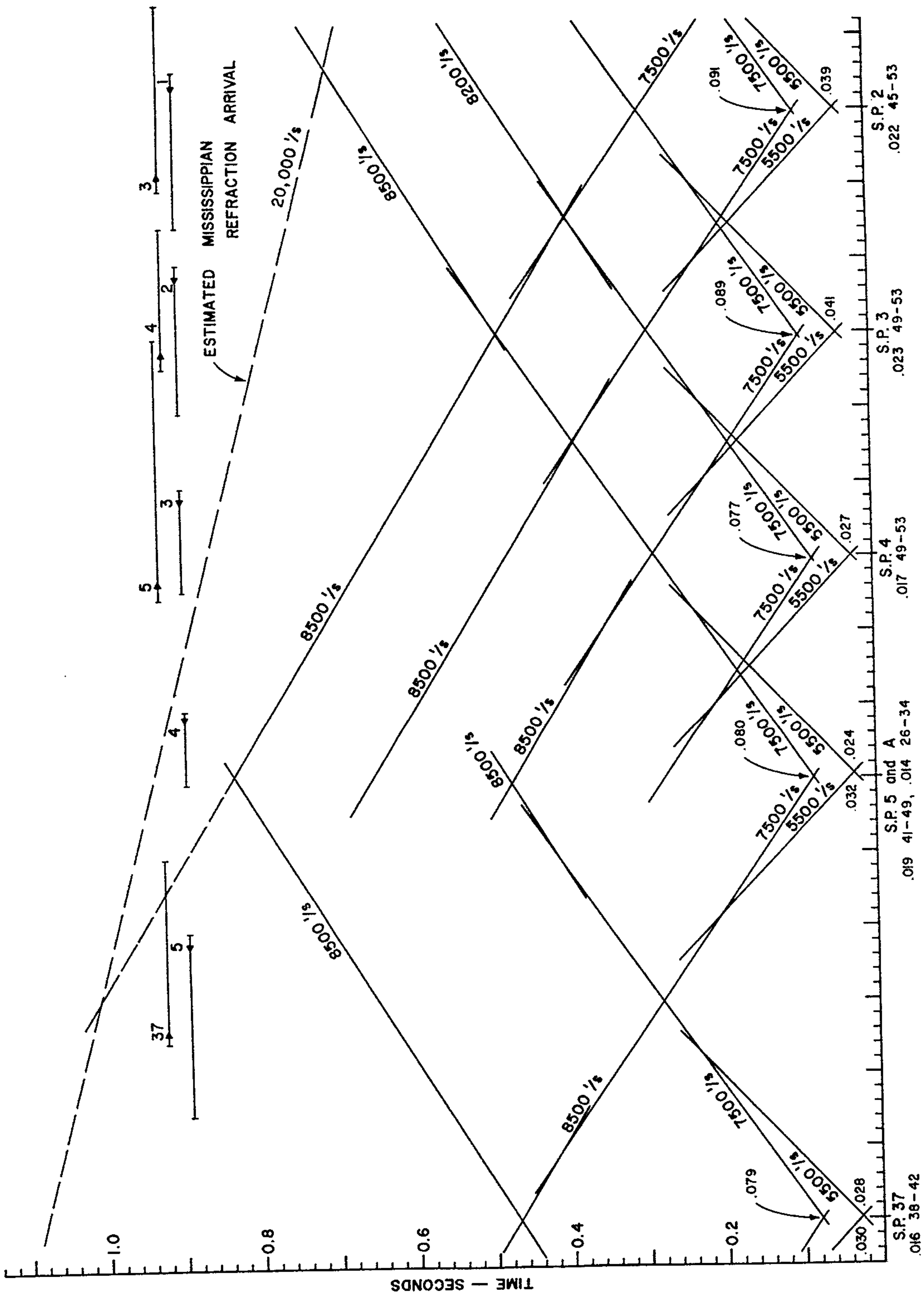

Figure 1/11
Time - Distance Plot - WATCHING HILL Site

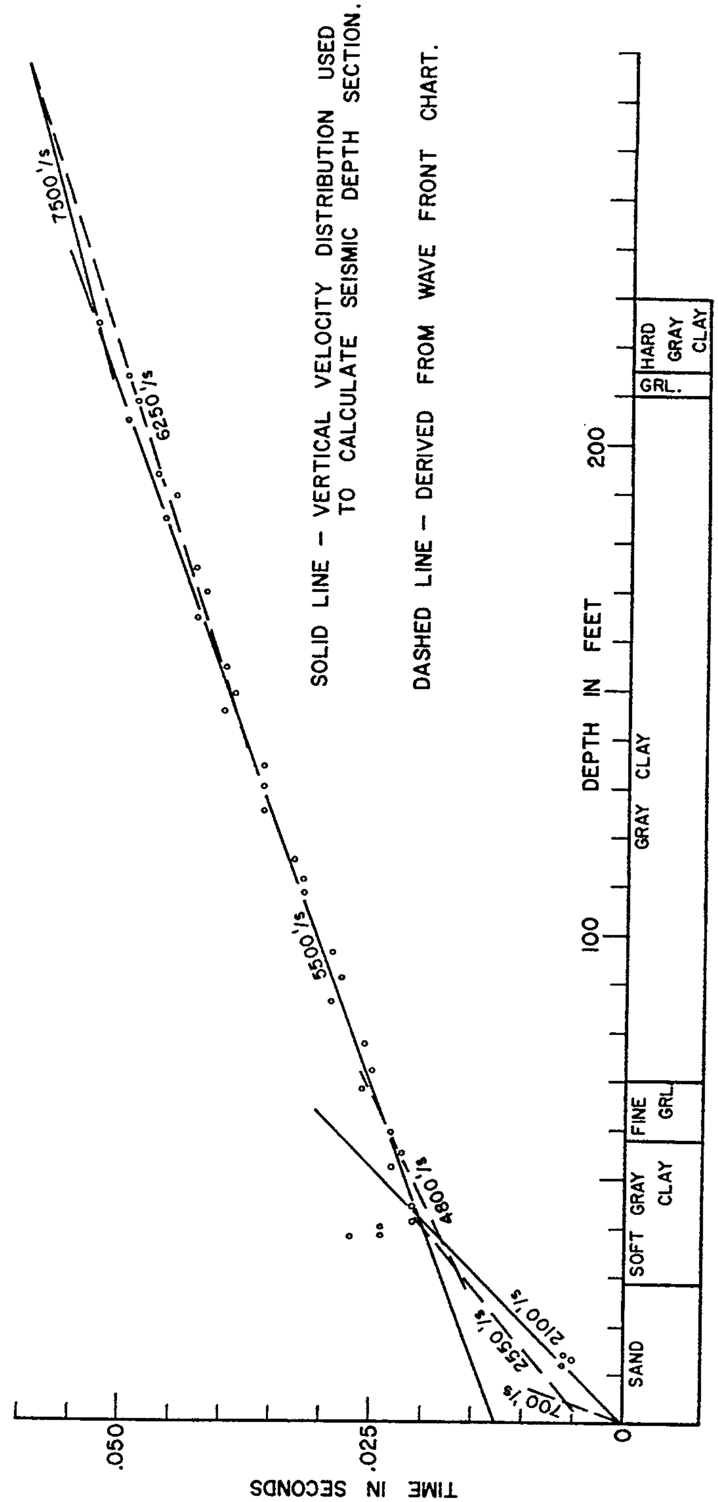

Figure 1/12
Vertical Velocity Survey - WATCHING HILL Site

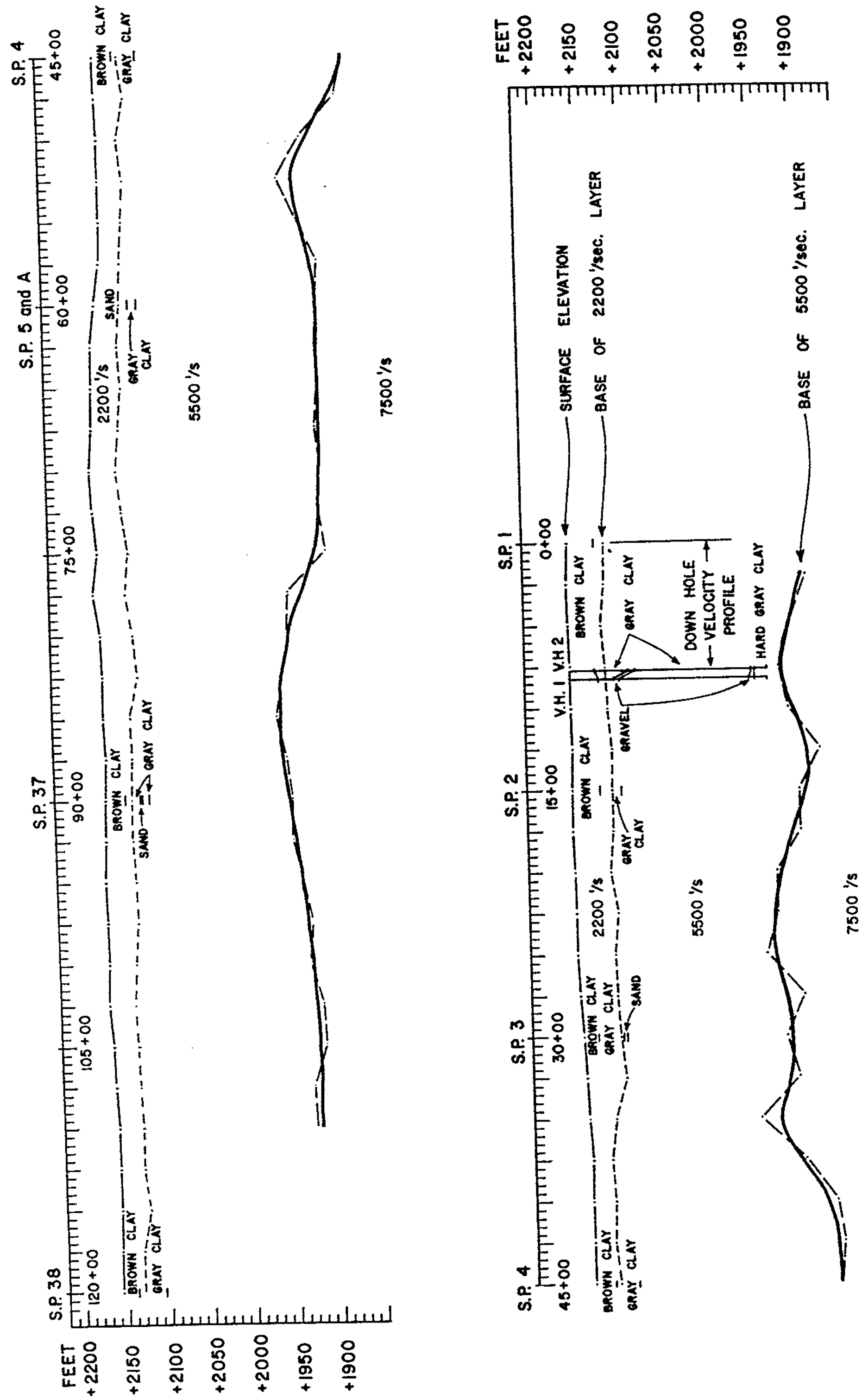

Figure 1/13
Seismic Section - WATCHING HILL Site

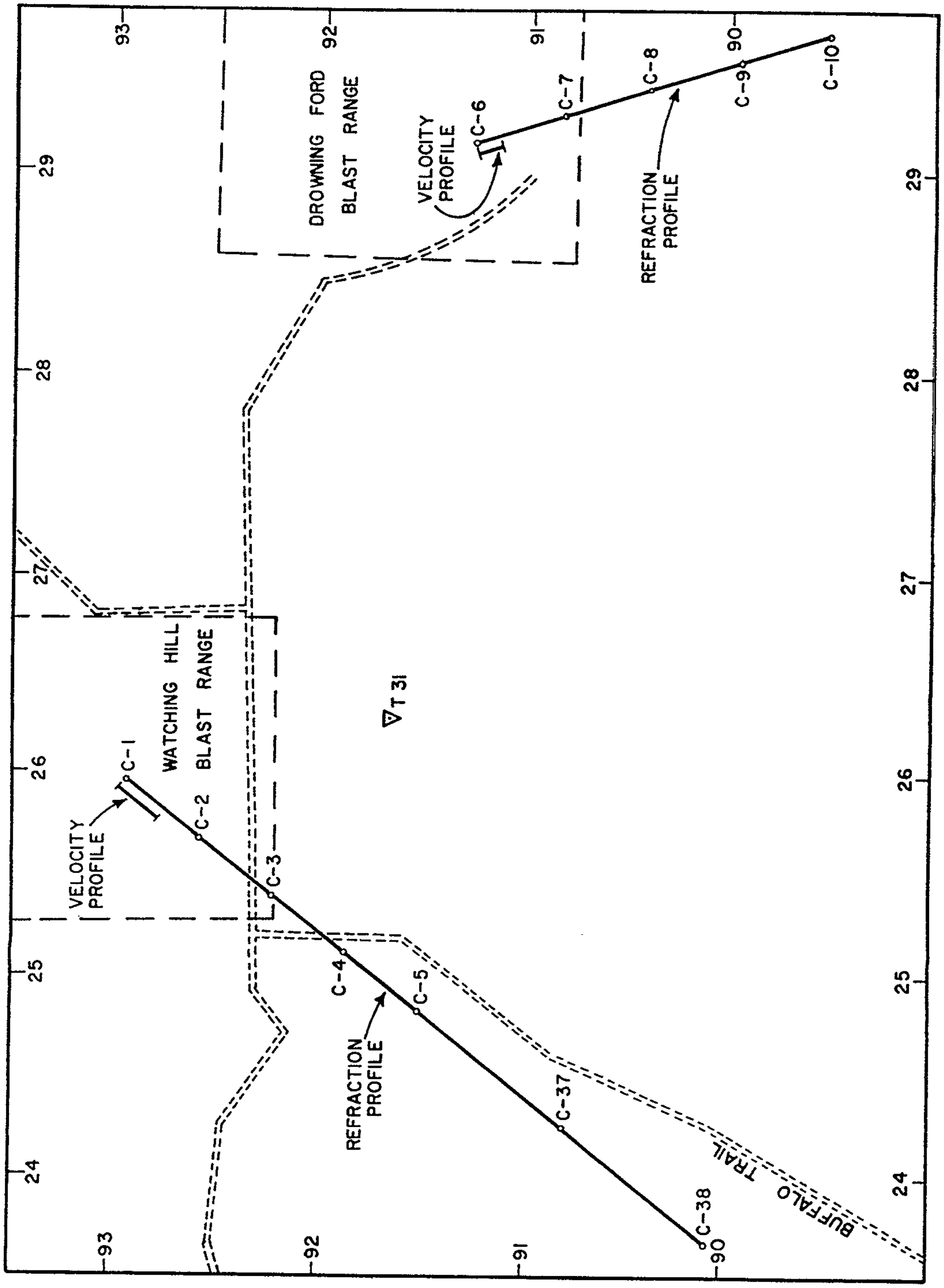

Figure 1/14
Location of Velocity and Refraction Survey - WATCHING HILL and DROWNING FORD Sites

1.4 CLOSE-IN SEISMIC EFFECTS OF THE DETONATIONS

As observed above, the initial scientific interest of the present author lay primarily in the nature of the close-in surface seismic effects of the detonations, as they increased in scale from 5 lb charges to the first 200,000 lb charge in 1961. A completely consistent picture emerged, with the dominant effect being a form of air-coupled surface wave of relatively large magnitude, the precise profile at any given radial distance being determined by the relative position of the airblast arrival to the crest of the cycle of the preceding Rayleigh type wave. The particle trajectories were, in general, prograde tilted ellipses, alternating with retrograde cycles of similar elliptical pattern but reversed tilt. There appeared to be a form of air-coupling to the transverse component also.

It was shown conclusively that the dominant seismic effect was due to the airblast coupling, not an effect of the disruption of the ground by the cratering process. For given solid explosive charges the seismic effects were independent of whether or not the charge was at such a height of burst as to allow cratering at all. This was confirmed at a late stage when multi-ton charges of gaseous explosive were used in major trials. These charges, although at zero height of burst, produced no cratering effect at all, but produced, at modest ranges beyond the original gaseous envelope, identical seismic surface waves as charges of solid explosive of the same yield. (The airblast effects were also identical between solid and gaseous explosives).

The seismic profiling of the upper layers of the test sites, shown in Figures 1/10 to 1/13 were used to calculate the dispersion curve for Raleigh waves on the site, and it was confirmed that the dispersion was such as to allow a form of air coupling to the continuously decreasing velocity of the progressing airblast wave.

As the surface seismic effects have been released to the public domain, they are not discussed further in this publication. For details of the analysis see Jones (1961, 1962 a & b), Jones, Maureau & Cyganic (1963), Jones (1963) and Hasegawa (1968). This brief discussion is included herein simply because the seismic effects were a notable feature of the trials, and may become significant in attempts at geophysical analysis and predictions relating to larger scale events. It will, for example, be seen later in this publication that there appears to be some correlation between the observed particle trajectories of the surface waves, and particle trajectories in the actual cratered ground, determined by excavation of marked elements within the craters.

All the original seismograms, relating to the surface waves, have been preserved. Virtually all the work of interpreting these records has been restricted to analysis of the radial and vertical motions. As has been commented above, it was observed that there was also some form of coupling between the airblast and the transverse (Love type) motion, but no detailed study, or theoretical interpretation of this coupling has yet been undertaken. This aspect does appear to deserve further study of the original seismograms.

The programme of explosion based trials at Suffield expanded very rapidly, and besides the international programme, the Canadian effort was expanded both in the form of additional scientific programmes, and the measure of support which was given to the trials by the Suffield Field Wing staff. As the number of scientific and technical support staff involved with the scientific programme grew, so too did the demands upon the field staff for technical support. With the advent of international programmes, the Blast Trials became the dominant programme on the station in terms of man power involved, and the cost assumed by the Canadian Department of National Defence through the Defence Research Board.

As will be seen later, interest in the trials eventually expanded beyond the "military orientated" agencies and this involved minor problems of security but, in the end, major problems with Canadian funding as the effort devoted to non-defence studies increased. It is much to the credit of the Defence Research Board that there was never a reluctance to allow their paid staff to deviate, in the cause of science, from the direct defence field. It was otherwise with the actual funding of very expensive field work, and here credit must be given to the United States of America, who provided funding through The Defence Atomic Support Agency to allow the present author and field team to continue with certain studies after 1961, and also provided support to some of their own non-defence agencies who participated in later trials.

Even before the planetary significance of the trials was recognized, some non-defence institutes and individuals cooperated on site, possibly the first being Carl Kisslinger who both participated in seismic investigations of the trials and advised the present author at an early stage in seismological research. Eventually, Kisslinger and a team of graduate students from St. Louis University participated directly in the 1961 Suffield 100 ton trial, sponsored by DASA, and produced a short but highly interesting report (Kisslinger 1962).

Although this present report gives precedence to those aspects of the Suffield craters which are of planetary significance, it must not be overlooked that the prime purpose of the trials had a military orientation. What was unique about the Suffield trials from the military connotation is that they form a discrete, thoroughly studied set of explosion craters in a type of ground not commonly used for nuclear trials. The fact that the craters produced show complex structures, including at least temporary zones of major flooding must not be overlooked in the military context. It is pointed out here that the majority of areas of dense population and urbanization tend to be characterized by geological conditions more similar to the Suffield area than to the essentially dry desert areas traditionally used for nuclear trials. Many of the most densely populated areas have, on a scale basis, quite shallow Water Tables and essentially silt/clay type overburden - think for example of London sitting on the London clay, New York on its seaside base, or even Winnipeg sitting on a close parallel with the actual Suffield site. It is suggested that the detonation of a near surface burst multi-megaton weapon in such locations is likely to produce craters of the Suffield type, rather than the Nevada type. Thus, the military significance of the Suffield craters may be greater than has, in general, been recognized.

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CHAPTER TWO

CRATERS FROM TWENTY TON DETONATIONS
and
TECHNIQUE DEVELOPMENT

2.1 INTRODUCTION

The explosive trials at Suffield were designed to simulate larger, mainly nuclear events on a scale model basis. The measurement of crater size was therefore fundamental, per se and as a predictive tool for positioning other experimental artifacts and equipment. As soon as the Suffield trials gained an international status some very experienced agencies entered the scene, and to some extent became dominant partners to the Suffield Geophysics team. In particular, the Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers introduced their sophisticated technologies, developed from years of studying both conventional and nuclear detonations. The Suffield team benefited enormously and became willing junior associates. It had already become evident that the Suffield craters, even at the low ton level, did not conform to the best predictions which could be made, with the Suffield craters becoming wider and more shallow than conventional scaling would predict. (The uncertainty is reflected in a predictive paper, Jones & Diehl (1964), but the earlier phase is currently being discussed).

It was in the earlier pre 1960 trials that the Suffield team developed expertise under the tutelage of WES, in particular that of the sand column technique in which vertical coloured sand columns emplaced pre-detonation were excavated after the detonation to determine ground displacement. The original technique had been developed by Beauregard Perkins Jr. at the Ballistic Research Labs, as described in a BRL Tech Note (Perkins 1954). WES had modified the technique for use on large scale trials, but DRES was also fortunate to have Perkins visit and discuss potential further developments on site. Subsequently, the Suffield team introduced an improved version, described later, which was used on the main trials after 1961.

The first serious use of the sand column technique, both in its WES form and in the later Suffield form was on trials at the 20 ton scale. In this chapter only trials at that scale are considered, even though they spread over several years and were interspersed with trials of larger scale. Among the reasons for presenting the trials in this way are, first, to demonstrate both the development of techniques and the reproducibility of the results, and secondly because the 20 ton scale is the largest scale at Suffield which produced craters which were essentially bowl shaped dry craters. Even so, they provided a few surprises.

2.2 FE 535 20T HEMISPHERE (WATCHING HILL, AUGUST 1960)

Although many of the earlier trials at the 5 ton scale had attracted foreign interest and participation, the August 1960 trial at the 20 ton level was the first truly international trial. A two volume report edited by the present author gives the early scientific results (DRES ANON 1961), while the ground displacement and crater data are given in Jones & Krohn (1960). This trial was the second in which the WES team installed sand columns according to their technique, with the Suffield team assisting and learning. The WES results are given in Strange & Sager (1962).

Visually, the crater was a dry, bowl shaped cavity with an elevated rim, in other words quite a conventional explosion crater. However, it was significantly larger than would have been predicted from smaller scale trials at Suffield by "cube root" scaling or even by the most sophisticated methods available.

Four days after the detonation, photographs were obtained of the crater from RCAF aircraft, and one of these is included herein as Figure 2/1. The white radial streaks were caused by the initial excavation to enable certain models to be surveyed. It will be observed that the crater is essentially symmetrical, bowl shaped with some sloughing of the upper inside wall, and has an elevated, quite uniform rim structure. In this view, in contrast with what will be seen in some later experiments, the ejecta blanket is not particularly evident. In fact, neither at the time nor in the photograph are there any evident effects of the detonation beyond the crater rim. None were expected at this time, in sharp contrast to what became the case later in the series of trials. The mean superficial dimensions recorded by ground survey showed an apparent diameter of 74.8

ft, a lip diameter of 87.2 ft, an "overall diameter" not precisely defined but probably to the edge of the obvious rim structure of 180 ft, a "fallout" zone of significant debris of 476 ft, a depth of 14.5 ft to the top of what was termed the "Fallback" in the crater, but of 18.4 ft to the bottom of this material. The lip height was 4.32 ft above the original ground level. These measurements were taken along four diameters, and with the exception of the "overall" diameter were quite remarkably consistent (see Table 1/1).

The excavation of the sand columns was supervised by the WES project team, but undertaken by Suffield staff. The results were published by Strange & Sager (1962) and are discussed below in terms of that report and later understanding. Data on ground displacement near the crater are given by Jones & Krohn (1960) and other data in the two volume report DRES ANON (1961).

Figure 2/2, after Strange & Sager, shows the detail of the sand columns as found after excavation, and this is typical of the results obtainable by the unmodified WES technique, and were not much different in appearance from those previously recorded at Suffield in the first WES trial, a 5 ton charge which is mentioned later in connection with the question of thrust faulting but is otherwise not relevant in the present context. Strange & Sager point out the peculiar form of the column 10 ft from GZ, in which the top part of the column is displaced into a semicircle facing towards GZ. This particular effect was not found on any other trial and remains unexplained in detail. Note that there is a suggestion of a conical thrust fault sub-parallel with the inner wall of the crater, but this is neither very evident nor was it noted at the time.

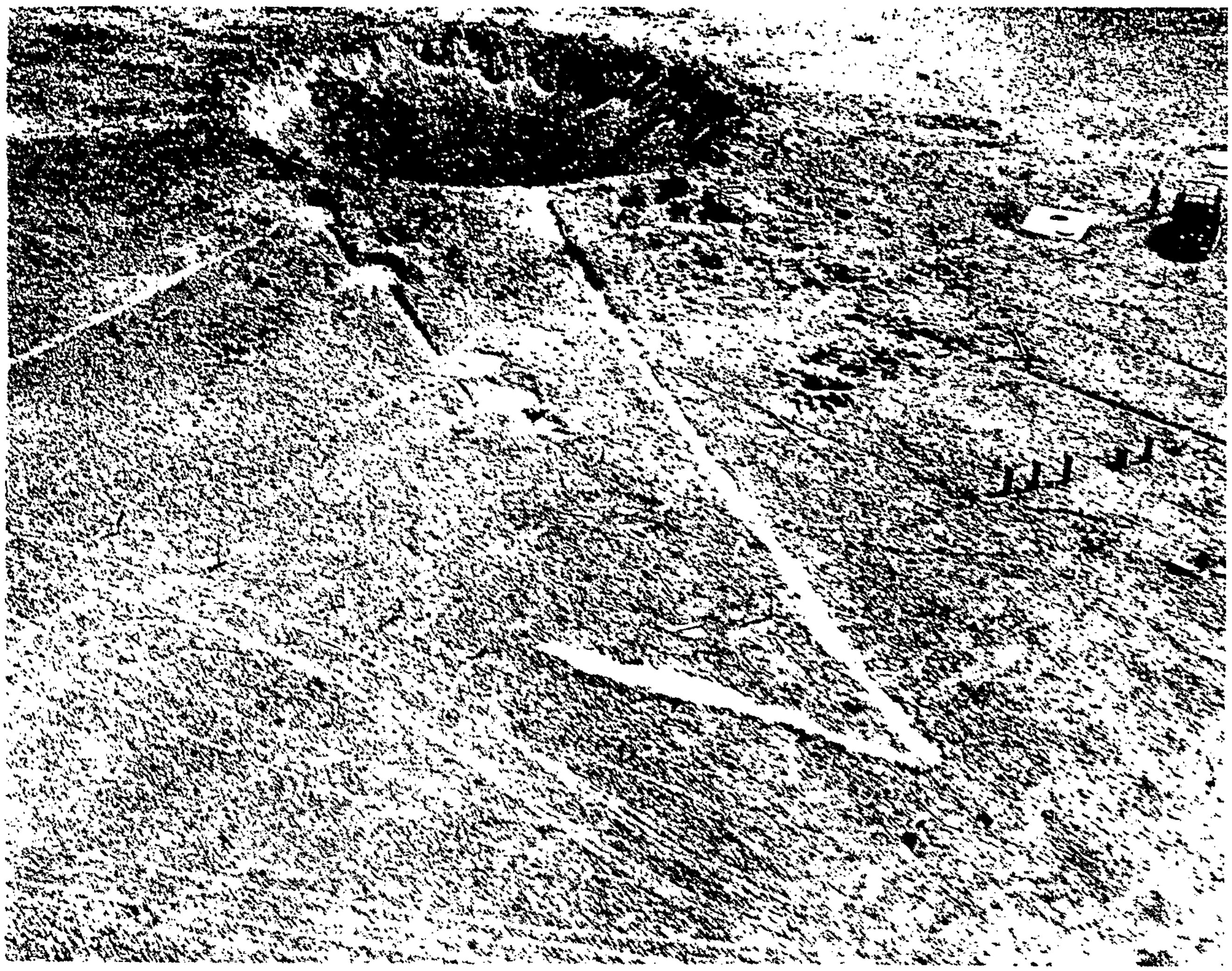


Figure 2/1
20 Ton FE 535 Crater 24 Hours after Formation

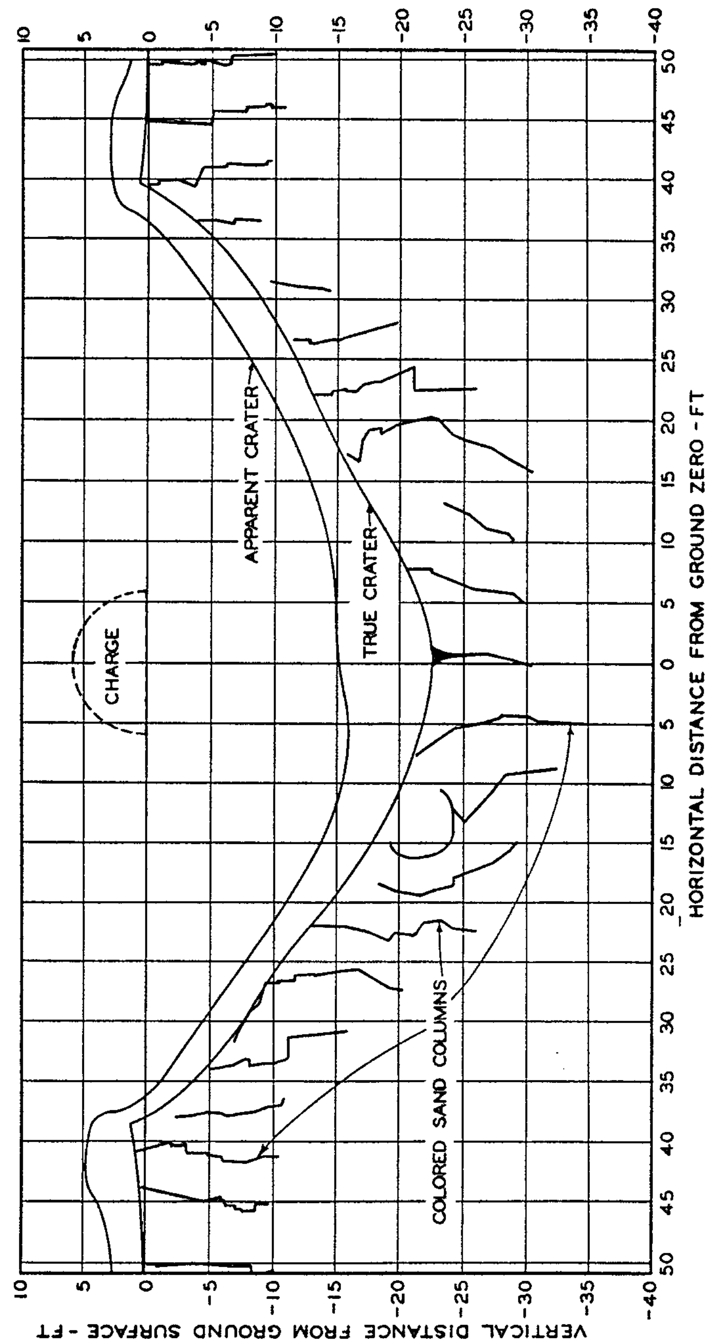


Figure 2/2
Profiles of Apparent and True Craters from 20 Ton FE 535 (from Strange & Sager 1962)

2.3 THE SUFFIELD SAND COLUMN TECHNIQUE

After the completion of the above described trial, the author asked the field team, consisting at the time of Messrs Diehl, Wyld, Krohn, Pinnell and Briosi, to find a method of improving upon the existing sand column technique so that marked elements of the columns could be traced from pre-shot to post-shot locations. According to our discussions with Beauregard Perkins, such attempts had been made in the past, using, for example, radioactive tracers or small steel discs. These attempts had proved unsatisfactory, partly due to the relatively small number of marked elements, and the enormous task involved in pre and post-shot survey, and the excavation. It was the author's opinion that, compared with the work already being undertaken on the columns, a suitable technique, if found, would involve relatively little work while adding enormously to the data obtained.

After considerable thought and experimentation, the team found a simple solution. This consisted of installing in the columns 35 mm film containers - easily obtainable in bulk - filled with the sand column material and coated externally with daylight fluorescent plastic. In the first effective trial, some 84% of the markers were recovered post-detonation, but only 81% identified, the difference being due to the fact that some markers were badly damaged. In later trials this problem was overcome by including numbered metal tags in the can fillings. Despite the development in 1960-61, the technique was first described in the open literature by Diehl & Jones (1965), but was used in most of the major Suffield trials after 1961.

For many years the WES team continued to install the sand columns, but the Suffield team slowed them down by installing the column markers. Excavation and Survey, carried out by the Suffield staff, was supervised jointly by WES and Suffield.

2.4 FE 556 20T HEMISPHERE (DROWNING FORD, JULY 1963)

In 1963 the Watching Hill range was unavailable due to the continued excavation of a 100 ton crater from 1961 and the preparations for a 500 ton trial in 1964. Nevertheless, there was a continuing need for relatively large scale explosions for the airblast programme and for damage studies on a wide variety of military hardware and buildings. Among other trials, two detonations of 20 ton charges took place barely a month apart in 1963. The first, and most significant of these was FE 556, in July, which was the first major trial in which the Suffield modification of the sand column technique was used.

As a great part of the target objects, and much of the essential electrical circuitry was already in place, unusually for Suffield and in contrast to the practice on Watching Hill, it was agreed to use a ground zero identical with that used for an earlier 5 ton trial (FE 551, August 1962). The 5 ton crater was relatively small, and it was considered that little would be lost by backfilling and tamping that crater. The greater part of the expected 20 ton crater would be breaching previously unexcavated ground though, possibly, ground partly compacted by the earlier detonation. In the event, no detected effect could be related to this earlier small crater. Results are given by Diehl, et al (1964).

Using the new Suffield technique a total of 245 markers were used in 12 sand columns, and of these the post-shot location of 207 markers were determined. The pre-shot location of nine of the recovered markers could not be determined due to damage, as mentioned above.

The sand column data plotted according to the WES technique, which stresses the sand column shears is shown in Figure 2/3. The visual impression is that the sand columns have been tilted bodily outward and downward.

However, using the identical survey, but with the addition of the surveyed marker positions, the Suffield technique gives quite a different picture, as shown in Figure 2/4. The ends of the displacement vectors, of course, coincide with the column positions as shown by the WES system.

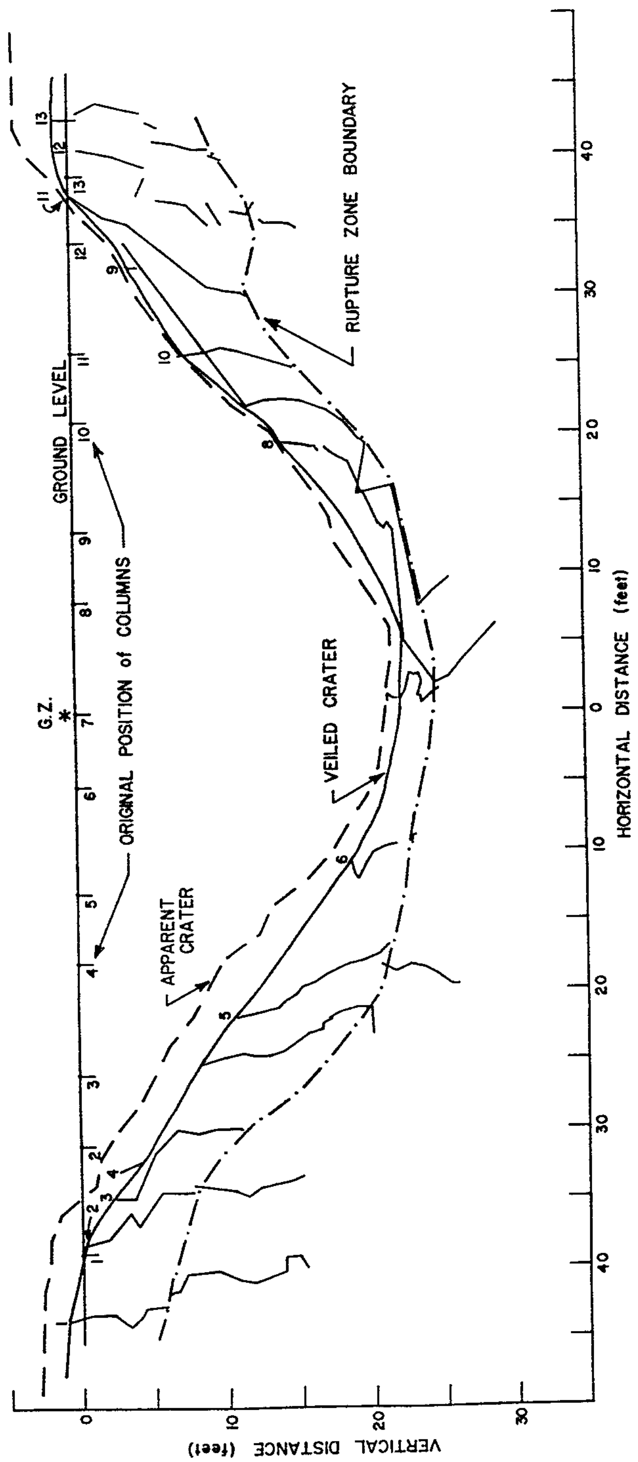


Figure 2/3

Excavated Sand Columns FE 556 20 Ton Hemisphere 1963 (WES Type Plotting)

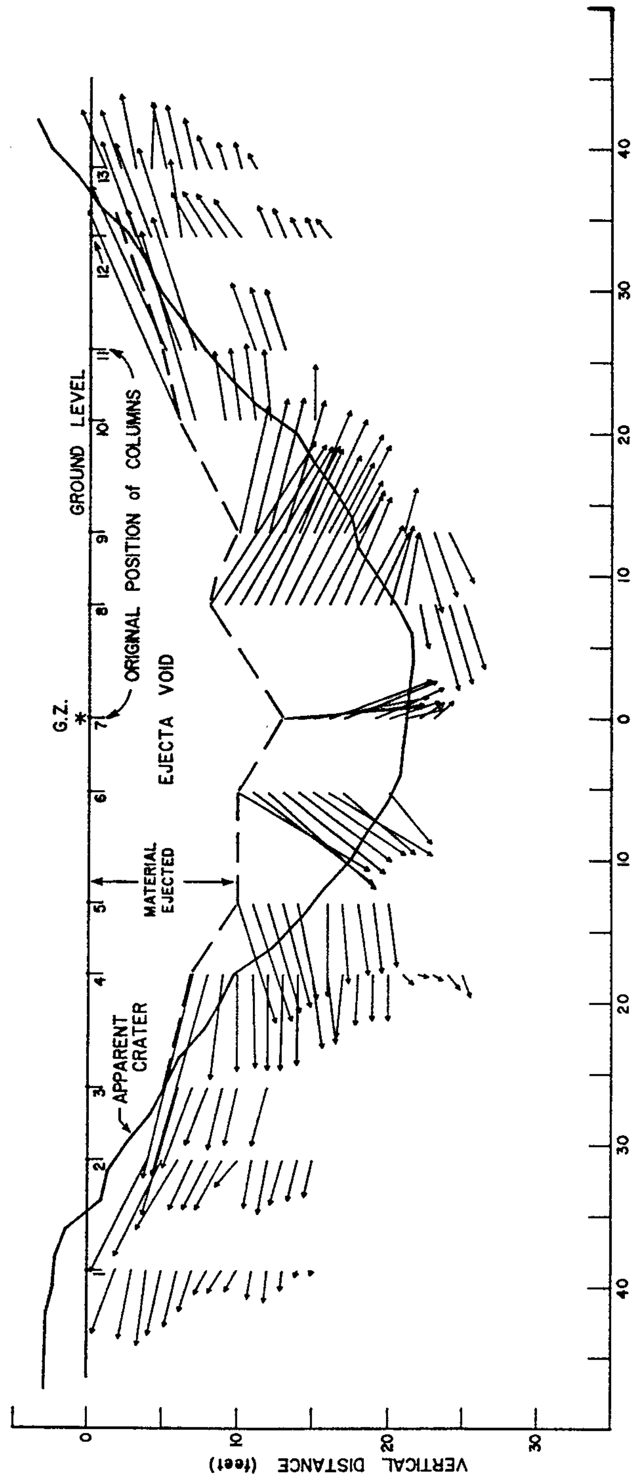


Figure 2/4
Displacement Pattern Shown by Suffield Markers FE 556 20 Ton Hemisphere 1963

The Suffield system shows that a large percentage of the residual crater void is produced by compaction of the cratered material, and this part is, of course, not available for ejection. The pattern of movement indicated is still, in general, outward, but is only downward in the middle ranges of the crater. Beyond some 20 ft from the ground zero vertical, the pattern changes to an outward and upward motion at this 20 ton scale. It will be seen in later, large scale trials that the picture becomes considerably more complex at the 100 ton and 500 ton levels. Nevertheless, at this 20 ton level (where the crater is essentially bowl shaped) the displacement pattern is remarkably similar to the pattern of the velocity field as calculated, for example, by Brode & Bjork (1960) for a megaton surface burst in isotropic media.

A caveat is necessary in regard to these displacement vectors shown by the Suffield technique. Viewing Figure 2/4 there is a natural tendency to think of these displacement vectors as particle trajectories. This is certainly not the case. The arrows show only the initial and final positions of the markers, and give no indication of the actual path travelled. It will be shown later that in at least some cases the actual travel path is an incomplete, tilted, prograde orbit not unlike the orbit of the air coupled seismic wave beyond the crater. It is however, doubtful that this is a uniform condition.

Additional details on the study of this crater, including data on the ejecta blanket and on ground displacements beyond the crater are given in Diehl, Wyld & Krohn (1964). However, it appears appropriate here to include photographs which show the appearance of the crater before and during the early stage of excavation, previously unpublished.

Figure 2/5 gives a clear impression of the elevated rim and the general uniformity of the crater. Figures 2/6 and 2/7 are closer, and show more clearly the inside of the crater, with some sloughing of the debris near the rim. Figure 2/8 is even closer at a different angle of approach. Both Figures 2/7 and 2/8 show a rather abrupt change of slope half way down the crater wall (also shown by the apparent crater profile in Figure 2/3), but this does appear to be due to sloughing from a particular stratum.

Figures 2/9 and 2/10 show aspects of the crater rim after removal of the ejecta blanket, and demonstrate that at this scale there is a quite definite elevation of the ground surface, a structural rim which is sharply terminated by the inside crater wall. No inversion of the strata was detected, but as such an effect was not suspected it was not looked for in the ejecta blanket itself.

The 20 ton charge level was the largest at Suffield which produced dry, bowl shaped craters, but also the first at Suffield in which a technique was available to provide data on actual displacements of marked elements, and on compaction in the cratered ground.

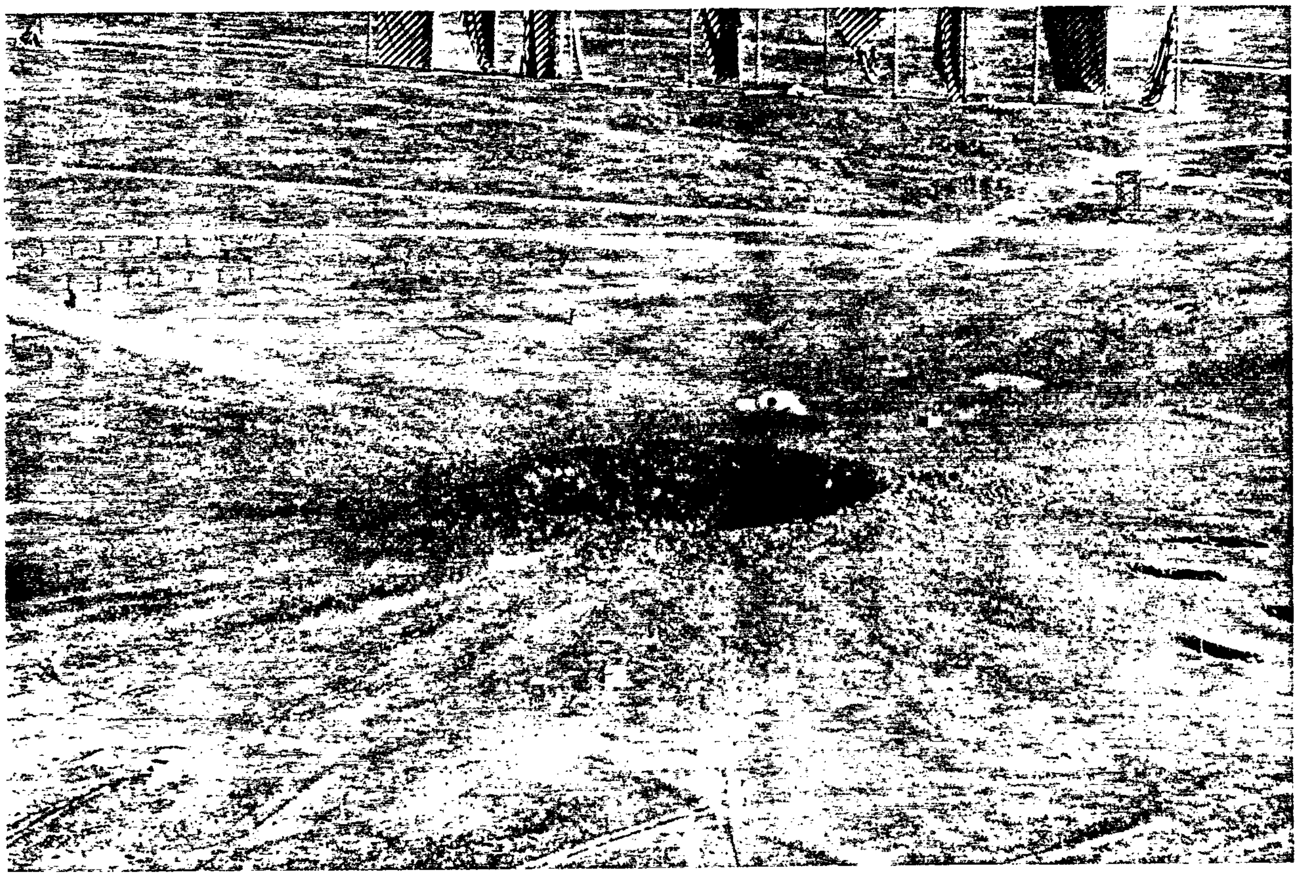


Figure 2/5
Aerial Oblique View of Crater Showing Elevated Rim
FE 556 20 Ton Hemisphere 1963

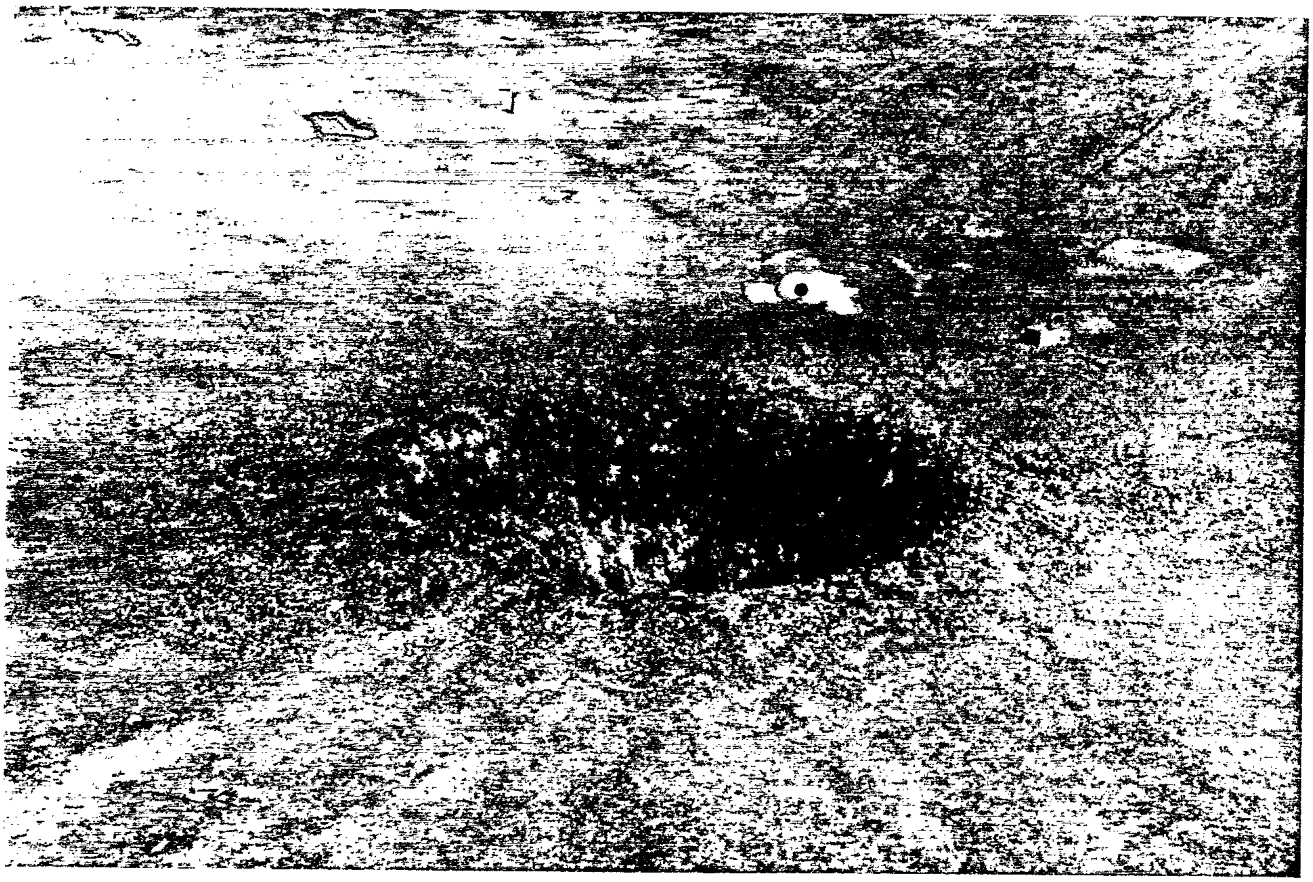


Figure 2/6
Close-up Oblique Overall View of Crater
FE 556 20 Ton Hemisphere 1963

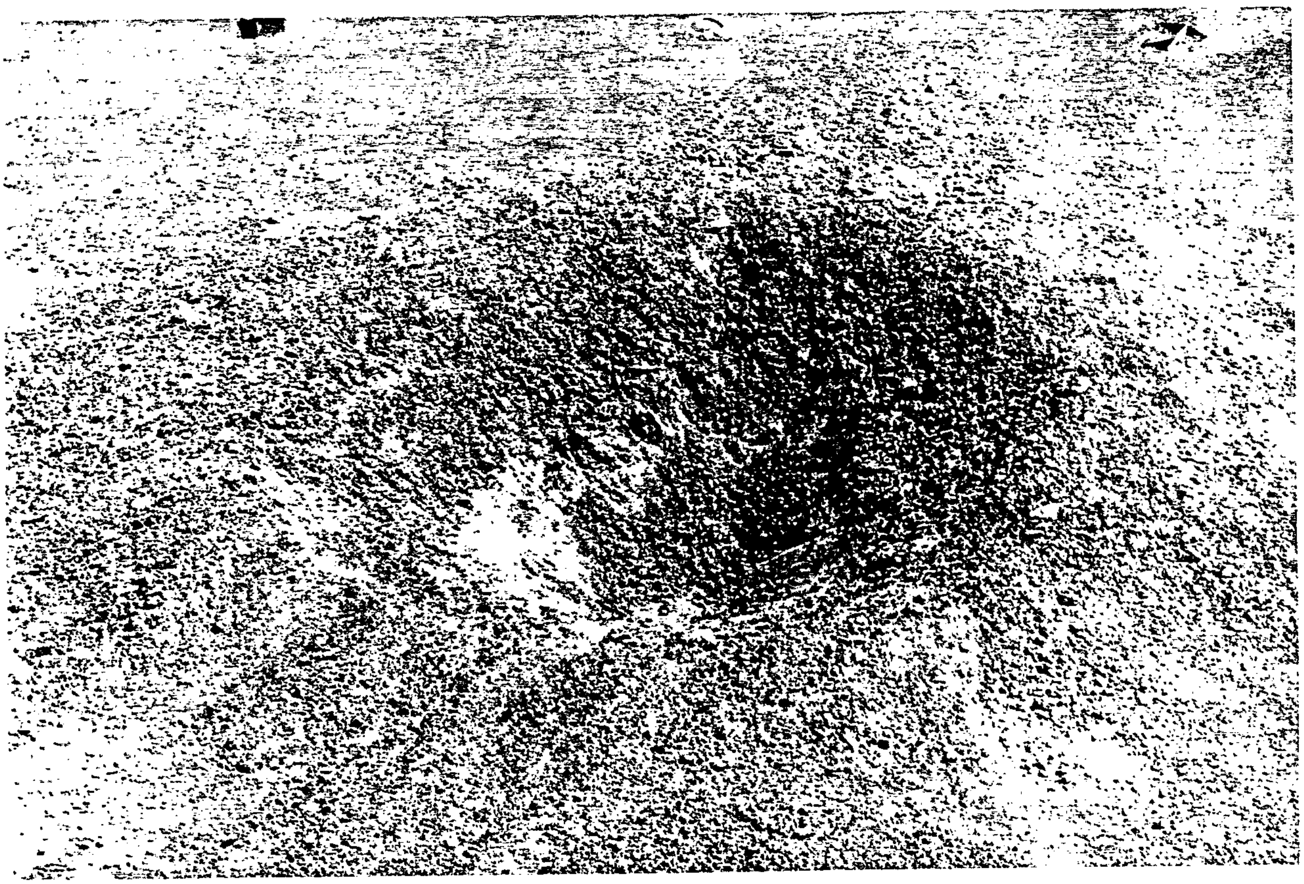


Figure 2/7
Rim Structure and Interior Showing Sloughing
FE 556 20 Ton Hemisphere 1963

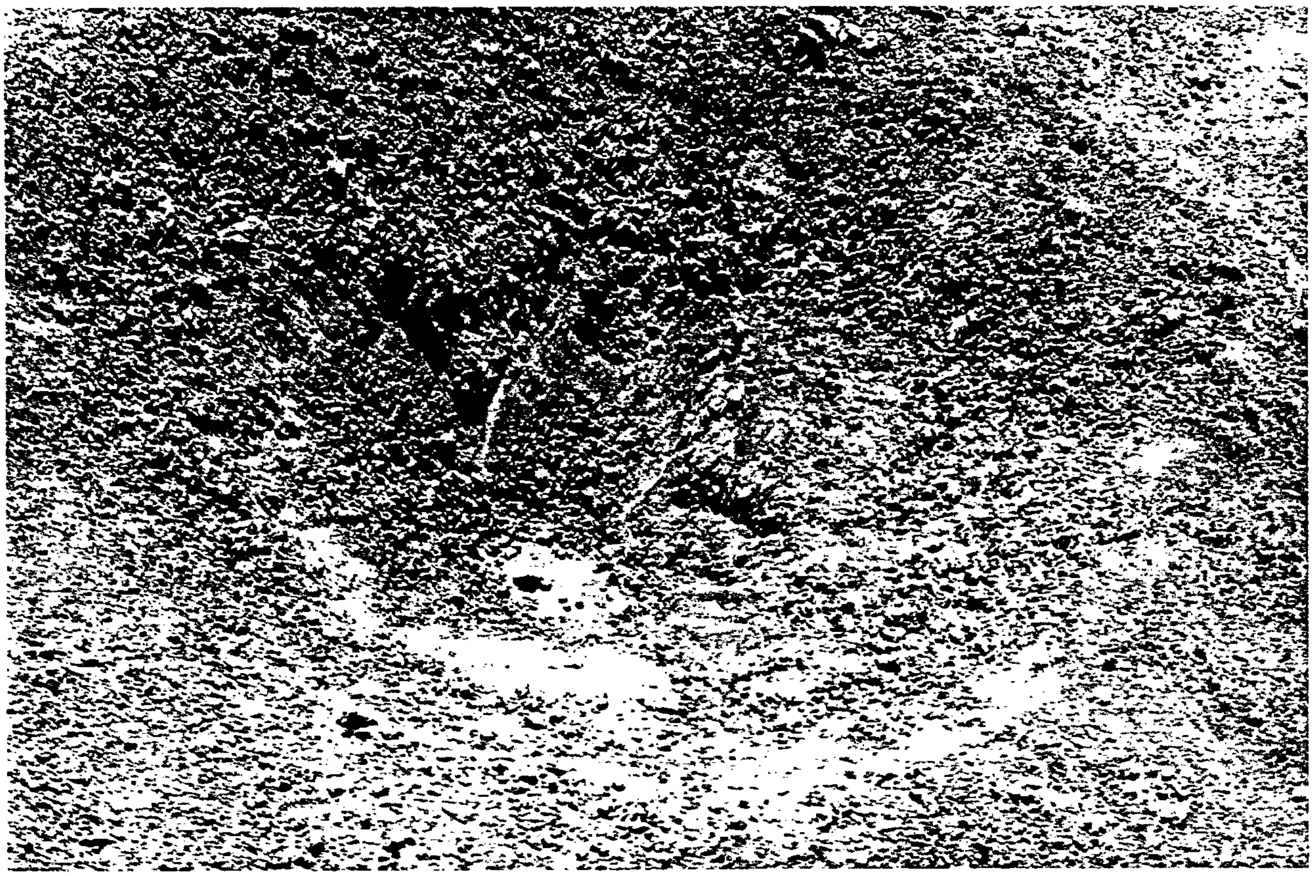


Figure 2/8
Interior of Crater
FE 556 20 Ton Hemisphere 1963

Figure 2/9
Elevated Rim Structure after Removal of Fallback
FE 556 20 Ton Hemisphere 1963

Figure 2/10
Close-up of Rim Structure Shown in Figure 2/8
FE 556 20 Ton Hemisphere 1963

2.5 LT 314 20T HEMISPHERE (DROWNING FORD, AUGUST 1963)

The year 1963 saw an unusual flurry of fairly large scale trials on the Drowning Ford test site. In addition to the FE 556 discussed above, two trials of 5 tons (FE 555 and LT 307) and a second 20 ton trial, LT 314, were carried out in rapid succession.

The primary objective of the 20 ton trial, LT 314, was to investigate permanent and transient displacements of model structures well beyond the crater rim. Although crater dimensions were measured routinely, they were not considered of primary importance and no sand columns were installed, nor was any excavation undertaken. The lip diameter was on average 89 ft, while the apparent and overall diameters were 81 ft and 140 ft respectively. As will be seen, the lip diameter is quite close to that found for the earlier, FE 556 20 ton trial, also on the Drowning Ford site.

Details of the above three trials and the displacement data have been given by Diehl, Jones & Krohn (1965) and are not of further direct interest at this time. However, a most interesting anomalous effect was observed, as described below.

At about two crater radii from GZ, a crescentic scarp was observed, subtending an angle of around 10 degrees, to GZ, the scarp face being away from, and circumferential to the crater rim. It was assumed on the trial day that this crescentic scarp, which happened to lie across one of the main radial lines of the displacement models, was probably due to some previous working of the ground, though such reworking was not apparent. Alternatively, it was considered likely to be a small normal fault.

However, in the later calm of the laboratory, when the displacement data for the models were calculated from the survey, quite a different, and far more significant picture emerged.

It was found that between the scarp and the crater the displacements of the models radially was about 3 ft initially instead of the anticipated, and more usual few tenths of a foot. This large displacement, radially outward gradually decreased with distance from the crater to about one foot, and then stopped abruptly. Beyond that point, displacements averaged little more than one tenth of a foot. The scarp location marked the transition from large to small displacements.

In view of these calculated data, it was obvious that the scarp represented the front edge of a thrust fault originating near the bottom of the apparent crater, and striking the surface at a shallow angle at roughly twice the distance from GZ to the crater rim.

This quite unanticipated finding of something, which the author considered to be of geological significance, led to a hurried return to the site with the field team, prepared to excavate the fault. Alas! The intensity of trials in that period had ensured that the entire crater had been bulldozed and recompacted ready for a 5 ton trial at the same GZ, in September. A lost opportunity of a type normally absent from Suffield as, in general, all trials were on separate, isolated sites. In some frustration, the author wrote to one of his mentors, Prof R.J. Uffen, later Vice Chairman and Chairman of the Defence Research Board but a respected geophysicist as well, describing the observation of a major thrust fault associated with a crater. Bob Uffen's response was rapid and effective, to the effect that the observation was to be followed up, and was possibly more significant than the avowed intent of the trial. To a large extent, this was the point where the attention of the author and the field team started to become divergent from the purely military interest.

Nevertheless, this location of a clear thrust fault scarp emerging at two radii distance was never seen again on any trial. What was found, however, was comparable surface contraction bounded by circumferential faults on major trials, as will be discussed later, and the occasional evidence of thrust movement underlying the (overturned) rims, and below the rims of the larger craters.

It was also known that occasional evidence of thrust faulting had been observed on impact structures, but these appeared to be localized and much nearer the GZ - for example, Shoemaker (1974) has demonstrated thrust faulting inside the inner wall of the Barringer Meteor Crater, Arizona. It was not until decades later, as a result of a query from Prof N.J. Price, who "required" such thrust faulting, that the overall data were examined and it was found that clear evidence exists for all the major craters of such thrust faulting in a cone sheet breaching the surface at approximately one radial distance beyond the rim. Attention is drawn to this effect in the appropriate locations in this publication.

It is commented that in the first trial in which WES installed sand columns, a 5 ton charge in 1959, there is a clear shear pattern in the sand columns which may be interpreted as a thrust fault. The sand column sections are given in an "anonymous" report by the U.S. Visiting Test team, a Suffield publication which bears no number (DRES ANON 1959). As the present publication concerns craters from 20 ton and larger detonations, nothing more is said of the large number of 5 ton and smaller shots.

2.6 DISTANT PLAIN 3 SPHERICAL 20T HALF-BURIED CHARGE (DROWNING FORD, JULY 1966)

After a three year gap, and following upon the discussions regarding the effect of charge shape and height, the Suffield programme reverted to the use of 20 ton charges, but this time in a spherical format, and buried to the level of the charge centre in a carefully excavated hemispherical cavity. In part, this series was an interpolation to help in the decision on charge configuration for a proposed 500 ton trial, which would be the second held at Suffield. The interpolated sequence was given the name DISTANT PLAIN, in which DP3 and DP5 were at the 20 ton level and DP6 at the 100 ton level. The DISTANT PLAIN 3 trial is discussed here, which was fired in the summer season, July 1966. From the crater study side, the details have been reported by Diehl, Briosi and Pinnel (1967).

The Suffield sand column technique was adopted, but as was usual, the data were reduced and plotted according to both the WES pattern, concentrating on the survey of the displaced and sheared columns, and by the Suffield pattern concentrating upon the displacement of marked elements. The results are shown plotted in Figures 2/11 and 2/12 respectively.

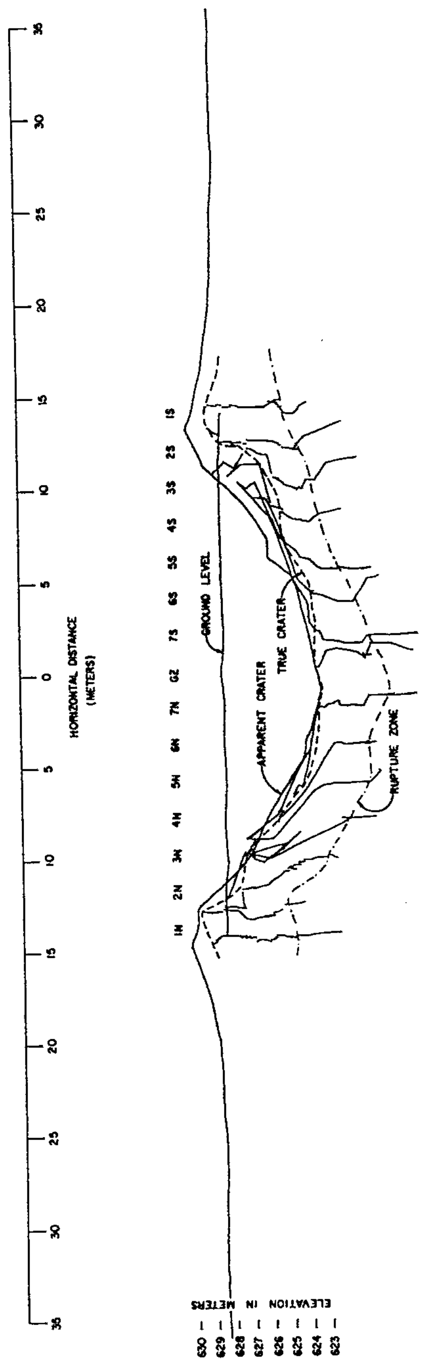


Figure 2/11

Excavated Sand Columns Showing Shears from DISTANT PLAIN 3

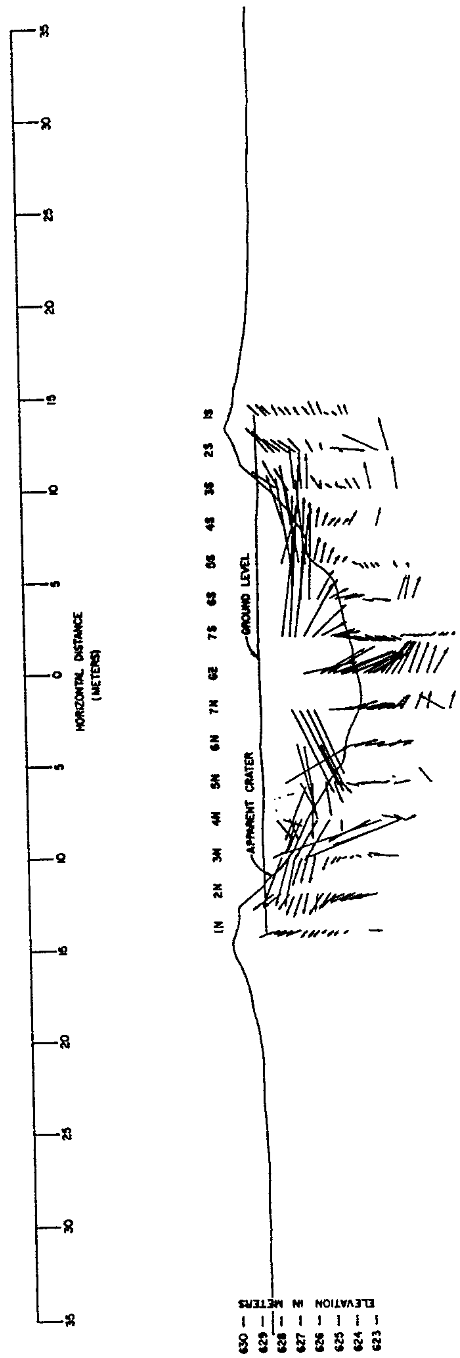


Figure 2/12

Displacement Pattern Shown by Marker Cans from DISTANT PLAIN 3

The general reproducibility of the results obtained by the Suffield technique is clearly demonstrated by the close similarity between Figures 2/4 and 2/12, both showing craters from 20 ton charges on the same ground, though with different charge configurations. It will be seen that the displacement vectors again indicate gross compaction of the ground below the crater. In Figure 2/12 the compaction is slightly greater than that shown in Figure 2/4, which is not surprising as in DP3, shown in Figure 2/12, with its half buried configuration the pressure wave from the lower half of the spherical charge proceeded directly into the ground, radially from the surface level charge centre.

Again, the Suffield technique shows that the movement is outward and upward as the rim area is approached.

The possible existence of a thrust fault is less clearly seen (in the WES plot), although the dotted line shown as the "rupture zone" may be interpreted that way on the right hand side of the crater as viewed. Examination of the marker displacements shown in the Suffield plot, for the same zone, appears to the author to define a shear plain rather more clearly, along a line which if extended would breach the surface at about the "two radii" point.

Figure 2/13 shows a general aerial oblique view of the DP3 crater, very soon after formation, while Figure 2/14 is a similar but closer oblique shortly after the field study had started, with a radial asphalt strip installed on the pre-shot surface cleared of fallout material. Figure 2/15 is a view of the inside of the crater. Note that there is a small mound in the center of the crater, which could indicate an incipient upthrust though it seems to have been interpreted at the time of the excavation as "fall back" and this is consistent with the displacement marker data in Figure 2/12.

Figure 2/16 shows the blocky nature of the rim, which is clearly upthrust in this crater. The photograph is taken along the line of the asphalt strip, looking towards GZ.

Particular attention is drawn to Figure 2/17 which shows two distinct types of shears in the asphalt strip (and also, as the field study showed, in the underlying and adjacent ground). Some of the shears, furthers from the camera, appear to be the marks of circumferential structures traversing the line of the asphalt strip, but the one closer to the camera is some form of "joint" which cuts diagonally across the asphalt. It is possible, but not certain, that this is a member of a set of conjugate joints, an interpretation which is possible from the photograph. However, this possibility was not clearly recognized during the field study. It will be seen in later chapters that virtually identical "shears" were noted on later larger scale trials where similar asphalt strips were installed. The field investigation on DP3 and the later trials indicated quite positively that the fractures were not controlled by the asphalt strips, as they could be followed in the ground adjacent, but well removed from the strips. The observations at the 20 ton level may well have been the second feature relevant to astroblemes found at the Suffield trials, after the thrust faulting, but this relationship was only recognized in retrospect, after the more spectacular results obtained from larger scale trials.

Despite the successful completion of the DISTANT PLAIN 3 20 ton trial, with the results shown in Figures 2/11 to 2/17 this trial was one of the least fortunate of the many trials carried out at Suffield. The trial was delayed two days beyond the scheduled date because of a severe thunderstorm, with high winds and heavy rain, which occurred on 25 July.

This storm flooded the charge excavation (prepared to take the lower half of the sphere). This was pumped out the following day, and a Herman-Nelson heater was used to dry out the soil. Charge building was carried out from 1800 hrs to 2100 hrs 26th July, and again from 0600 27th July until it was finished at 1130.

A bad accident occurred during the checking period for this trial. Power was turned back onto the layout at 0945 on the 28 July, after arming the charge, and at 1000 hrs an American participant, Mr. T.D. Witherly, was checking one of his gauges (which contained an integral explosive charge) when the gauge detonated prematurely, wounding him severely - some thirty metal fragments penetrated his body. Fortunately, a helicopter was on site and Mr. Witherly was flown to the Medicine Hat Hospital. There is little doubt that this prompt medical evacuation saved not only his life, but his sight.

This accident was one of the only two accidents directly related to on-site activities. Regrettably, on an earlier occasion one of the Suffield Field workers became a fatal casualty during the installation period for a major trial, when a "smoke rocket" used to disperse a trail of chloro-sulphonic acid fired when he was installing it, and passed through his body.

Many agencies, concerned with the effects of nuclear weapons on buried targets close to the detonation, were interested in the ground shock profile very close to the charge. In the case of DISTANT PLAIN 3 the Sandia Laboratories, Albuquerque used the slifer cable technique to study the advance of the ground shock and there exists a limited circulation report by Bass (1967) which gives some interesting figures of value in the present context. Peak stress levels of 10 and 3 Kilobars were observed at ranges of 2.5 m and 3.75 m respectively, measuring from the center of the charge (which in this case was at the ground surface level). The shock front was essentially symmetrical, but the effects of air shock and refraction became severe at short distances. However, in the limited space involved in symmetrical expansion, it appears that the radius-time profile is comparable with that from a contained nuclear detonation of similar yield.

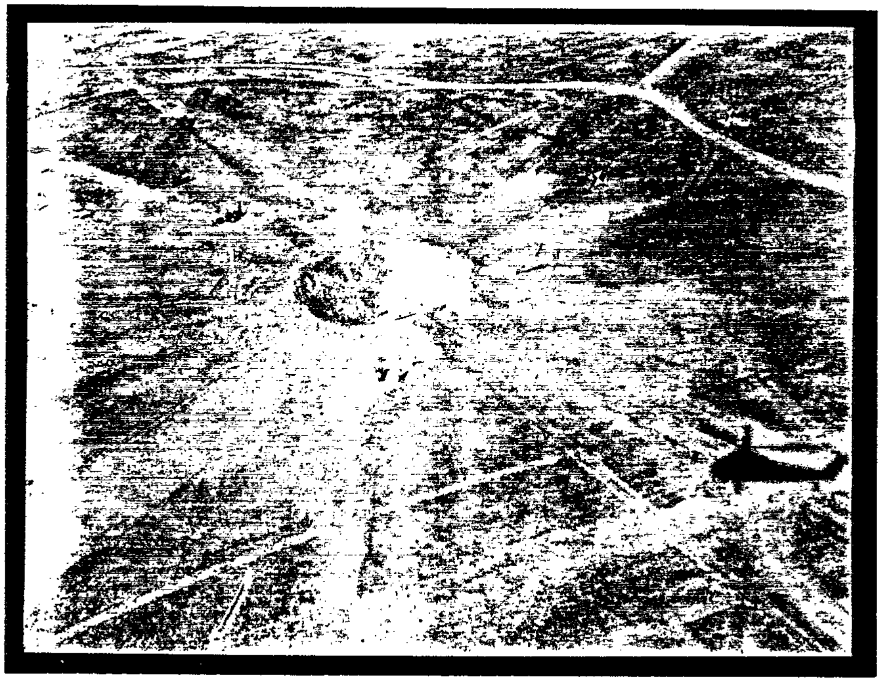


Figure 2/13
Aerial Oblique View of Crater from DISTANT PLAIN 3 20 Ton Half Buried Sphere
1966

Figure 2/14
Close-up View of DISTANT PLAIN 3 Crater

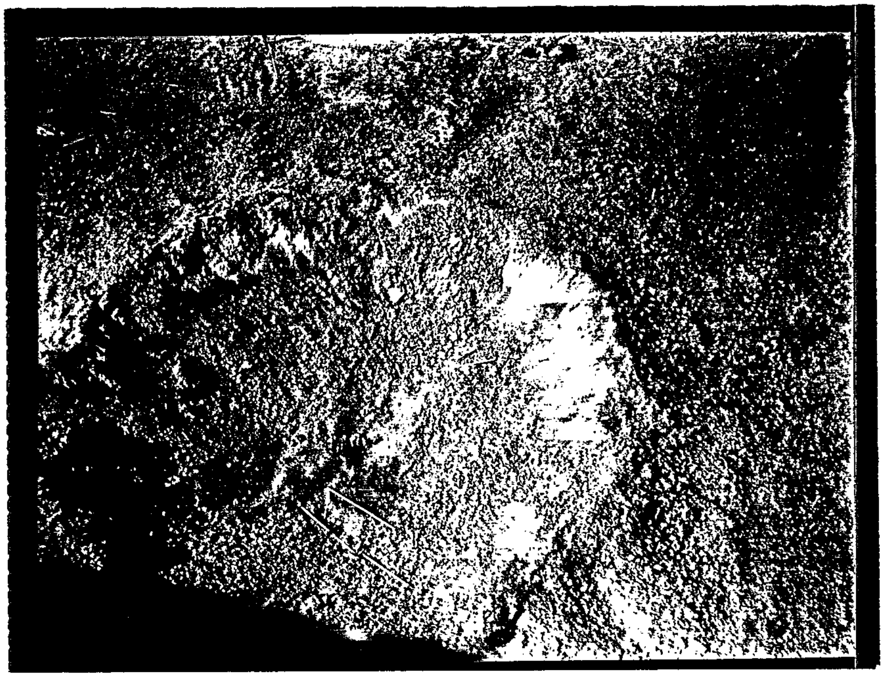


Figure 2/15
Interior View of DISTANT PLAIN 3 Crater

Figure 2/16
View of Crater Rim after Removal of Fallback from DISTANT PLAIN 3 Crater

Figure 2/17
View of Shears in Asphalt Strip after Removal of Fallback from
DISTANT PLAIN 3 20 Ton Half Buried Sphere 1966

2.7 DISTANT PLAIN 5 SPHERICAL 20T HALF-BURIED CHARGE (DROWNING FORD, FEBRUARY 1967)

DISTANT PLAIN 5 was a replicate, in charge details, of DISTANT PLAIN 3, that is a block built spherical TNT charge of 20 tons, half buried on Drowning Ford. However, while DP3 was detonated under the normal "summer" conditions for Suffield, in the case of DP5 full winter conditions prevailed, which means that the upper layers of the ground were frozen hard in February 1967.

It would appear from the records that this shot must have been fired more for the airblast than for the cratering effect, as no sand columns were installed, nor was there an ejecta study. Nevertheless, the superficial crater dimensions were surveyed, and aerial photographs taken. Details are given in Diehl et al (1967) and are tabulated elsewhere in this publication. Effectively, the only change noted between the summer DP3 and the winter DP5 was that the winter crater was very slightly smaller overall, the lip diameter reducing from 25.4 m to 23 m, while the depth reduced from 5.04 m to 4.65. Visually there was nothing to choose between the two craters, as will be seen by comparing the two aerial photographs in Figure 2/18.

Figure 2/19 is a contour plot, which is described by Diehl et al as being of DISTANT PLAIN 5. However, the present author believes that this is a typographical error in that text which is not improbable as DP3 and DP5 are frequently discussed in close association. It has not proved possible to verify this allocation. For most applications, the two craters are so similar that little is lost if the DP3 contour map has been wrongly attributed. In fact, all five of the 20 ton craters are quite similar, and do not provide any reason to expect a gross change in morphology with increase in scale.

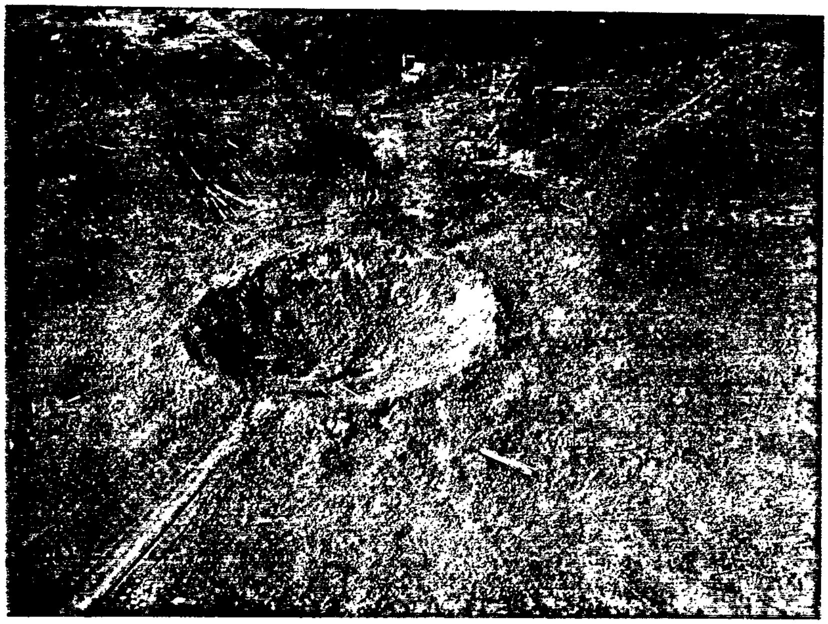


Figure 2/18 (A)
Aerial View of Crater DISTANT PLAIN 3

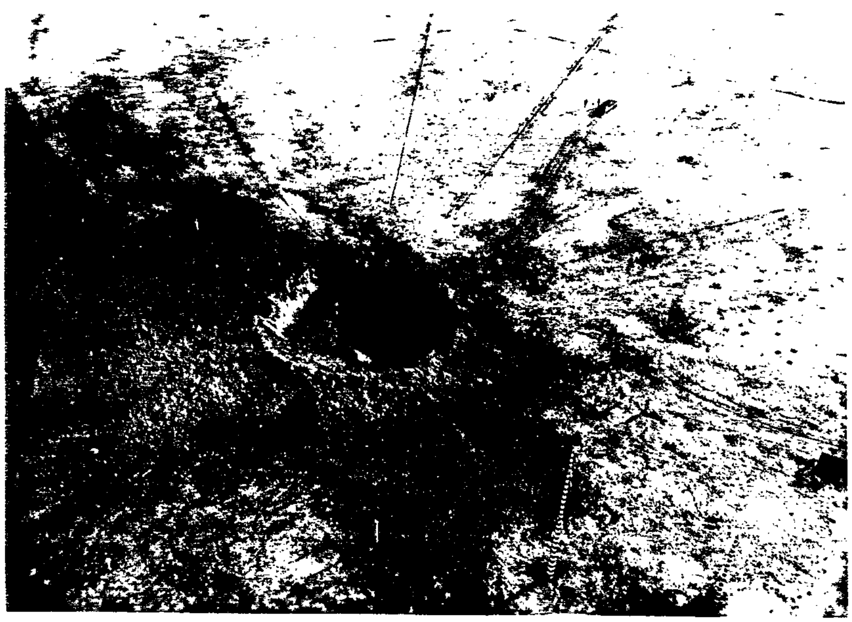


Figure 2/18 (B)
Aerial View of Crater DISTANT PLAIN 5

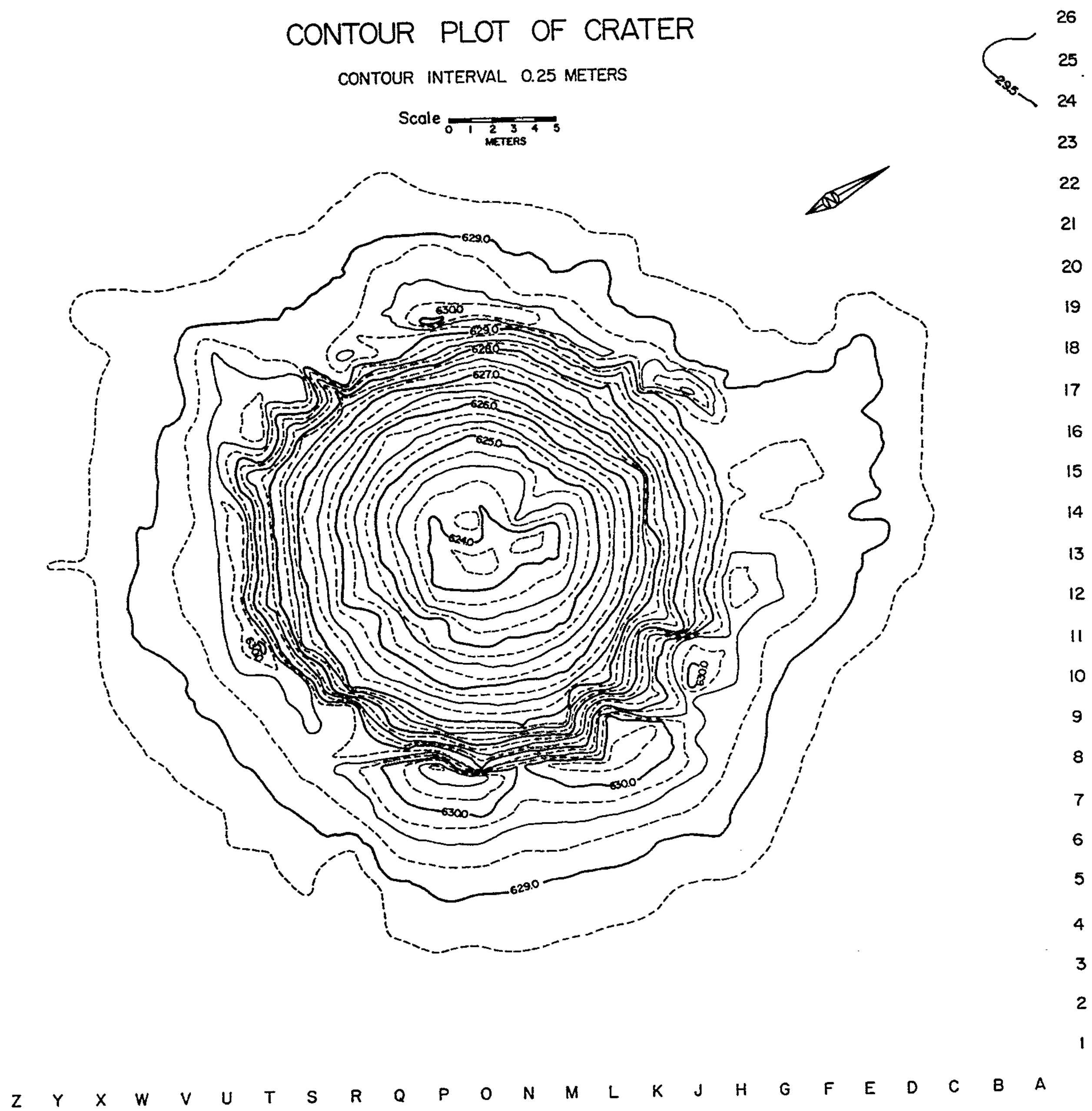


Figure 2/19

Contour Plot of DISTANT PLAIN 3 Crater (similar to DP5)

CHAPTER THREE

CRATERS FROM 100 TON DETONATIONS

3.1 INTRODUCTION

We now look at three craters formed, several years apart, by the detonation of 100 ton charges. However, these charges were not replicates, as they were all of different shapes and heights of burst and in one case even explosive type. There were several reasons for this change of pattern, but the main cause was the fact, as will be seen below, that with the increase in scale from 20 tons to 100 and then 500 tons, the craters changed from their (apparently) simple form to increasingly complex forms, and these forms were not at all similar to much larger, nuclear events at the Nevada Test Site. It is probable that the majority of participants in the international trials found this a most frustrating development, casting doubts upon the validity of the Suffield trials for the prime purpose, the simulation of nuclear weapons. The explosions were, of course, designed as tools for applied research, substitutes for the real military weapons, and any marked disagreement with the known military effects were viewed with alarm, and gave rise to a tendency to discount data from close-in sub-surface measurements.

On the other hand, looking at the experiments as cratering experiments it was a classic example of the need to be prepared to observe what has actually happened, rather than be put off by the apparent "failure" of planned data collection. There was, without doubt, some loss to the applied research but an immense potential for an increase in understanding of the nature of certain geological processes. It was always clear that no agency would fund such expensive trials for limited special interests outside the Defence field. One could therefore only be grateful that other trial participants (and their masters) viewed with tolerance the sudden enthusiasm of the author and field staff for arcane studies of the very odd craters being produced. A great deal of cooperation was obtained in collecting, on all the later trials, information on the host of "unplanned" effects. Particularly in the case of the first "anomalous" craters, recording of observations took precedence over rapid interpretation, as nobody really understood what was happening.

3.2 THE 1961 SUFFIELD 100T HEMISPHERE (WATCHING HILL, AUGUST 1961)

A crater was formed by the detonation of a hemispherical charge with a radius of 9.92 ft, built of 6126 TNT blocks and 14 blocks of Tetrytol, each 12 x 12 x 4 inches. The total weight of the charge was calculated as 200,040 ± 200 lb. Initiation was by means of two No. 8 detonators inserted from opposite sides into two 4 oz Tetrytol primers recessed into the supporting base of three 3/4 inch thick plywood layers. All evidence indicated that the charge detonated at high order at 1300 + 1 Sec + 01 Sec MST (1961 Aug. 3 1730 IGCT) at 50°30' North, 110°40' West.

The above description is given in full for interest sake, being provided by the Suffield Field Wing but now abstracted from Jones, Kisslinger and Cyganik (1961). Similar data are a matter of record for all multi-ton charges fired at Suffield.

For the sake of uniformity in the trial conditions, and to avoid damage to remote areas by focusing of the airblast wave, all such charges were detonated in still air conditions after the early morning inversion had ended. The required conditions were determined by the normal met systems including radiosonde and free flight balloons, and by the calculation of ray refractions based upon the temperature and wind profiles.

It so happened that conditions were particularly stable at the firing time on the day of the trial, and this was evidenced by the production of a large stable "smoke ring" which rapidly rose to several tens of thousands of feet. An early stage is shown in Figure 3/1. This is not an unusual phenomenon when large stacks of explosive are detonated, but it was the only time it was observed at the Suffield Trials reported herein.

3.2.1 Immediate Post-Formation Appearance Of The Crater

Immediately after the detonation, the attention of all was distracted from the ground level effects by the totally unexpected formation of the "smoke ring" shown in Figure 3/1. This ascended, more or less vertically, at initially quite a rapid rate and the senior observors were as excited as school boys. It is to this excitement must be attached their immediate request to the captain of a Neptune aircraft, which was immediately above the GZ at the time of detonation, that he return to that position and

Figure 3/1
"Smoke Ring" Rising Above the Post-Detonation Plume
1961 Suffield 100 Ton

then attempt to fly through the ring! When he did so, it was obvious even to ground observers that the aircraft was suffering quite severe turbulence and it was not long before the anguished pilot called off the attempt. Normal reactions restored, licensed participants re-entered the test area, soon to be followed by, generally, well controlled but nevertheless distracting visitors.

At first approach, there was little to distinguish the crater from earlier, smaller craters at the 20 ton level. There was, in particular, a normal elevated crater rim which appeared to be remarkably uniform, as is shown in Figure 3/2. During this initial approach, however, probably about 15 minutes after the detonation, a sudden small "gusher" of water was observed perhaps 200 yards from the rim of the crater in one location. This lasted for a few seconds only and beyond being remarked upon was not paid much attention. Also, it was observed that a succession of small "dust devils" developed in a ring around the crater, at perhaps 100 ft from the crater rim.It was observed that this "devil dance", which at times had as many as a dozen Imps whirling at the same time, though some died and some new ones appeared, rotated anti-clockwise around the crater, at a fair clip but much slower, of course, than the individual Imp rotations. They remained dancing for quite a long time - perhaps half to three quarters of an hour - and at all times remained in the circular orbit around the crater. As will be seen below, there was a significance to this devil dance not appreciated until many years later when the Suffield trials were long over and done with.

Despite the initial appearance of "normality", it became evident as soon as the crater lip had been climbed that, from that viewpoint, things had "gone wrong" in terms of planned experiments. Figure 3/3, an aerial view of the crater, shows what was found. The crater was filling with water! Also, there was a pair of lumpy hillocks inside the crater, which appeared more shallow than expected, and the water flow was building a sand structure near the middle of the crater. Discussion of this will be deferred for the moment, and attention is now drawn to three effects visible outside the crater rim.

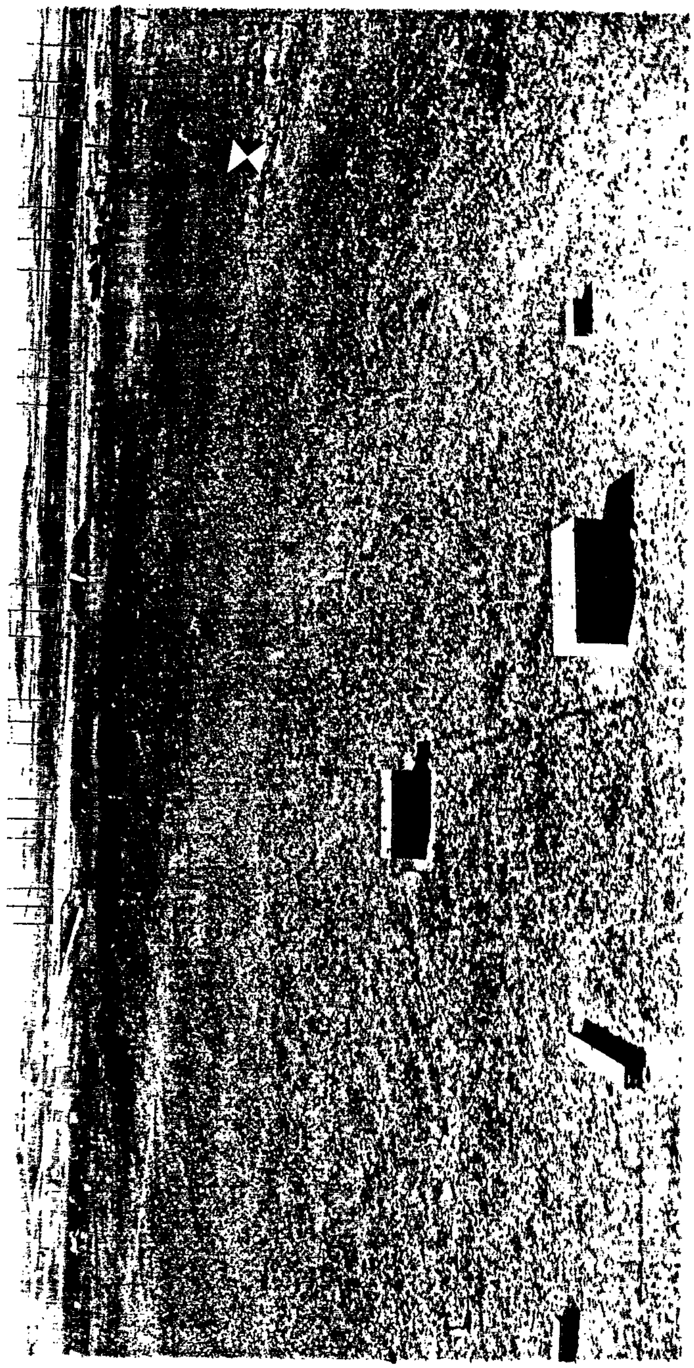


Figure 3/2
First View of 1961 Suffield 100 Ton Crater, Shortly After Formation
Showing the Elevated Rim of the Crater

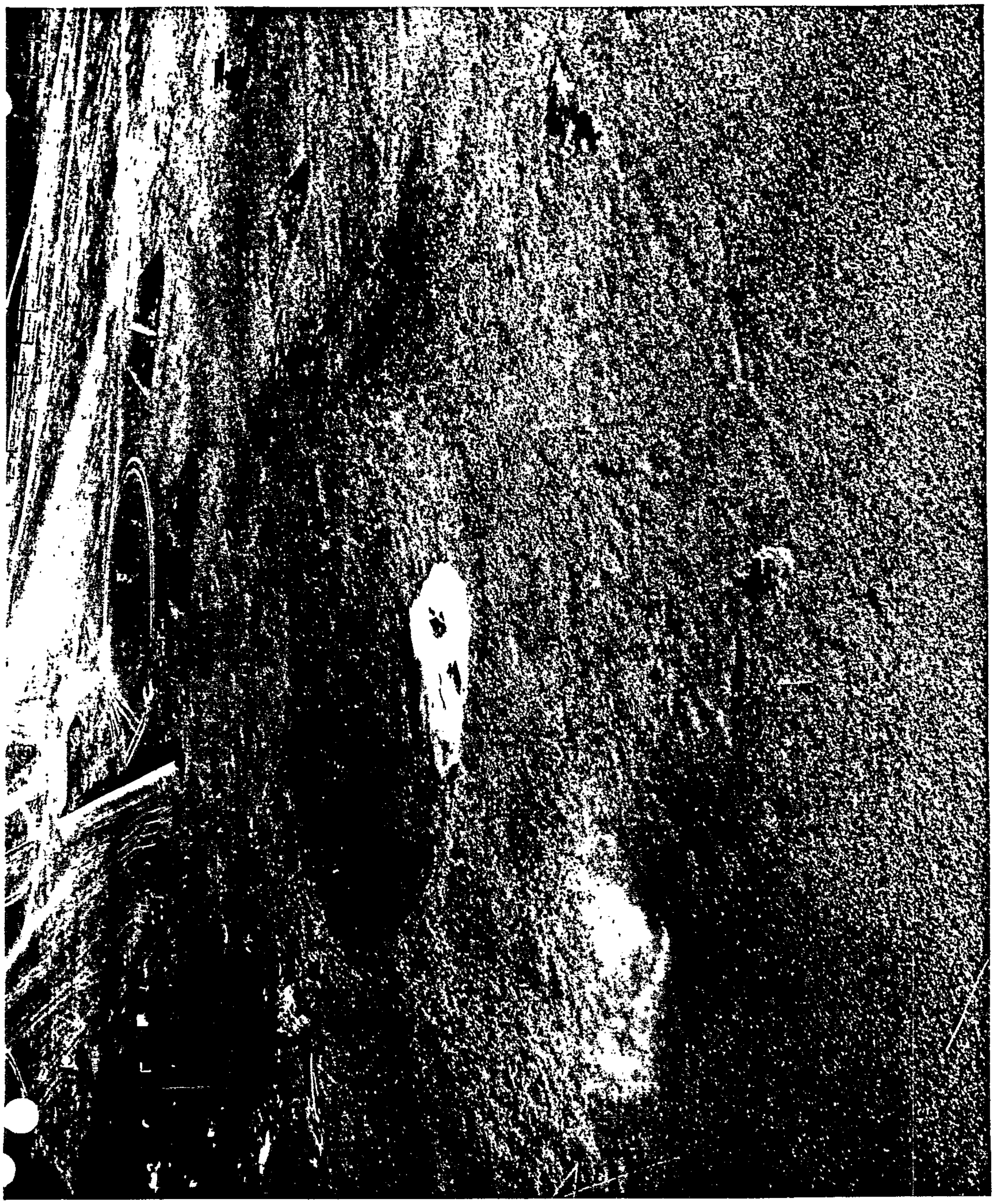


Figure 3/3
Aerial View Showing Inside of 1961 Suffield 100 T Crater
Immediately after Formation

First, at roughly 4 o'clock from GZ in Figure 3/3, there is a puddle of water with a white sand structure inside it. Second, at about 6 o'clock, there is a hollow in the ground, a collapse pit. Third, at about 8 o'clock, there is an obscuration which can only be a dying "Imp" from the devil dance described above. A careful study of the photograph shows that these three elements appear to be at identical radial distances from GZ, and there is faint evidence of some sort of circular, circumferential feature connecting the three features.

This correlation of disparate features was not noted at the time, nor was any significance seen in the features themselves. Thirty years later it is clear that there is evidence in this photograph of a circumferential crack or fault system around the 1961 Suffield 100 ton crater. It will be seen in later chapters that such fault systems were observed more clearly on later trials, particularly at the 500 ton scale.

There is no visual evidence, in this photograph, of inward slumping of the crater walls, nor of any form of terracing within the crater. However, the sand columns, described later, did give some evidence of an "inward" movement of the upper layers below the crater rim.

The inside of the crater is shown in a closer aerial view in Figure 3/4. In this photograph the blocky nature of the original peaks contrasts sharply with the smooth "pseudo-volcanic" sand cone produced by the main inflow of water. There is visible evidence of secondary sand cones inside the crater, and as pointed out above, there is at least one such cone external to the crater, on the circumferential fault.

Figure 3/5 shows a long range aerial oblique view of the crater from a direction roughly at right angles to that of the earlier figures. The elevated rim is again clearly visible, and essentially uniform. Thus the initial impression of this crater is that it was a "normal" bowl shaped crater, complicated only by a breaching of the water table. This feature was, indeed, considered to be more frustrating than interesting, though there was some inconclusive discussion on the nature of the "central peaks", with the majority view being that they consisted of fall-back material.

Figure 3/4
Close-in Aerial View of Crater

Figure 3/5

Long Range Aerial View of Crater Taken at Right Angles to Figure 3/3

3.2.2 The Sand Column Excavation Data

At the time of this detonation, the Suffield Marker system had not been developed, and the columns installed were of the WES-developed Perkins pattern. The Suffield team worked in support of WES, but responsibility lay with WES and the only report on the excavation is a short report in the standard WES format by Strange & Pinkston (1962), and the following material is based largely upon that report, with some interpretive modifications based upon hind sight.

Eleven coloured sand columns were installed, three in the close vicinity of GZ, to depths of 60 ft, and two diametrally opposed sets of four columns each, placed in the anticipated location of the crater rim. These columns ranged in depth from 30 ft to 20 ft, the deeper columns being those nearer to GZ, and anticipated to lie just within the crater. Excavation of the sand columns was delayed to the period of 11 to 21 days after the detonation, partly to allow other projects to be completed and partly in the hope that the crater void would dry out. That hope was not fulfilled, even after an attempt to pump out the water. As a result, no attempt was made to excavate the central columns.

This failure to obtain data from the central columns meant that the nature of the original, blocky central peak was not determined, and there is no field evidence that a structural central uplift existed. Nevertheless, the final crater morphology did include a central "pseudo-volcanic" peak.

Strange & Pinkston also report that they had some difficulty in excavating the more remote columns, because the dry sand and clay would not stand in the cuts. However, by using shallow cuts and final hand work, the excavation of these columns was successful.

Essentially, the predicted location of the crater rim was confirmed, and the two exterior sets of columns therefore lay in a pattern through the inner wall of the crater, up to or slightly beyond the high point of the rim. The final positions of the eight rim area columns are shown in Figure 3/6 after Strange & Pinkston. The upper profile ("apparent crater") is a composite of survey data and a smoothing of the central regions, ignoring the blocky peaks and the pseudo-volcanic cone. The lower, estimated true crater is based on survey only in the region of the sand columns on the left hand side of the crater as viewed, and is of dubious value.

Figure 3/7 shows the excavated sand columns in greater detail, and is re-plotted in a different format from the Strange & Pinkston data. Caution is required in viewing this figure as although the relative positions of the sand columns in the individual sets is reasonably well retained in the figure, the overall picture is not to correct horizontal scale, being shortened in the central region of the crater. The depths below the pre-shot surface are to scale, as shown, and this also applies to the displacements of the column elements from their original vertical positions, which are indicated by the dashed lines.

Attention is drawn to the fact that some regions of the columns indicate movement inwards, towards GZ, even though the predominant column movement is outward. Strange & Pinkston attribute this inward movement to a 5 ft horizontal shear that developed at a depth of approximately 19 ft below the surface, and relate this to a change at a depth of about 18.5 ft from a stiff clay to a more soft clay and silty clay. However, the present author points out that when the data are re-plotted as in Figure 3/7 above, there is clear evidence of a low angle thrust, or series of thrust faults, cutting through the sets of columns. It is thus reasonable to postulate a thrust fault system in a cone sheet around the (probably) uplifted central peaks of this crater. The inward movement in certain regions may thus indeed be due to the transition from stiff to softer material at the particular depth, but in the form of a reverse slippage down the previously thrust-faulted region. Attention will be drawn in the next chapter to a similar effect on one section through the 500 ton SNOWBALL crater. While proof does not exist on the present crater, it is probable that the fracture system controlling the inward movement occurred during the original expansion of the crater, rather than due to post formation slumping. It is also reasonably clear, in both sets of columns, that there are two distinct sets of shears, one striking the columns initially at a depth of about 20 ft, and the second set at a depth of about 27 ft below the surface. At GZ these would correspond, very

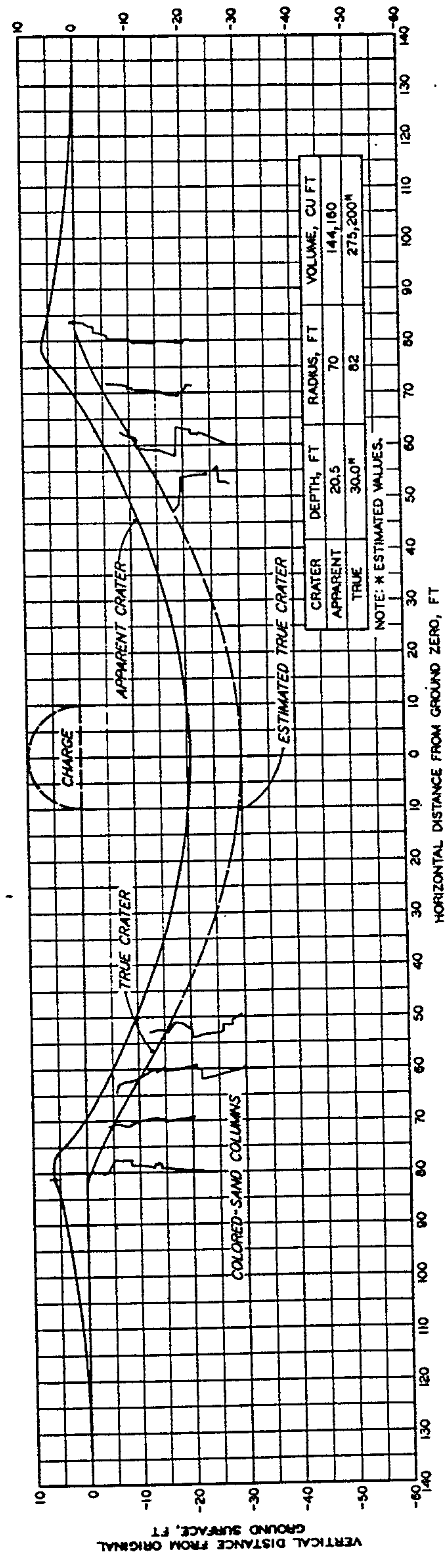


Figure 3/6
Excavated Sand Columns 1961 Suffield 100 Ton Hemisphere
(from Strange & Pinkston, 1962)

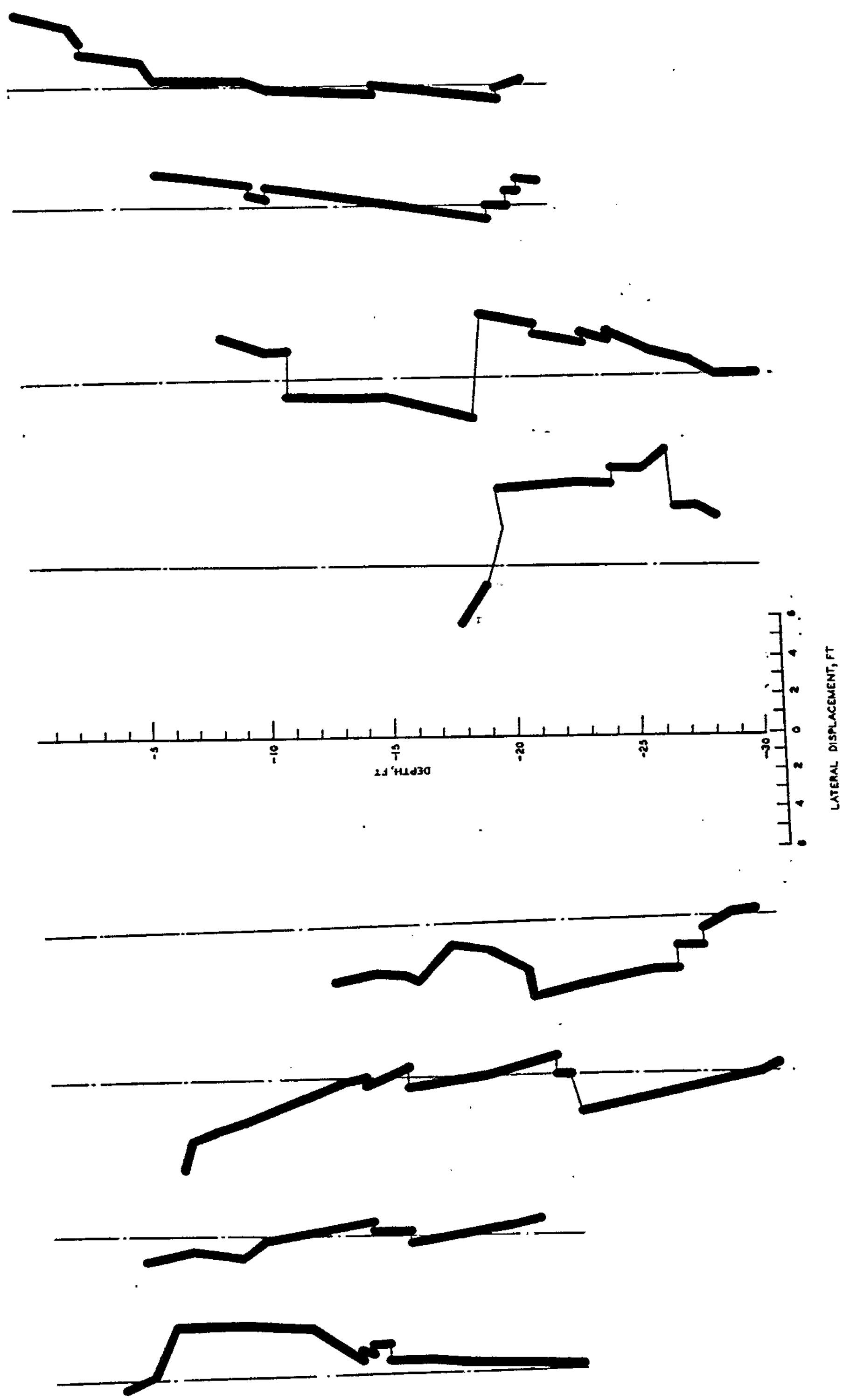


Figure 3/7
Enlarged and Replotted Sand Column Data 1961 Suffield 100 Ton
(after Strange & Pinkston 1962)

roughly to depths of 35 ft and 45 ft below the surface, that is well below the estimated depth of the true crater shown in the earlier figure, and somewhere in the region of the base of the central uplift structures.

3.2.3 Data From A unique Horizontal Marker System

One of the British teams involved in the 1961 trial installed an experimental array along a diametral line passing horizontally some one foot below the ground zero point of the detonation. The post-detonation excavation and survey was carried out by the Canadian survey team, in support of the British. As this team was also that involved in excavating the WES sand column technique, recovery of the experimental array from the British experiment gave considerable impetus to the eventual development of the Suffield sand column marker technique, as in addition to the elements found in situ (though displaced), most if not all the "disrupted" elements, found in what was then considered to be the Fall Back blanket were also surveyed and recorded.

Some years after this trial, these data were looked at again by the author and it was recognized that valuable information existed in relation to the nature of the crater formation process. Through the courtesy of D.J. (John) James, the relevant data were released to the present author with permission to place an interpretation in the public domain, which was done (Jones, 1978). The cited paper suggests that a form of hydrodynamic wave, breaking in the plunging pattern, may be involved in the emplacement of the "ejecta blanket", using that term in its widest sense. However, here undue speculation is avoided and the recorded data with minor interpretive comments are merely presented.

The abstracted data, in so far as they concern the crater study are shown plotted in Figure 3/8. The crater void is to the left of the top diagram, and to the right of the bottom one, and the data extend from about 75 ft from GZ to about 135 ft, that is through the entire "rim" structure of the crater. There is a marked difference in the recorded distribution of the "ejecta" sections on the two sides of the crater. In the south side, the fragmented material lies in an almost horizontal, single line, connected directly to the undisrupted but displaced lower line (the in-situ material). In contrast, on the north

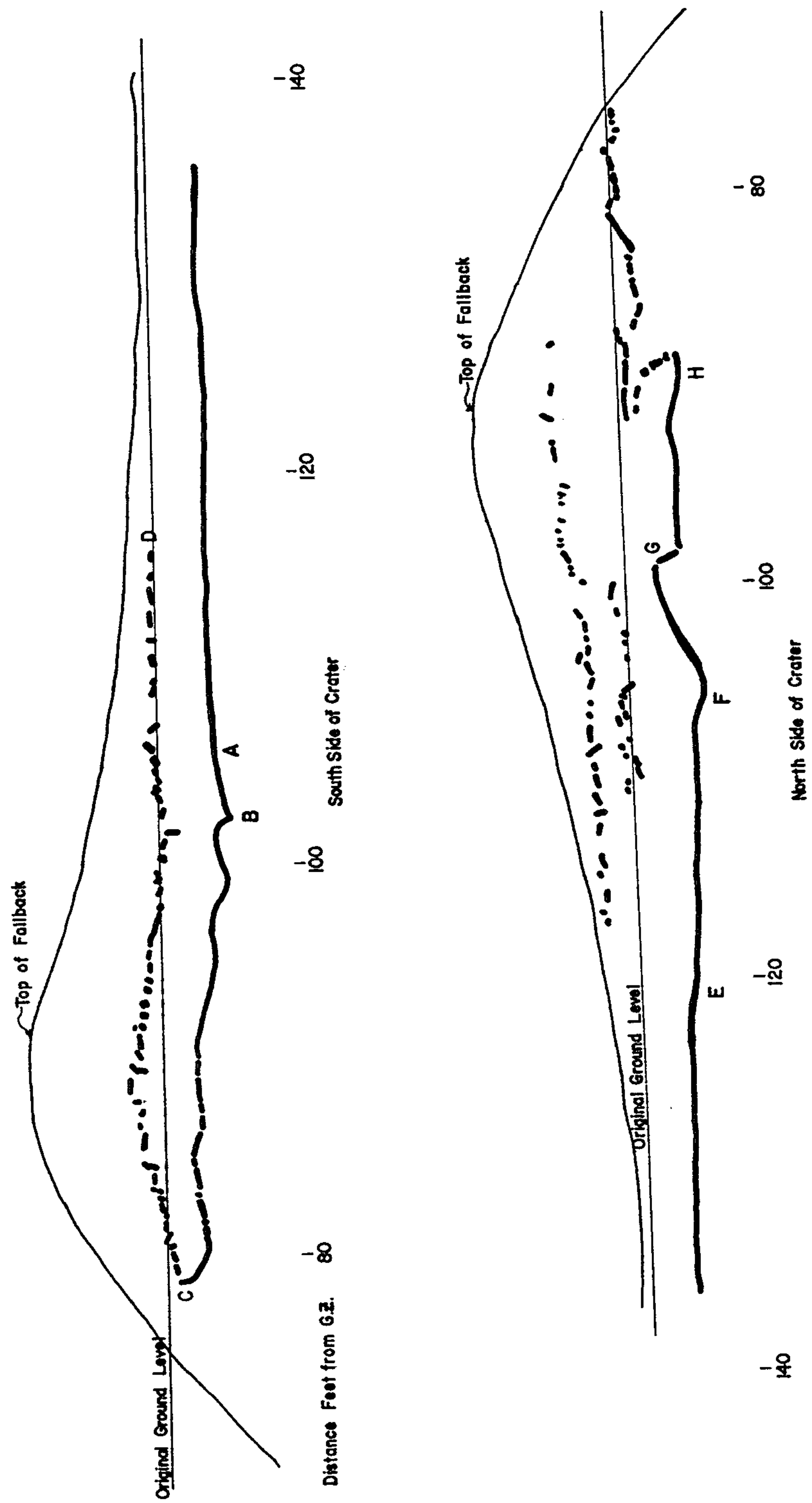


Figure 3/8

Section Elevations Through 1961 Suffield 100 Ton Crater Showing Post Shot Locations of Original Horizontal Marker Chain side of the crater this disrupted material lies in two superposed lines, the upper line being located materially higher in the crater lip than the single line of the other side. Jones (1978) has discussed the possible significance of this difference, suggesting that on the north side there is a recumbent fold - essentially a nappe structure - rather than thrust fault.

The non-disrupted material, shown in solid lines, which represents the markers excavated in which the structure was still in essential contact with the original bedding, ie. the uncratered ground below the crater rim, is of less interest at this time, but does give clear evidence of relatively sharp termination of the ground dislocation, at points market B and F, and a probable thrust fault mode of failure at point H.

3.3 DISTANT PLAIN 6 100T TANGENT SPHERE (JULY 1967)

The anomalous results of the 1961 Suffield 100 ton were more than confirmed by the first 500 ton (SNOWBALL) trial in 1964, which will be discussed in the next chapter. As the primary purpose of the trials, on the international scale, was to model nuclear detonations, there was considerable discussion regarding the observed departure from the norm, as seen on nuclear trials in Nevada. For most participants no problem arose, as the blast wave obeyed the expected scaling laws, and it was the blast wave interaction with above ground structures that dominated the experimental programmes. However, it was far otherwise with those participants who were interested in the crater itself, and the response of gauges and structures placed near the crater rim.

As additional trials were scheduled at the 500 ton level, it was decided to carry out an intervening series of trials with a variety of charge sizes, configurations and heights of burst, partly, but only partly, to address this problem of similarity between the large HE trials and nuclear trials. This new series was given the name "DISTANT PLAIN" and included trials at 20 tons, 50 tons, and 100 tons. We are not here interested in the intricacies of this series of trials, beyond noting that eventually it was agreed that the configuration of a sphere tangent to the surface should be adopted for the succeeding 500 ton trials.

The largest trial in this DISTANT PLAIN series was a 100 ton detonation, named DISTANT PLAIN 6, in the tangent sphere configuration, and it is the crater from that trial that is now the focus.

Operation DISTANT PLAIN 6 was based upon the detonation of a block built, spherical stack of TNT, tangential to and above the ground surface. The spherical stack was supported by an externally cylindrical stack of styrofoam blocks to give it stability, as shown in Figure 3/9. The total weight of explosive was 200,737± 0.01%, and was detonated at 11:30 local time on 26 July 1967.

Due to the exploratory nature of the entire DISTANT PLAIN series, only those projects considered vital to the overall programme were funded, and even the "vital" programmes were somewhat restricted. Thus, only a relatively limited funding was available to the Suffield crater study team, and this restricted the number and location of sand columns installed, and the proposed post-detonation excavation. As it developed, the actual mechanics of the excavation dictated that in the event almost complete recovery of sand column data was achieved. The lack of direct funding was also largely compensated by the fact that by the time of this trial, the Suffield Team had the cooperation of several agencies, in addition to WES, with particular cratering expertise, including the U.S. Geological Survey Branch of Astrogeology and the members of the cratering group at the (then) Dominion Observatory of Canada. The immediate post-detonation results were recorded by Diehl, Pinnell & Jones (1968), by Davies et al (1971) of WES and by Roddy (1968a) of the U.S. Geological Survey. Much of the following is derived from the above cited reports, but concentrating in hindsight upon those aspects deemed relevant to the prime purpose of this text.

Unlike many of the other trials, the entire area around the crater was given a final "sooty" coating, which reduced contrast for general photography, and which indicated "lobing" of the ejecta blanket more clearly than on earlier trials. Figure 3/10 is an oblique aerial view of the crater area shortly after the detonation and shows the soot enhanced lobes. Stereo pairs taken by the Cold Regions Research Engineering Laboratory

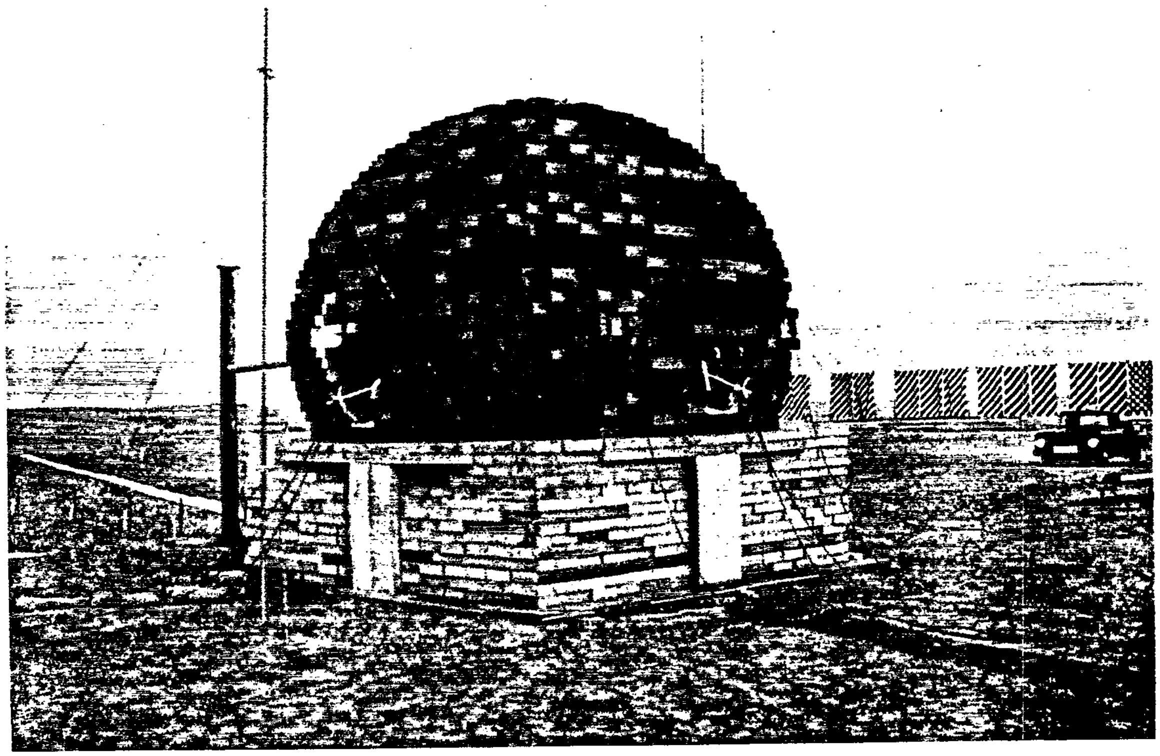


Figure 3/9
The DISTANT PLAIN 6 Charge Supported by Styrofoam

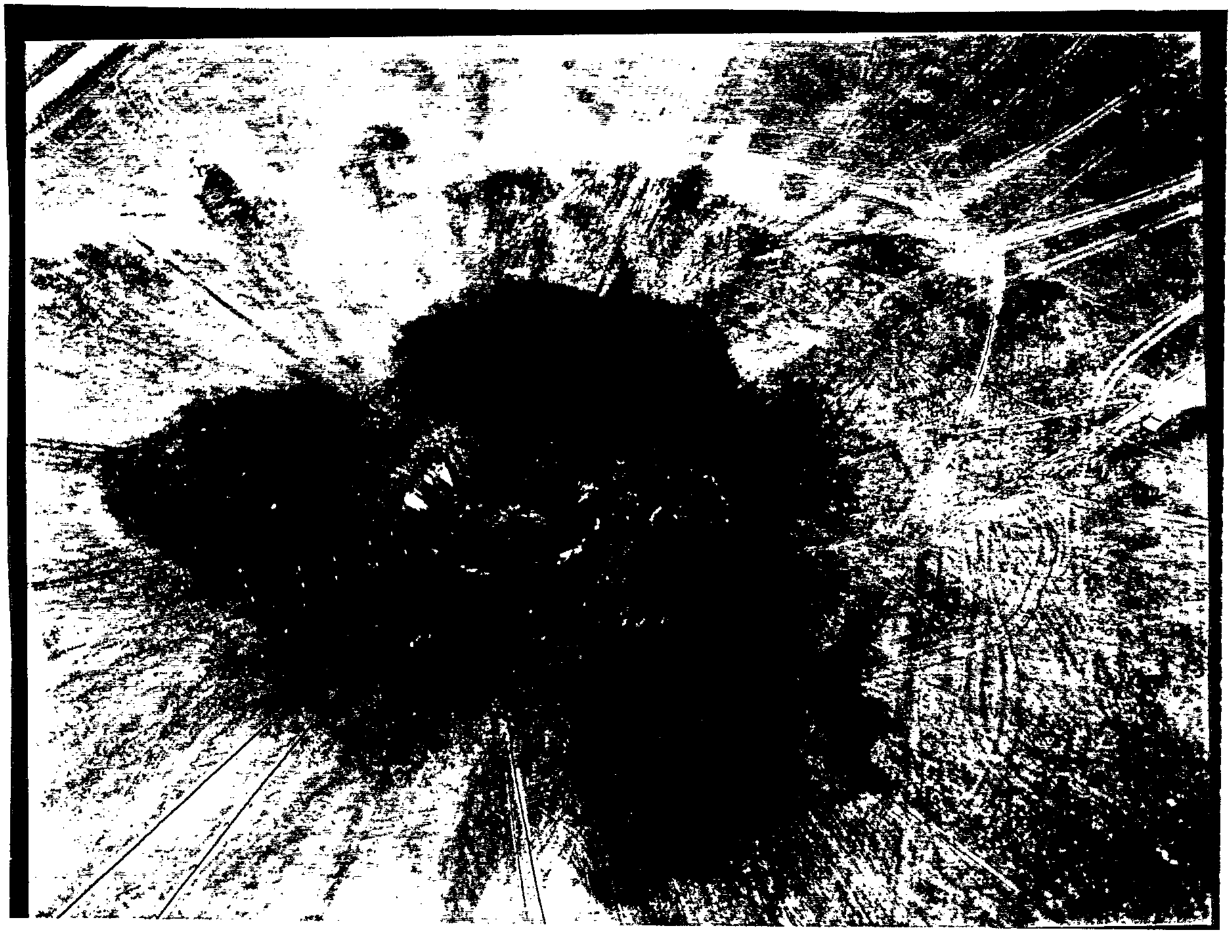


Figure 3/10
Oblique Aerial View of DISTANT PLAIN 6 Crater

(CRREL) are shown in Davies et al (1971) and may still exist as archival negatives (shown later in Figure 3/22).

As the detonation was of high order, it is unlikely that the soot derived from the charge, but may well have come from the styrofoam support structure. However, the emphasising of the lobes is not without interest as some lunar craters show similar lobed ejecta blankets.

The crater itself was materially smaller than the 1961 Suffield 100 ton crater. This was anticipated as a result of changing the charge shape from surface hemisphere to tangent sphere. To this extent, it is understood to have scaled reasonably well with predictions based upon the nuclear detonations in Nevada. The comparison of the two TNT charges is given in Table 3/1.

TABLE 3/1

COMPARISON OF DIMENSION OF TWO 100 TON CRATERS

	100 Ton Hemispherical 1961 Suffield Trial	100 Ton Spherical DISTANT PLAIN 6
Apparent Crater Diameter	46.90 m	26.80 m
Apparent Lip Diameter	55.50 m	34.23 m
Apparent Depth	6.05 m	4.90 m

If these measurements were the only data available, it is unlikely that two such craters would be even considered to be formed by comparable detonations. This highlights the difficulties which will be encountered in any attempt to discuss the nature and scale of the energy sources when geological structures of unknown origin are examined. As will be shown below, the fact remains that these two craters, so apparently different in scale, proved to be morphologically almost identical, with far more similarity with each other than with craters at either the 20 ton or 500 ton level.

As copious detail of the immediate post detonation and later excavation data exist in the limited circulation reports cited above, attention is now concentrated only on those aspects of the crater which are either of interest in comparison with the 1961 Suffield 100 T crater, or which appear to the author to be significant in connection with the study of larger, geological structure of the crypto-explosive or "astrobleme" pattern. As the DISTANT PLAIN 6 crater was subsequent to the detailed study of the first 500 ton crater (SNOWBALL), field workers were alert to observe facets of the crater which may have been missed on the 1961 crater, and also some new techniques were in use.

3.3.1 Circumferential Structures Outside The Crater Rim

Although the probable existence of a circumferential fault on the 1961 crater was only recognized years after the event, such a structure was a major feature of the 500 ton SNOWBALL shot, which preceded DISTANT PLAIN 6 by some years. Care was therefore taken on DP6 to record all evident folding or cracking under the ejecta blanket, immediately evident and those exposed at later stages as the ejecta blanket was removed. Figure 3/11 shows a plot of the observed structures. It is clear that although no single fault or fold was traced around the full circumference, a complex series of folds and faults, quite obviously encompassing the crater, was recorded. It is further commented that despite this intensive search, no faults/cracks radial to the crater were observed on this trial (but were observed on SNOWBALL, and so were looked for on DP6).

For a purpose unconnected with the above (actually to record details of the ejecta blanket), a number of cold rolled asphalt strips 41 cm wide and some 7 to 8 cm thick were installed on the pre-shot surface, radial to GZ and separated by 60 degree angles. When these asphalt strips were excavated as part of the ejecta study, it was found that the strips (and the underlying ground) showed anticlinal and synclinal folding, as shown in Figure 3/12, and shears and fractures further out from the crater, as shown in Figure 3/13. This system of folding and cracking was more evident along one of the strips than the others, and although the systems are believed to be continuous concentric structural features, reflected in the pattern shown in Figure 3/11, no definite proof of this

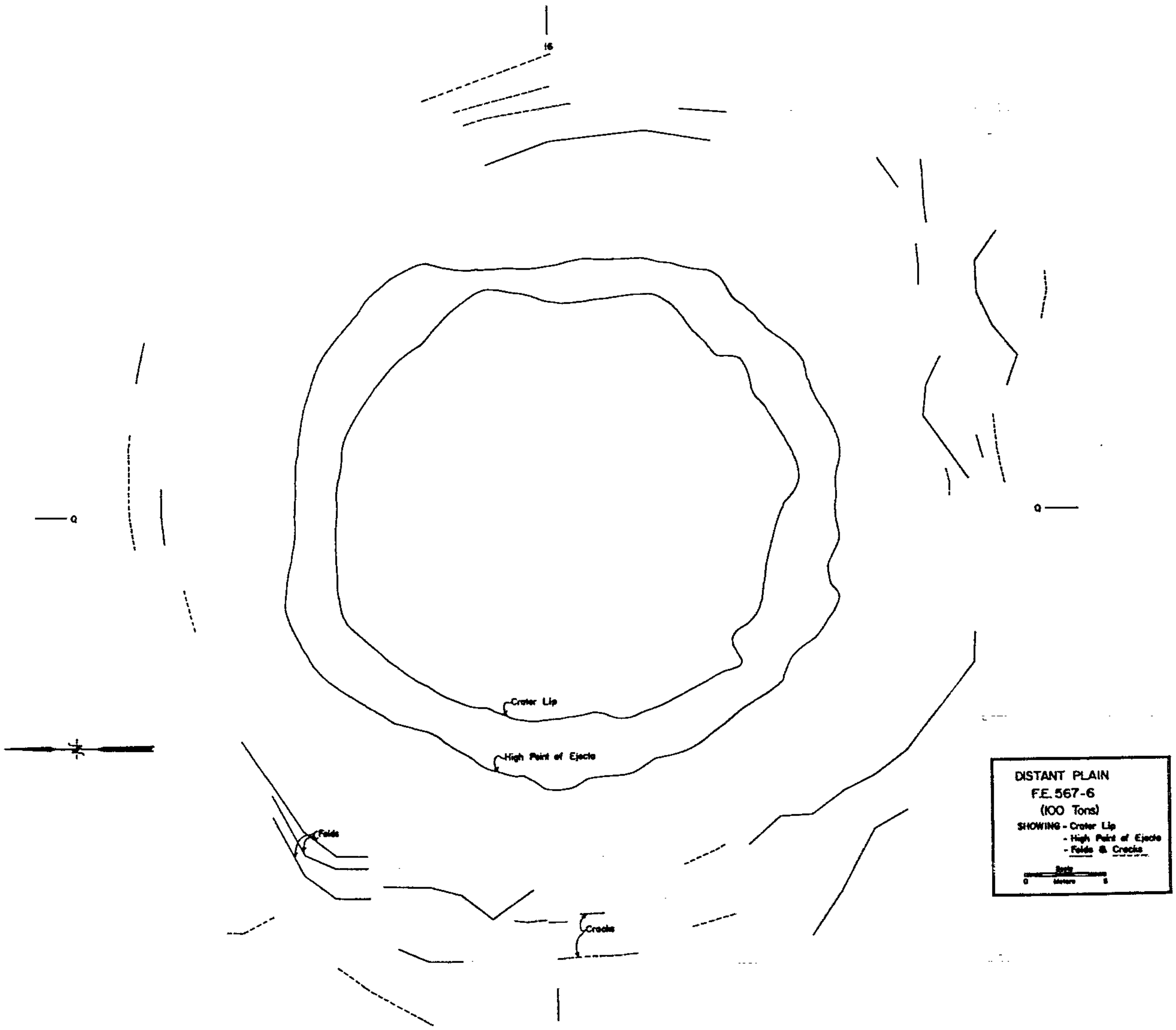


Figure 3/11
Circumferential Cracks and Folds
DISTANT PLAIN 6 Crater

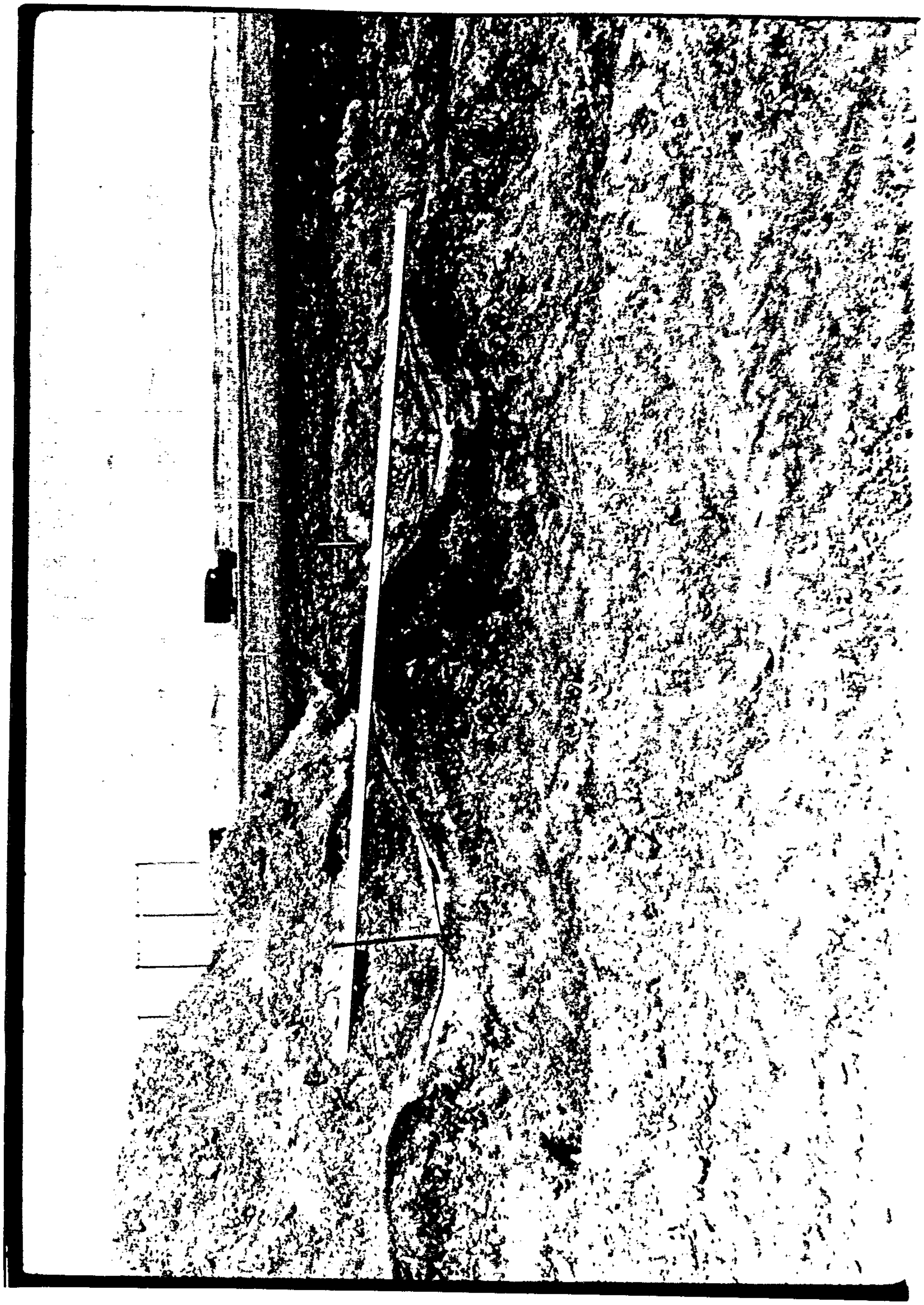


Figure 3/12

Folds in Radial Asphalt Strips DP 6 100 Ton Crater

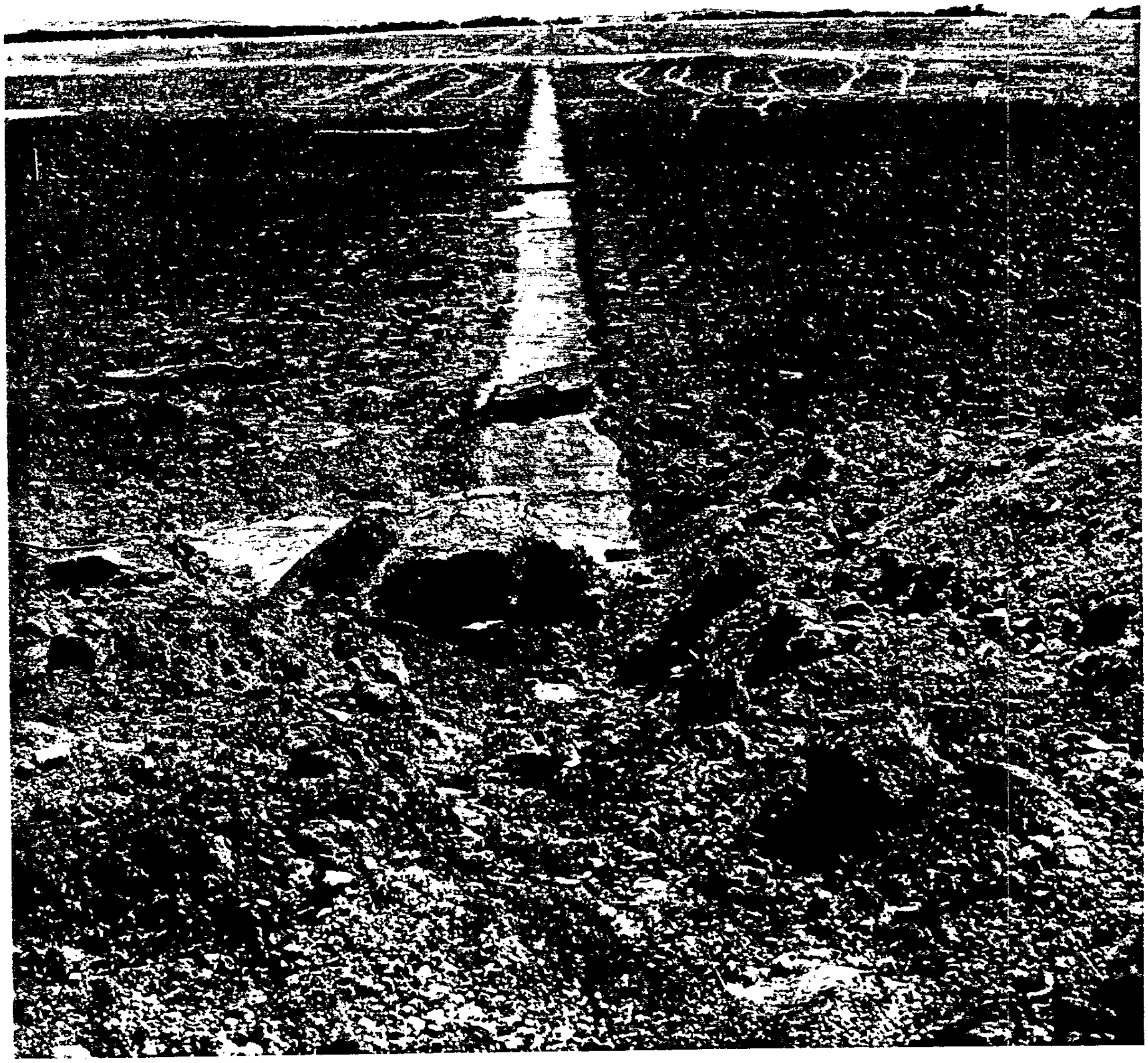


Figure 3/13
Faults and Folding in Asphalt Strips DISTANT PLAIN 6 Crater

can be presented today, from the archival records studied. However, the structural and circumferential integrity is confirmed by the structure found within the crater rim, described next.

3.3.2 The DP6 Rim Structure

As was the case with the 1961 Suffield 100 ton trial, the DP6 crater had an uplifted rim, in this case a structural uplift of about 1.5 metre overlain by some fallback material. However, the greater interest lies in the structure found rather deeper under the rim, which was found during the excavation of the sand columns. This structure was a major anticlinal fold, which is shown in Figure 3/14 and plotted in Figure 3/15. Folding in the lower part of the anticline, most clearly exposed in the west sand column cut, decreased in amplitude and at a depth of about 3 m below the ground surface the strata were essentially horizontal. Cuts through other areas of the rim proved similar, showing that there was a concentric rim anticline with an axial trace that plunged irregularly along the crater walls. Many small en-echelon faults were superimposed on the anticline, and the limb of the anticline was usually truncated by the crater wall.

It is remarked that at neither of the 100 ton craters was any evidence of a coherent overturning of the strata recognized at the time, despite the horizontal markers on the 1961. However, at greater depth than the structure described above, there was in at least one location clear evidence of an upthrusting of the strata, which is shown in Figure 3/16 taken from Davies et al (1971). At a later stage, when we describe the structures underlying the rims of the 500 ton craters, attention will be drawn back to this structure. The precise location of the structure shown is not recorded in the presently available archives, but it would appear from the cited paper that the top lip of the upthrust was at about 3 m below the original ground surface, and probably closer in to GZ (ie. at the inner crater wall) than the anticlinal structure somewhat higher under the rim.

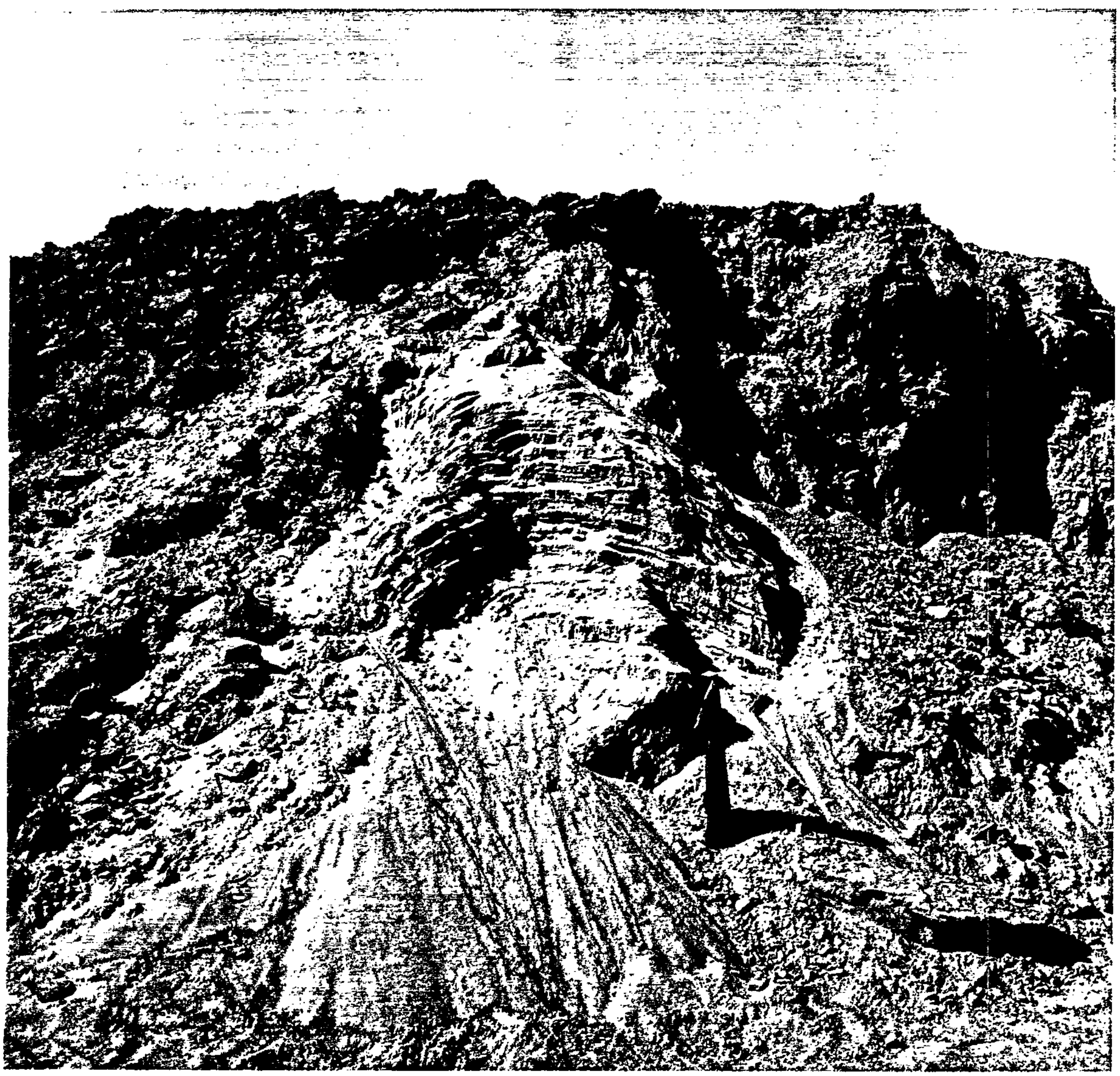


Figure 3/14
Anticlinal Fold in Rim of
DISTANT PLAIN 6 Crater

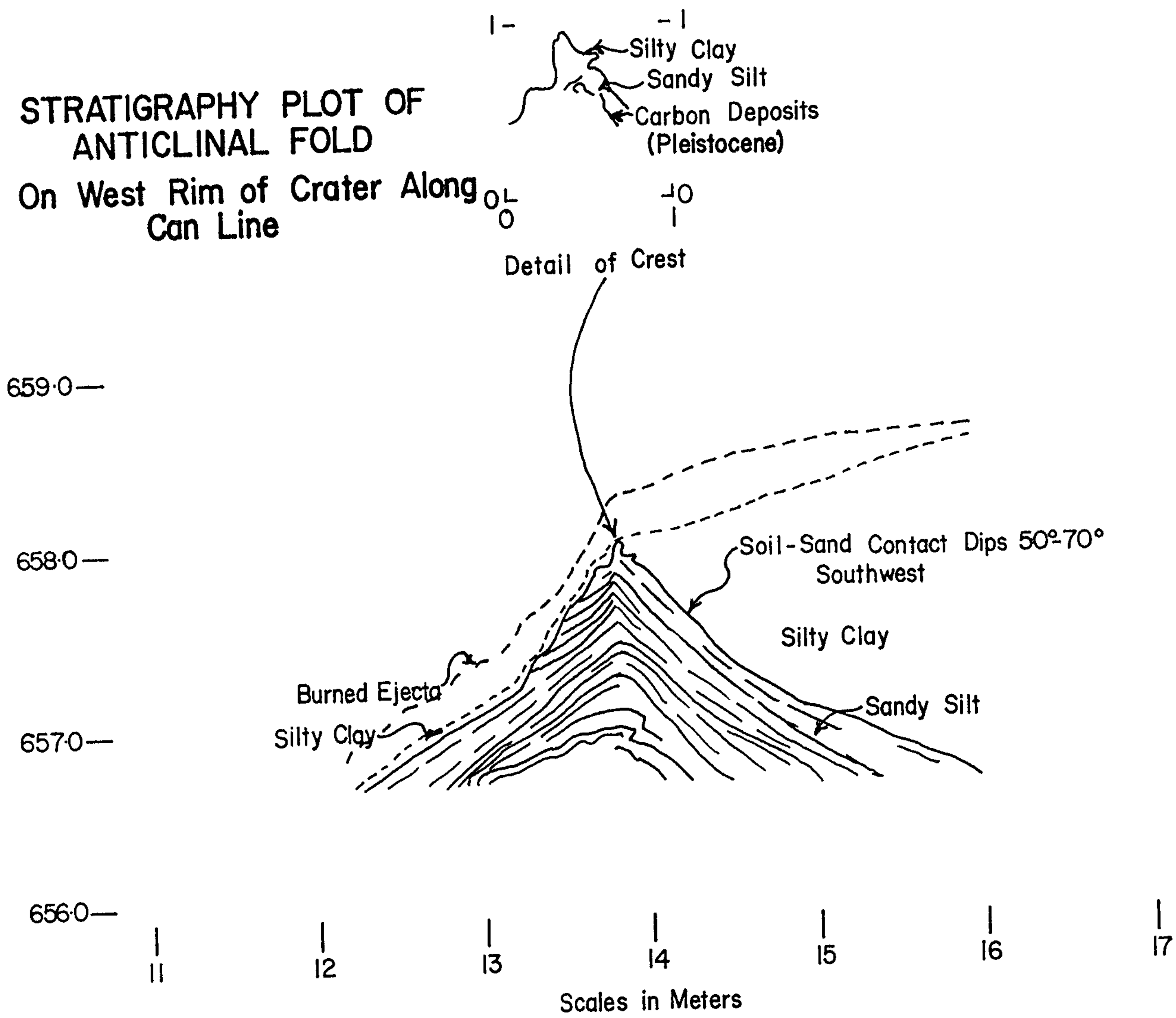


Figure 3/15
Plot of Rim Anticline DISTANT PLAIN 6 100 Ton Crater

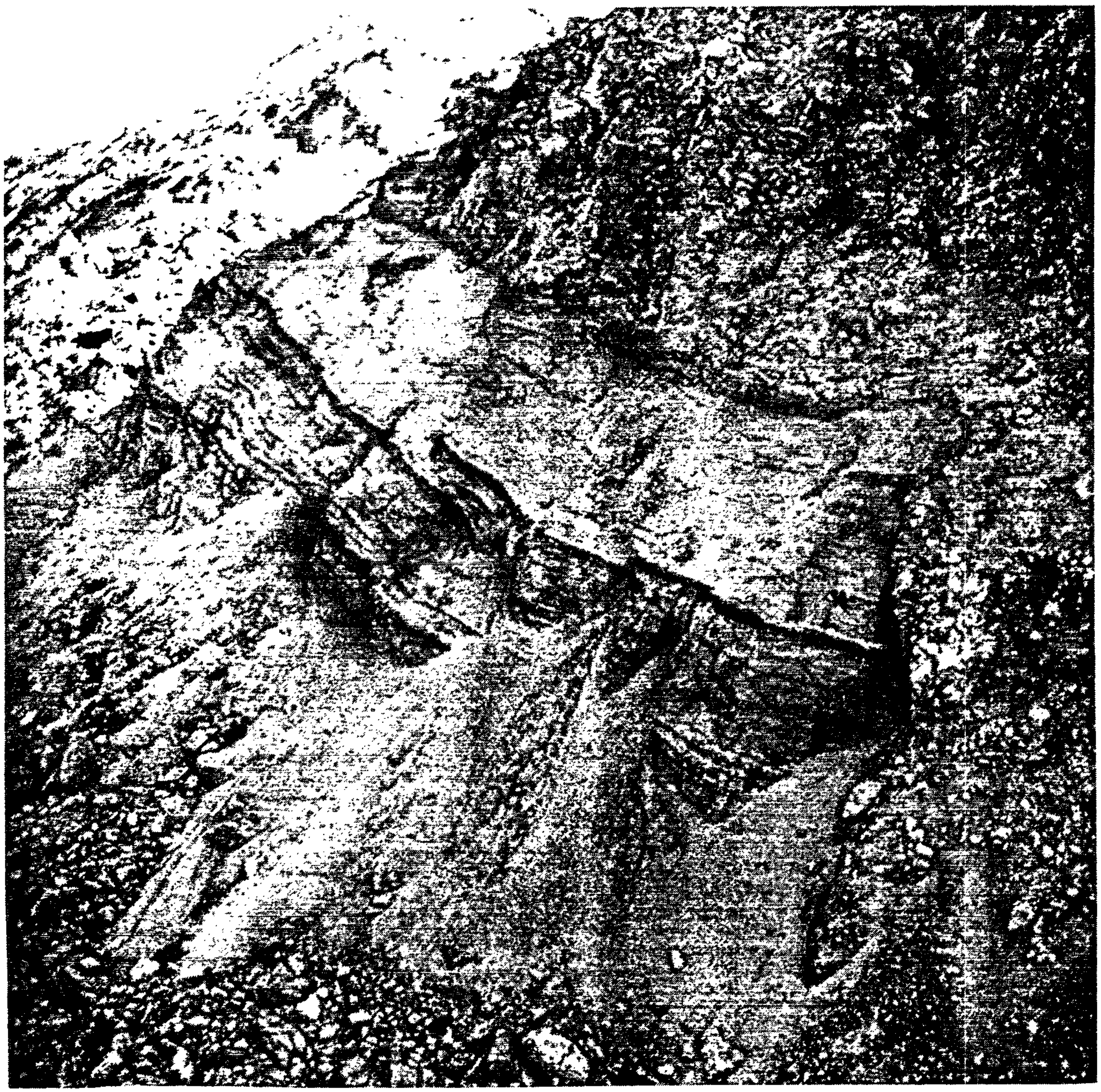


Figure 3/16

Sand Stratum at Edge of Event DP6 Crater Upthrusted by the Detonation and Later Exposed by the Sand Column Excavation. The Crater is to the Left of the Photograph.

3.3.3 The Central Uplift

Unlike the 1961 crater, that produced by DISTANT PLAIN 6 was essentially dry, with no serious inflow of water. However, as in the 1961 crater, there was a structural uplift, which in this case was fully visible and occupied, in effect, the entire inside of the crater as a dome abutting onto the crater walls, or rather onto what would have been the lower part of the crater wall in a bowl-shaped crater. This is shown in Figure 3/17 and also in Figure 3/18, which shows that there was in fact a very small flow of water, scarcely more than a trickle, from near the top of the dome. This trickle of water first appeared about three hours after the detonation and continued for about another six hours, but so slowly that beyond cutting a small channel the water was absorbed into the floor of the crater without forming a pool.

It is interesting to note that old beliefs die hard, and despite the fact that years earlier excavation of the SNOWBALL crater had proven without doubt that structural central uplifts were being created, most participants continue to refer to the dome as "Fallback" and this even appears in some of the printed reports. However, excavation of the central dome in DP6 revealed the structure shown in Figure 3/19, and in many other similar sections. The figure shows sharply folded, and in some places faulted clay strata, uplifted from depth as integral units. In fact, the central uplift on DP6 was a very close parallel with the (much bigger) central uplift excavated on SNOWBALL, as will be shown later by comparable photographs. The extent of the uplift will also be indicated in the next section, which deals with the sand column data.

Figure 3/17
Aerial View of DISTANT PLAIN 6 Crater

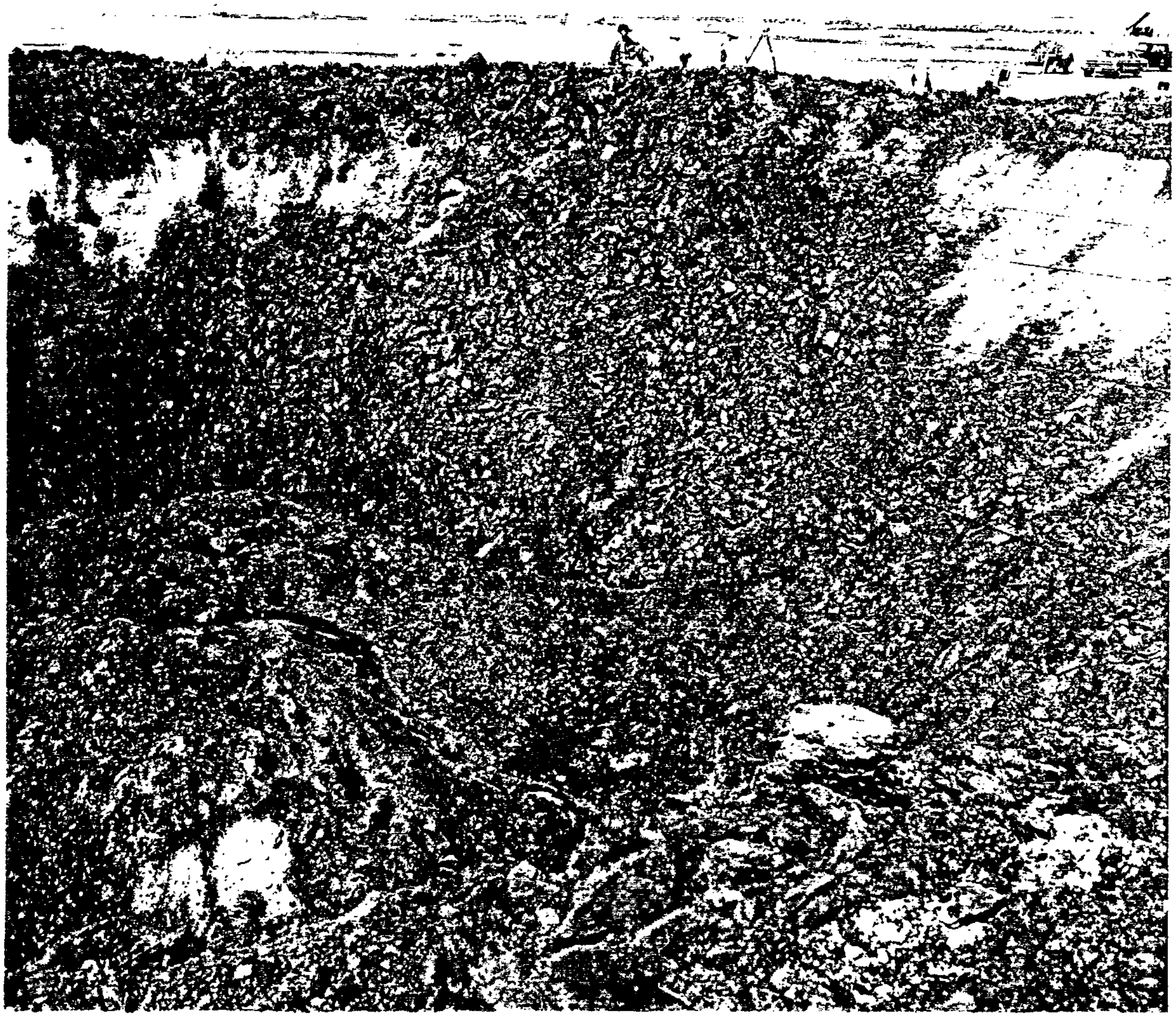


Figure 3/18
Flow of Water from Top of Central Mound
DISTANT PLAIN 6 Crater

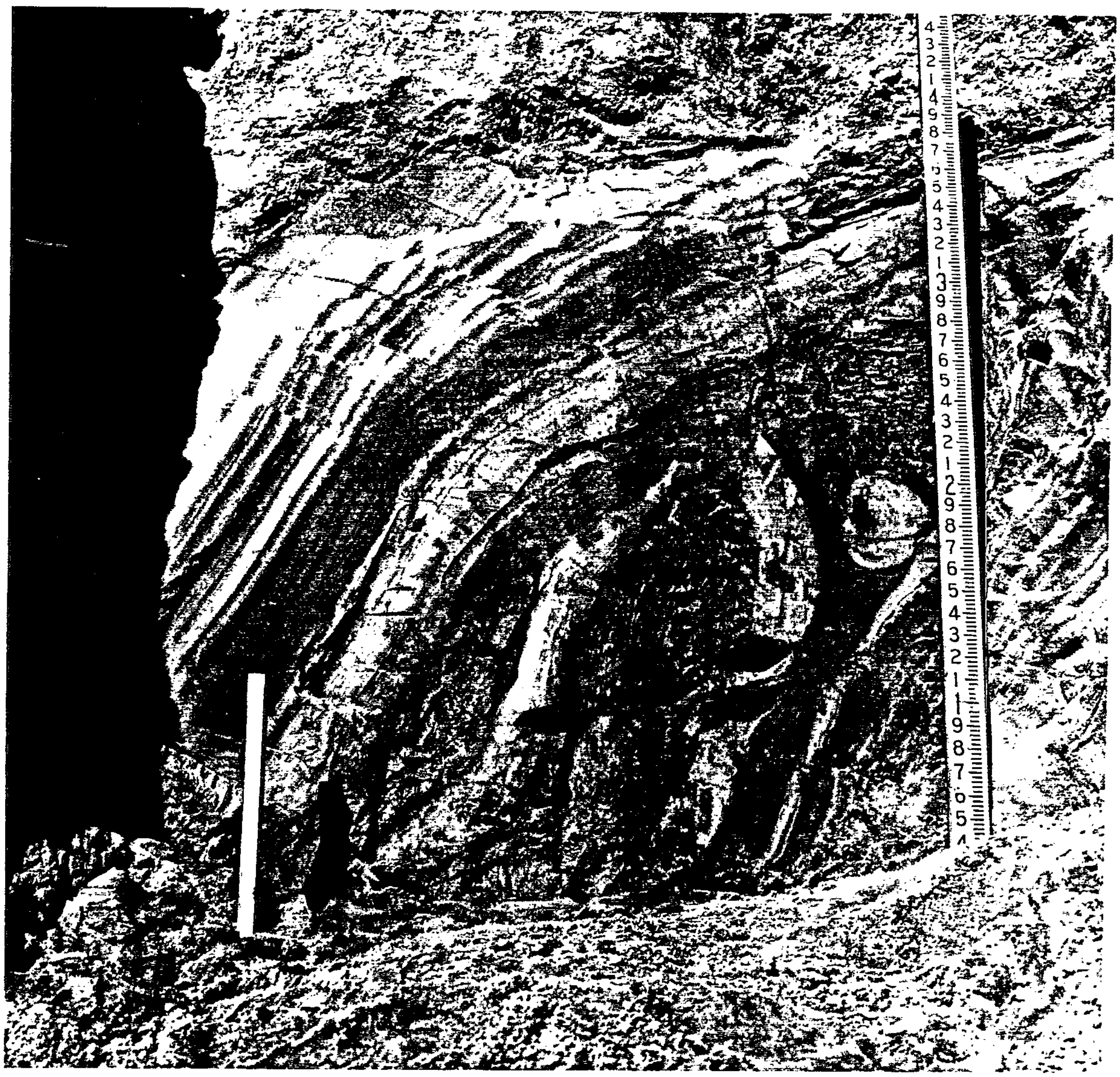


Figure 3/19
Cuts Through Central Mound
DISTANT PLAIN 6 Crater

3.3.4 Results From Suffield Sand Column Technique

For this trial, fifteen sand columns with the Suffield market system were installed along one diameter through GZ, with maximum installation depths ranging from 20 m at GZ to 3 m in the most remote column, at 75 m from GZ. As mentioned above, funding limitation on this trial meant that, formally, the intention was only to map the crater profile - for comparison with nuclear craters - by excavating to such depth that the top two in-situ markers would be recovered. However, the technique known as Nelson's Blind Eye, together with the perfectly valid need to drive in a suitable roadway for the excavating machinery resulted in a much greater retrieval of data than was mandated. The results obtained are given in detail in Diehl et al (1968) and are shown plotted in Figure 3/20, in which the top section shows the displacement recorded by the Suffield technique, while the bottom section, using the same survey, shows the shears in the column plotted in the standard WES pattern. Figure 3/21 is an enlarged plot of the displacement data recorded for the most central three columns.

We may observe, as the most immediately significant fact that the data confirm a central uplift structure with an uplift of at least 5 m in the region below GZ.

Under the rims of the crater, the markers again indicate a generally "upward and outward" displacement, which requires no additional comment here. However, attention is drawn to the evidence, in both forms of the data plot, of a low angle thrust fault type movement under the rim, but with no clear evidence that this fault eventually emerges at the surface remote from the crater. This type of faulting will be discussed later in connection with other craters, and was neither expected nor looked for in DP 6.

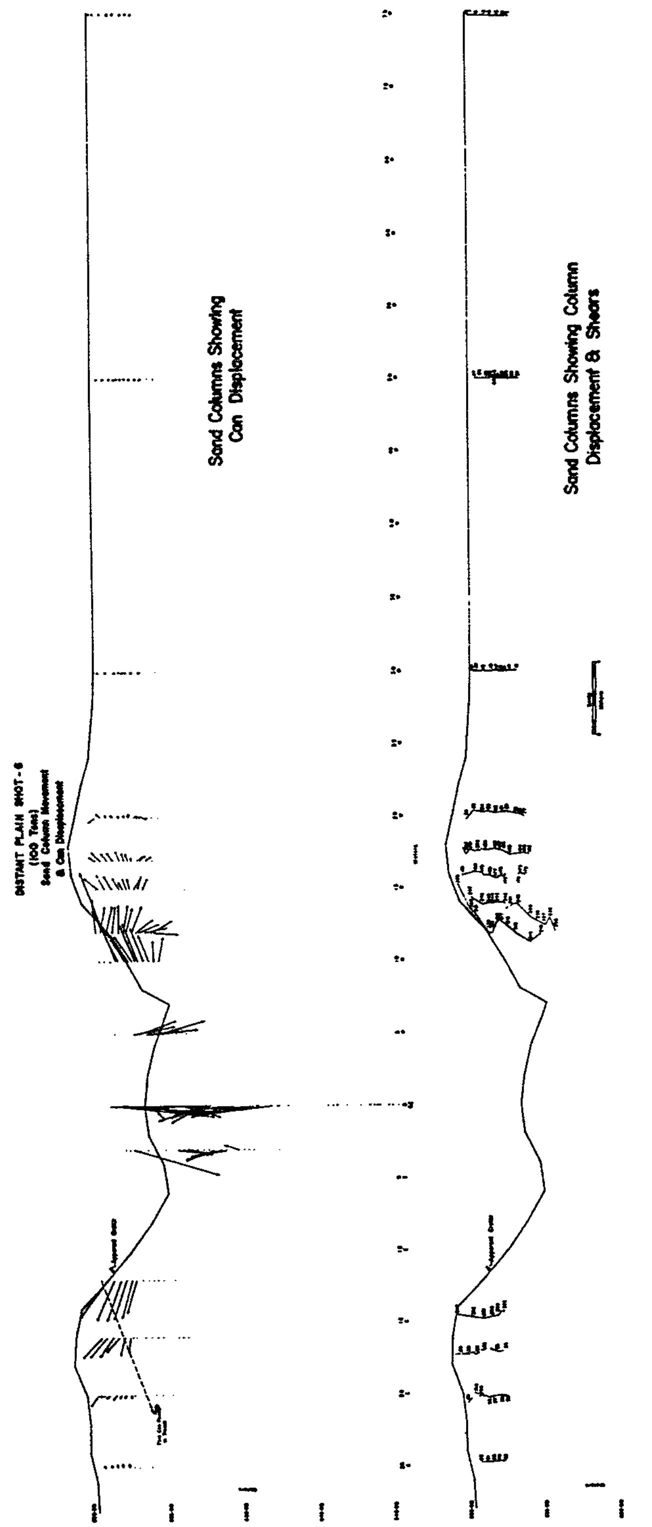


Figure 3/20

Suffield and WES Type Data Plots of Excavated Sand Columns for DP6 100T Crater

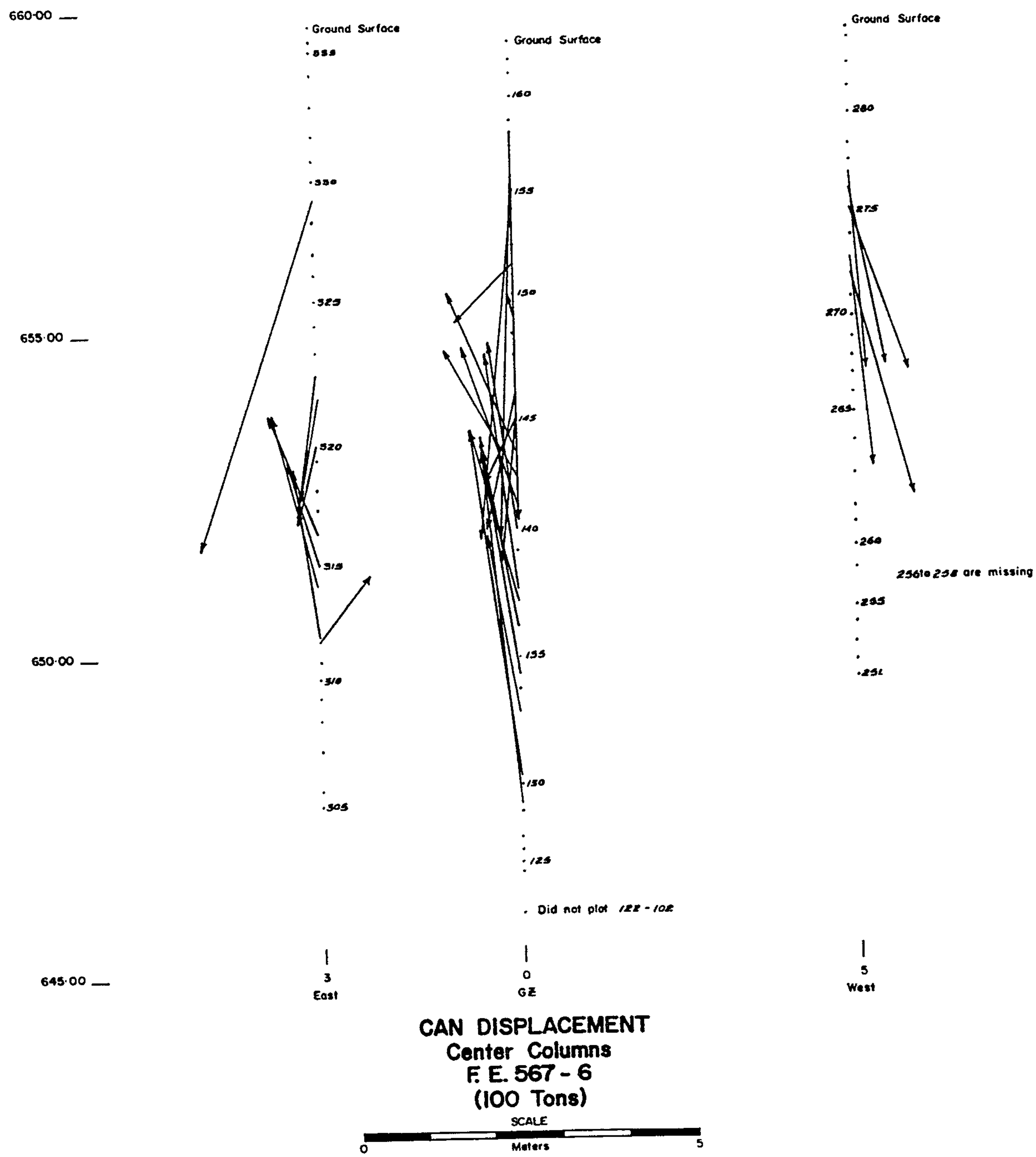


Figure 3/21

Details of Central Column Marker Displacement Showing Extent of Central Uplift of DISTANT PLAIN 6 Crater

3.3.5 Anomalous "White Sand" Between Crater Wall And Central Uplift

Immediately after the first entry to the crater, an unusual material was observed. This was a "rock flour", intensely white, which contrasted sharply both with the carbon coated fallback material, and the "normal" brownish silts and sands of the upper parts of the cratered medium.

The immediate comment of the present author, familiar with the local badlands geology, was that this material was "bedrock" material from the Foremost formation. This identification was based not upon the general mass of the flour-like white material, but on the frequent inclusion in it of fist-sized "rock" fragments. These fragments were but mildly indurated, but were not particularly friable to normal handling. They also had a remanent fine structure similar to that of the Oldman/Foremost bedrock, and also contained tiny particles of carbonaceous material, also seen in the local bedrock.

However, such an identification leads to a serious problem, as so far as was determined the contact with the bedrock lay some 60 m below the original surface. Even if we allow for a 20 m undetected knoll in the bedrock immediately below the charge -- the maximum allowable in terms of the relief in the seismic profile given in Chapter One - this would imply a 40 m uplift.

We must consider the observed placement of the material. During excavation, it was found that the "white sand" layer was emplaced well up the side wall of the crater, and similarly on the central mound. It quite clearly underlay the carbon coated fallback material, as a distinct layer, though during excavation alongside the central mound some carbon coated material was detected in the white sand at some depth. Continued excavation showed that this white sand material appeared to form a ring of varying thickness around the central mound, and was gradually sloping inward in the form of a "cone sheet". Deep excavation to trace the sheet could not be carried out, as the planned excavation was already far exceeded. As it happened, at the depth actually reached a very wet quicksand like material was encountered at a depth of 8.2 m below surface level.

While the observed material was conspicuously white and dry, upon wetting it turned brown and virtually indistinguishable in general appearance from the silty material of the upper layers of the ground. Thus the true depth of the cone sheet - if that is what it was - is indeterminate.

For these reasons, alternative explanations were sought, primarily related to "shocking" of the cratered material. Petrographically there was no evidence of shock metamorphism, beyond what may be termed brecciation of material similar to the upper sand/silt layers, and the general opinion soon became that the white sand was due to the action of the shock wave on the upper layers. If this is taken to be the case, the evidence is that the material was formed at a very early stage, before the emergence of the central uplift, and before the descent of the fall back material. On this theory, the material coated the initial bowl-shaped crater, and was then in-folded as the central uplift arose, becoming trapped between the uplift and the side wall of the crater. Naturally, as the sediments themselves derive from the bedrock, petrographic analysis can only be inconclusive. The evidence against this theory is (a) the existence of indurated hand sized specimens and (b) the apparent rarity of the phenomenon in the dozens of Suffield trials with similar charges on similar ground. However, as will be discussed later, a small quantity of similar material was observed on the later 500 ton PRAIRIE FLAT crater, which had the same charge configuration as DP 6.

There is no doubt that the simplest explanation, and the one that found most favour, is that the material was a shock-change of the upper layer material, emplaced between the time of maximum expansion of the crater and the rising of the central uplift.

Nevertheless, a question remains and elsewhere in this present text reference will be made to other observations which indicate the potential for major transport of material from depth, in addition to that delivered to the surface by water flow.

Editorial Note

See the insert on page 3-54 which finally gives an explanation for the 'White Sand' on the basis of new observation and interpretation dated September 1995.

3.3.6 Topographical Mapping Of DP6

By the time of the DP6 trial, topographical mapping was de rigeur, and in contrast with the earlier trials there is a wealth of data in the archives. In the present section, recourse has not been had to original data, but to data preserved in reports. Nevertheless, it is virtually certain that original data have been preserved in various archives.

Figure 3/22 is a copy of an aerial vertical stereo pair of photographs, while Figure 3/23 and Figure 3/24 show pre-detonation and post-detonation topographical maps, derived from such photographs. In their present form, these are derived from Davies et al (1971) but it is not known who actually produced the photographic cartographic reduction.

It is of particular interest that this crater was also mapped by DRES staff by ground survey, and another topographic map, shown in Figure 3/25 was produced. This independent survey correlates quite closely with that produced by reduction from the stereo-pairs, but it is interesting to note that one is metric while the other is English system, and the metric survey on the ground uses a different contour interval and thus provides additional, but not conflicting data. With this measure of ground control, and the detailed data on the structure of the crater found by excavation, it would be of considerable interest to have a comparable analysis made by the Astrogeology Branch, U.S. Geological Survey, including the ability of the latter agency to produce maps with added perspective through virtual oblique illumination.

No further comment appears appropriate at this time.

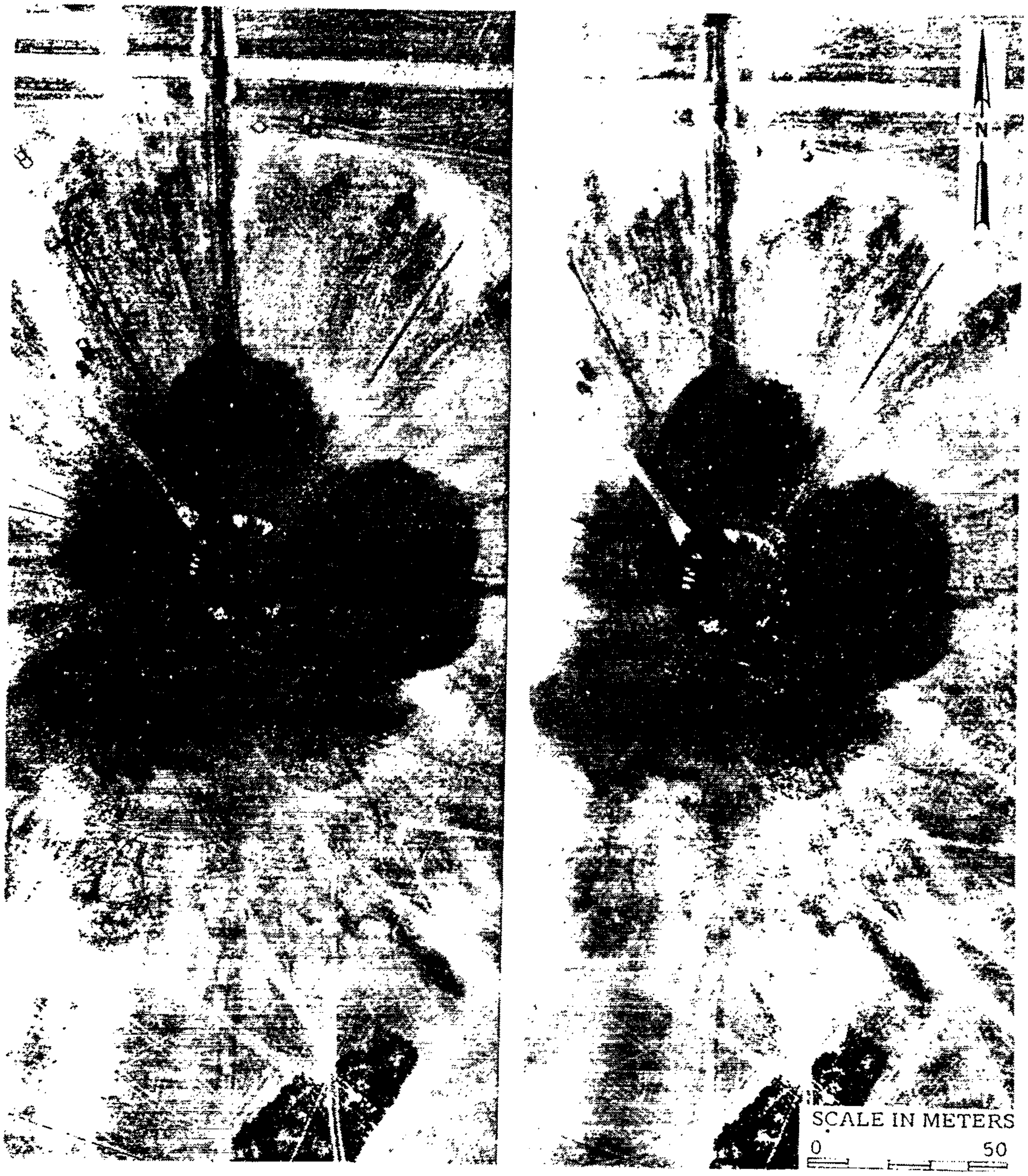


Figure 3/22

Aerial Stereopair of Event DP6 Crater. Dark Apppearance of Crater and Lip Due to Covering of Soot or Black Dust, which has been Disturbed by Spectator Path (upper left) and Slides of Loose Sand Around Inside Crater Rim. (CRREL Photograph from Davies et al 1971).

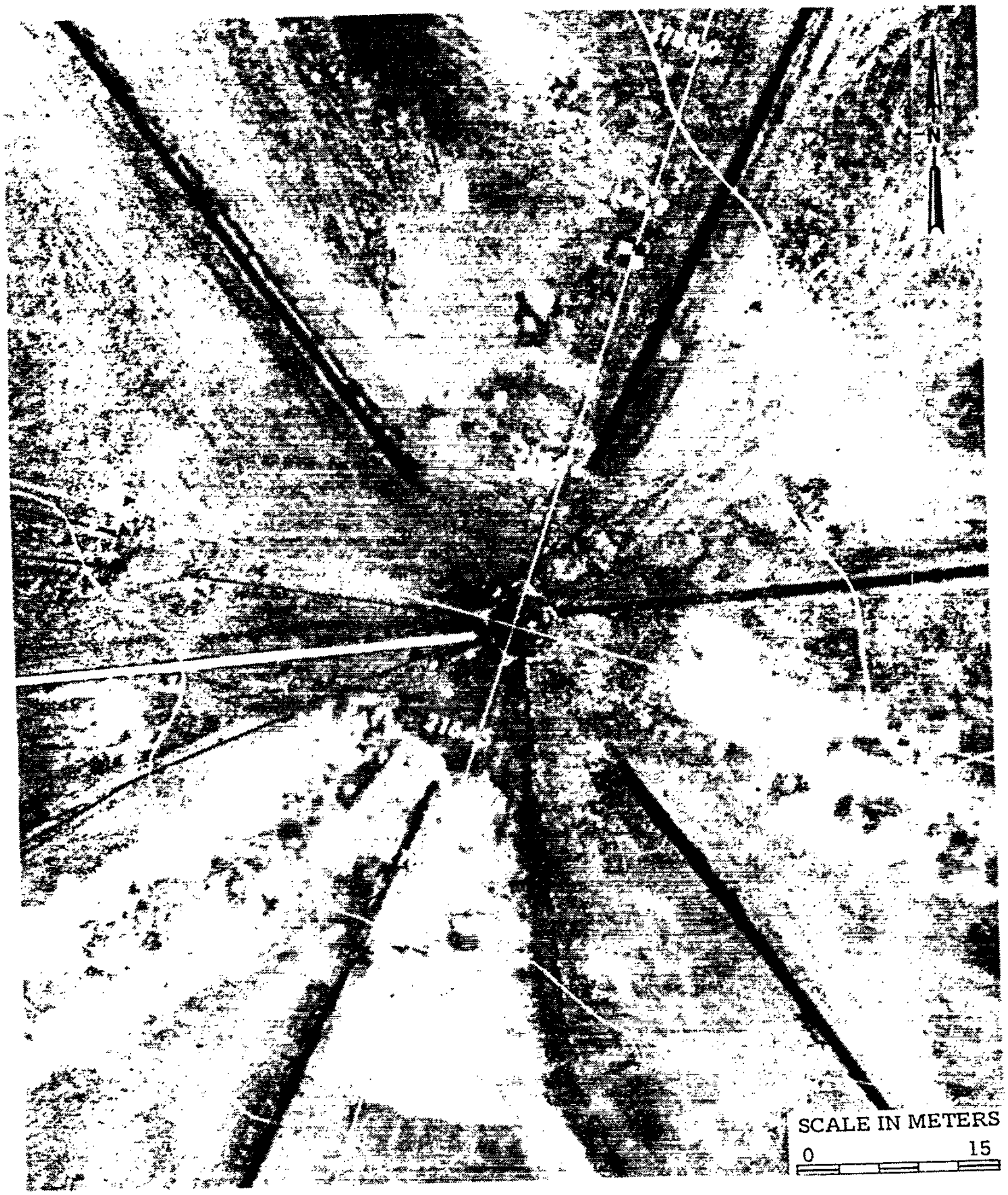


Figure 3/23

Preshot Contours of Event DP6 Crater Area - Elevations In Feet above Mean Sea Level; Contour Interval of 1 Foot. Black and White Lines Radiating from Stacked Charge are Asphalt Strips. (CRREL Photograph From DAVIES et al 1971).

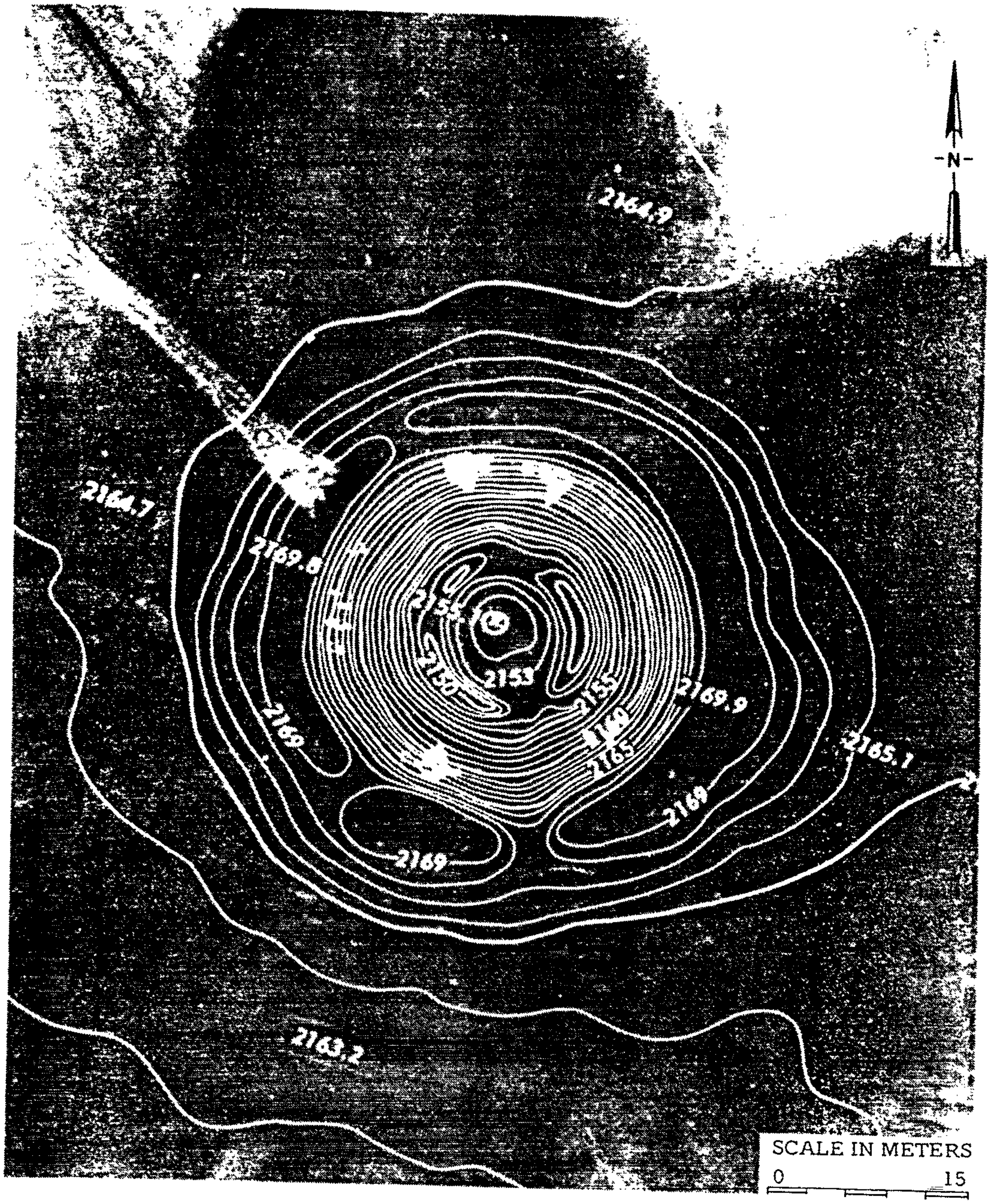


Figure 3/24
Postshot Contours of Event DP6 Crater Area. Elevations in feet; Contour Interval of 1 foot. Ground Zero is Marked by "x" in Center of Crater.
(CRREL Photograph from Davies et al 1971).

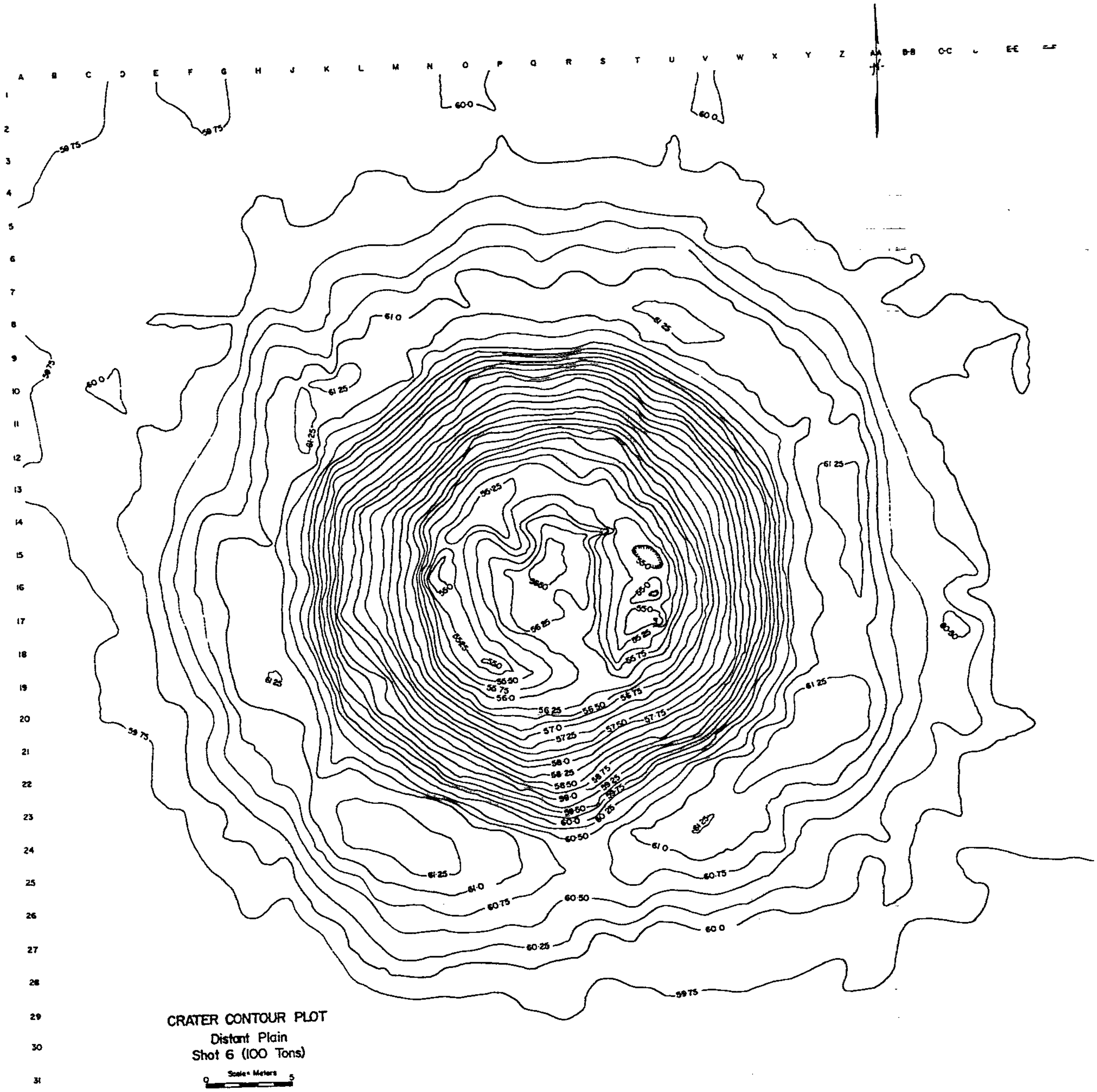


Figure 3/25

DRES Data for Crater Contour Plot in Metric Units from Diehl et al (1968)

3.4 ANFO 3 100T CRATER (WATCHING HILL, 28 AUGUST 1969)

Although Suffield had experience with charges of Ammonium Nitrate/Fuel Oil in the late 1950's, attention had been diverted to TNT due to the regularity of TNT detonations, and the availability of ample supplies which could be provided from the U.S.A. but cast by the Suffield Explosives Group. Nevertheless, by the late 60's attention was again being given to ANFO charges, for several reasons, among which was the belief that ANFO charges scaled rather well to the Nevada Test Site small nuclear detonations, the growing belief that in due course charges of thousands, rather than hundreds of tons would be required, and would probably be detonated on the White Sands Proving Ground in New Mexico rather than at Suffield. The explosive would be cheaper, and could be mixed on site. To this end, considerable work had been carried out by the U.S. Naval Ordnance Laboratory, initially reported by Sandwin and Pittman (1969). At a meeting of Panel N2 of TTCP (who had coordinated all the blast trials at Suffield) it was decided to hold three trials with ANFO explosive at Suffield, two at the 20 ton level, and one at the 100 ton level.

It is the trial at the 100 ton level that is being discussed in this chapter, but it should be mentioned that in the first 20 ton trial, ANFO 1, a circumferential crack was observed in which water had been forced to the surface, bringing with it fine sand. This of course was similar to effects seen on larger trials, but the location of the circumferential crack was considerably closer to the crater lip than the more usual "two radii", being in fact closer to 1.5 radii. We do not discuss the 20 ton events further here, as little else of relevance was noted. Neither 20 ton crater had a discernible overturned flap.

ANFO 3, nominally at the 100 ton level, is of rather more interest, but in the climate of the time comparatively little effort was devoted to the crater studies on this (or any) ANFO shot. Attention was primarily on the airblast. It is noted, further, that the GZ of the ANFO trials coincided with some earlier trials (HEST trials) which may have caused some distortion in the crater data. No sand columns were installed for this trial.

The charge was mixed on site and installed by the U.S. Naval Ordnance Laboratory staff, and consisted of loose ammonium nitrate prills dosed with fuel oil, contained in a hemispherical plastic container with an open top. The ANFO was boosted by means of a 150 lb hemispherical booster of Tetrytol, fired by primacord initiated by a detonator external to the main charge. The ANFO detonated at high order and consumed completely. In theory, ANFO can have a higher yield than TNT, but in practice is usually lower, around 90% for large charges. In ANFO 3 the actual charge weight was 200,900 lb, but the precise yield (less than 100 tons TNT) is not known to the present author but could be obtained reasonably closely from the airblast data. Full details of the data obtained on all three ANFO trials have been given in a two section report, Part 1 Anderson & Patterson (1970) for the airblast and Part 2 Diehl & Pinnel (1970) for the crater studies. In addition, the U.S. Geological Survey Branch of Astrogeology carried out a field survey of the ejecta blankets and aerial photogrammetric mapping of the craters, under the control of David Roddy supported by the Suffield Crater group. Results of that study have been given by Roddy.

The contour map of the ANFO 3 crater as produced by ground survey is shown in Figure 3/26 (this and later figures are all after Diehl & Pinnel. The present author had by this time left Suffield but the team continued active until 1970).

Although very little money was available for the crater studies on the ANFO shots, the team of Diehl and Pinnel made a very creditable study of the rim of the crater, and even of part of the crater floor. Visually, the crater was rather uninteresting, compared with the earlier TNT 100 ton craters, as there was little if any inflow of water, and if any central uplift existed it was inconspicuous, and no opportunity existed to excavate that region to look for possible structural uplift.

However, there was a small water source detected almost exactly at GZ, and the floor of the crater, where it was excavated, showed a pattern of synclinal-anticlinal ridging, which by 1969 were familiar features at the Suffield craters. In addition, there was a clear indication of an overturned flap, which was consistent around

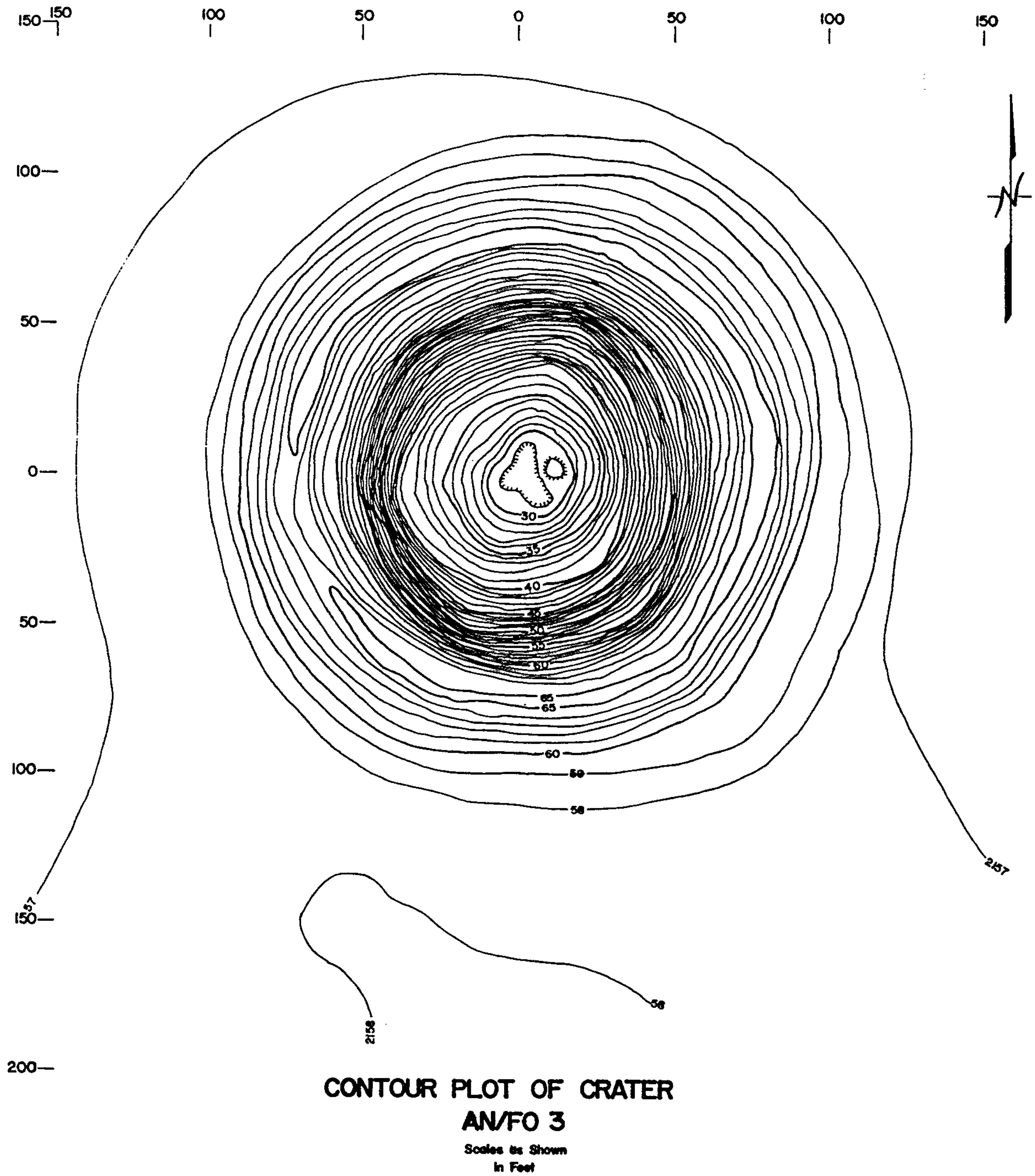


Figure 3/26

ANFO 3 Crater Contour Plot from Diehl & Pinnell (1970) the entire periphery of the crater. This overturned flap was not, however, either as consistent and deep nor as easily traced beyond the rim structure as in the major Suffield 500 ton craters. In fact the evidence was closer to that seen in the ancient, and disrupted flaps around some impact craters, and would not have been clear evidence of coherent overturning rather than sequential, inverted fallback.

The excavated sections are shown in Figure 3/27 (a & b) and Figures 3/28 and 3/29. Note in Figure 3/27 in particular the position of the small water sources, which compare closely with data shown in later chapters for the 500 ton Suffield trials.

In comparison with the earlier 100 ton trials, and even more the 500 ton trials, yet to be described, ANFO 3 appears relatively uninteresting which of course demands an explanation.

The first point is that the explosive charge itself was different, both in chemical composition and in method of installation. The yield was, presumably, somewhat less than the nominal 100 tons TNT equivalent. However, the difference could hardly have been sufficient to explain the morphological differences actually observed in the craters.

It is thought, by the present author, that the explanation lies in the nature of the test site itself. Although nominally a Watching Hill test site, the GZ was removed from those of the 1961 Suffield 100 ton, and the later 500 ton trials, by several thousand feet, and did not lie on the area of clearly lacustrine, horizontal stratification. The site was to the East of the Watching Hill feature, and relatively close to the escarpment of the Drowning Ford site. Diehl & Pinnel note that "there was very little layering in the soil" and certainly in the sections of Figures 3/27 to 3/29 few quite thick layers of presumably similar texture are identified. As Roddy was on site and cooperating with Diehl and Pinnel in geological mapping, this observation may be taken at face value as it is certain that any clear marker horizons would have been recognized. It is also probable that the water table was marginally lower in view of the proximity to the Drowning Ford escarpment. However, as will be seen in later chapters, the crater has sufficient commonality with the later, 500 ton complex craters that it can not be considered an exception to the rule that large scale craters at Suffield tended towards a complex suite of overturned flap, and water sources associated with circumferential structures. Figure 3/30 is copied from a 35 mm transparency which shows the overturned flap. Other such slides are in the archives associated with this publication. It will be noted in Figure 3/30 that there is a single clearly visible sand stratum which, it seems to the present author, indicates that immediately under the rim there was a form of coherent overturning, of the type which will be indicated with a wealth of detail in the chapter on the PRAIRIE FLAT crater.

It is perhaps worth showing two additional photographs of this visually uninteresting crater, Figure 3/31 is a view looking across the crater, before excavation started, with the main Watching Hill site in the distance. The figures and vehicles give an idea of scale. Figure 3/32 is a view across the rim of the crater, but looking towards the main Watching Hill feature in the distance. The blocky, but mainly disintegrated and unstructured nature of the debris even at the crater rim is evident.

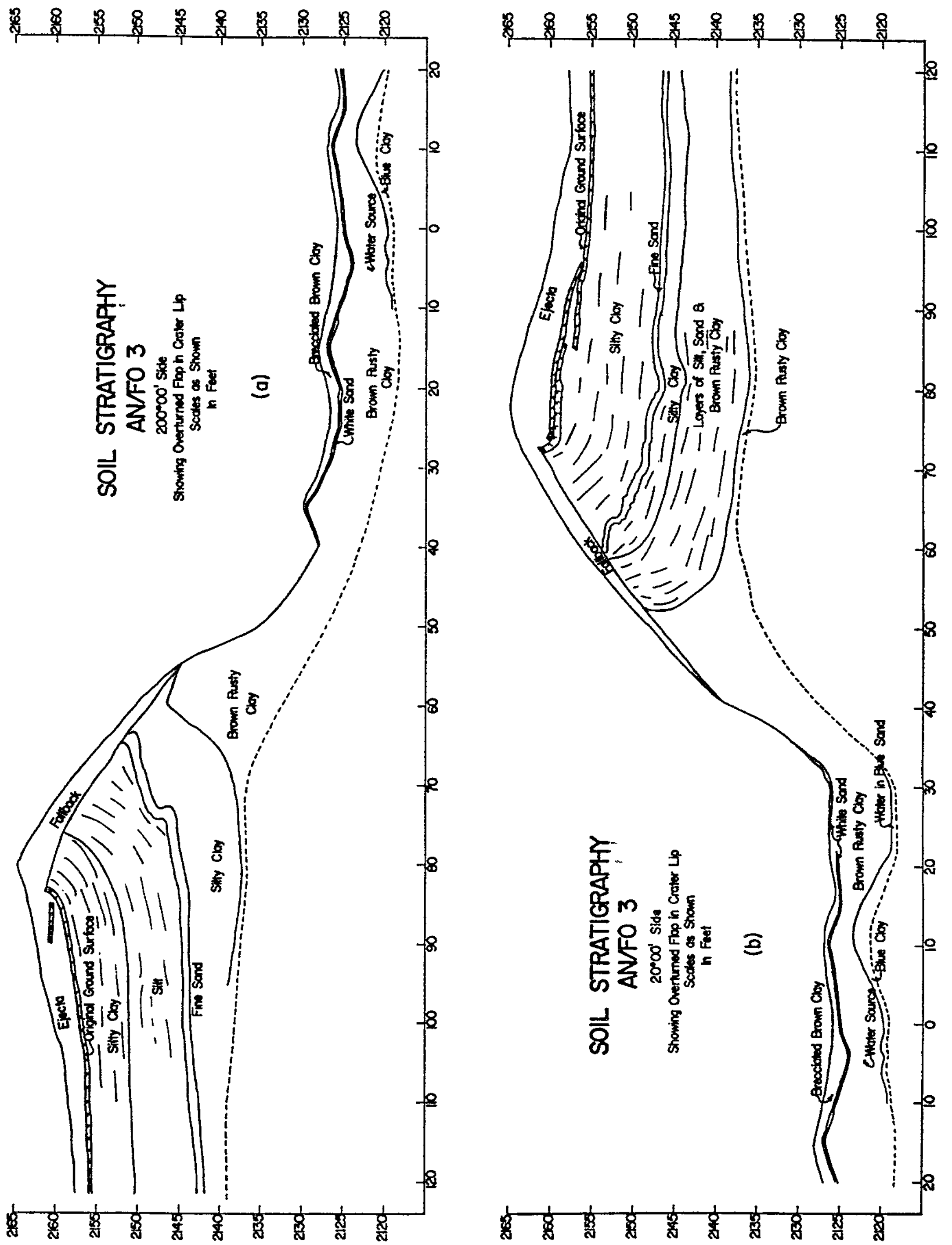


Figure 3/27

ANFO 3 Soil Stratigraphy Sections From Diehl and Pinnell (1970); (a) Left Rim; (b) Right Rim

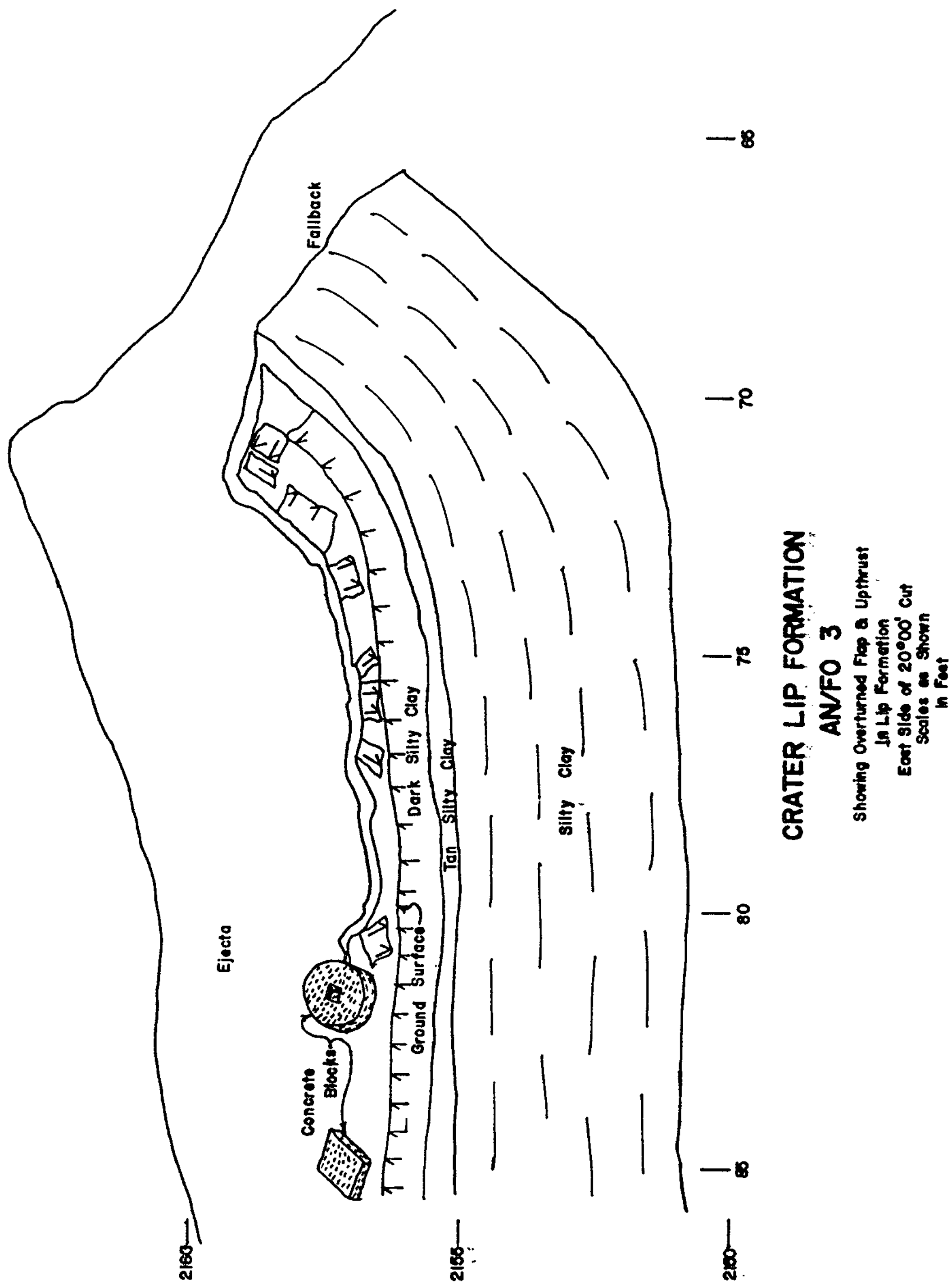


Figure 3/28
ANFO 3 Crater Lip Formation (East 20^0) from Diehl and Pinnell (1970)

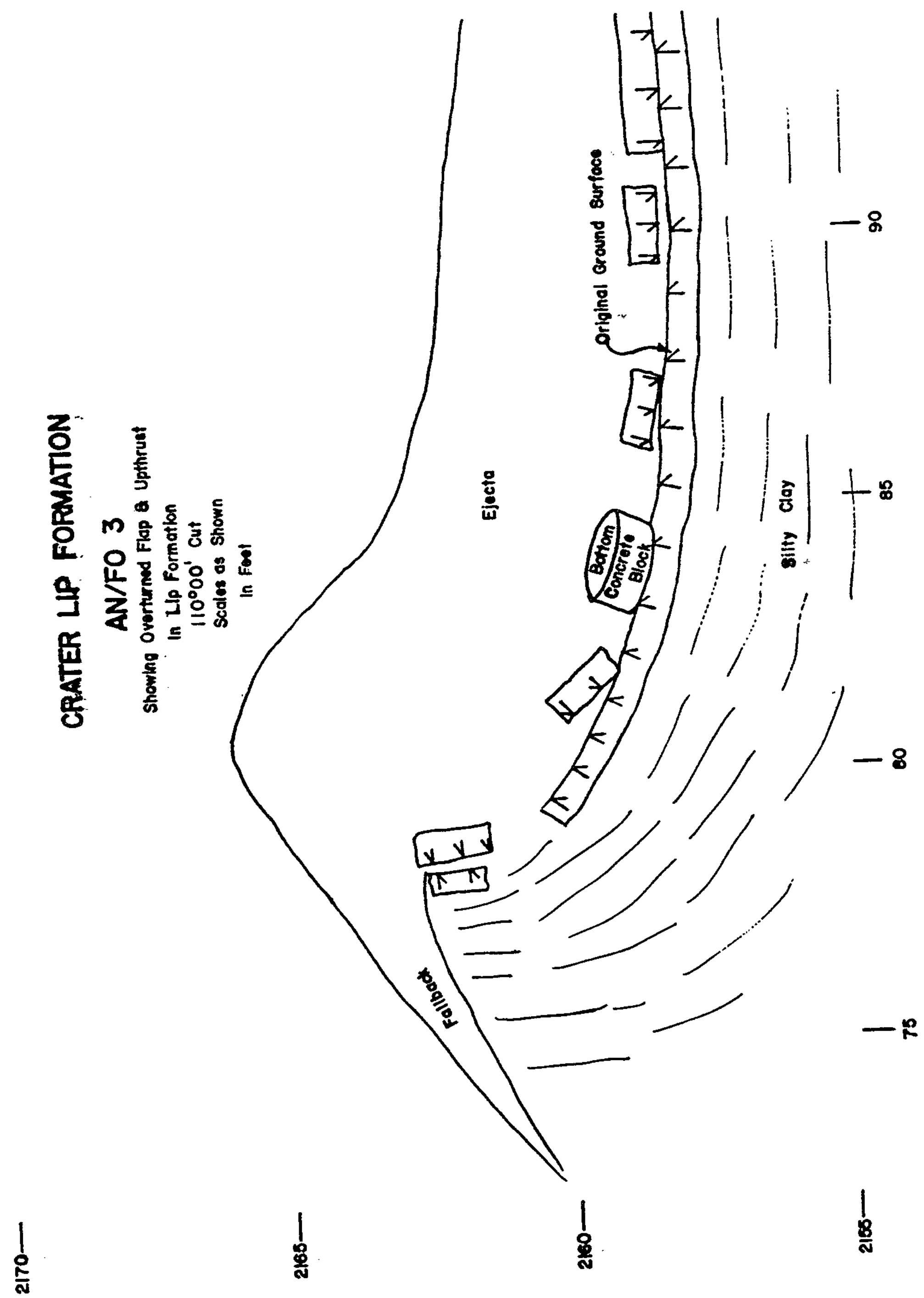


Figure 3/29

ANFO 3 Crater Lip Formation (East 110^0) from Diehl and Pinnell (1970)

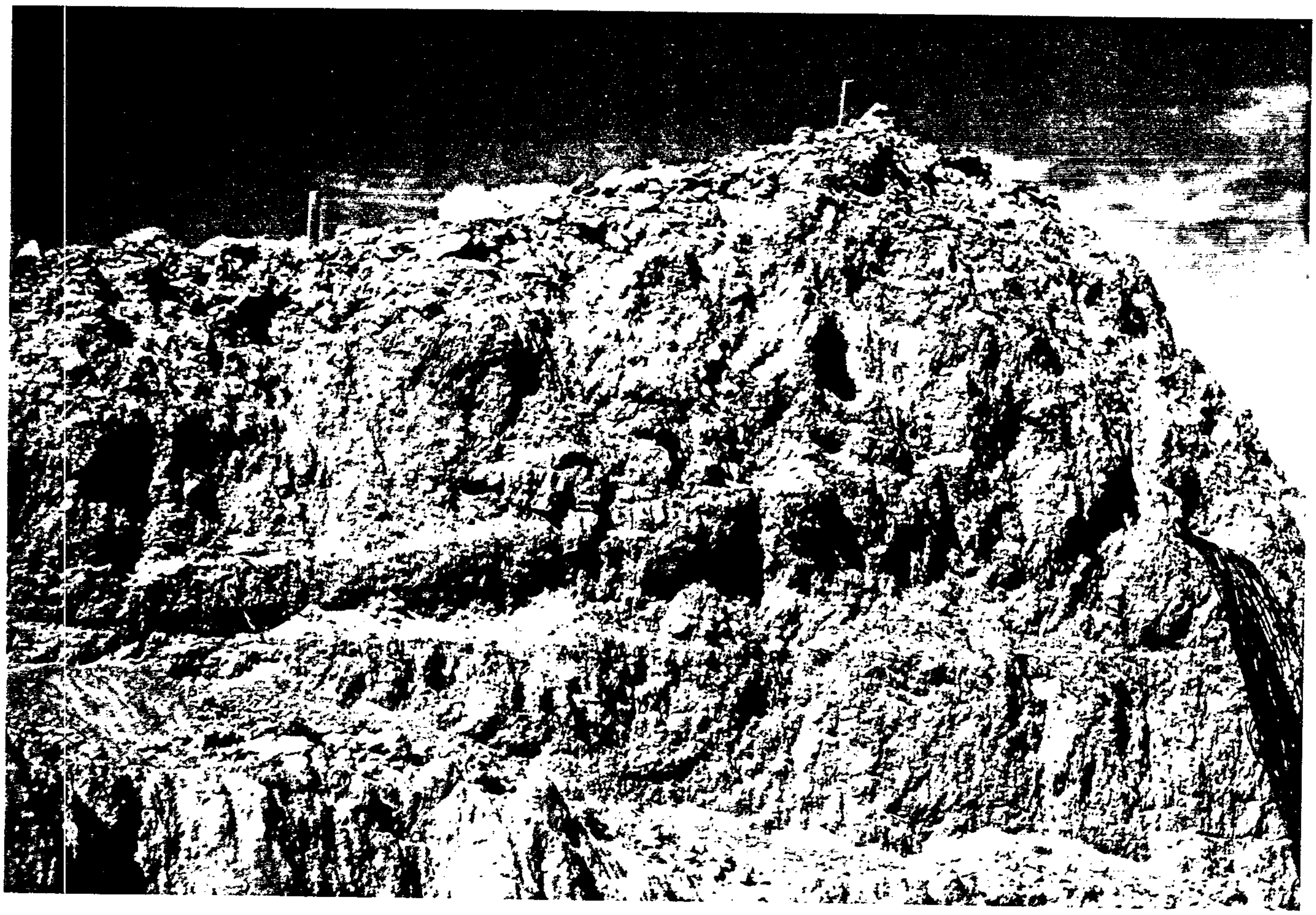


Figure 3/30

Overturned Rim Section of ANFO 3 100 Ton Crater
(note coherent overturning of sand stratum)

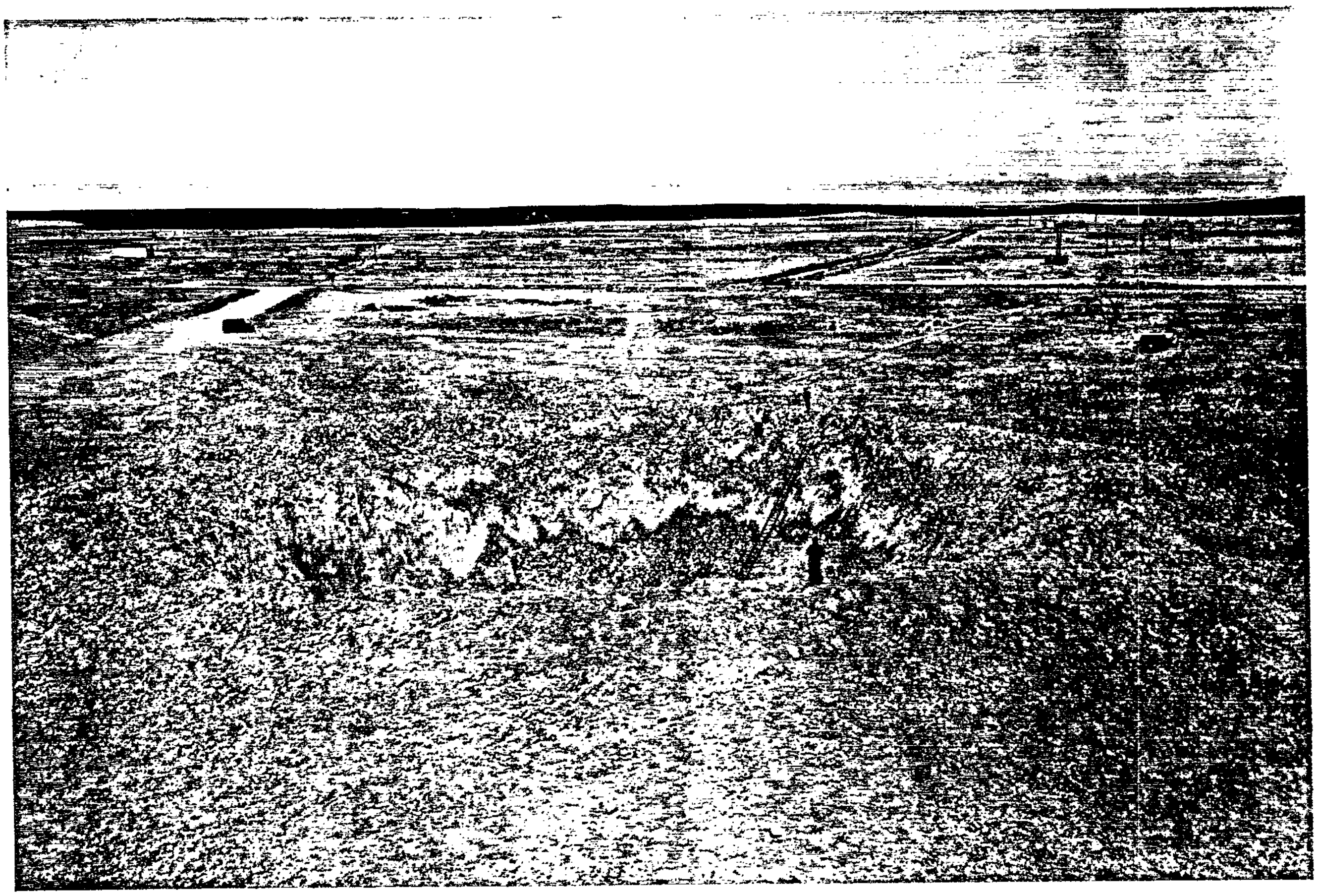


Figure 3/31
View across ANFO 3 with Watching Hill Test Site Beyond

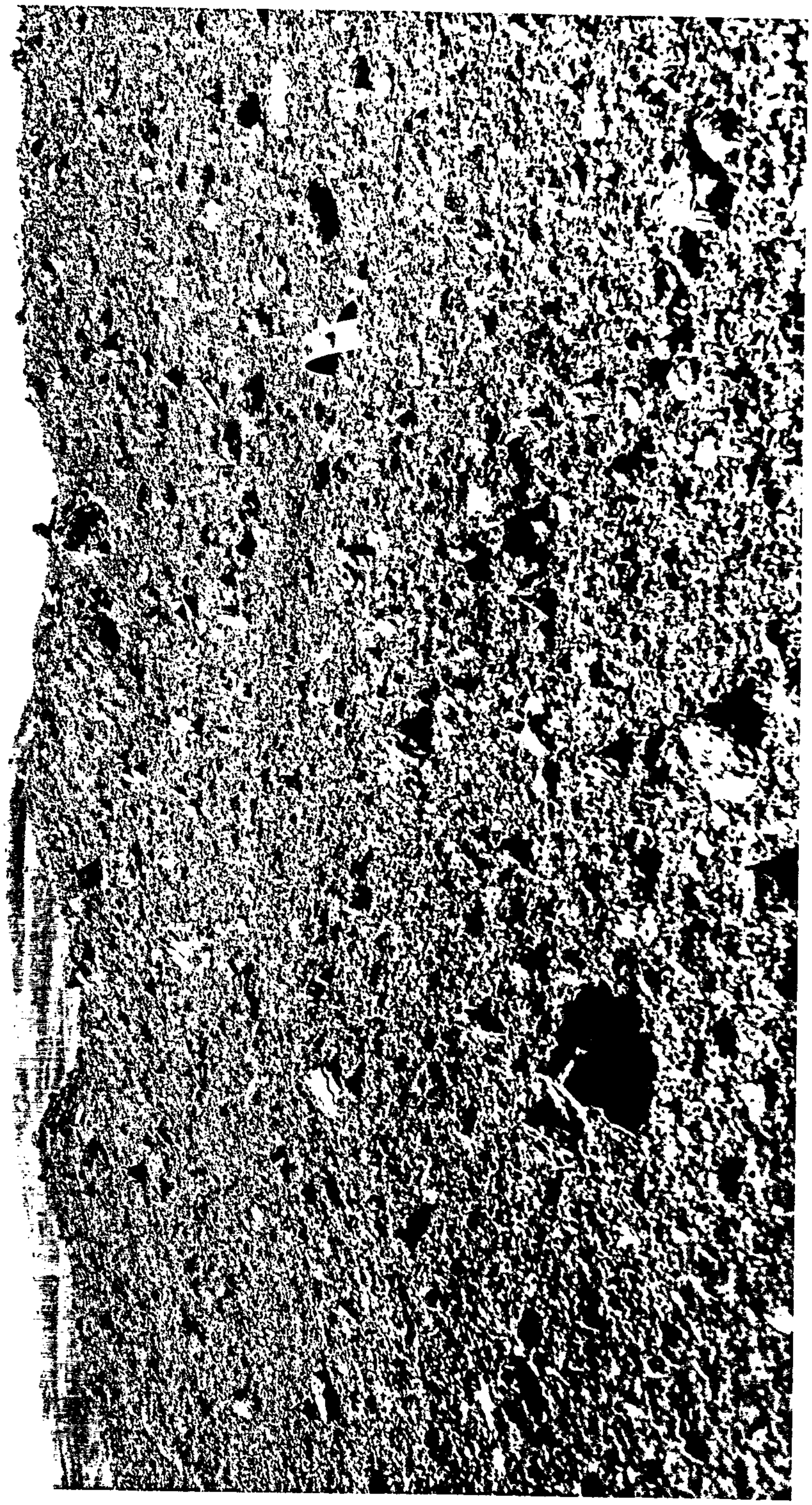


Figure 3/32

Rim of ANFO 3 100 Ton Crater with Watching Hill Beyond

Insert: Continuation of Section 3.3.5 (Page 3-37) giving New Observation and Interpretation dated September 1995 for the "White Sand"

In September 1995, the author was supervising the excavation of new 'Dugouts' on the Yeast Longhorn Ranch, on the south edge of the Cypress Hills, located in southeastern Alberta, just south of the Eagle Butte Structure discussed in Chapter 7, Section 7.2. In one of the dugout locations, underlying some four feet of recent alluvium, the excavation reached a Blue Clay, reminiscent of that found uniformly beneath the Watching Hill test site.

It was observed that roughly one foot below the top of the Blue Clay there was a thin seam - less than three inches thick - of Bentonite, quite dry and basically white in colour. Bentonite is a devitrified volcanic ash, and several such layers are found in the clay/shale strata of the Bearpaw formation, which overlies the Oldman bedrock in Southern Alberta. The Blue Clay appears to be a colloidal marine clay, and Baculites fossils occur in it and the underlying strata. The beds of Bentonite probably derive from the Sweetgrass volcanics in Montana. It is this Bentonite, mixed with clay, which forms the difficult Gumbo soil, making access to some areas impassable by wheeled transport in wet seasons. However, in situ in the clay, the material remains dry. The author observed that as the back hoe excavated the clay, through the layer of Bentonite, the dumped soil became covered with a white 'flour', and also with hand-sized specimens which had a remanent structure. This phenomenon was directly comparable with that observed at the Distant Plain 6 crater, which at that time was dismissed by most participants as a 'shock phenomenon'. The author, however, considered it 'bedrock' but could not correlate this with the known depth of the Oldman strata.

It now appears that the DP6 crater did penetrate 'bedrock', but that it was, in fact, the Bearpaw clay overlying the Oldman. The Bentonite stratum is universal in the Bearpaw, and at the time of formation of the crater - well before the effusion of water from greater depth - such a layer would be dry, and highly mobile when disrupted. As it now appears certain to the author, the DP6 crater disrupted such a stratum at a depth comparable with that of the final crater. Thus the observation of a crater coated with 'white flour or sand' but containing hand-sized specimens with remanent structure is explained. The material is indeed from bedrock, but from the overlying Bearpaw marine clays and shales, not the arenaceous Oldman. At the time of the trials, and for the following years, the Blue Clay layer underlying Watching Hill was thought to be of glacial origin. However, it is now considered by the author to be Bearpaw, and the horizontal lacustrine deposits that constitute the major test site area to sufficient depth was deposited in a Pleistocene lake lying on the Bearpaw clay bottom. Although at the Rapid Narrows Gorge on the South Saskatchewan River just east of the test area, the Bearpaw clay formation over the Oldman bedrock is exposed in the cliffs, it should be pointed out that excavation of the various large-scale blast craters rarely penetrated deeper than the top of the Blue Clay. Also, the craters, in general, were 'wet craters' due to the effusion of water. Bentonite, when wet, is not easily recognised; and was certainly not detected at the time of the trials. Therefore, it was not suspected at the DP6 crater. However, the new observation and interpretation of the soil composition and strata, finally provide the information necessary for explaining the occurrence of the 'white sand' at the time of the large-scale blast trials.

CHAPTER FOUR

THE 500 TON SNOWBALL CRATER (17 JULY 1964)

4.1 INTRODUCTION

The SNOWBALL Crater, produced by the detonation of a 500 ton hemispherical charge was in all probability the most significant of all the Suffield craters. It was the first crater which unequivocally demonstrated that complex structures simulating "crypto-explosive" structures on earth, and lunar craters, could be produced by surface explosions of known characteristics.

Consequently, it marked the advent of cooperation of agencies whose prime concern was with natural, geological structures rather than with the military effects of nuclear weapons. This of course was not an immediate effect, but resulted from the progressive alerting of the scientific community by the Suffield team as the study of the crater progressed over the remainder of 1964 and throughout 1965. In particular, Dr. C.S. Beals, the recently retired Dominion Astronomer for Canada, and the doyen of the community that believed crypto-explosive structures were the scars of meteoritic impacts, was influential. He alerted both his old department, which had an active programme studying probable impact structures in Canada, and the American Astronomical Society. As a result of the latter action, Dr. Eugene Shoemaker, himself an expert on the Arizona Meteorite Crater, alerted the United States Geological Survey, and arranged, among other things, for Dave Roddy, at that time involved in the study of the Flynn Creek central uplift structure, to visit the Suffield test site part way through the excavation of the SNOWBALL Crater. Subsequently, the USGS, specifically Roddy, participated in later explosive trials at Suffield. While these were the initial "outside" contacts, the ripple effect was considerable. In this chapter, the field evidence collected at the SNOWBALL crater itself, over a two year period of study and excavation is presented.

One other point needs to be stressed in these introductory comments. The "anomaly" of the 1961 Suffield 100 ton crater had not been ignored, and it was planned before the SNOWBALL trial that the study of the expected crater would be greatly expanded by not only the Suffield team and WES, but also by other agencies. In the event, the SNOWBALL crater was given extensive photographic coverage from within minutes of the detonation, and throughout the two year study period. Many hundreds of photographic negatives have been preserved in various archives. With the very heavy pre-planned programmes of all agencies, the demand upon the authorized photographers was rather overwhelming. The Suffield team was not averse to asking for support from other agencies, and was given complete and willing support. In due course, Suffield was provided with original and copy negatives from many agencies, and particular note must be made of the late Dana Parker, of the University of Michigan, and of Hackman both of whom provided extensive, and superb collections of photographs to the present author. Many of the more notable features were the subject of many photographs, some effectively duplicating, but many sequential as the crater matured. Where the record is clear, due acknowledgement of source is given, but this has not always proved to be possible, hence this general admission of debt.

With the vast accumulation of data, it is inevitable that over the years there have been numerous releases and interpretations relating to the SNOWBALL crater itself, and the hierarchy of Suffield craters. As a result, some photographs have been used in other publications, both restricted and in the public domain, by many agencies. However, no single publication has covered the SNOWBALL crater from its earliest formation to its mature, and then excavated stage, and it is that task that is attempted here, based upon the collected archives and a considerable degree of hindsight. It is most unlikely that full understanding of this remarkable crater will be achieved, as over the past three decades "new questions" have been asked time and time again, which has demanded a fresh study, and sometimes fresh interpretation of the field data.

Figure 4/1 is an aerial view of the SNOWBALL crater, taken days after the detonation. It is, probably, the appearance of the crater which remains in the minds of most participants, but in some ways it is misleading, as it shows an ephemeral stage which only existed from after the first day for the first few weeks. As will be demonstrated, the appearance of the newly formed crater was quite remarkably different, but the first phase only lasted a matter of hours. Later, too, the water vanished from the crater, leaving a structure which was dry, but considerably modified from the original structure. It was only very much later, during the excavation phase, that the degree of modification became apparent.

What was, however, quite clear from the outset was that the SNOWBALL crater was unique, and while clearly different from previously known explosion craters there were facets of the structure which on the first day led to it being called the "first man made Moon Crater".

4.2 THE SNOWBALL CRATER IMMEDIATELY AFTER THE DETONATION

Hitherto, very little attention has been paid to the nature of the freshly formed crater, and certainly little has been placed in the public domain. In this section, attention is concentrated upon the appearance of the crater as it appeared within minutes of the detonation, and as it developed during the first 24 hrs.

Figure 4/2 shows what was found on first approach to the crater, within less than 5 minutes of the detonation. The smoke background (which had nothing to do with the detonation) and all the structures which are highlighted against that background, lay beyond the crater, some fairly close but in the main several hundred feet beyond. There is no visible evidence at all of a crater, even though it lay in the middle of the field of view and a matter of a few hundred feet away from the photographer. This photograph should be compared with Figure 3/2, which shows the 1961 Suffield 100 ton crater from roughly the same relative position, though at a relatively late time. In that photograph, the crater is immediately evident, and the primary feature is the elevated rim.

This photograph of SNOWBALL will be mentioned again in a later section

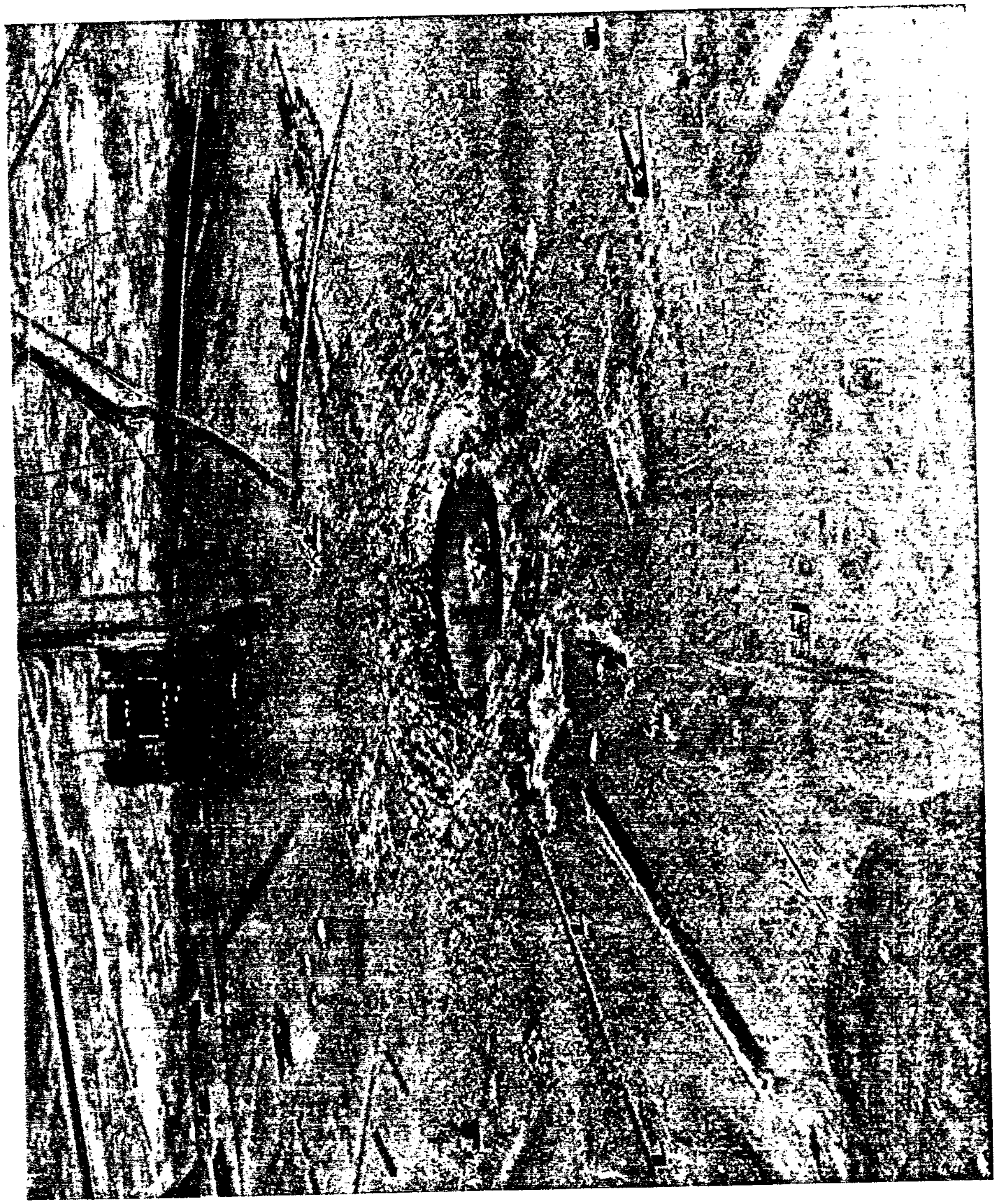


Figure 4/1
Aerial Oblique of SNOWBALL Crater Two Days after Formation

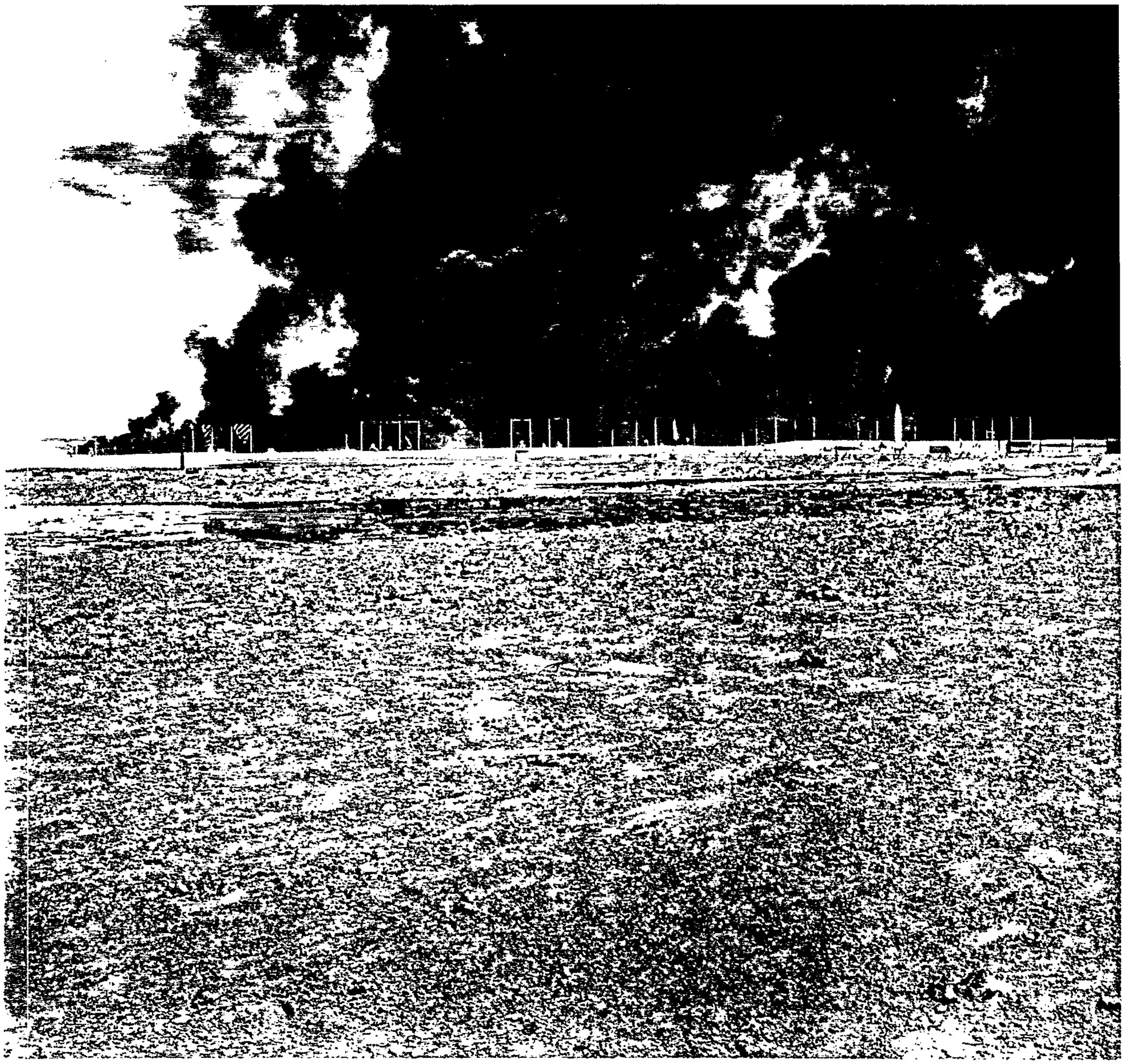


Figure 4/2

Ground Level View Across SNOWBALL taken Five Minutes after Zero
(Note lack of rim and the early water on surface)

when discussing the inflow of water. For the moment, the focus is on the strange lack of a visible crater. As a closer approach was made, it was found that there was a general, though not very rapid, inwards slope to the ground surface, even above the ejecta layer. In effect, there was found a very wide - several hundred foot diameter - shallow "saucer", and it was only in the middle of that saucer that there was a sudden, sharp descent into the "crater proper". Even that crater had no perceptible elevated rim structure, though there were occasional mounds of blocky "ejecta" visible. Figures 4/3, 4/4 and 4/5, all of which were taken from the edge of the crater at T+10 minutes, show what "rim" there was, including some of the blocky "ejecta", using that term in a loose sense of material from within the crater void, however deposited.

Figure 4/6 was also taken at T+10 minutes, looking across the crater void, and over the central uplift. It will be noted that at this stage the crater is essentially dry, though some water is appearing as a slow trickle, both from the central peak and from the edge of the crater wall.

The above photographs, and others from the same location were taken by the late Dana Parker, of the University of Michigan, who provided immediate copies to the present author. These, and others from the same location, were combined into a panoramic view across the crater, as shown in Figure 4/7, which it is believed was used in a University of Michigan report. Similar panoramas exist for later times, specifically T+114 Minutes, T+117 minutes and T+9 hours and 7 minutes, but these are not included in this section as they show the various stages of the filling of the crater with water.

This panoramic view of the crater, when it was no more than 10 minutes old, shows the unique nature of the pristine SNOWBALL crater, an essentially dry, rimless hollow in the centre of a wide, shallow saucer, with some form of central hill. If this structure had retained its initial appearance and been found in that state, it is highly improbable that it would have been recognized as a crater produced by a surface explosion, even by a geologist familiar with experimental explosion craters.

It was observed, on the initial approach to the crater, that long open cracks existed in the ground surface "outside" the crater rim. Figure 4/8 is an example of such a crack as first seen, a wide dry crack with some inward slumping of the walls. There are many photographs in the archives, from various sources, which show these cracks and their development over time. At first it was not appreciated that there were several sets of such fractures, some radial to the crater, and others circumferential. They were most evident on the south side of the crater, but as will be seen in Figure 4/9, an oblique taken several days after the detonation, there are certainly two circumferential cracks in a close pair, and probably a third at roughly twice the distance from the crater rim, which circumscribe the crater. A possible fourth circumferential crack, quite close to the crater rim, and intersecting a major radial fissure, is shown in Figure 4/10, which is slightly misleading due to excavation along the radial.

The reason that the full nature of the intersecting sets of fissures (or faults, as will be seen later) was not immediately recognized lay in the fact that in general they were hidden by a light layer of ejecta, except where the ejecta had fallen into the void.

Figure 4/11 is the best photograph available showing the main pair of circumferential cracks, obscured by fallback, while Figure 4/12 shows the author demonstrating the (minimum) depth of a crack only locally exposed. The photographs in Figures 4/11 and 4/12 were taken by Hackman and provided to the author as duplicate negatives. Many other such photographs, from several sources exist in the archives.

The radial cracking was not observed on other major Suffield craters, even the later craters where detailed mapping of cracks and folds was undertaken. The extensive nature of such radial cracks on SNOWBALL is shown in Figure 4/13, which shows the longest radial crack found. The crack is visible in the photograph but also marked by stakes. This is a relatively late photograph, taken after the water flow had ended. It may be noted that in this case the sources distributed along the crack are in the form of slight hollows. Discussion is deferred to the next section.

Note that there is a visible trace of a circumferential crack just on the viewer side of the nearest stake. At this late stage identification of this crack is uncertain, since even at the time of the photograph it was not as pronounced a feature as the main pair of circumferential cracks which must have lain quite closely behind the photographer's position.

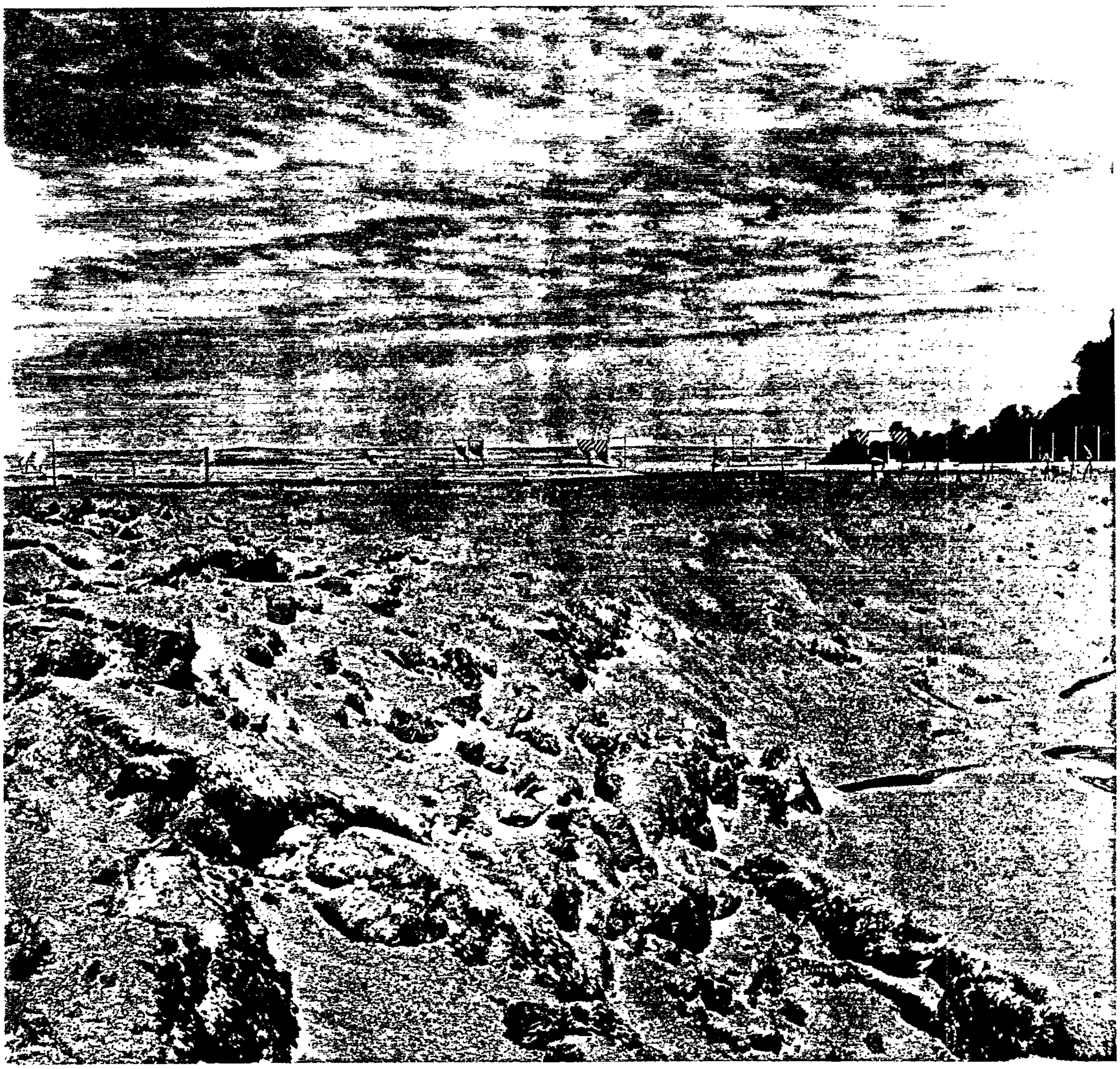


Figure 4/3
Rim Area of SNOWBALL Crater at T+10 Minutes

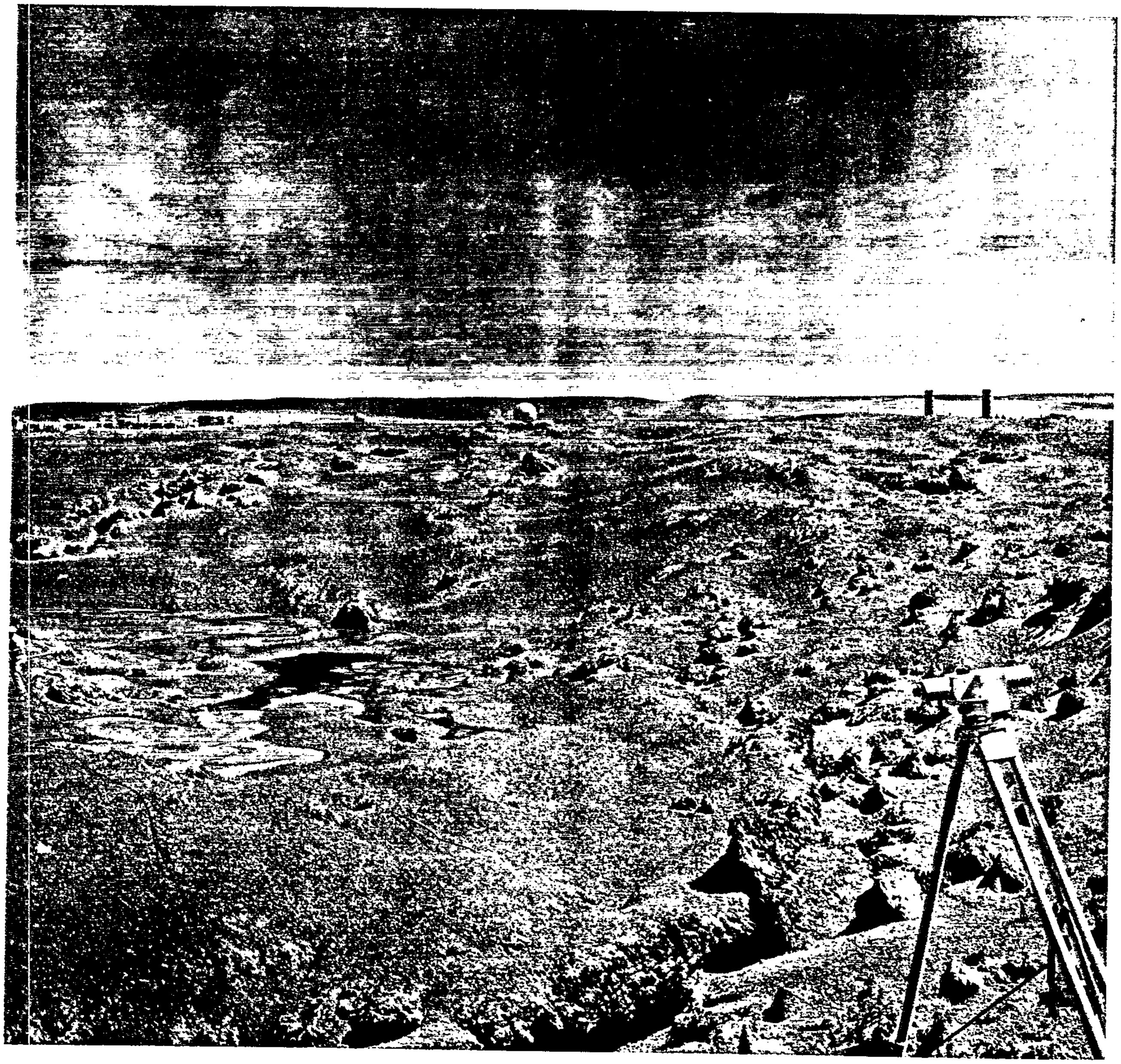


Figure 4/4
Slow Release of Water at T+10 Minutes, SNOWBALL Crater

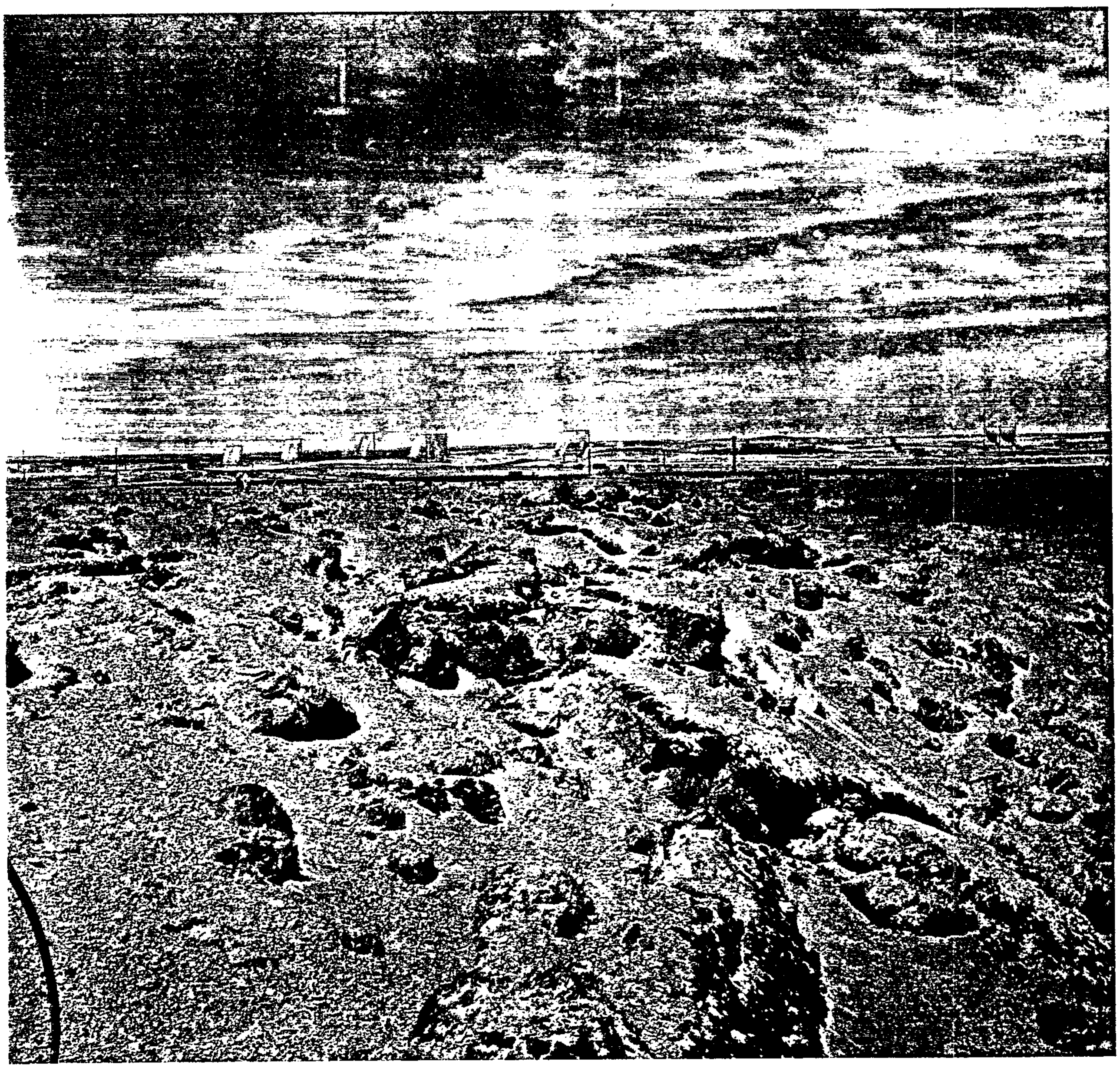


Figure 4/5
Blocky Terrain on Rim of SNOWBALL crater, at T+10 minutes

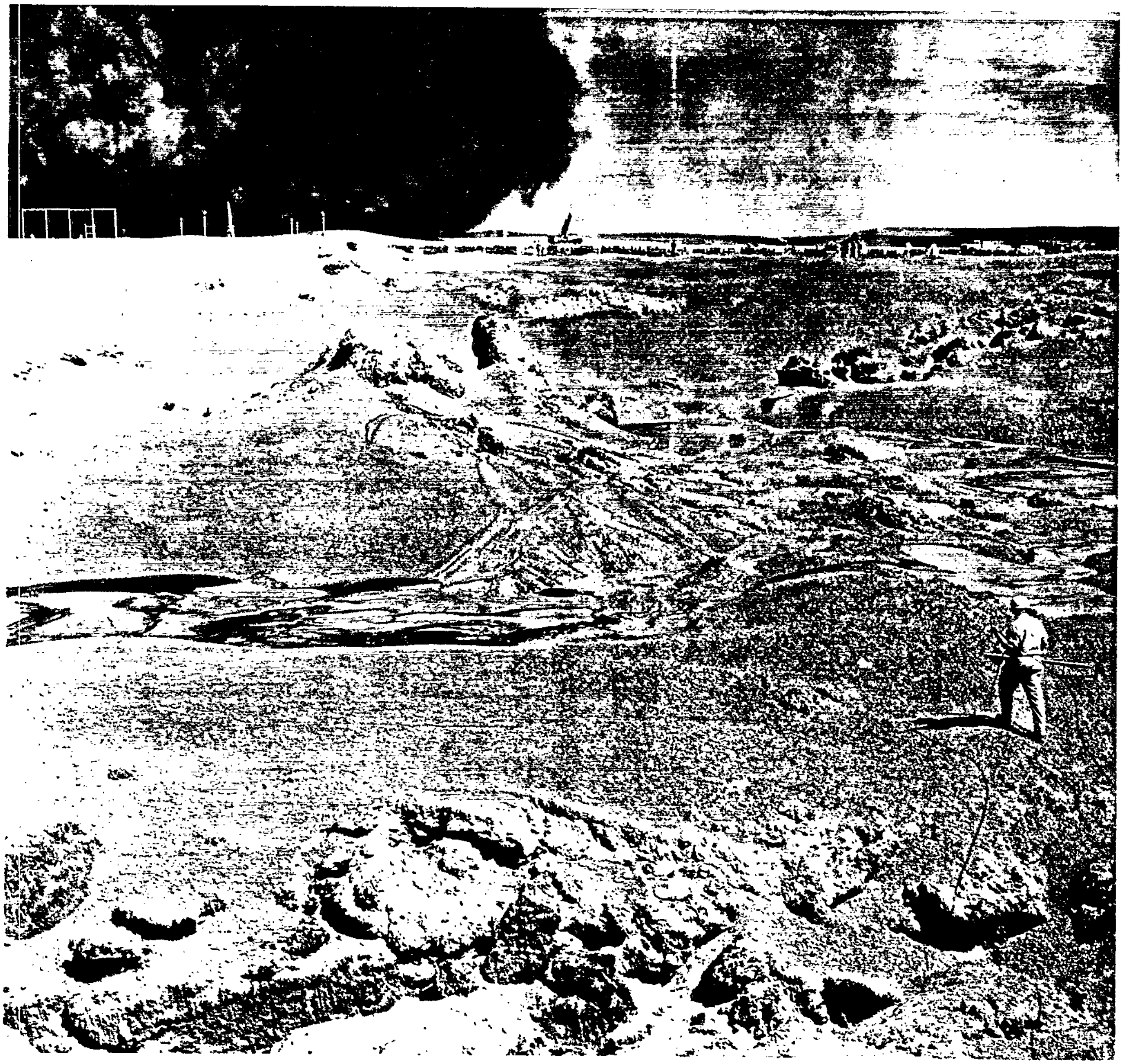
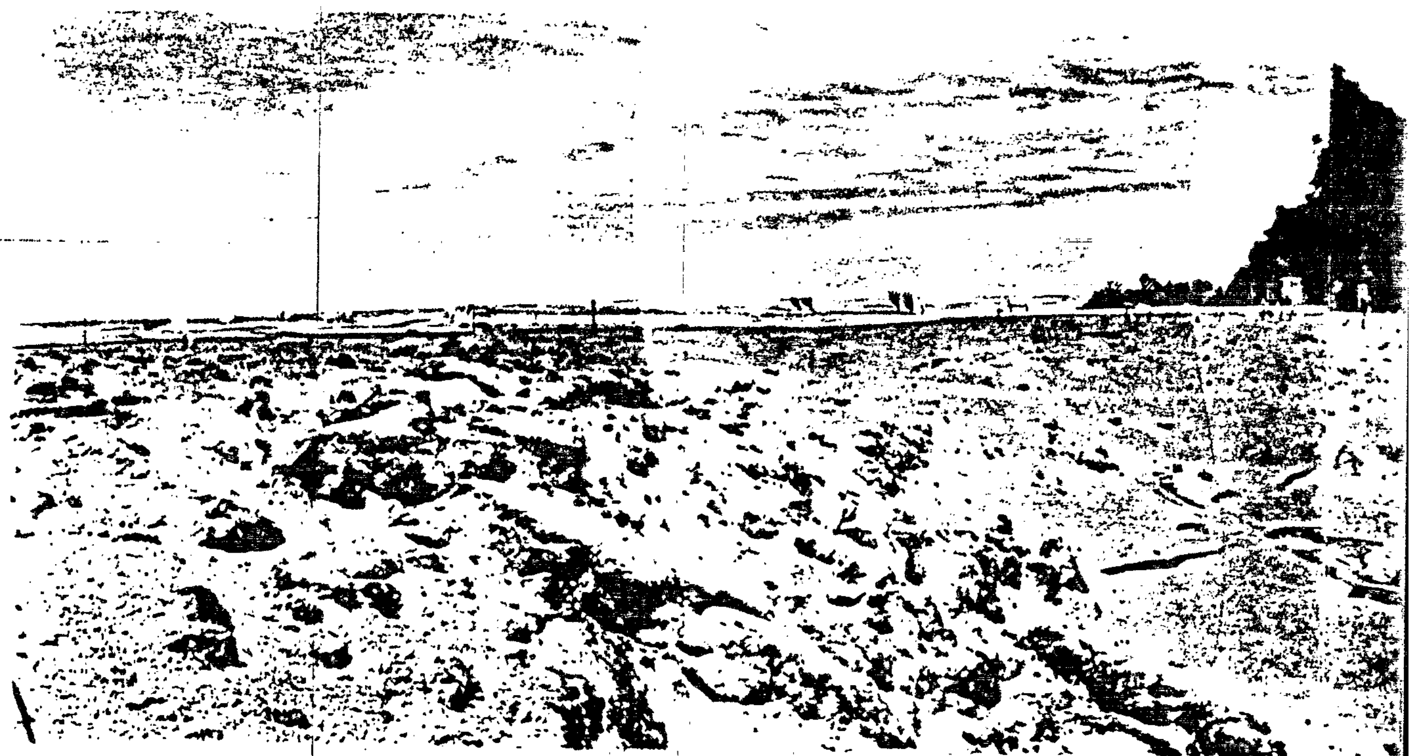


Figure 4/6
View across Central Uplift of SNOWBALL Crater at T+10 Minutes



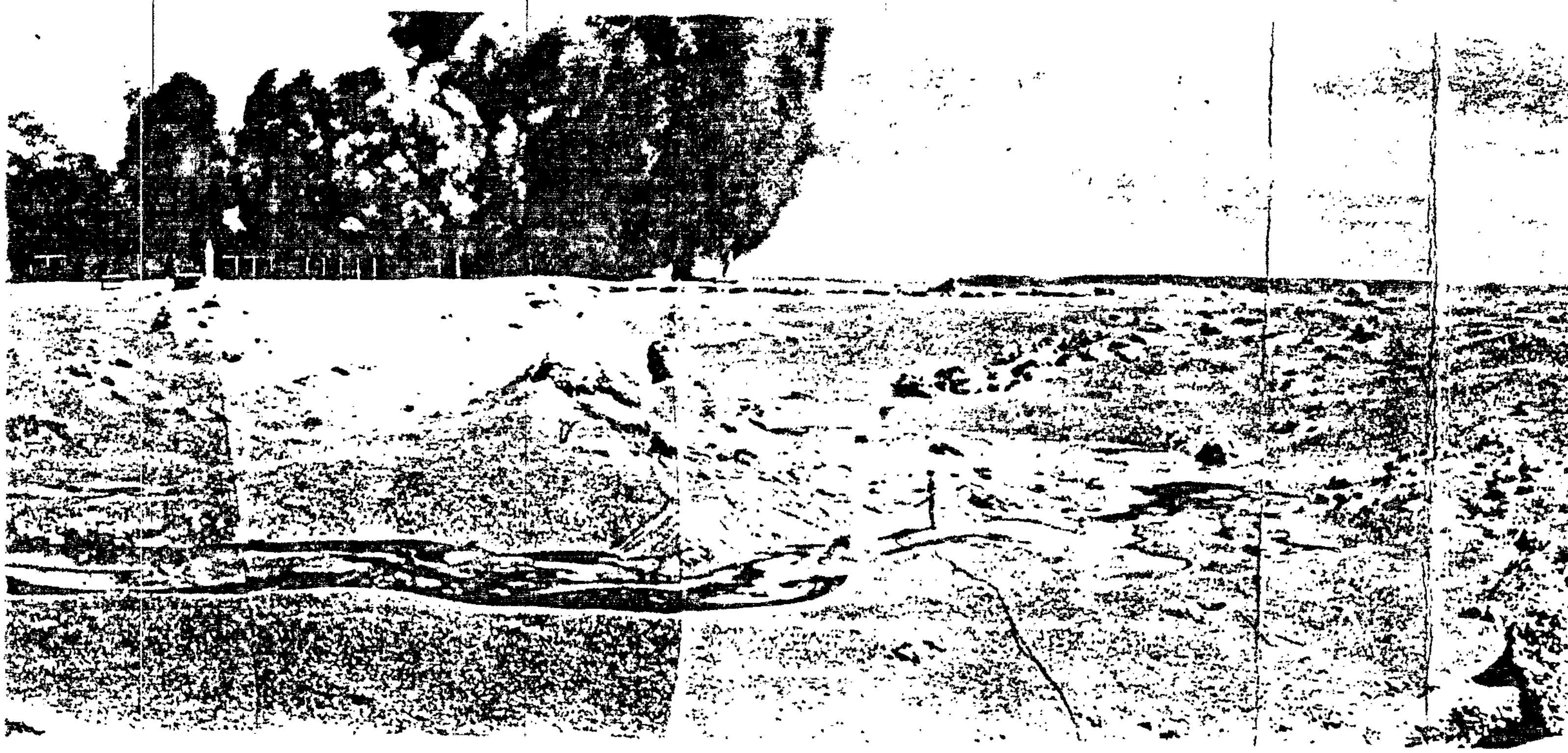


Figure 4/7
Panoramic View across SNOWBALL Crater

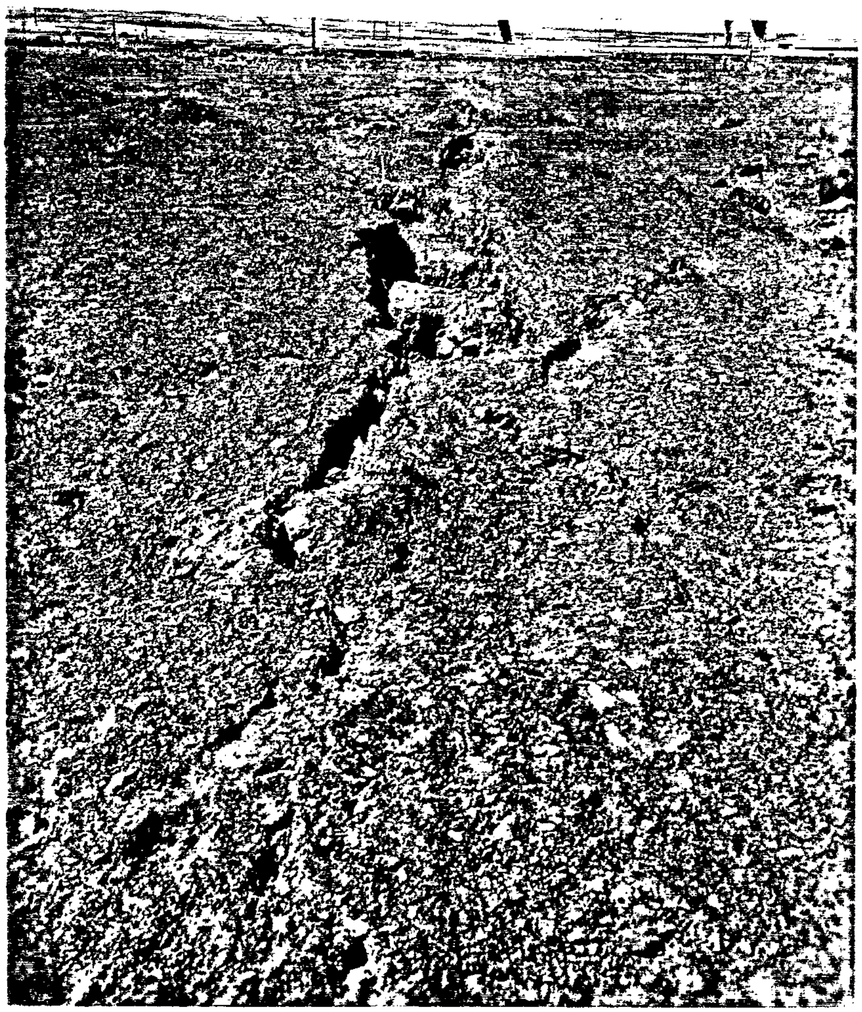


Figure 4/8
Initial Appearance of Circumferential Crack SNOWBALL Crater

Figure 4/9
Aerial Oblique after Main Water Flow Ended SE View of SNOWBALL Crater

Figure 4/10
Intersection of Radial and Circumferential Cracks Near Rim SNOWBALL Crater

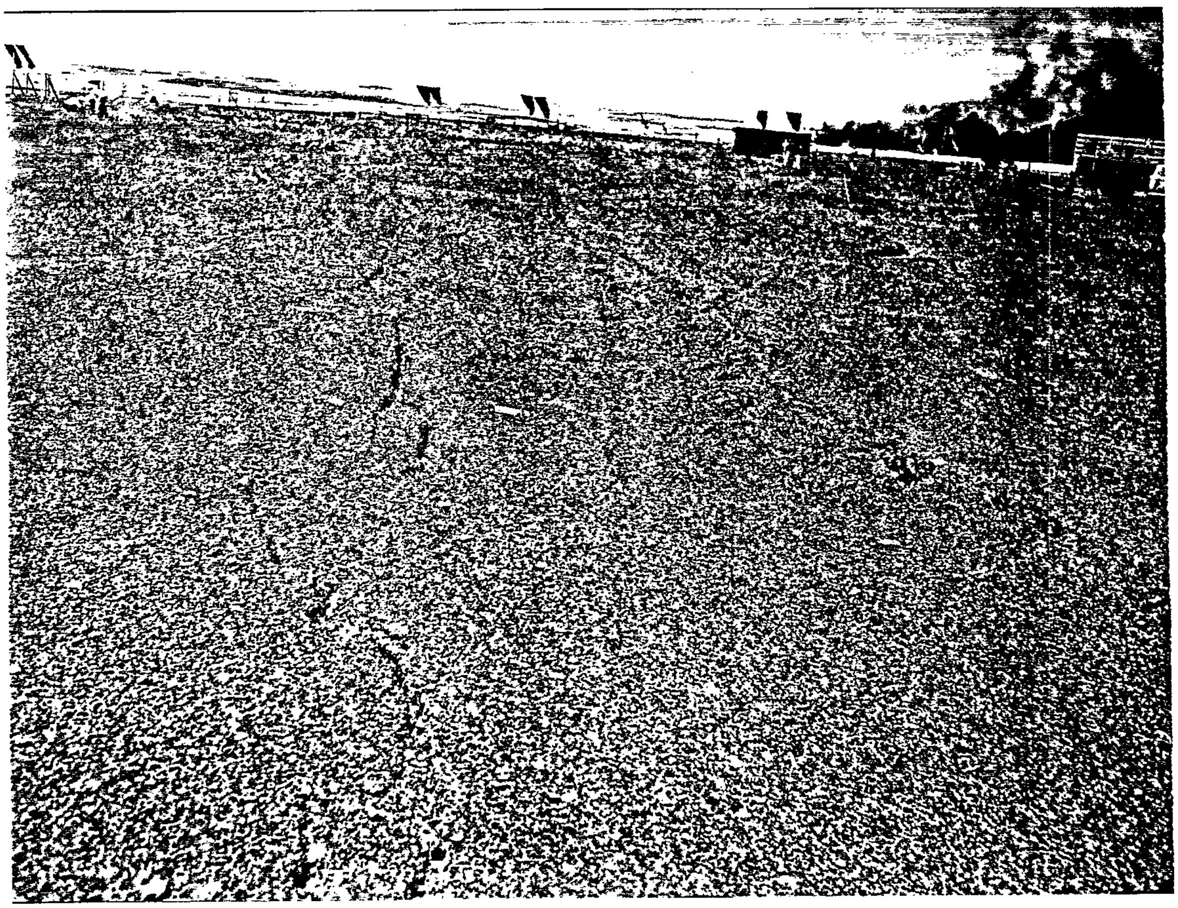


Figure 4/11
Main Pair of Circumferential Cracks as First Visible in Ejecta of SNOWBALL Crater

Figure 4/12
Author Demonstrating an Isolated Exposure of Crack Below Ejecta
SNOWBALL Crater

Figure 4/13
Radial Crack Traversing Surface Flooded Area of SNOWBALL Crater

4.3 PSEUDO-VOLCANIC ACTIVITY RELATED TO THE SNOWBALL CRATER

In an earlier chapter attention was drawn to the existence on the 1961 Suffield 100 ton trial of a single smooth sand cone generated by the release of sand-laden water from the central uplift of that crater. However, it was on SNOWBALL that this type of activity first became a major phenomenon. The activity was dubbed "pseudo-volcanic" both due to the appearance of individual cones, and the similarity observed between the effects on SNOWBALL and the distribution of small, presumably volcanic, cones associated with major lunar craters. As will be seen, excavation of the SNOWBALL crater confirmed that the analogue to volcanic activity was more than superficial.

Attention is drawn back to Figure 4/2, which shows a flooded area observed on the first approach to the crater. The location is roughly four to five times the radial distance from GZ to the crater rim. As this photograph was taken within less than five minutes of the detonation, and before there had been any significant release of water in the crater void itself, the mechanism of release is rather a mystery. In the case shown in Figure 4/2 there is no obvious point source, nor is there evident accumulation of a sandy deposit - the area is simply a large surface wet patch of ground. At this distance from GZ, it is highly improbable that transient ground pressure due to the detonation could be large enough to compress the upper layers of silt to the point where connate water would be released. The implication is that by some mechanism water was elevated from the upper "perched" water table through a minimum height of between 25 and 30 feet, with no evident fissuring of the surface.

Although several such areas, wetted virtually at detonation time, were noted, in general the water flow did not start until around ten minutes after the detonation, as is shown by Figure 4/6 in the previous section. At a time between 15 and 30 minutes after the detonation, "explosive" eruption of water occurred, both at the central uplift and external to the crater. The effect at the central uplift will be discussed below, but Figure 4/14 shows the appearance of the crater, particularly the external regions, some days after the formation of the crater.

In this photograph there will be observed many pseudo-volcanic provinces, which appear white in the photograph, and these are generally associated with one or other of the major circumferential and radial cracks. Attention is drawn first to the province shown in the bottom right hand corner of the photograph. Although the province extends across the outer member of the major circumferential pair, it is actually controlled by the long radial crack, shown previously at ground level in Figure 4/13. Observe also the province in the upper left hand corner of Figure 4/14, between the crater and the white linear pipe structure. In this province there are two quite distinct "volcanic" cones, of significant height and presumably the main source of the flooding.

Note that these pseudo-volcanic provinces are, in the main, disposed at about two plus crater radii from GZ, and associated with the outer member of the paired circumferential cracks. At SNOWBALL, it took several days to one week after the detonation to complete the process, and the resulting deposits were no more than inches thick, except in the main cones which could be over a foot high. If one thinks of these as being analogous to flood basalts associated with major impact structures, in a 100 km impact structure the flood basalt provinces would cover some hundreds of square kilometers and could be substantial fractions of a kilometer thick. The appearance of one of the "flood provinces" associated with a circumferential crack is shown in Figure 4/15, while the deposit was still wet. In this case it is obvious that the flooding was in the form of a slow upwelling of water, loaded with sand. However, it was common to have more localized, and presumably higher pressure sources which formed "volcanic" cones, as shown in Figures 4/16 and 4/17, which show both the impressive scale of the structures and their alignment along a controlling fissure. Scaled up to the size of a major planetary impact the analogue would be a substantial chain of volcanic mountains.

Figure 4/18 shows a most interesting compound structure of four associated pseudo-volcanic calderas gracing a substantial compound mountain chain. Clearly, the "pipes" feeding the activity while obviously associated with a continuous fracture remain quite discrete throughout the active period.

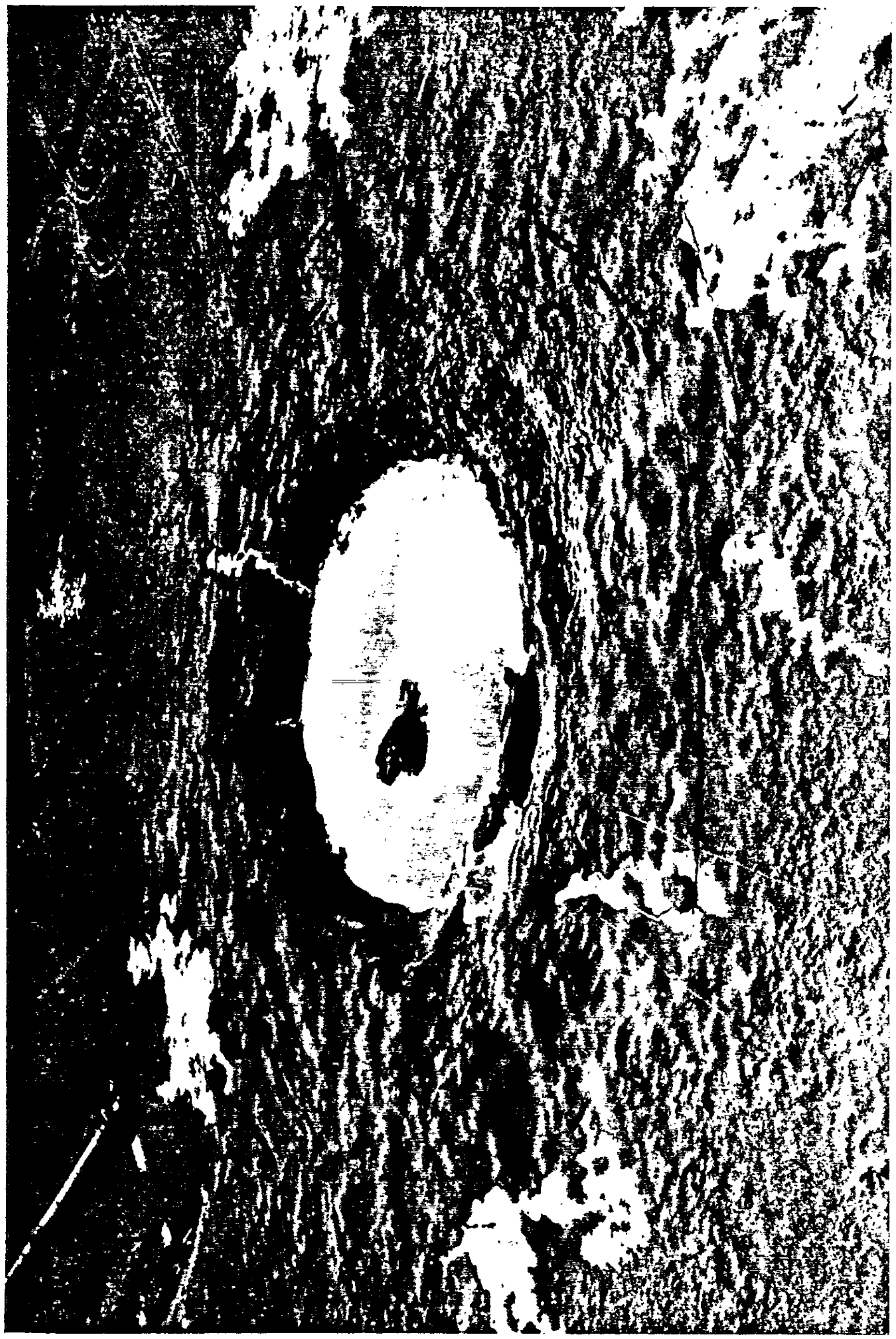


Figure 4/14
Oblique View of SNOWBALL Crater after External Flooding Complete

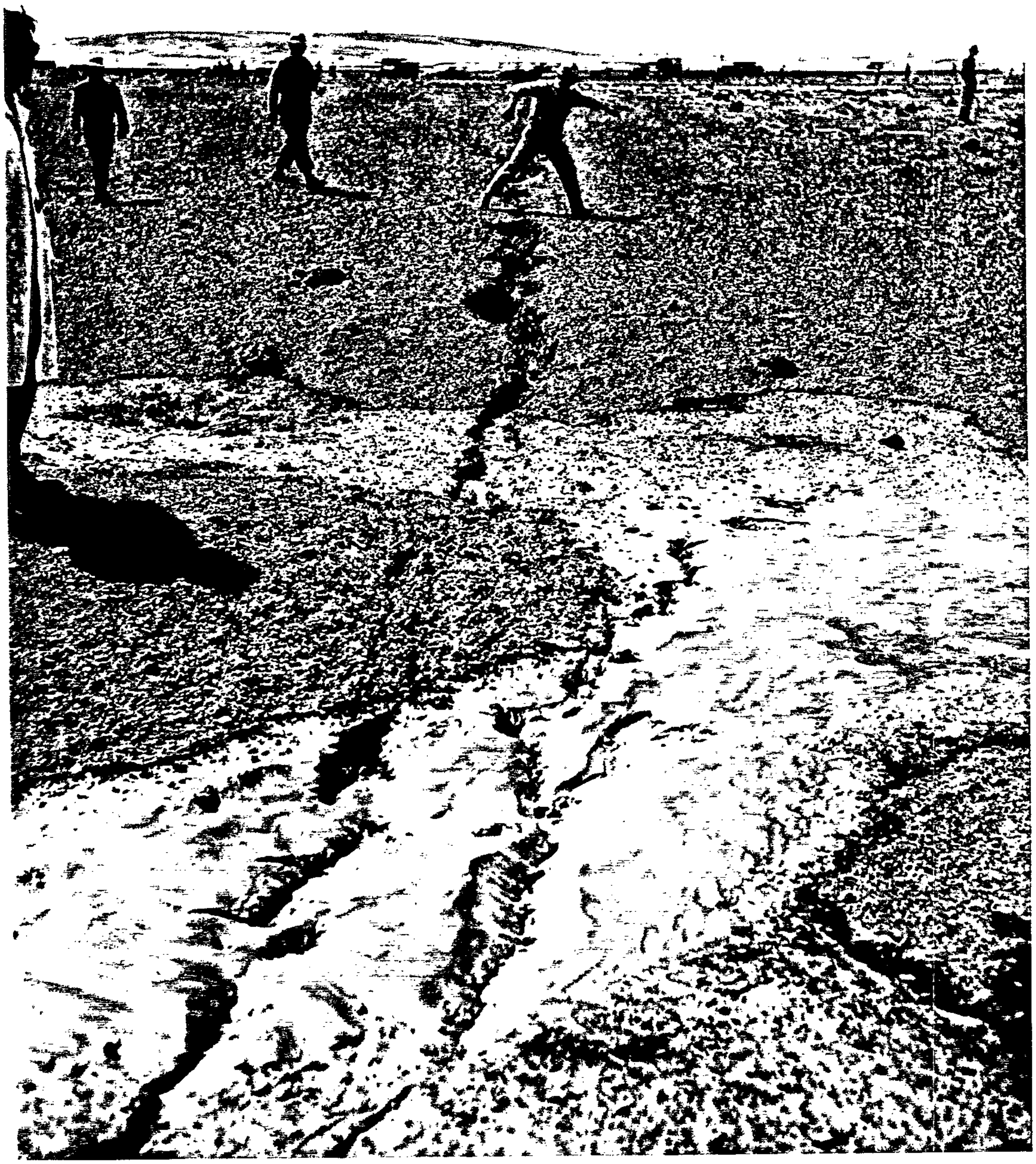


Figure 4/15
Flood Deposit Associated with Circumferential Crack of SNOWBALL Crater

Figure 4/16
Major Pseudo-Volcanic Peak External to the SNOWBALL Crater

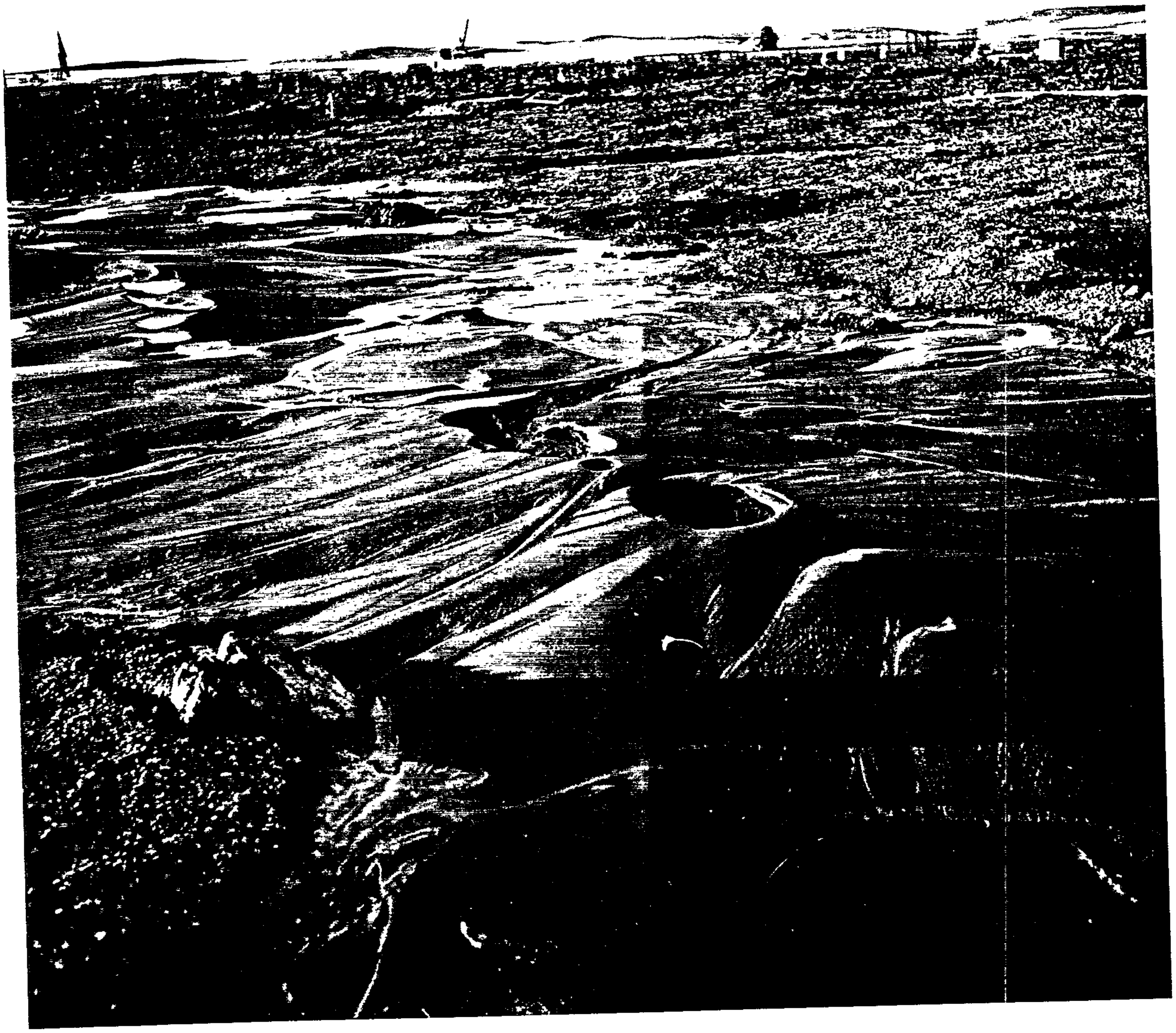


Figure 4/17
Alignment of Volcanic Peaks and Caldera External to SNOWBALL Crater

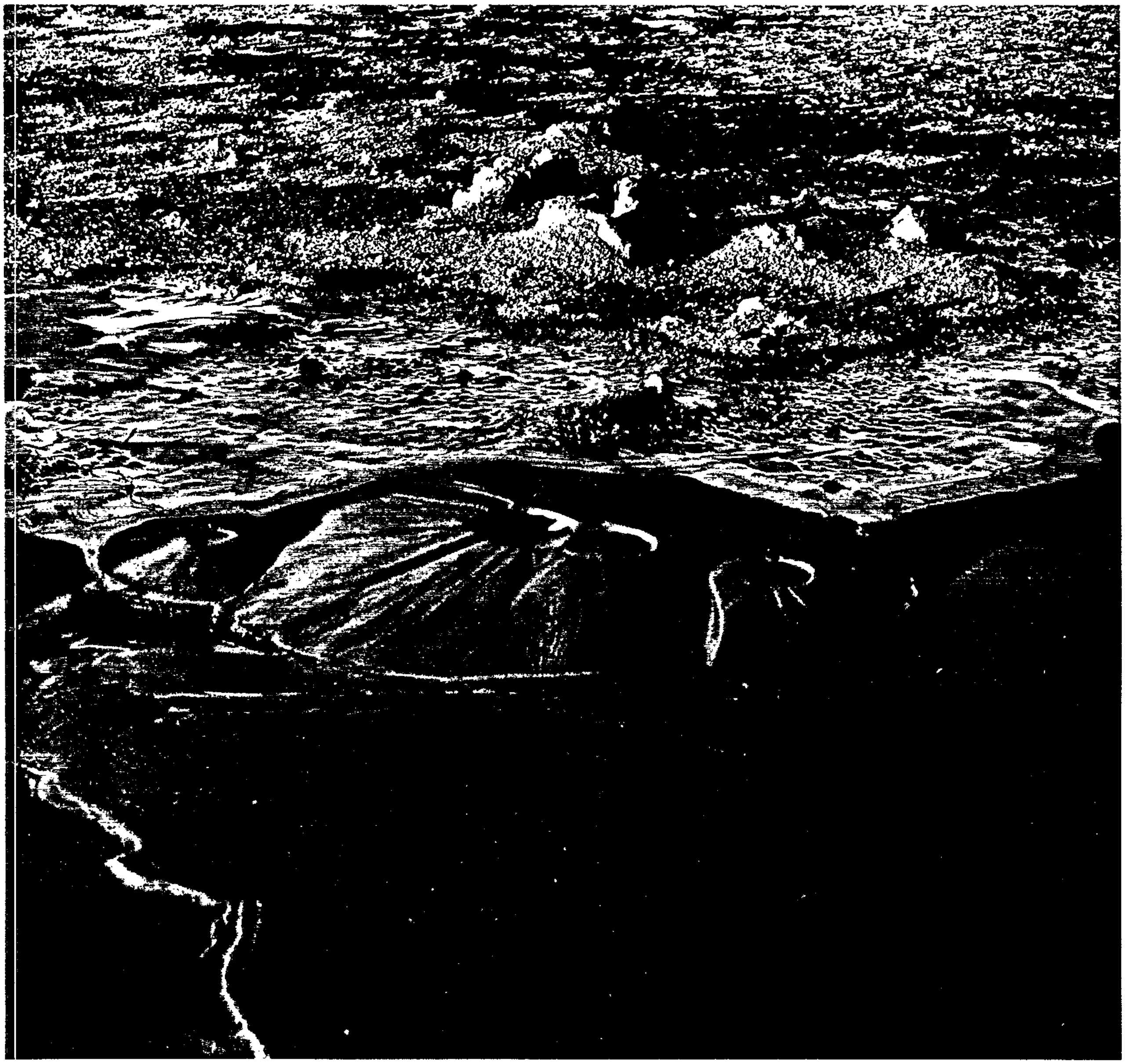


Figure 4/18
Analogue of Volcanic Calderas in a Compound Structure of SNOWBALL Crater

In the above descriptions, the various cones and provinces have been referred to as being "external" to the crater. This, of course, is simply a convention, as the crater structure, both in fact and as analogue, is vastly greater than the void bounded by the "rim" of the crater. Attention is therefore drawn to Figure 4/19, which is a print from a series of aerial vertical stereo pairs obtained by the Waterways Experiment Station (WES). It will be noted that the "crater" outlined by the rim structure, is miniscule in comparison with the total area effected by the detonation. However, on a scale basis a large scale analogue would probably show smaller extension of the ejecta blanket, as this is controlled by the initial ejection velocity and by gravity.

Discussion is now focussed on the developments within the crater void itself, that is within the region bounded by the sharp declivity corresponding with the "rim" of the crater. As already seen in Figures 4/3 to 4/7, for the first ten minutes after the detonation, the crater void was essentially dry. It is true that a slow trickle of water started flowing within minutes, but the surface remained dry and firm enough for surveyors to traverse the crater with ease.

However, after some quarter of an hour there was an almost explosive venting at the central uplift, on the south side of the uplift but almost exactly at GZ, as the location of the central uplift was displaced slightly to the north of GZ. A vent somewhat more than a foot in diameter was opened, and from that vent a gusher of sand laden water rose to a height of some three or four feet, and continue for many hours. In fact the flow continued to be quite rapid for some three days, and then gradually slowed to an effective end within the first week. At the same period, that is starting some quarter of an hour after the detonation, the pseudo-volcanic provinces external to the crater started to form, leading to the overall situation shown earlier in Figure 4/14. It will be noted in that figure that in two locations there is a trace of water flowing into the crater void from points external to the crater.

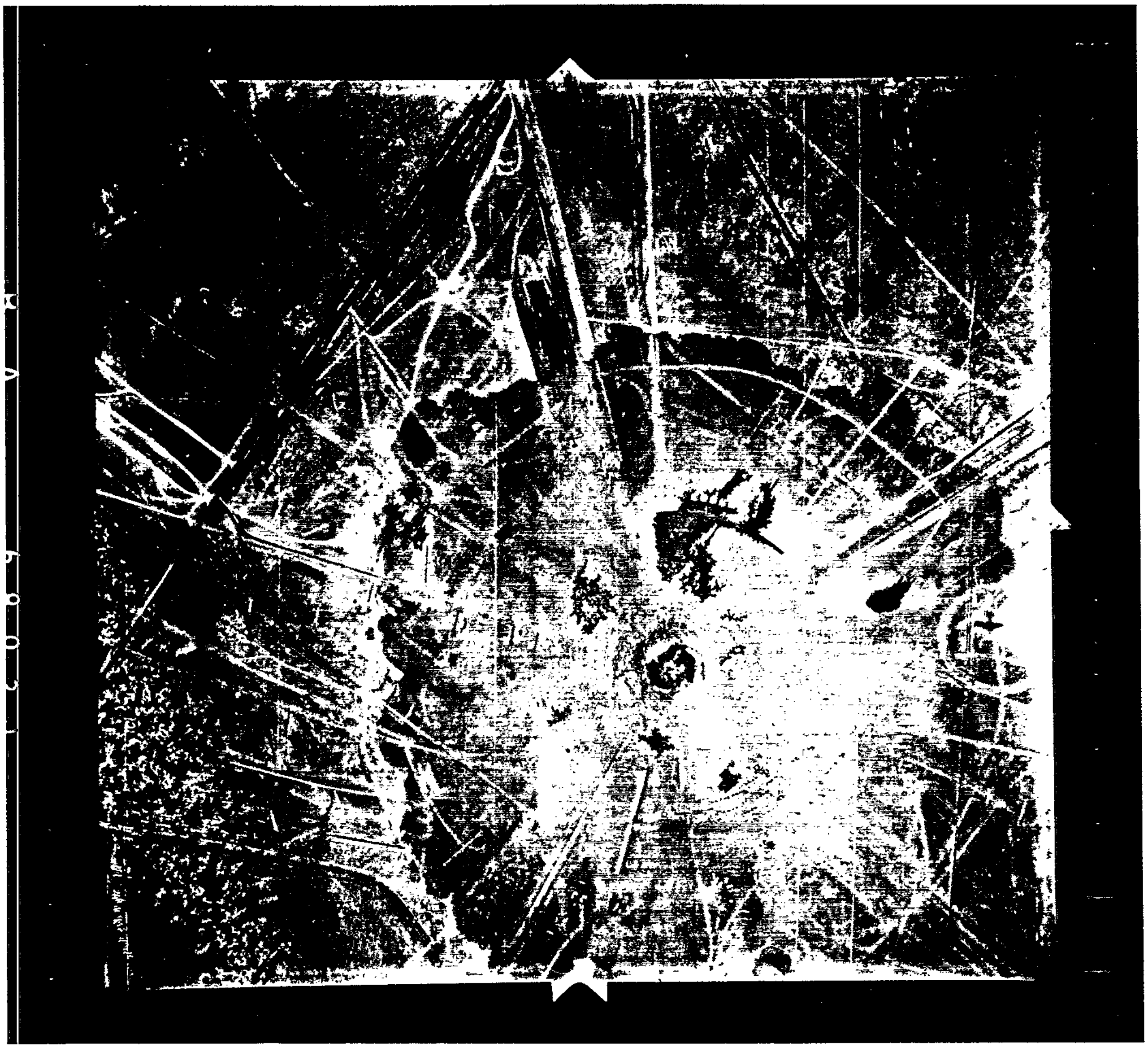


Figure 4/19
Aerial Vertical Photograph of the SNOWBALL Crater
(Waterways Experiment Station Photograph)

Figure 4/20 shows the internal appearance of the crater at the end of the first week, when the inflow of sand and water was virtually ended. The vent in the central uplift is clearly visible but at this stage most of the internal structures, both the original and the pseudo-volcanic are masked by the interior lake, shown here at its maximum extent.

However, attention is also drawn to the bottom area of this figure, which shows on the right hand side a series of concentric ripples, obviously deriving from a submerged point source of water. Associated with these ripples, note also the small black peaks of "rock" visible in the central and left hand region. It is clear that these indicate the trace of the crest of an internal ring structure on the inner floor of the crater, between the central uplift and the wall of the crater void. Very roughly, this internal ring appears to correspond with the position of the surveyor in Figure 4/6. The existence of this inner ring was not recognized at the time of the trial, and was masked at a later stage, as will be shown, by the "pseudo-volcanic" deposit which was laid down during the in-filling period. Attention will be drawn back to this structure in a later chapter when the ringed craters formed by later 500 ton detonations will be discussed.

Figure 4/21 is a view of the inside of the crater taken many weeks after the detonation, at such time that the lake filling the crater had almost vanished. Attention is drawn first to the light coloured terraces at the base of the crater wall. It is clear that these structures - and many similar ones shown in other photographs in the archives - represent a ring of pseudo-volcanic cones aligned circumferentially along the base of the crater wall, possibly on a second inner ridge. The final terraced appearance is due to successive "raised beaches" formed by erosion as the lake level fell. Similar erosion terraces are evident in the pseudo-volcanic deposits which surround the central uplift. It is not evident to the author why these terraces should be so evenly spaced, but it may be due to diurnal variation in the erosion regime. On the other hand, it was noted in much earlier experiments that the surface layers in and near the Suffield craters, at all scales, showed a form of relaxation for days, and possibly weeks, after the detonation. In fact, the photograph of Figure 4/21 itself bears striking witness to this effect in the long, linear cracks visible beneath the surface of the residual lake, an area which had never been dry. These cracks may be seen to contrast sharply with the cracks due to sun drying, in the region no longer covered by water between the two pools in the photograph. It is observed that the circular disks mounted on stakes were installed by the University of Michigan immediately after the detonation, and were subjected to both survey and time-lapse photography for some days after the detonation, precisely to study this effect. It is understood that no major heaving effect was recorded in this way, but reference may be made to the University of Michigan report.

Although the discussion has not yet reached the excavation phase of this study, Figure 4/23 is mentioned at this point. The figure is a photograph taken during the excavation phase, in which the continuous upper white line is a paint enhancement of the top of the original crater floor, before the infilling with water and sand. In the photograph, the rise to the central uplift is shown at the left side, the dark band below the white line is true fallback material covering the "crater", whose profile is shown by the lower of the two continuous white lines. The scale of the sand infilling is clearly shown, with a maximum depth of some 4 ft or more. Somewhat greater thicknesses were recorded elsewhere, where the crater surface had deeper hollows. The final upper surface of the "pseudo-volcanic" sand infilling was, as will be noted, virtually a "flat floor" to the final crater form, though with slight quaquaversal slope from the central uplift.

Figure 4/20
Lake Filled SNOWBALL Crater Showing Vent in Uplift

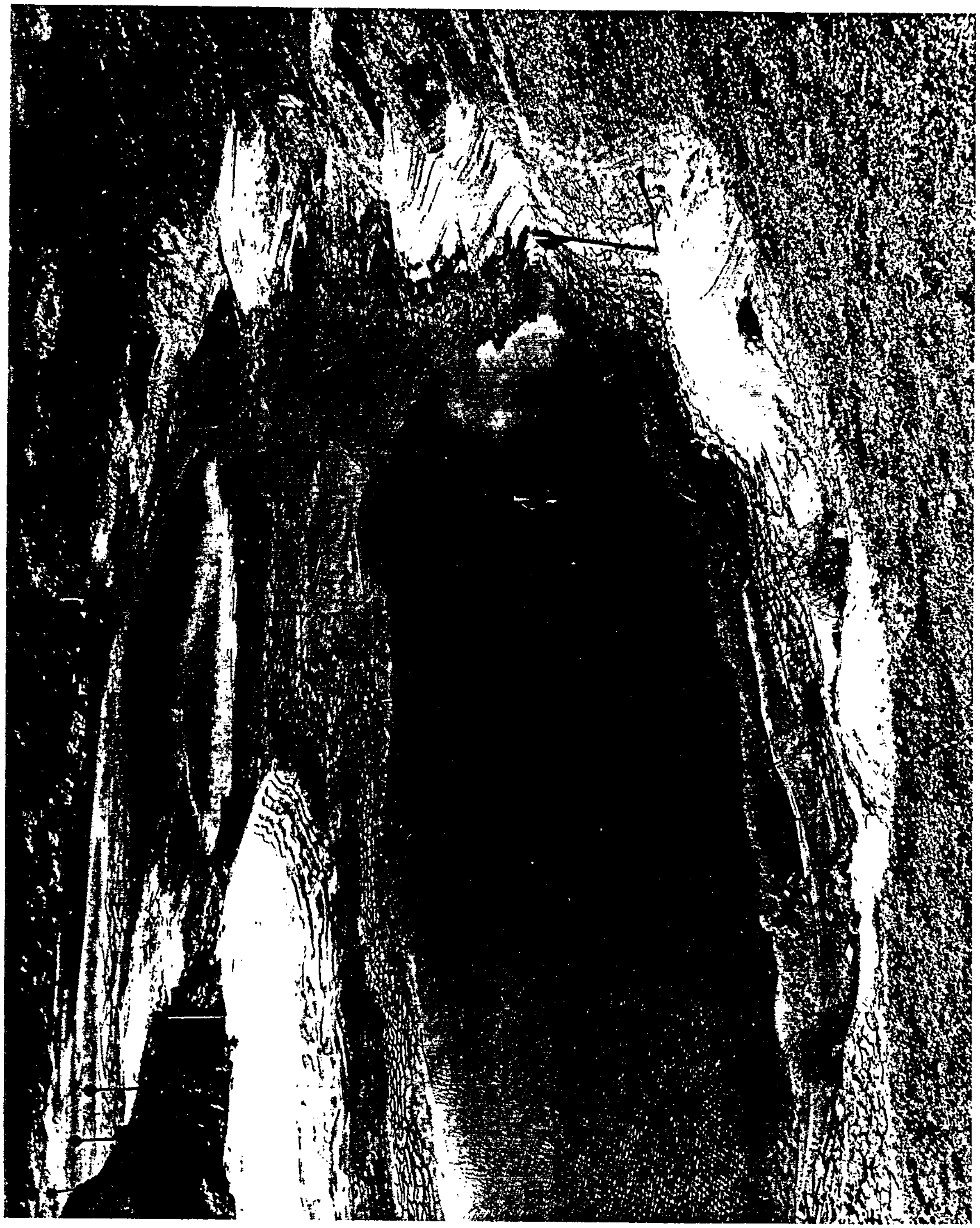


Figure 4/21
View of Eroded Pseudo-Volcanic Terraces inside SNOWBALL Crater

4.4 EXCAVATION OF SNOWBALL CRATER SAND COLUMNS

The excavation of the sand columns along the North-South and East-West diametric lines and of other sections across all or parts of the SNOWBALL crater as revealed in Figure 4/22 was not a simple post-detonation operation. In the earliest phase, the excavators needed to cooperate in retrieving data for many other participating agencies, a situation which, while slowing down the initial excavation, also allowed for extensive pre-excavation recording, and additional planning. The actual excavation proceeded in relatively small stages, concentrating on the main North-South sand column installation, but with many subsidiary lines which were also recorded as fully as possible. As the excavation was spread over two years, sufficient time elapsed to allow the Suffield team to bring in representatives of other agencies, not primarily interested in the effects of nuclear weapons, but with expertise in large scale terrestrial impact structures. One, quite typical, photograph of an excavated section is given in Figure 4/23. Various techniques had been tried to give prominence to the various contact surfaces, but that used in Figure 4/23 proved effective, but extravagant in the use of spray cans of white paint.

In contrast to the earlier, smaller scale craters, SNOWBALL was so large that it is not possible to present all the sand column data in a single, relatively small figure. The original plotting of the section, at a convenient draughting scale, entailed the use of twenty foot lengths of four foot wide paper. These were successively reduced photographically, but even so could not be presented as a single figure. For the purpose of this report, the grossly reduced sections as published in Jones (1977) are included.

As these sections are already in the public domain, discussion here is limited to pointing out certain major points which relate to planetological considerations, and to comparisons with the earlier data on 20 ton and 100 ton craters.

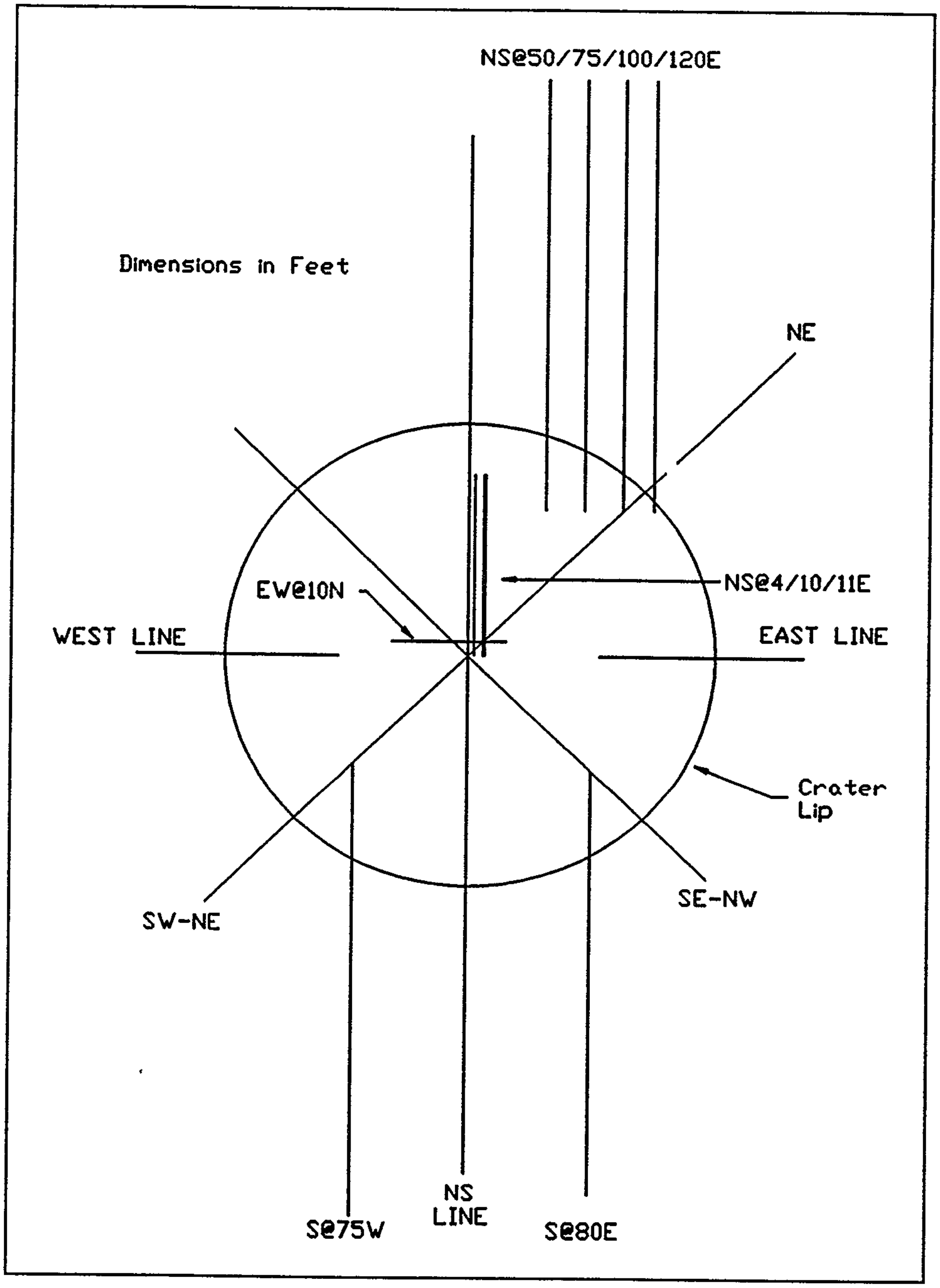


Figure 4/22
Excavation Lines for the SNOWBALL Crater

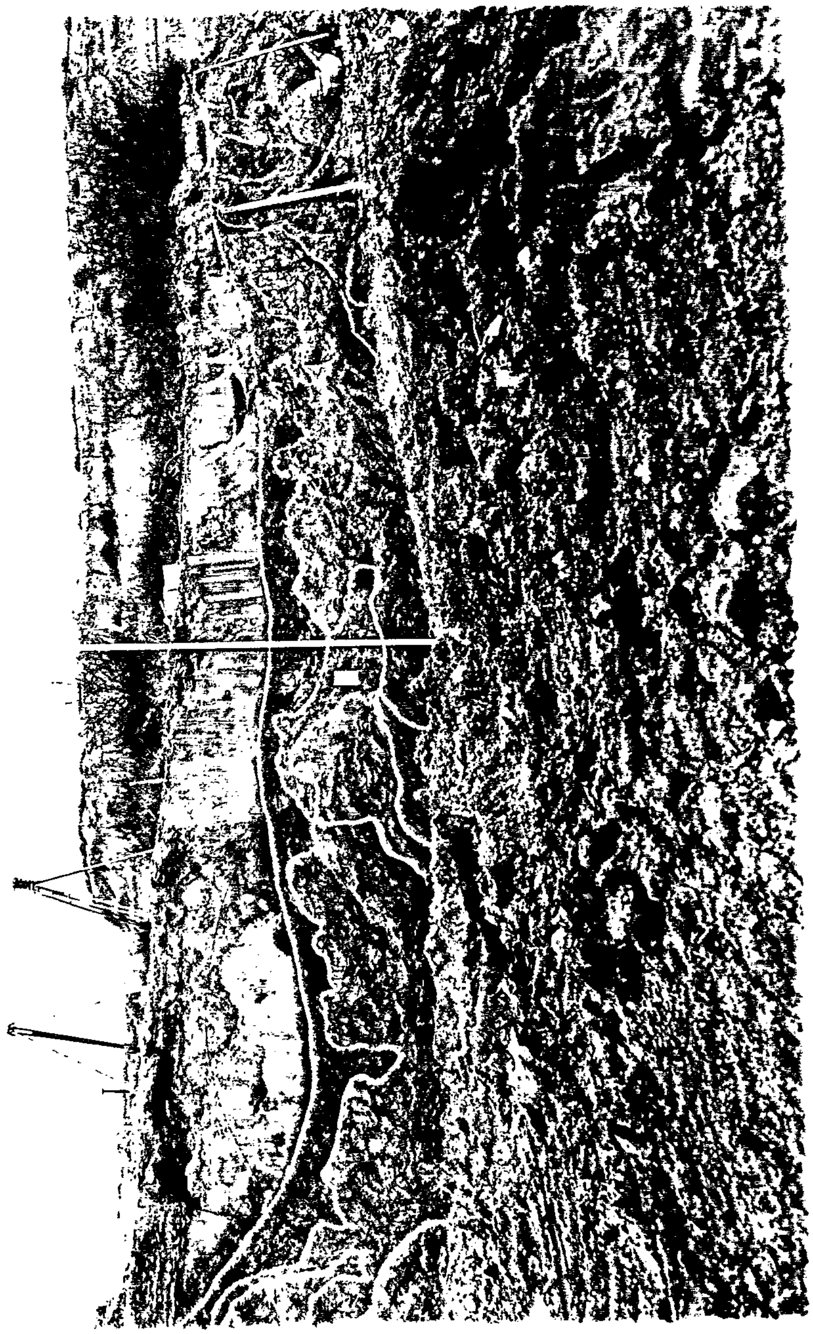


Figure 4/23
Excavated Section of SNOWBALL Crater Floor Showing Pseudo-Volcanic Infilling

4.4.1 The North-South Sand Column Line

Consider first the pattern shown by the outermost columns, beyond the major circumferential fractures, as shown in Figure 4/24 and 4/28. It will be seen that the displacement pattern is consistently **outward and downward** in all the three outermost columns on both the south and north lines.

In contrast, the columns, which correspond with the edge of the crater shown in Figures 4/25 and 4/27 show a much more confused pattern, the dominant movement being **inward** and downward. In Figure 4/25, the south side of the crater, this is a consistent pattern and corresponds with a clear downwarping of the deeper lying strata, essentially an inward slumping of the beds above the downwarped strata. On the other hand, on the north side of the crater, shown in Figure 4/27 we see a rather different pattern. The upper markers again show inward and downward movement, and this corresponds to the final attitude of the upper strata. However, there is a change in the displacement of the lower markers, where the movement becomes **outward** and downward. The separation of the two modes of final displacement are aligned along a shallow angle intersection, which represents a thrust fault. The inward slumping in the upper layers may thus be interpreted as a late stage reverse slump along the thrust fault. It is thought that the same type of thrust faulting followed by reverse movement can be attributed to the south section, but the evidence is not so clear.

Consider now the pattern shown in Figure 4/26, which covers the interior of the crater, including the central uplift. All the markers, from those close to the crater wall to those in the central uplift demonstrate clearly the existence of gross upward and inward movement. There can be no doubt of the structural nature of the central uplift. The column markers at 30 ft north and 40 ft south show mirror-image movements centred on GZ, and so one would anticipate that the central uplift would indeed be centrally disposed around GZ. However, the final motion recorded by the more central columns shows that this uplift movement became uniformly displaced to the north side of the crater. All the recorded movement remains upward, and the lower markers indicate that this upward movement exceeds 40 ft of vertical uplift (and as much as 60 ft of horizontal displacement). As these elements are the deepest markers available, they do not reflect, of necessity, the maximum extent of the uplift in the central regions. It is, in fact, notable that the deeper the marker the greater the recorded uplift.

As plotted some of the displacement vectors may appear to casual interpreters as contradictory, as vectors cross each other in the plotted figure. This is an incorrect interpretation resulting from the planar plotting. In addition to the relative movement in the plotted plane, it was found in the field that the central regions of the uplift had suffered gross distortion of the strata, resulting in a rotational motion superimposed upon the planar. The field evidence was quite clear, as the sand column material (which was coloured) could be followed as thin, extruded filaments from the original to the final position, and the filaments from adjacent columns, moving in opposite directions, passed by each other without mutual interference. However, it is conceded that the bottom two markers in column 20 ft south of GZ may represent a different mechanism, as the markers were recovered at an early stage of the investigation at the contact between the fallback material and the true crater. It could be thought that these markers were disrupted from the column by the high pressure water, and brought to the surface. However, that is not the author's interpretation, as the water eruption was on the south side of the uplift, while the markers were found on the north side.

Evidence to support the author's belief that the gross movement of even the lower elements is a real displacement effect, not hydraulic transport, may be seen in Figure 4/29, which show the trace of the sand column filaments, with gross sub-horizontal, but not disrupted movement of sand column elements. Clearly, such a movement could account for the 40 ft uplift and 60 ft horizontal displacement recorded for the sand column markers at 20 ft south of GZ, and original depths of some 45 ft below the original surface. These photographs were taken when the effect was first noted, during the excavation of the crater floor. Regrettably, at this date the precise location of these sand columns is not recorded beyond the fact that they were taken in Sept. 1964. They may not record the excavation of the 20 ft south sand column, but they do demonstrate the coherent motion of the type indicated for that column.

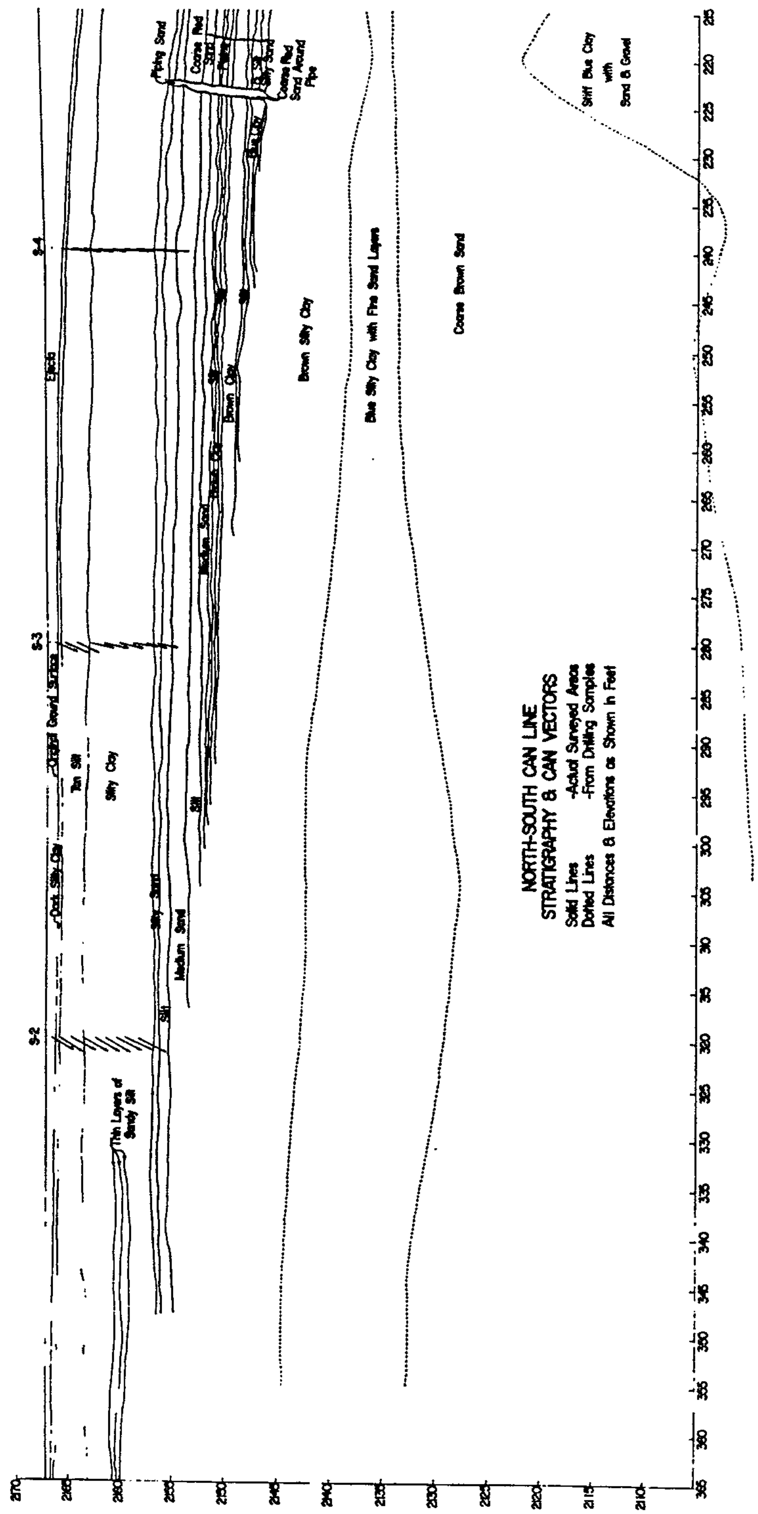


Figure 4/24

North-South Can Line Stratigraphy and Can Vectors for SNOWBALL Crater Section (Part A South Region)

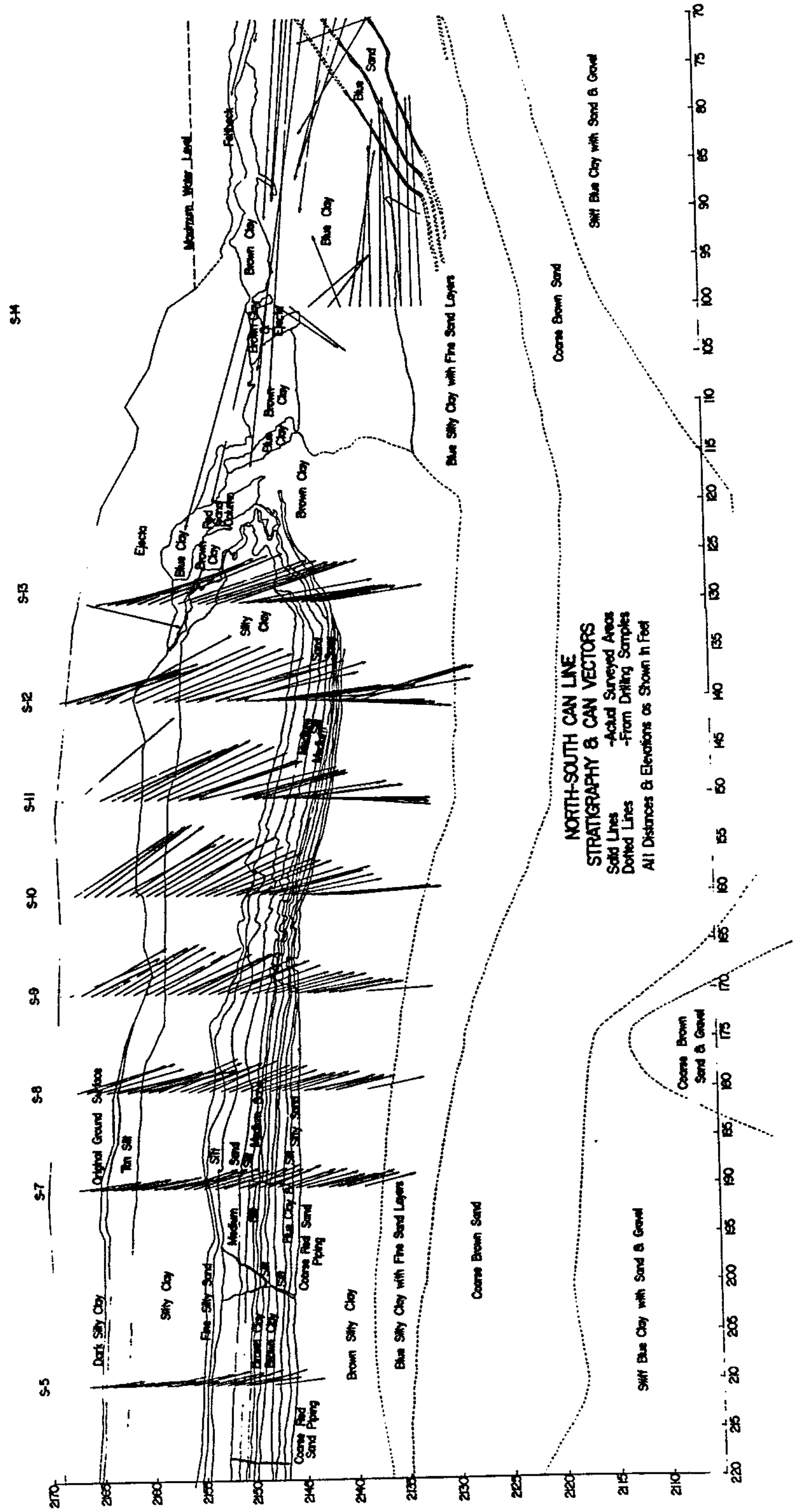


Figure 4/25
North-South Can Line Stratigraphy and Can Vectors for SNOWBALL Crater Section
(Part B South Rim)

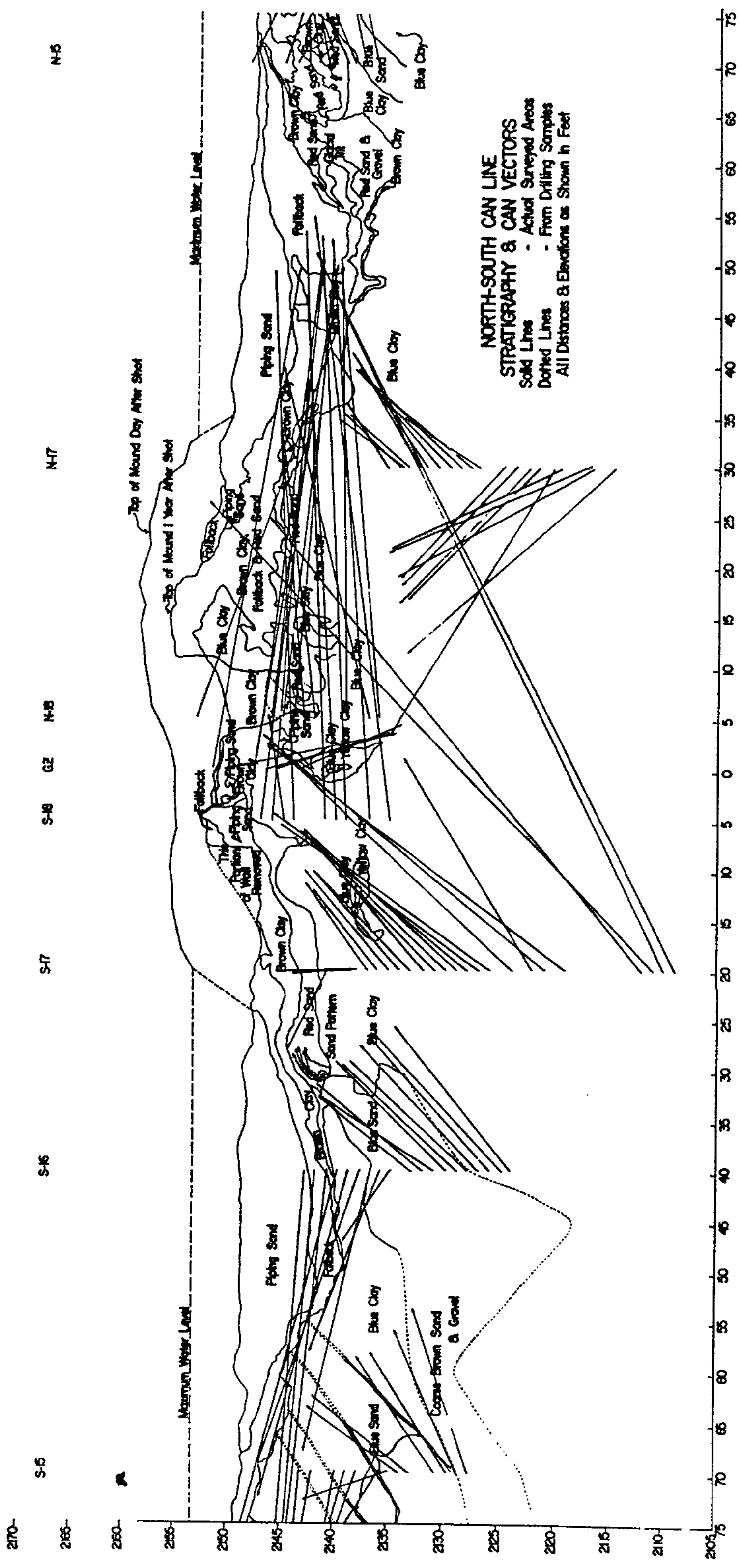


Figure 4/26
North-South Can Line Stratigraphy and Can Vectors for SNOWBALL Crater Section
(Part C Central Region)

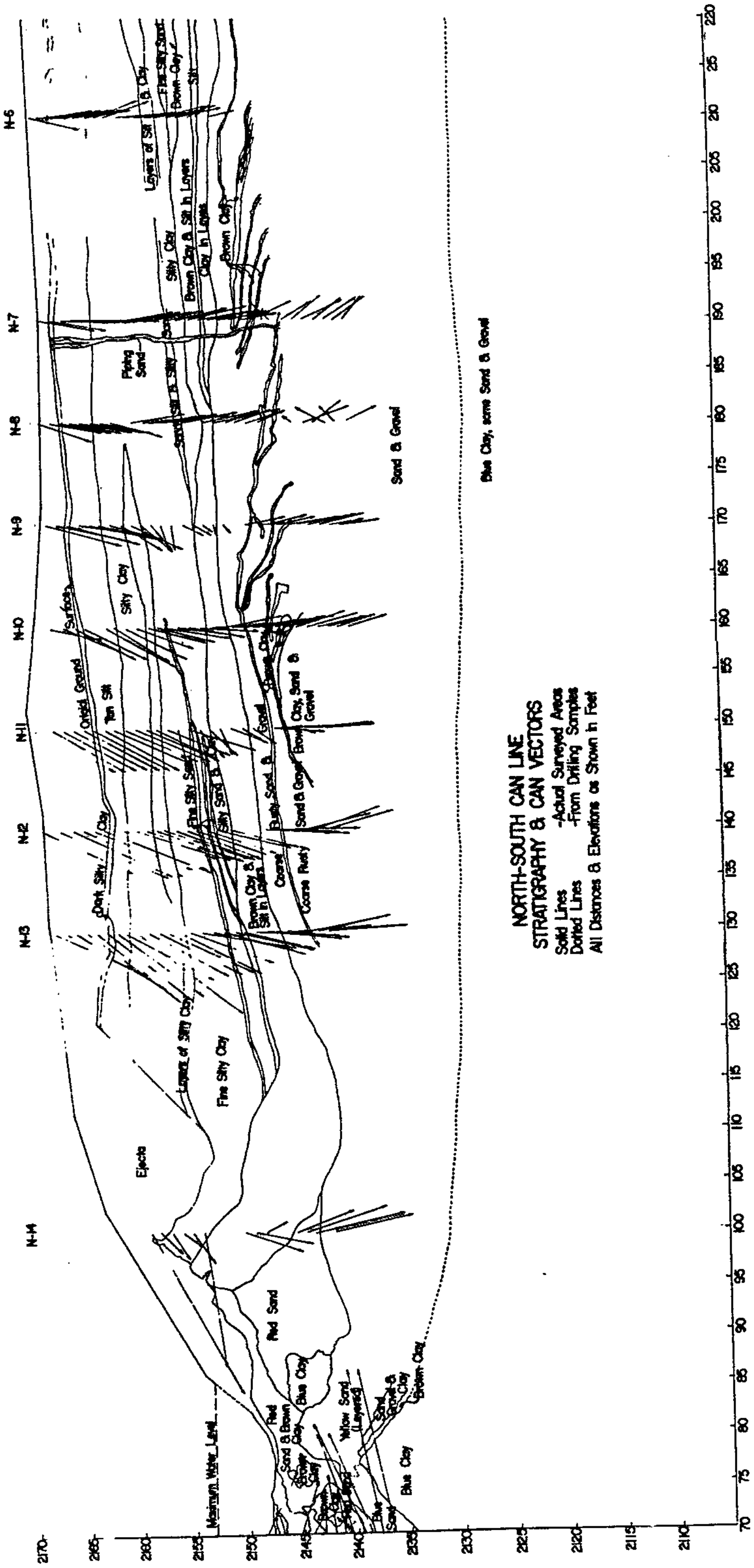


Figure 4/27
North-South Can Line Stratigraphy and Can Vectors for SNOWBALL Crater Section
(Part D North Rim)

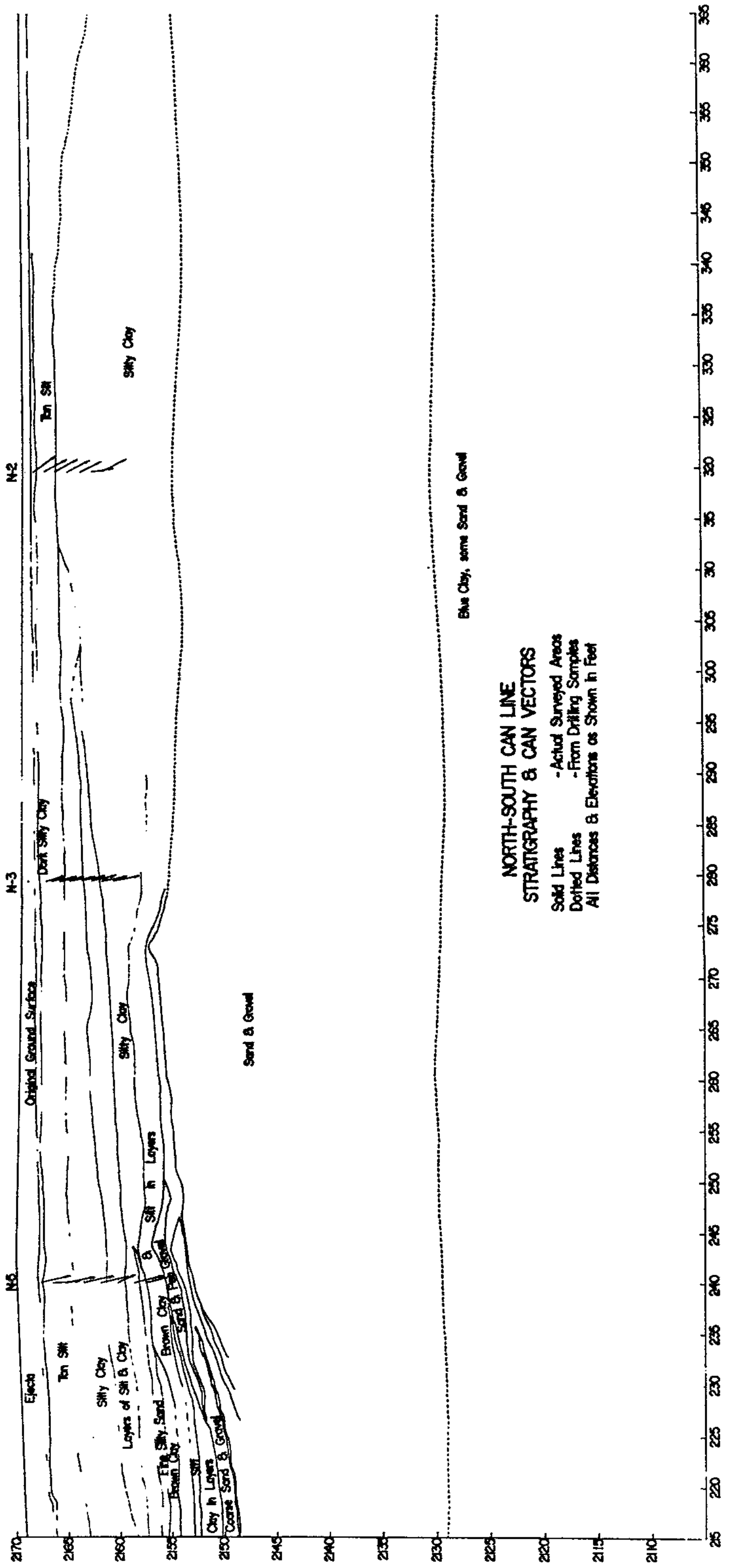
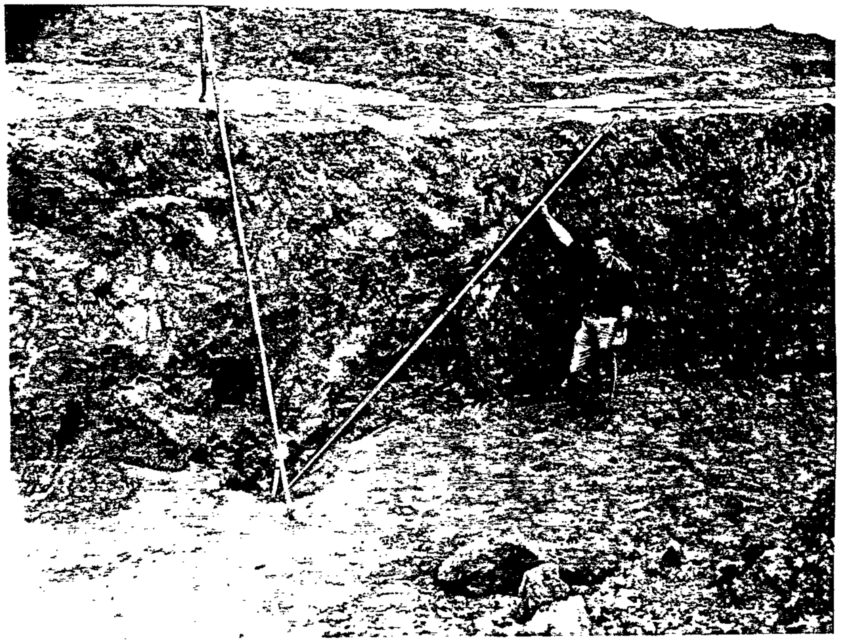


Figure 4/28
North-South Can Line Stratigraphy and Can Vectors for SNOWBALL Crater Section
(Part E North Region)



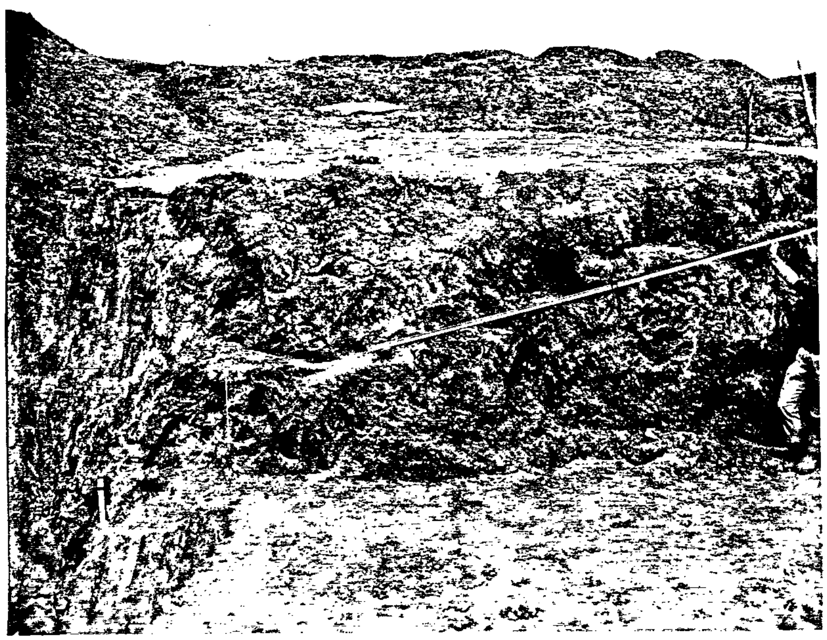


Figure 4/29

Excavated Evidence of Filament Extension of Sand Column in Horizontal Direction

4.4.2 The East And West Sand Column Lines

The SNOWBALL crater was unique, at Suffield, in having two sets of sand column lines, running at right angles to each other. The main north-south line, which had columns spaced along the full diameter, has been published in the open literature and repeated in the previous section.

The line at right angles was in two sections, one running west from 120 ft to 220 ft, and the other half running east, similarly spaced from 120 ft to 220 ft. Thus the east and west lines could give no data relating to the crater void proper, that is inside the rim. The data plotted from the east and west lines have never been recorded in any publication, and it is now necessary to correct that failure. The data have been plotted as two separate figures, one for each line section.

The sand column data for the West line is given in Figure 4/30. The first impression, in an overview of the total plotting of the markers, is the remarkable degree of consistency from column to column. In essence, all the columns show that the upper markers moved "inward and downward" while the lower markers moved "outward and downward" with reference to GZ and the original surface. However, more detailed examination showed that the movements while remarkably "patterned" do show a rather complex sorting of the final displacements. This is best observed by starting the detailed study at the outermost column at 220 ft, and then moving progressively inward.

The outer column shows every marker moving consistently downward, and at the same low angle, showing that at 220 ft the bulk movement is radially outward, but slightly depressed overall. The three bottom markers show a marginally greater outward movement which probably indicates that they lay in a single stratum, more mobile than the overburden.

At the W2 column, at 200 ft, the picture is quite different as the top six markers show a very slight inward, but almost vertical and major (over five feet) downward motion.

The middle block of markers show almost vertically downward but slightly outward movement. Below that level, the bottom group shows movement at close to 45 degrees, downward and outward. As we approach closer to the crater we shall find this tripartite division persists.

Columns W3, W4, W5, W6 & W7 show complete consistency in the pattern of displacement, that is to say top third inward and down, middle third essentially vertically down, and the bottom third outward and down. While the pattern remains unchanged, the extent of the vector displacement increases, at a sensibly uniform rate, nearer to the crater. The first twenty foot depth of the sediment is forced sharply downward, but the upper layers tend to move towards the crater, while the deeper layers move consistently outward. The middle is mainly downward, but "dragged" inward or outward by the upper and lower beds. It is noteworthy that the recorded post-detonation ground surface is in complete conformity with the downward movement recorded by the columns.

The innermost column, W8, is superficially different, though not significantly so. The top two markers, close to the ground surface before the detonation, in this area which is part of the rim, are driven outward and down, to finish up just below the now depressed surface. It is not certain, but they appear to have retained the integrity of their ground contact. Below this level the markers are driven sharply and almost vertically downward, with slight inward movement. The lower markers, generally move downward and outward, consistent with the columns farther out. However, the very lowest markers show a massive degree of inward movement, the upper three recovered markers moved inward and down, with displacement of about 10 ft, while the bottom marker shows a similar inward, but in this case upward motion. Referring back to column W7, we see that the bottom marker there also shows massive downward movement, but only a "tendency" to inward movement.

Reviewing the entire set of data again, we see that it implies that the original displacement was uniformly outward and down, as might well be expected, but that the

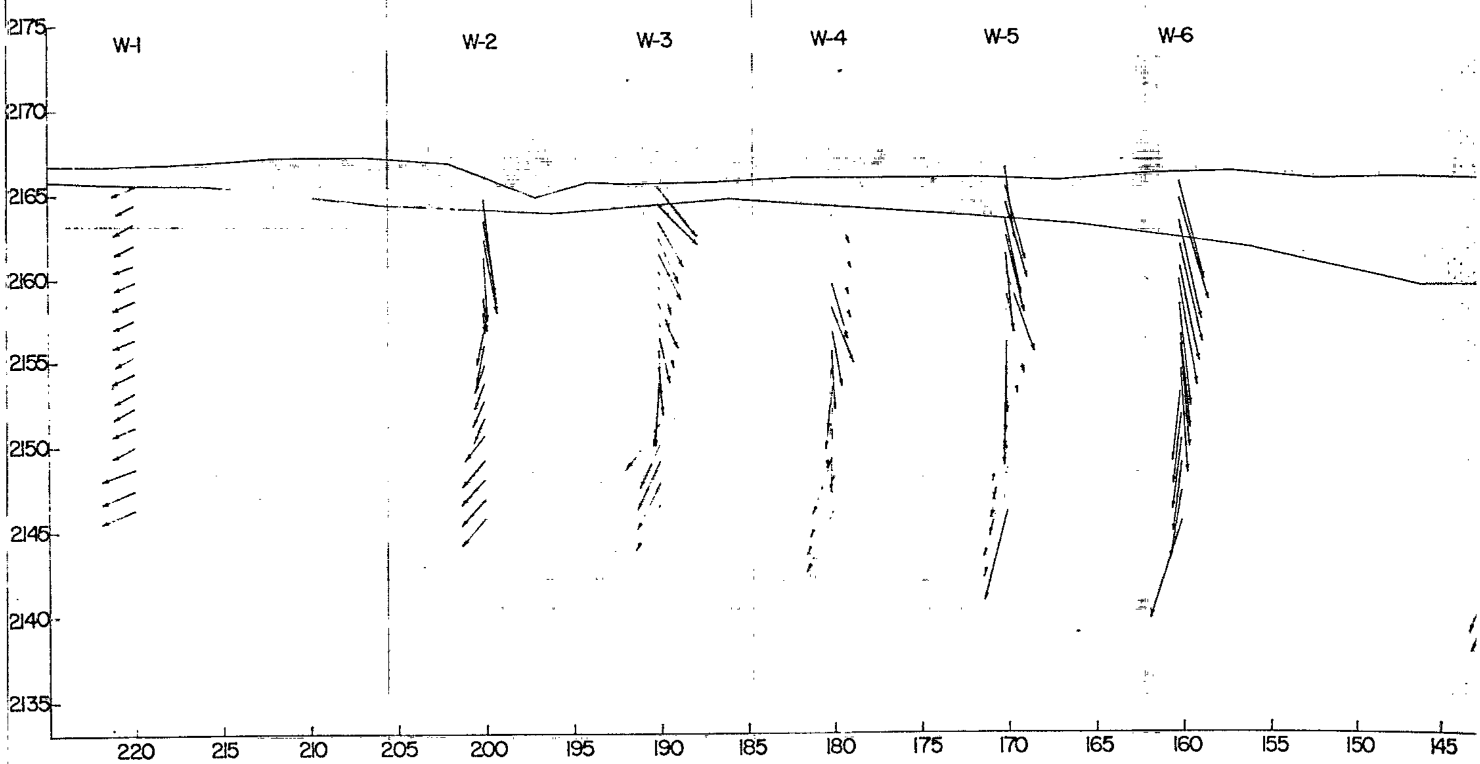
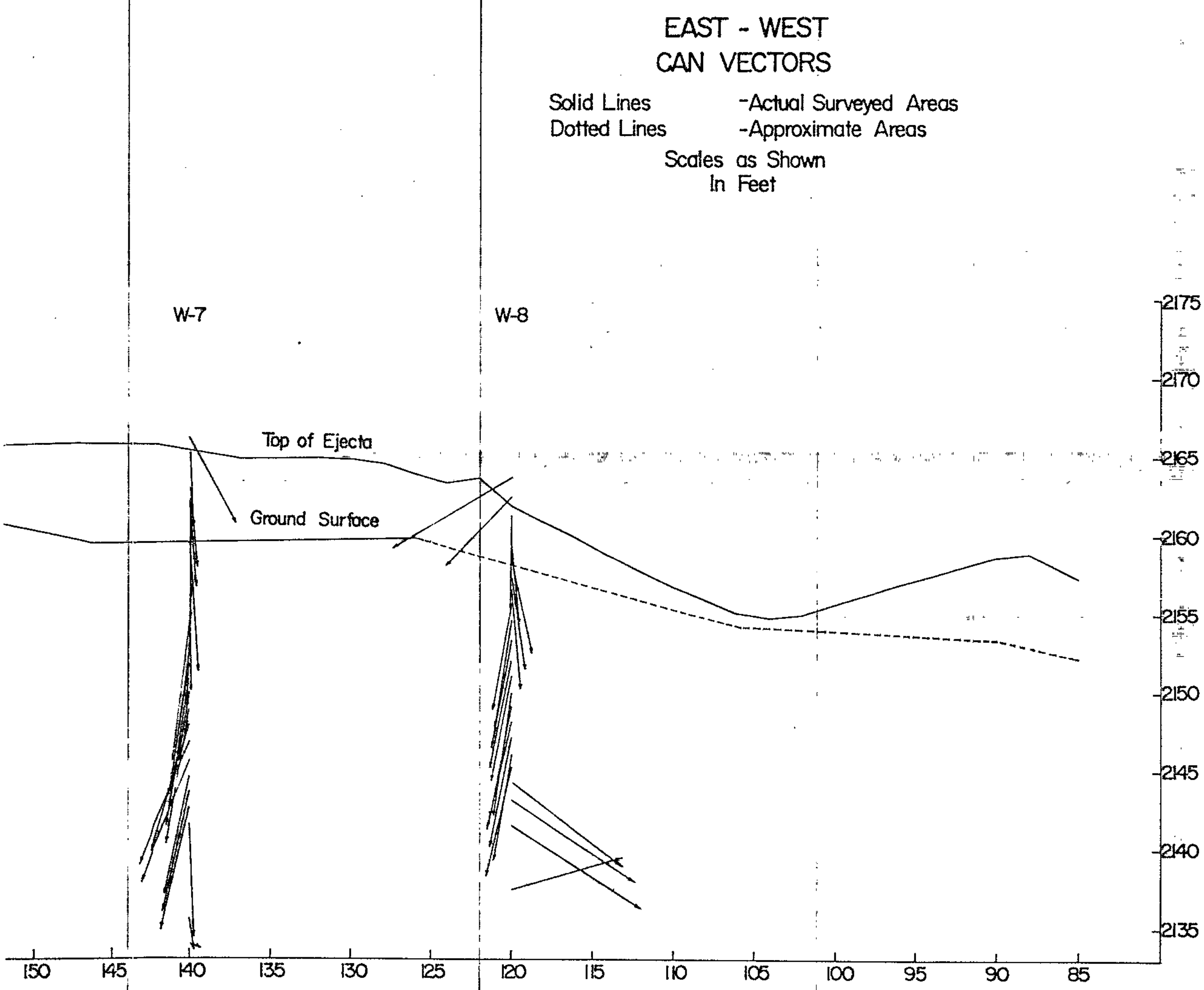


Figure 4/30
Sand Column Data from the West Line of SNOWBALL Crater


EAST - WEST
CAN VECTORS
Solid Lines -Actual Surveyed Areas
Dotted Lines -Approximate Areas
Scales as Shown
In Feet
W-7
W-8
Top of Ejecta
Ground Surface
2175
2170
2165
2160
2155
2150
2145
2140
2135
150
145
140
135
130
125
120
115
110
105
100
95
90
85

depressed ground immediately below the surface recoiled to beyond the original starting point. There is no clear evidence from the markers relating to an overturned flap, but it would not be expected at these distances. It is remarkable, however, that the very lowest markers in W7 and W8 are anomalous in precisely the way that would be expected if a hinge was being formed in the 80 to 110 ft region.

Attention is now turned to the east line shown in Figure 4/31. The first, overall impression viewing the plot as an entity, is that the ground to the east of the crater was significantly more resistant to radial and vertical movements. The overall pattern is not wholly different from that on the west line, however, the bulk movement appears to be more consistently inward and downward. Even in the most remote column, E1 at 220 ft, only the upper half is displaced outward (and downward of course). The bottom half moves inward, in contrast to the uniformally outward movement of the equivalent W1 column.

Columns E2, E3, E4 & E5 show quite consistent, mainly small downward and even small inward movement.

Column E6 is anomalous, as although the movement is still mainly a downward depression, the bottom half moves slightly outward, in sharp contrast to the columns on either side, E5 and E7. The author can think of no convincing cause for this anomaly, which while small, is real enough.

The two inner columns are quite different, but consistent with each other. In these cases the upper markers have suffered massive outward, and relative small downward movement. Below these upper markers, all the other markers show massive downward and slightly inward displacements. These two columns, of course, at 140 and 120 ft from GZ are located under the outer "rim" of the crater. It is possible, but superficially unlikely, that the anomalous major outward movement of the tops of W7 and W8 are connected with the formation of a hinge/overturned flap mechanism, but this appears unlikely to the present author.

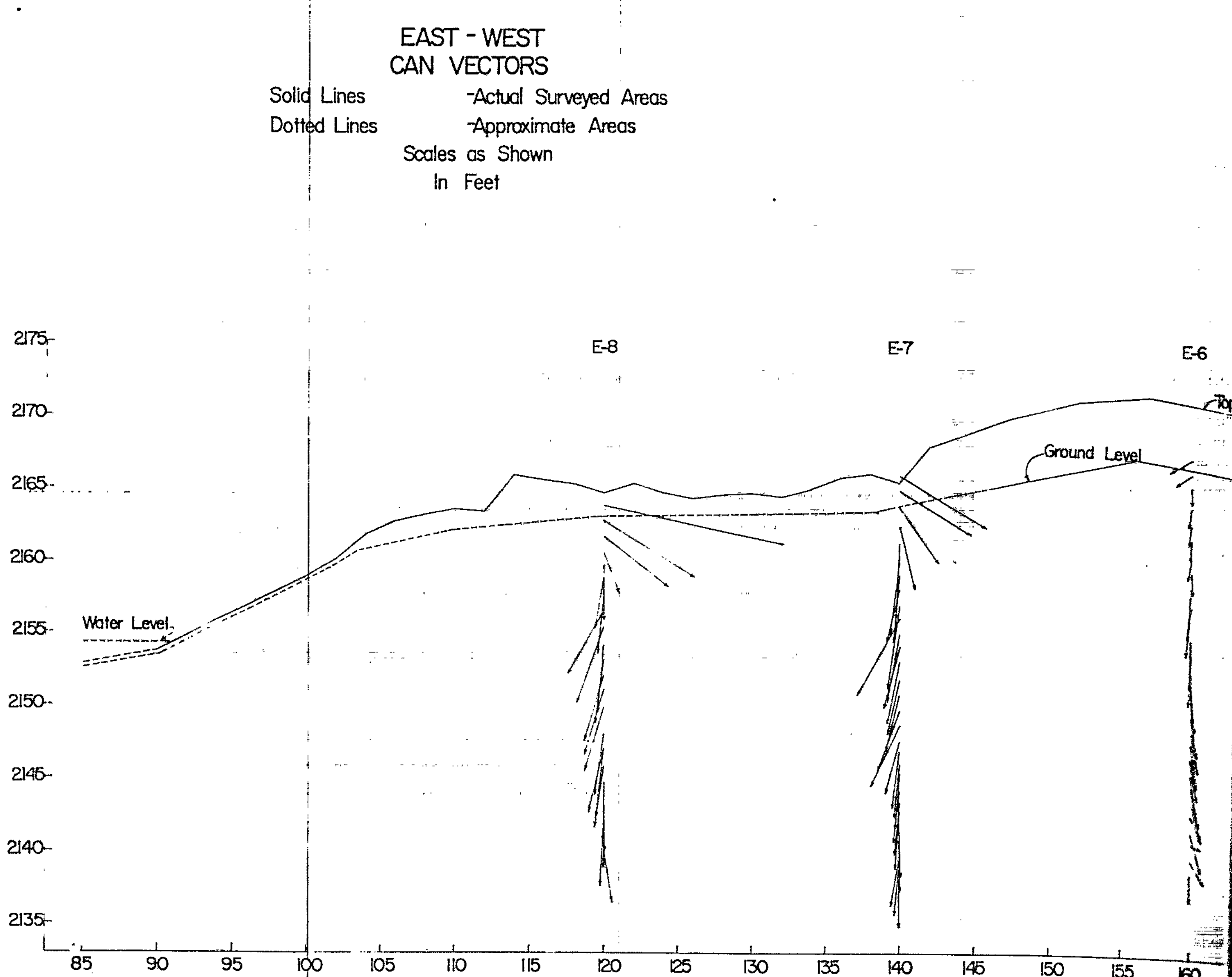
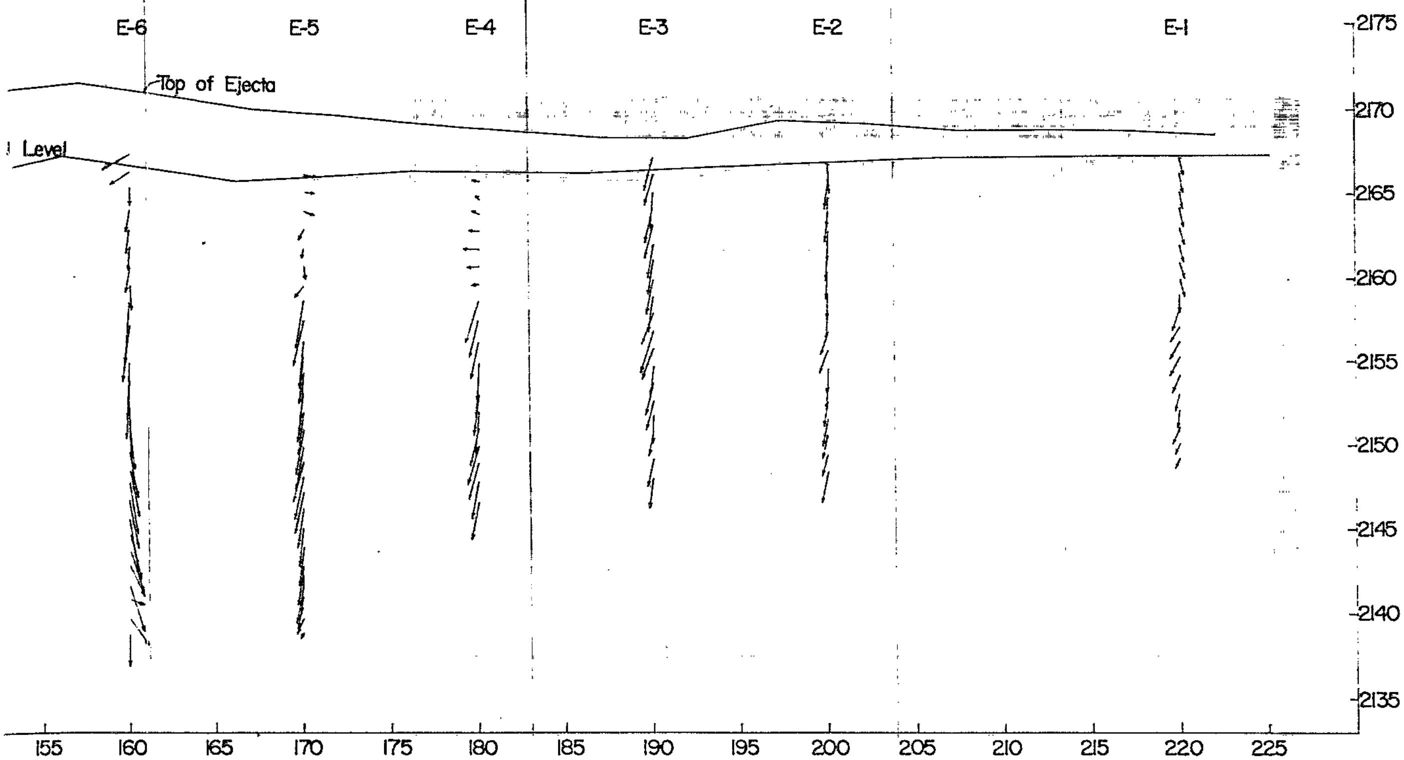


Figure 4/31
Sand Column Data from the East Line of SNOWBALL Crater


E-6
E-5
E-4
E-3
E-2
E-1
Top of Ejecta
Level
2175
2170
2165
2160
2155
2150
2145
2140
2135
155
160
165
170
175
180
185
190
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200
205
210
215
220
225

4.5 GENERAL DISCUSSION OF EXCAVATED SECTIONS ILLUSTRATED BY PHOTOGRAPHS

Attention is now drawn to the stratification recorded by both excavation and deeper core drilling in the region between the south crater wall and the central uplift (vide Figures 4/25). It will be seen that a downwarping of the strata beneath the rim and just inside the crater floor, changes to an inward and upward movement - recorded also in Figure 4/26 - so that a synclinal trench abuts onto an anticlinal ridge (which were, of course, circumferential structures). Particular attention is drawn to the low angle filaments of sand which were extruded from deeper layers into the blue clay layer, as shown on the right side of Figure 4/25 and also, further under the north rim in Figure 4/27. These shallow angle sand stringers may be due to the effect shown in Figure 4/29 (b), or hydraulic fracture. It will be shown later that a form of hydraulic fracturing, without breaching the surface, was frequently found during the excavation, both in the central uplift and far beyond the crater rim.

The displacement recorded by the sand column markers on SNOWBALL is essentially consistent with that for the central regions of the DISTANT PLAIN 6 crater, shown earlier in Figures 3/20 and 3/21. The gross upward movement, on a scale basis, is consistent between the two trials, but in both cases the movement recorded can only be considered as limited by the depth of the recovered markers. Much greater uplift may well have existed, in the plastic upward flow of deeper elements than those recorded.

We now turn briefly to the photographic evidence, but limiting the inclusions in this text to the immediately relevant. Many more photographs exist in the attached archives, with comments on the more significant ones added.

The first photograph, Figure 4/32, shows the structure revealed in the central uplift by a minor collapse of the outer layer, before excavation started. The structural nature of the central uplift is clearly revealed, with a closely folded set of strata. Note that this folding is virtually at GZ, on the flank of the central uplift, which was proved on excavation to be highly contorted, with some of the more plastic strata enfolding separated elements of higher strata. Compare this photograph with that of

Figure 4/32
Structure in SNOWBALL Central Uplift

Figure 3/19, which shows a strikingly similar structure excavated on the 100 ton DISTANT PLAIN 6 crater. There is no room for doubt that the mechanism involved in both the central uplift structures is identical, so that we are dealing with a uniform process of central uplift, not simply an elevated structure variously formed by a basic, but variable effect of high pressure hydraulic fracturing and uplift of disrupted material. The uplift structure, however, may well be modified at a late stage by hydraulic fracture and injection of material from greater depth. The evidence for the latter process is clearly seen in Figure 4/33, which shows a hydraulic fracture with inlaid sand traversing a contact between blue clay and yellow clay. The photograph also shows a major inclusion of the yellow clay enveloped in blue clay, evidence of the plastic flow of the blue clay during the uplift process.

Figure 4/34 shows the nature of the sand infilling in a vertical dyke in a fissure opened beyond the rim of the crater. This was one of the circumferential faults discussed earlier, and it is notable that, although almost vertical, the sand dyke is bounded by what is essentially a normal fault, with the downthrow on the side nearest to GZ. It is suggested that this faulting, and downthrow, preceded the later slumping inward which is such a marked effect on SNOWBALL. It is further pointed out that the sand infilling which on excavation was a closely packed material, while referred to as a "pseudo-volcanic" deposit, could at this small scale become, in time, an indurated sandstone dyke. As will be discussed in a later section, such vertical sandstone dykes actually exist in the not far distant Eagle Butte structure, now considered a relatively small impact structure. Further, there is absolutely no evidence that the high pressure water which deposited the dyke material had any tendency to spread into the poorly consolidated horizontal sand strata. This really is quite puzzling, as it seem unlikely that the lithostatic pressure at these depths could have been sufficient to seal the horizontal strata against the pressure of the water rising from depth and creating the pseudo-volcanic effects at the surface, and creating the vertical circumferential dyke shown here. The edges of the dyke conform to the fault faces on each side. That is quite different from the effect, noted elsewhere, of

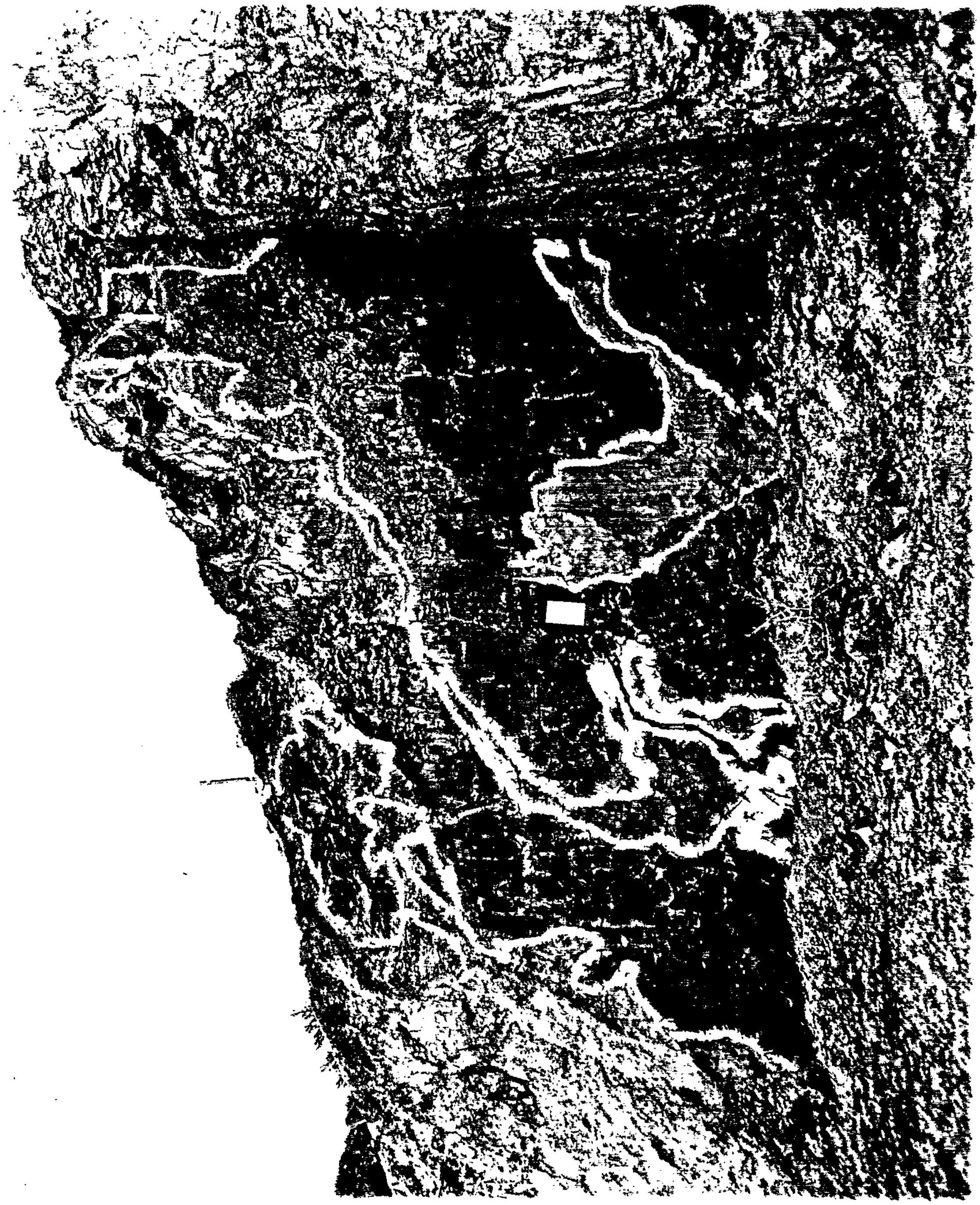


Figure 4/33

Section of SNOWBALL Central Uplift Showing Hydraulic Fracture

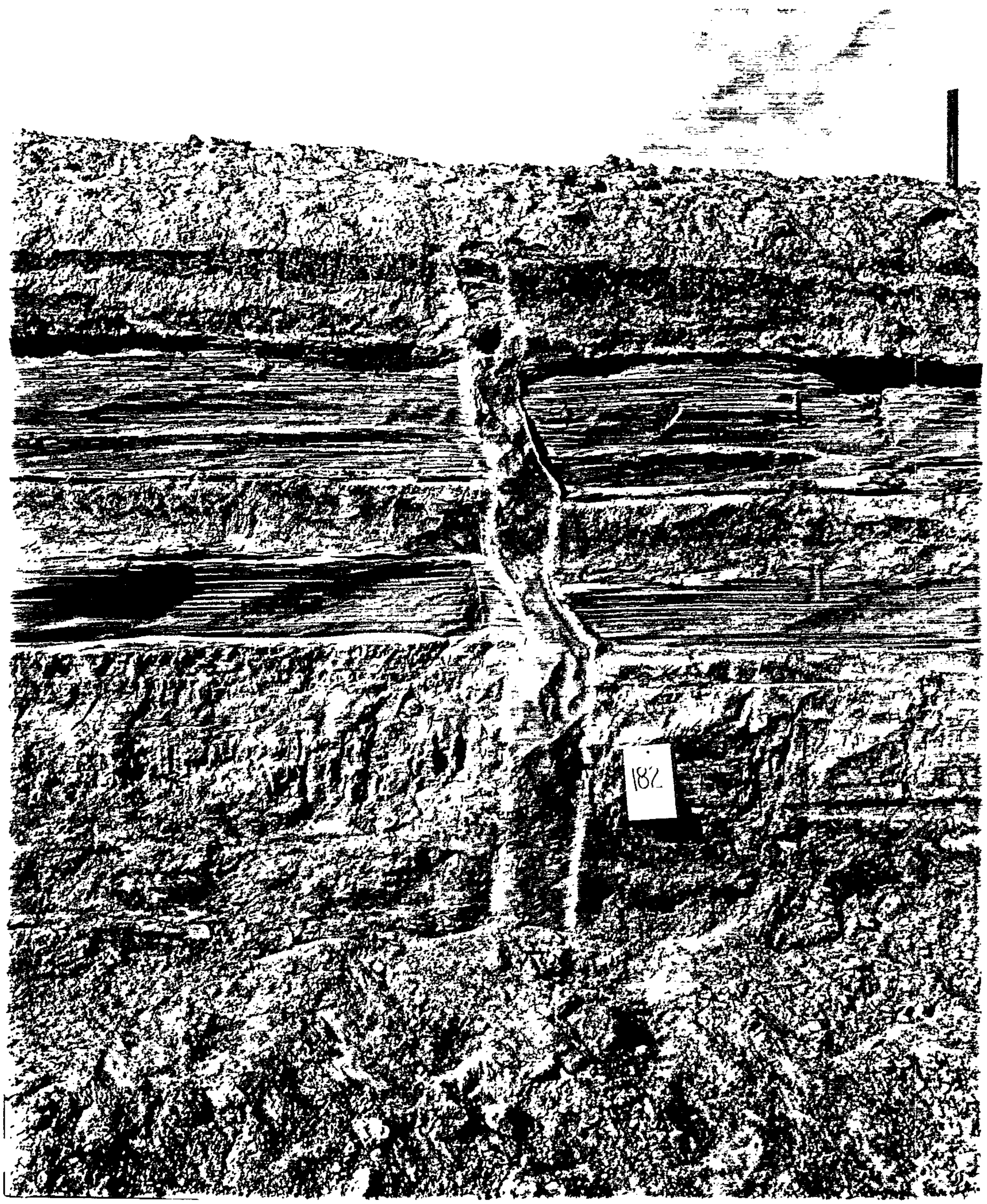


Figure 4/34
Circumferential Sand Dyke Filling Normal Fault on SNOWBALL Crater

hydraulic fracturing. Here the pre-existing fault controlled the later formation of the dyke. Other, but similar photographs exist in the archives, confirming that this was not an isolated situation.

We now turn to two sections taken through the rim structure, which show quite distinct, contrasting effects on the south and north rims. Figure 4/35 is a section through the upper part of the south rim, but taken some twelve months after the detonation, by which time the "ejecta", so called, which lay on the pre-shot surface had been removed. At the time of that removal, the coherently overturned nature of the overlying deposit had not been recognized. Discussion of this "hinge region" on SNOWBALL is therefore deferred until the next chapter, dealing with the PRAIRIE FLAT crater, where a closely comparable hinge region will be discussed in more detail.

Figure 4/36 shows one of the rather deeper sections through the north rim of the crater, with the crater void to the right of the photograph. Clearly, the normal field interpretation of this structure would be to call it an upthrust rim, which is what it is visually. However, cross-correlation with the sand column markers for this region (vide Figure 4/26) proves conclusively that the actual motion has been a **downward** residual displacement; a downwarping of the pre-existing ground. There does not appear to be a recognizable "hinge" motion at this part of the underlying strata, though the "visually upward" motion is not inconsistent with this. At the time of excavation, evidence of coherent overturning, which was only fully recognized during the excavation of PRAIRIE FLAT, was not looked for, though it was suspected at a late stage of the SNOWBALL study, too late for field verification due to removal of the "ejecta" blanket, and limited time and funding.

Note also that on SNOWBALL there was no recognition of a deeply buried rim anticline, as seen later on DISTANT PLAIN 6 (vide Figures 3/14 and 3/15), nor were the inner circumferential ring anticlines recognized. These aspects will be discussed further in Chapter Five (PRAIRIE FLAT).

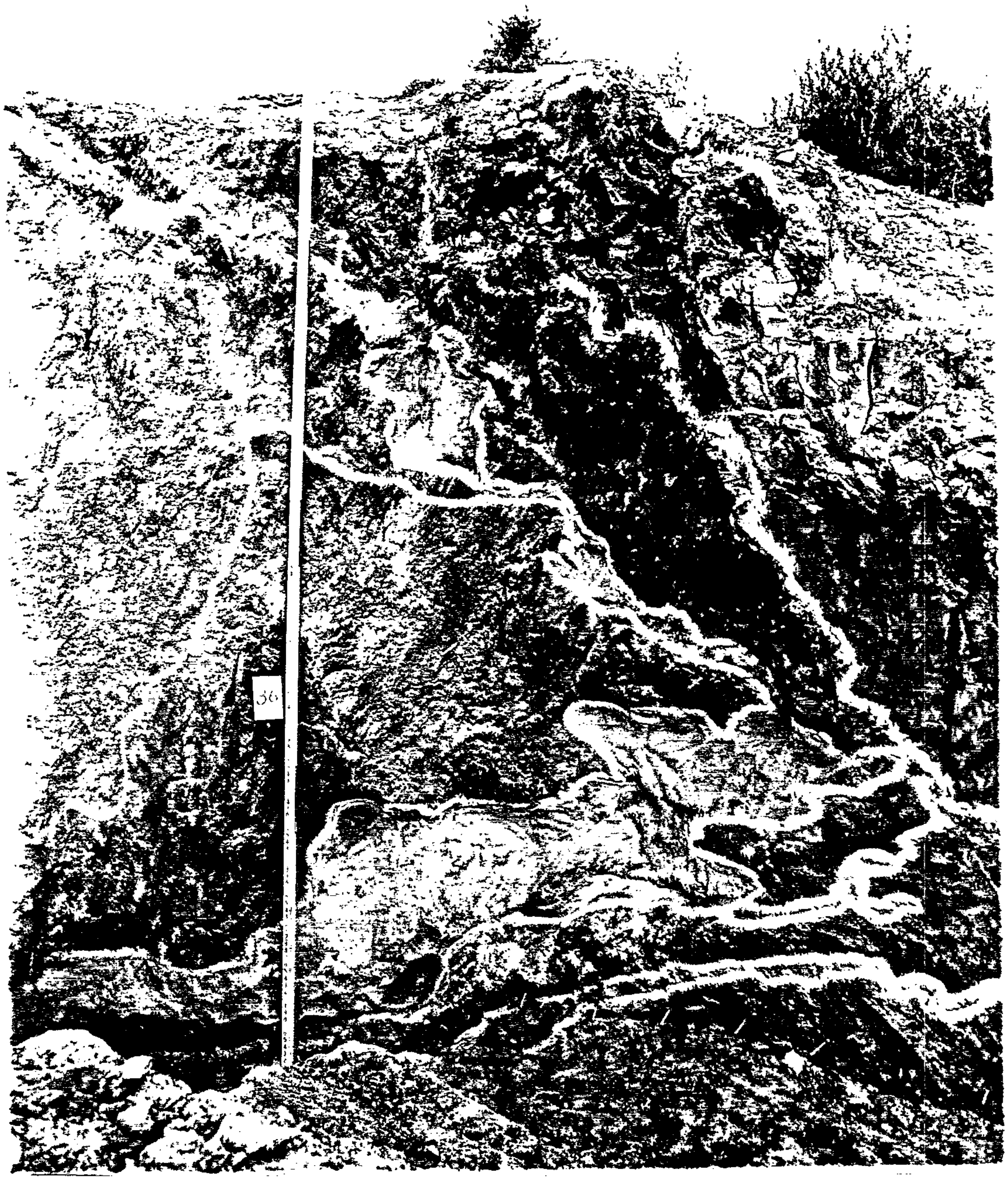


Figure 4/35
Hinge of SNOWBALL South Rim but with Overturned Flap Removed

Figure 4/36
Visually Upthrust, but Actually Downwarped North Rim of SNOWBALL Crater

4.6 THE STRATIGRAPHIC SECTIONS OF THE SNOWBALL CRATER

As far as the author's recollection, and the available publications reveal, no publication has ever been made of the stratigraphic records made during the excavation of the SNOWBALL crater, but the original plots were found in the author's collection. The plots are similar to those given later for PRAIRIE FLAT, but in contrast to the "integrated" sections which exist for PRAIRIE FLAT, the SNOWBALL plots are individual, detailed original excavation sections. Some are of direct relevance to the new interpretations in this report, and are therefore discussed individually in terms of present day understanding. For that reason, no attempt is made at full integration of the sectional stratigraphy.

4.6.1 The Central Mound Excavation, East-West Cut 10 ft North Of GZ

The cut wall in Figure 4/37, which is viewed from the south, shows clearly the central upthrust, offset from GZ and the uplifted strata almost vertical in the GZ region. A large central Red Sand pipe is visible in the central region, but in this particular section it does not break the surface, but would probably do so virtually at GZ. Roughly 30 ft west the main sand filling of the crater floor shows a pipe penetrating through the fallback debris on the flank of the central uplift, but in this section the penetration to depth is not evident.

The East side of the mound shows extensive piping, but in the form of an infilling of dendritic hydraulic fracturing.

In the section as plotted, the bottom dotted line represents the limit of excavation. However, if memory serves, the excavation was in this case terminated in the region between 5 ft and 20 ft east at the contact with an updomed blue clay. While this memory is unverified, it will be seen later (PRAIRIE FLAT and DIAL PACK) that just such an updoming, in the form of a concentric ring anticline, is a common feature at this location in the 500 ton craters.

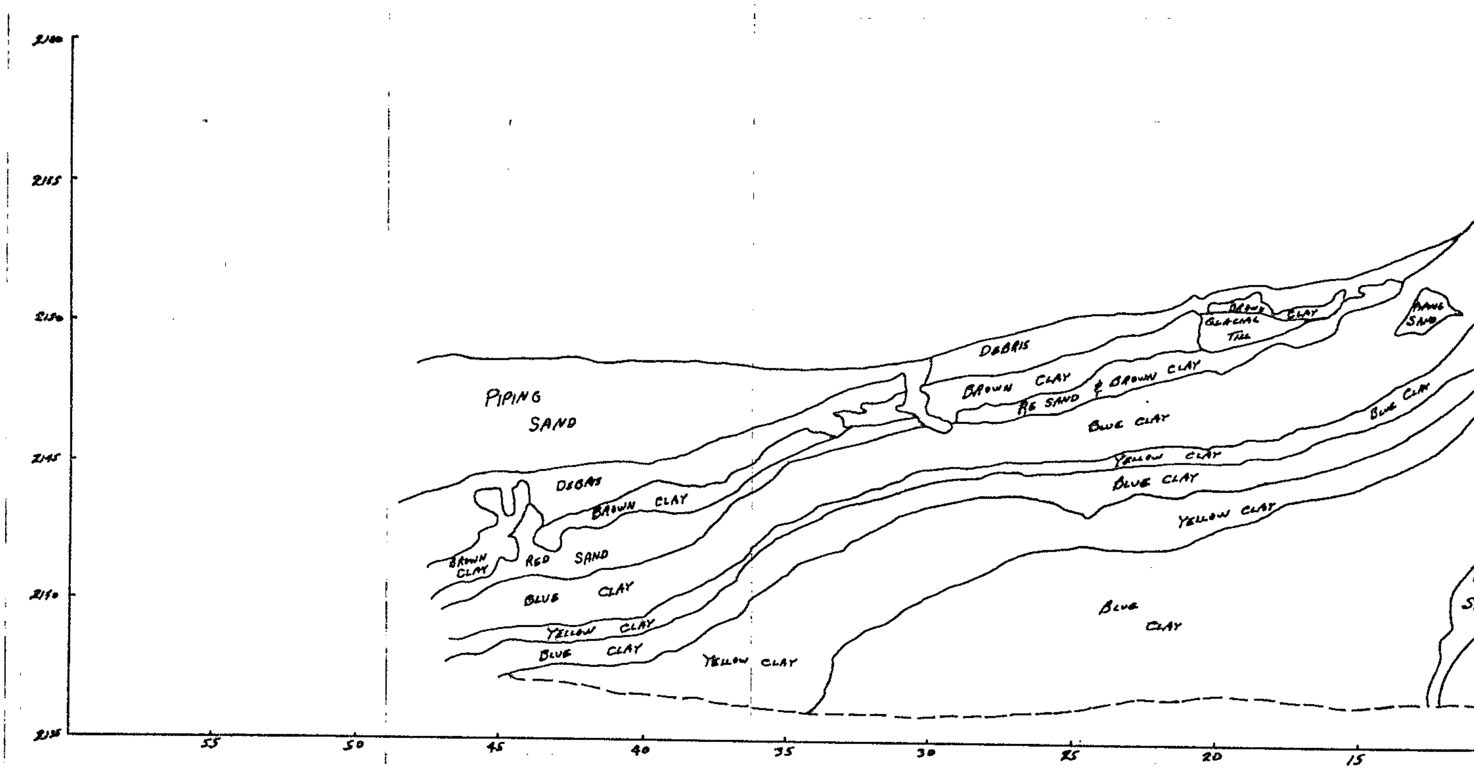
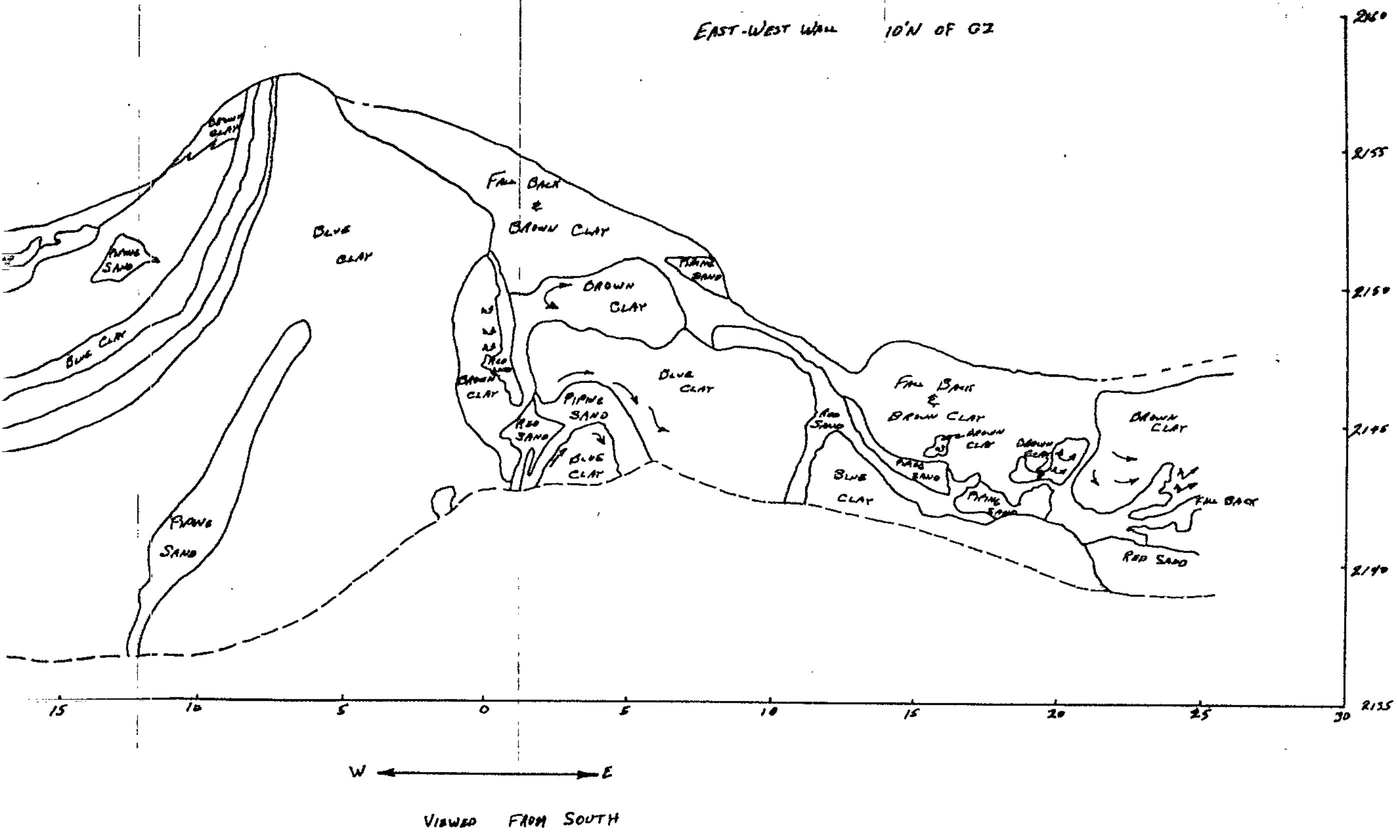


Figure 4/37

East-West Excavation of the Central Mound Uplift 10 feet North of GZ of SNOWBALL Crater



EAST-WEST WALL 10'N OF GZ
FALL BACK & BROWN CLAY
BLUE CLAY
BROWN CLAY
PIPING SAND
BLUE CLAY
RED SAND
BLUE CLAY
FALL BACK & BROWN CLAY
BROWN CLAY
RED SAND
FALL BACK
W
E
VIEWED FROM SOUTH

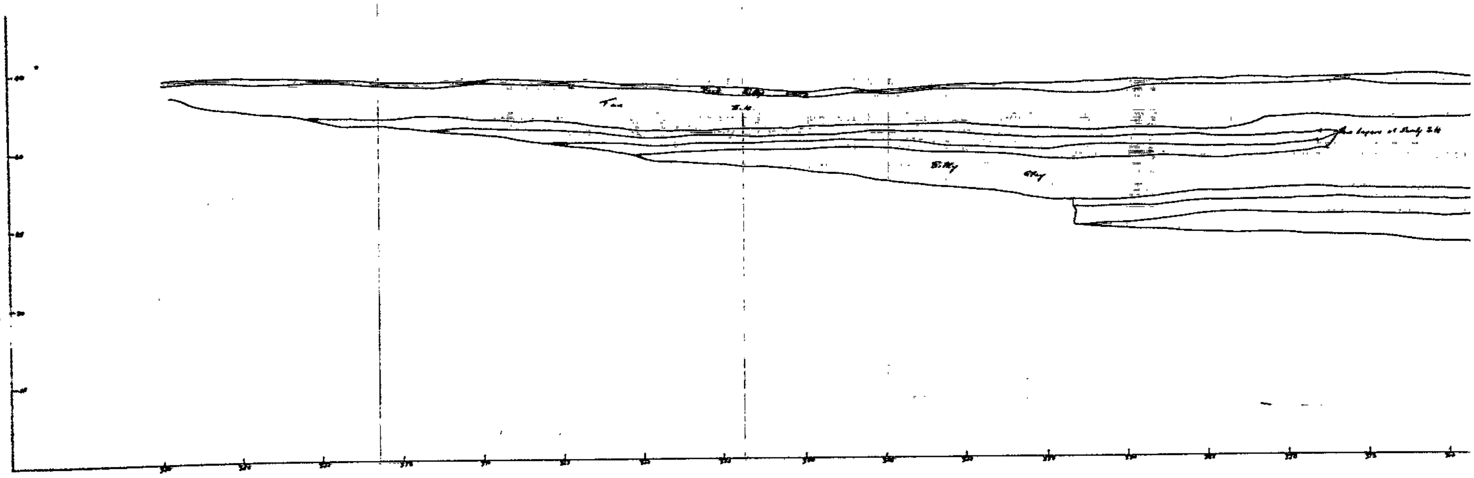
4.6.2 South Excavation, 75 ft West Of North-South Sand Column Line (Field Plots 1 and 2)

The plot in Figure 4/38, which was originally 22 adjoining field sections, and the plot in the following section (Figure 4/39), similarly composed, are supplemental to the sections plotted with the North-South sand column data in Figures 4/24 - 4/28. However, as these walls were surveyed without the complication of recovering and surveying sand column markers, they show additional, and confirmatory stratigraphical data.

The section in Figure 4/38 starts at the "hinge" region of the crater rim, about 100 from GZ, and in this region shows the strata rotated into a vertical attitude; the outer region between 95 and 100 ft essentially smooth and "stretched", while the inner part between 100 and 105 ft, inside the curve of the overturning, shows the "wrinkling" that one would expect in a coherent overturn, in this region.

Beyond the "hinge", the strata at this depth show a smooth, slightly synclinal inward dip, corresponding with the inward dipping surface bounding the edge of the crater (saucer depression). This is consistent with the general attitude of the overlying strata, but at about 135 ft from GZ a significant change is noted. The upper strata in this section (which is well below the pre and post-shot surface, previously excavated) shows a sharp break or declivity, while the lower strata are ruptured, along a line sloping towards the crater at an angle of some 15 degrees from the vertical. Between 140 and 155 ft the lower strata show a series of small block faults and drag folds, but the upper stratum is almost exactly flat and horizontal. The disturbed lower strata are then bounded by a line which has the opposite, but roughly equal tilt to the boundary, at 100 ft. It would appear that in the region between 100 and 160 ft, there has been some form of vertical slumping within the confines of what is, essentially, a block fault bounded by opposed normal faults. Why this should underlie a flat lying "mesa like" structure of similar scale is not clear to the present author.

Possibly more easily understandable is the odd looking structure which lies between 160 and 175 ft, which is bounded at depth by yet another "normal" fault at 175



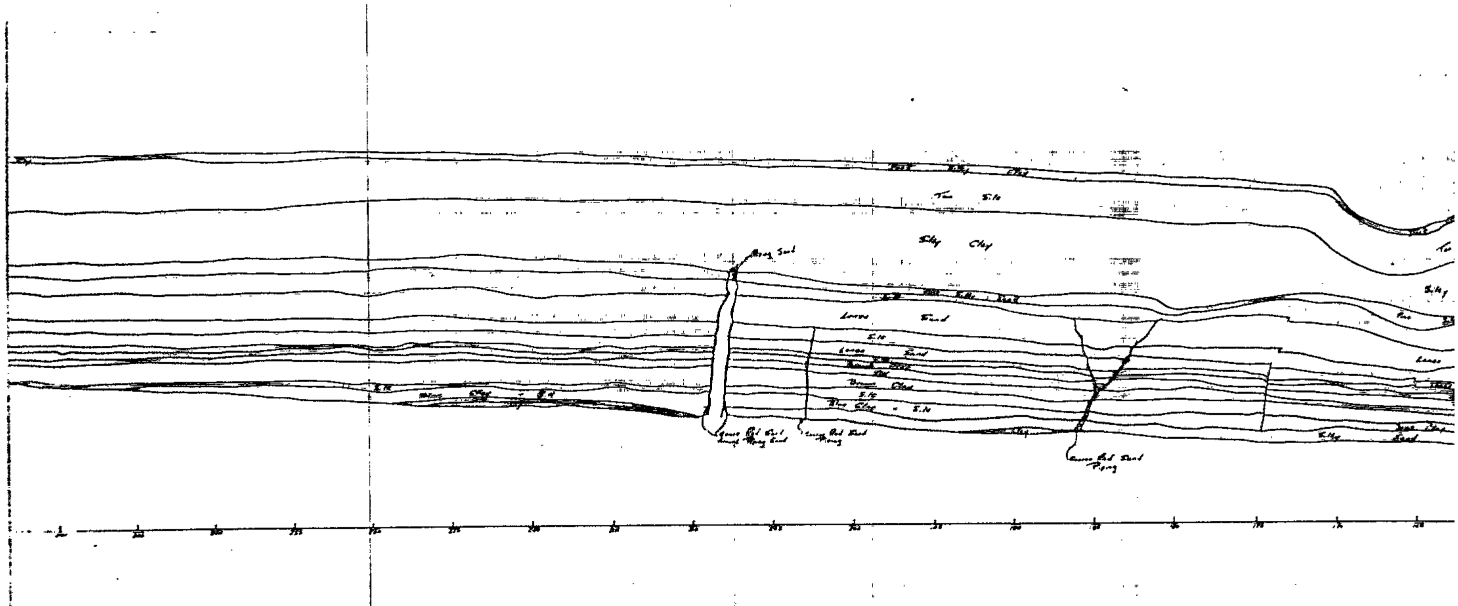
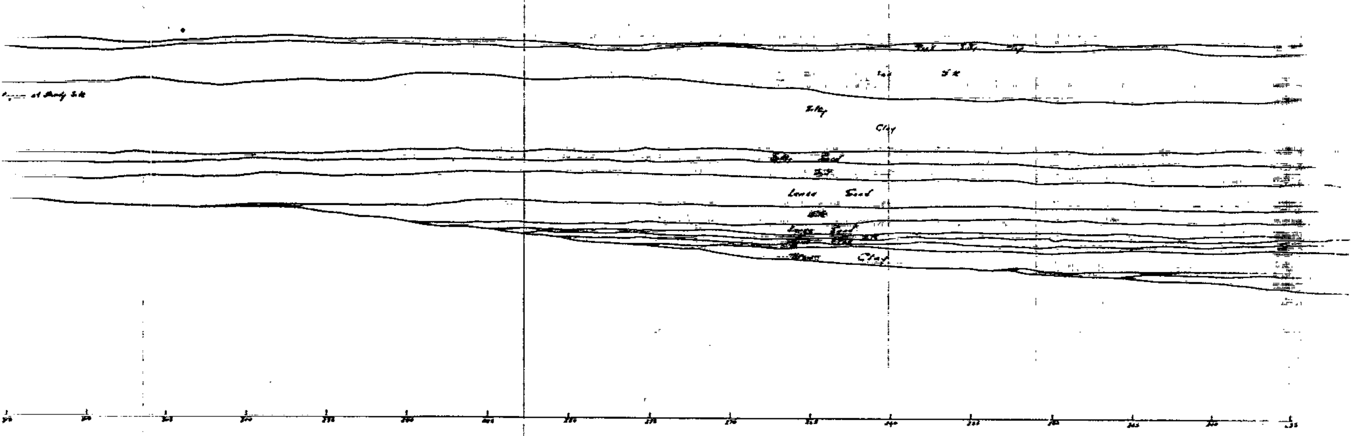


Figure 4/38
South Excavation 75 feet West of North-South Sand Column of SNOWBALL Crater



PLOT #1 Sheets #1 to 13
PLOT #2 Sheets #2 to 11

ft, tilted towards the crater and with but little downthrow on the crater side. Extending this fault, and the equivalent, but less clearly fractured boundary between 150 and 160 ft, a second block fault is observed, but this time with inwardly opposed boundaries, which terminates at the surface (of this section, not the original ground) as a sharply defined syncline between 160 and 170 ft. This, presumably circumferential feature, appears to correspond with an essentially similar region of faulted lower strata and synclinal upper strata shown on the sand column section, in a closely similar location.

Moving out from the crater beyond this point, to the region between 180 and 210 ft, an almost exact match is seen between this section and the same region in the sand column section, even to the same Y-shaped "hydraulic" fracture and the major "sand dyke" at 210 ft. This confirms that these features were circumferential dykes, not isolated vertical pipes.

The section is plotted, continuously, out to 390 ft, but reveal no further structures that call for comment.

4.6.3 South Excavation, 80 ft East Of North-South Sand Column Line (Field Plots 10 & 11)

This section, Figure 4/39, again plotted from 19 field sections, is taken on the other side of the sand column section, from the "opposite" wall direction, so that in this case GZ is to the left of the section. Again, it is a partial section taken as a concluding set of data associated with the sand column excavation. As before, it starts with a small "rotated" section of strata, the base of the hinge region, which appears a little closer to GZ in this section, between 85 and 95 ft, rather than 100 ft plus of the previous section. However, there is no significance in this change, which clearly shows the same feature, which was never "fully" exposed at any given stage.

The general low angle, inward slope of strata beyond the hinge is again visible, and between 155 and 175 ft again a clear definition of a downward moved block fault is seen, bounded by opposed normal faults, in a similar position to that noted above, which tends to confirm that this dropped block faulting is also circumferential to the crater. However, in this section there does not appear to be a surface synclinal trough evident.

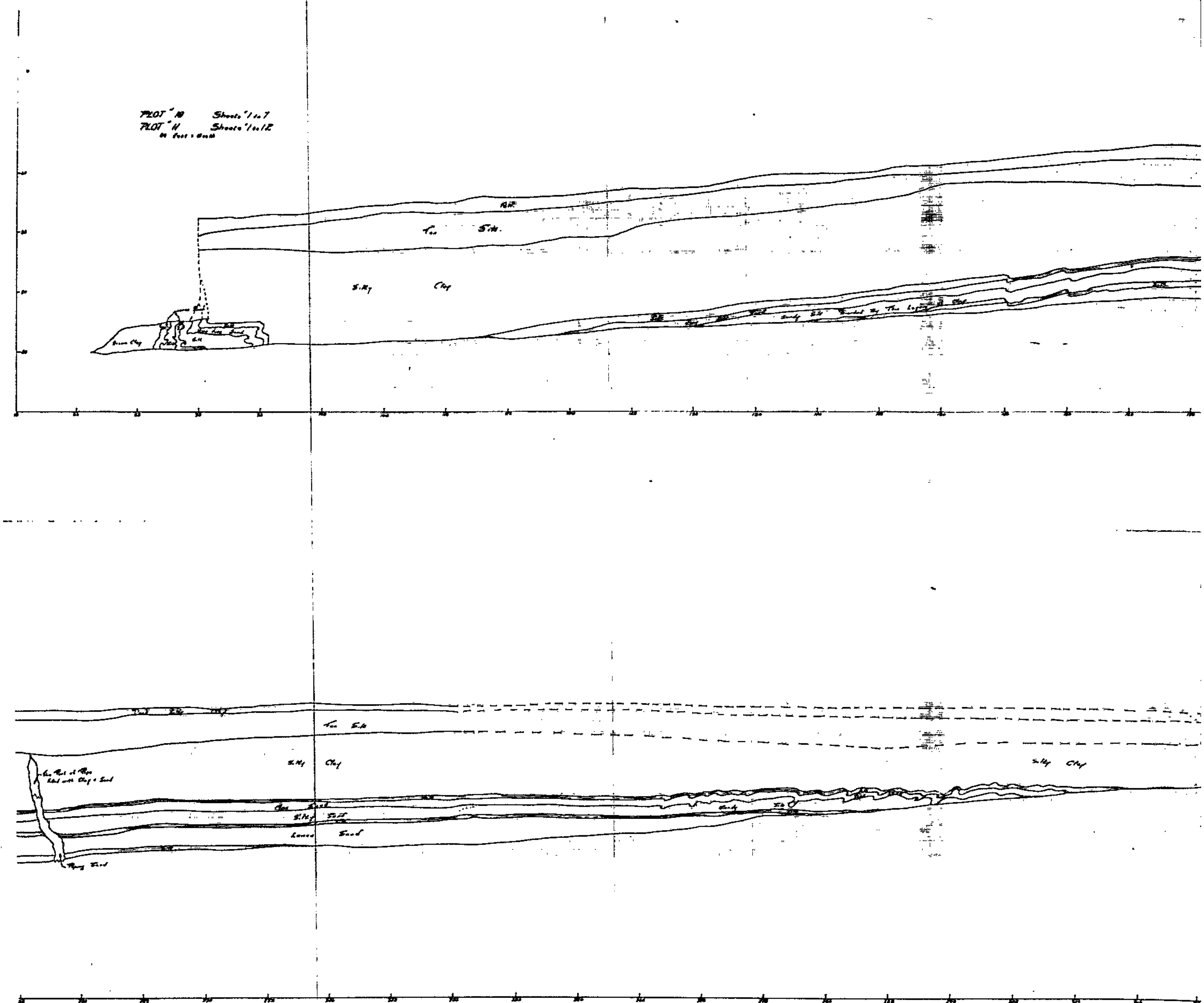
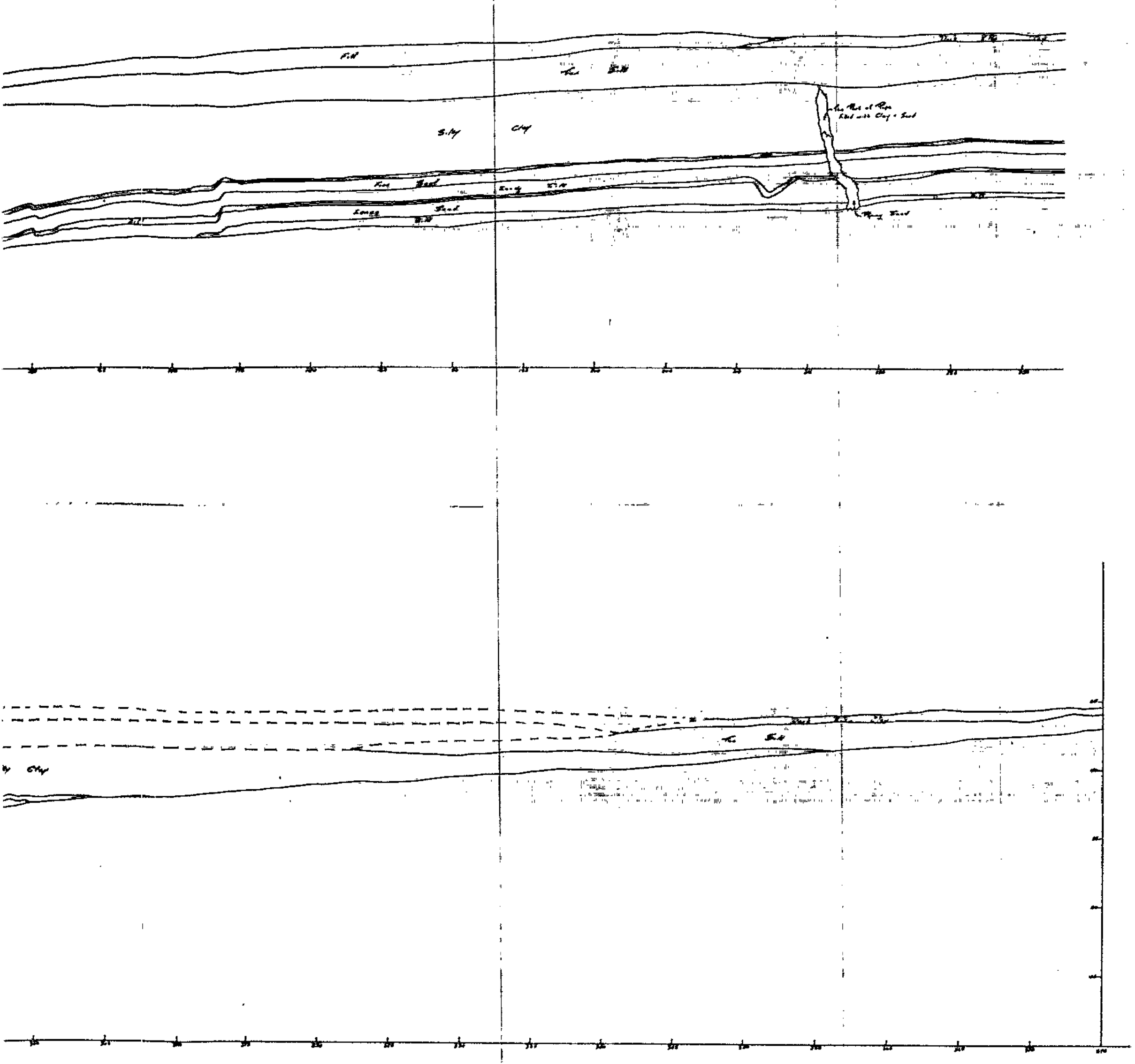


Figure 4/39
South Excavation 80 ft East of North-South Sand Column of SNOWBALL Crater



The sand dyke circumferential to the crater is again sectioned at between 215 and 220 ft. The only other remarkable feature in this section is that between 265 and 300 ft the lower strata are "rippled" by what appear to be drag folds. It appears to the author that at this region, the residual movement is outward, basically compressing the strata radially outward, from the original surface to an appreciable depth. This is confirmed by the sand column displacements, which become vertical on column S4 at 240 ft from GZ, then show progressively greater outward displacement on columns S3, near 250 ft and S2 at 320 ft.

4.6.4 The South-West Cut Wall (Field Plots 32, 33, 35 & 42)

The section in Figures 4/40 - 4/42, based upon 13 field plots, is along a radius well removed from the sand column line, which had already been excavated. Moving South-West from GZ, the section of the central mound from about 8 ft to 35 ft is basically similar to parts of the earlier East-West cut and does not call for further comment. However, at between 45 and 100 ft SW from GZ, rising from under the major pseudo-volcanic sand deposit, there is a clear section through an up-domed region, similar to the circumferential ridging which, as will be seen later, is more exposed on PRAIRIE FLAT and DIAL PACK. It is also comparable with the confused feature showing Red Sand covering a ridge as discussed in the North-South sand column excavation. However, although there is some injection of silt and sand, in this case a dome of blue clay overlies a dome of brown clay. This is an inversion of the pre-shot stratigraphy, and the mechanism is unclear to the author at this time. The section of the dome, as plotted, ends at about 95 ft, that is well within the crater from the hinge region. However, immediately below the hinge region the plot is blank, indicating that excavation was either not done at all, or if done was on a previous, currently unrecorded excavation of the rim.

The hinge region itself, on this cut, is much less coherent than on the main North-South sand column line, and there is some evidence of "piping sand" intrusion, and rather blocky brown clay shown as "brecciated", but conforms to the general tendency to form an upturned hinge. Readers are advised that care must be taken in interpreting the

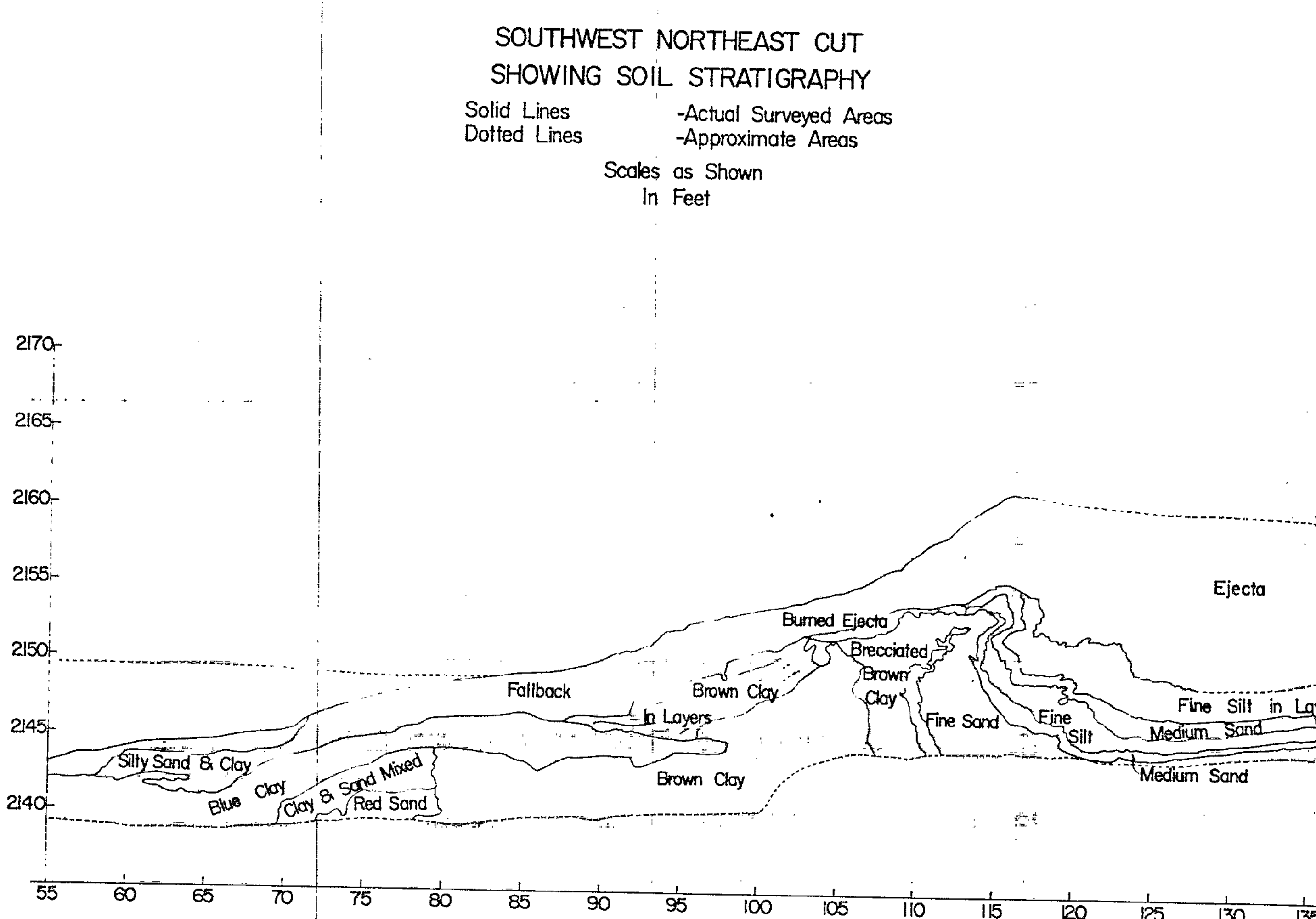
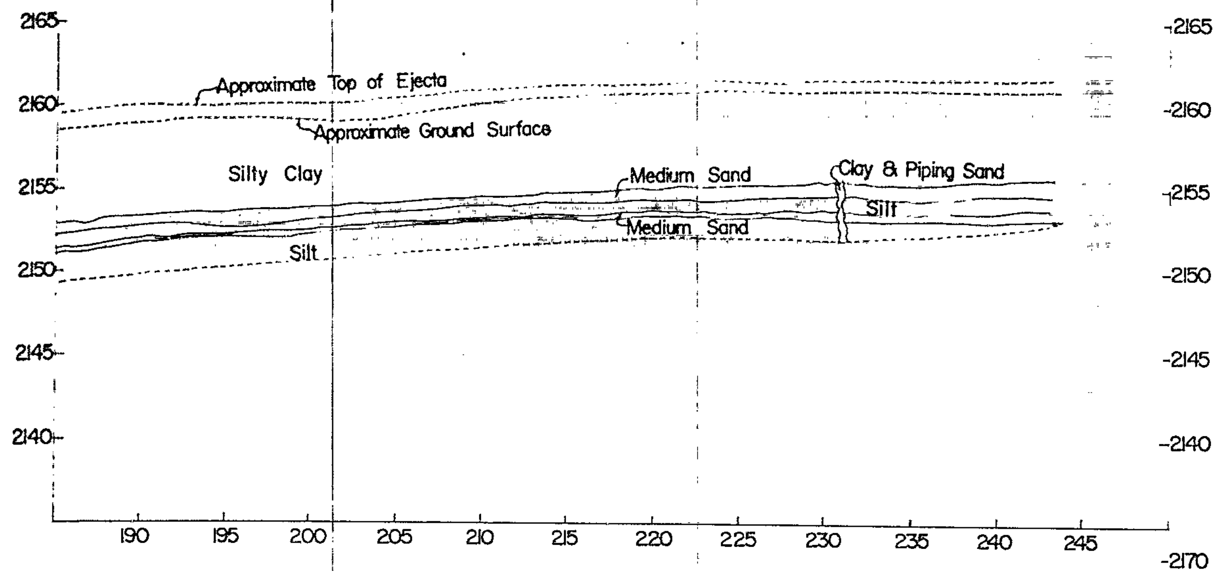
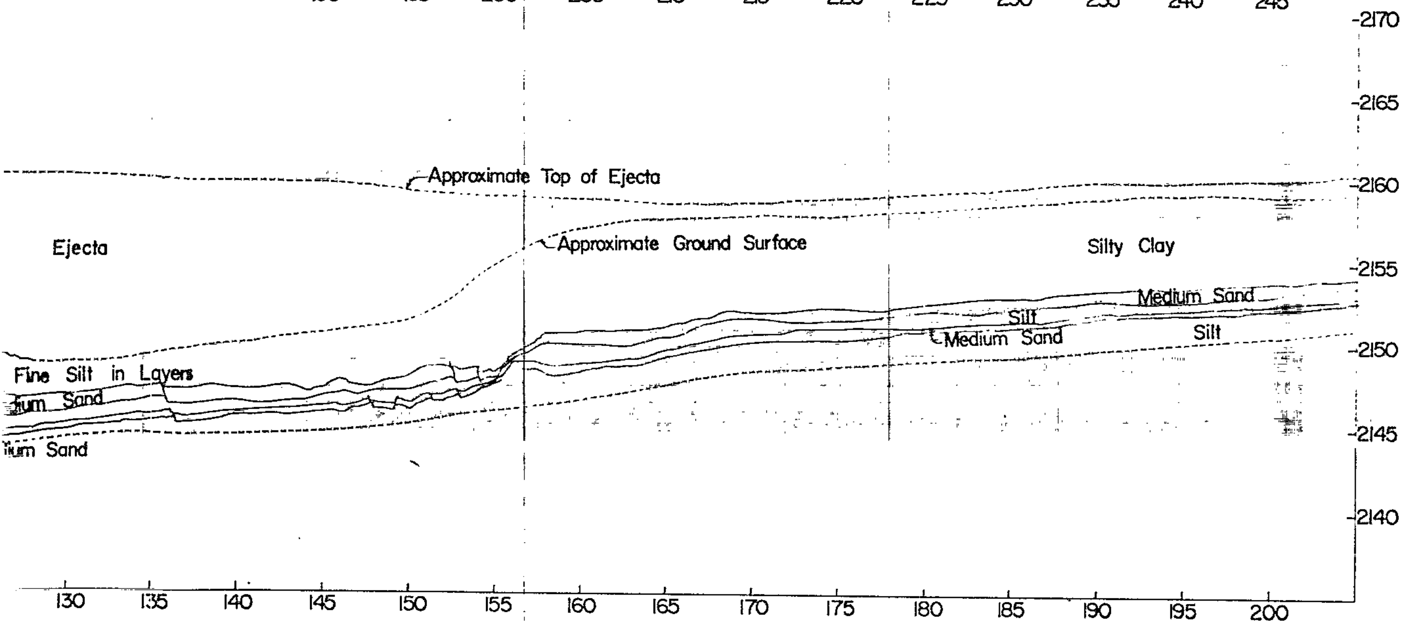


Figure 4/40
The South-West North-East Cut Wall of SNOWBALL Crater
(S55 to 245 ft)


2165
2160
2155
2150
2145
2140
Approximate Top of Ejecta
Approximate Ground Surface
Silty Clay
Medium Sand
Clay & Piping Sand
Silt
Medium Sand
Silt
190
195
200
205
210
215
220
225
230
235
240
245


-2170
-2165
-2160
-2155
-2150
-2145
-2140
Approximate Top of Ejecta
Approximate Ground Surface
Ejecta
Silty Clay
Medium Sand
Silt
Medium Sand
Silt
Fine Silt in Layers
ium Sand
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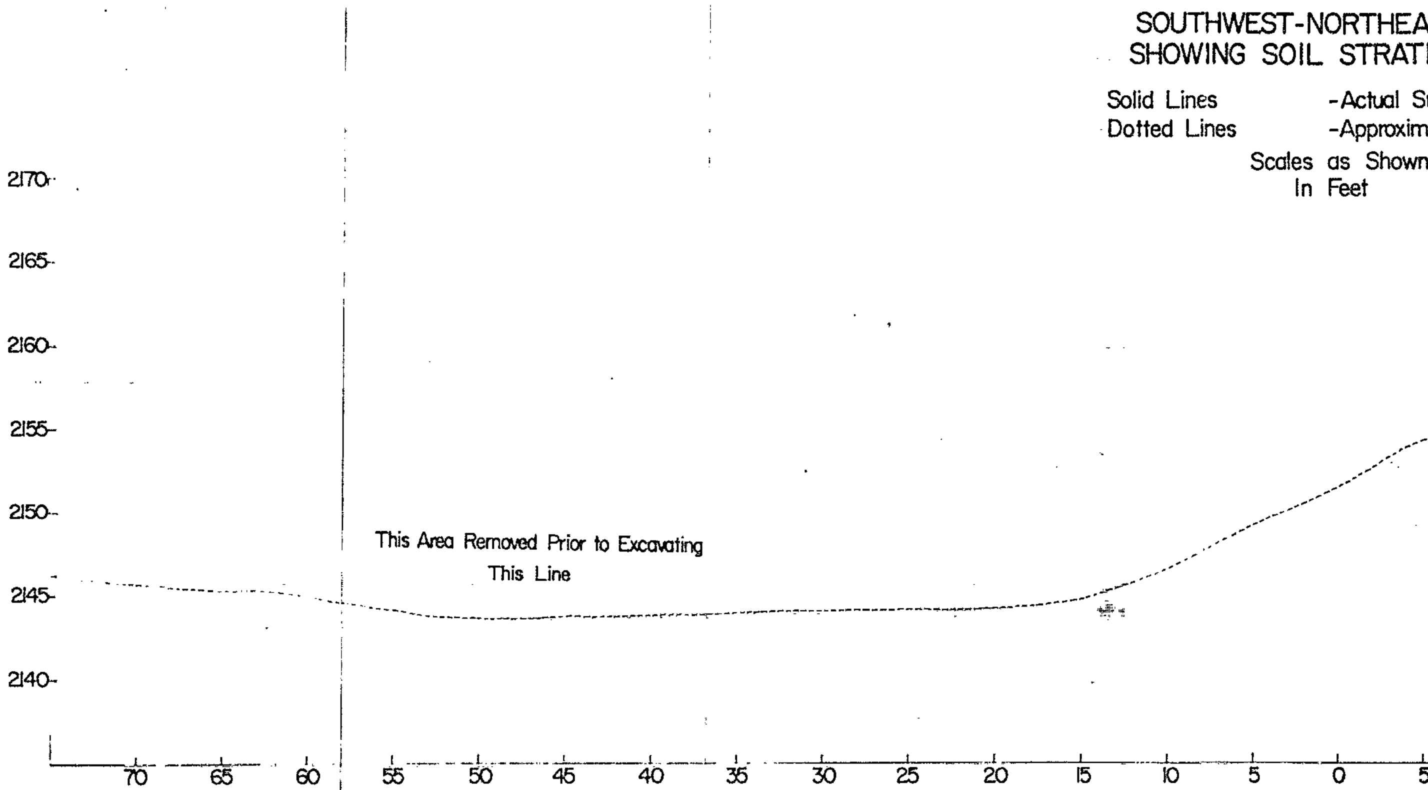
200


SOUTHWEST-NORTHEAS
SHOWING SOIL STRATI
Solid Lines -Actual Su
Dotted Lines -Approxima
Scales as Shown
In Feet
2170
2165
2160
2155
2150
2145
2140
This Area Removed Prior to Excavating This Line
70
65
60
55
50
45
40
35
30
25
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15
10
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5

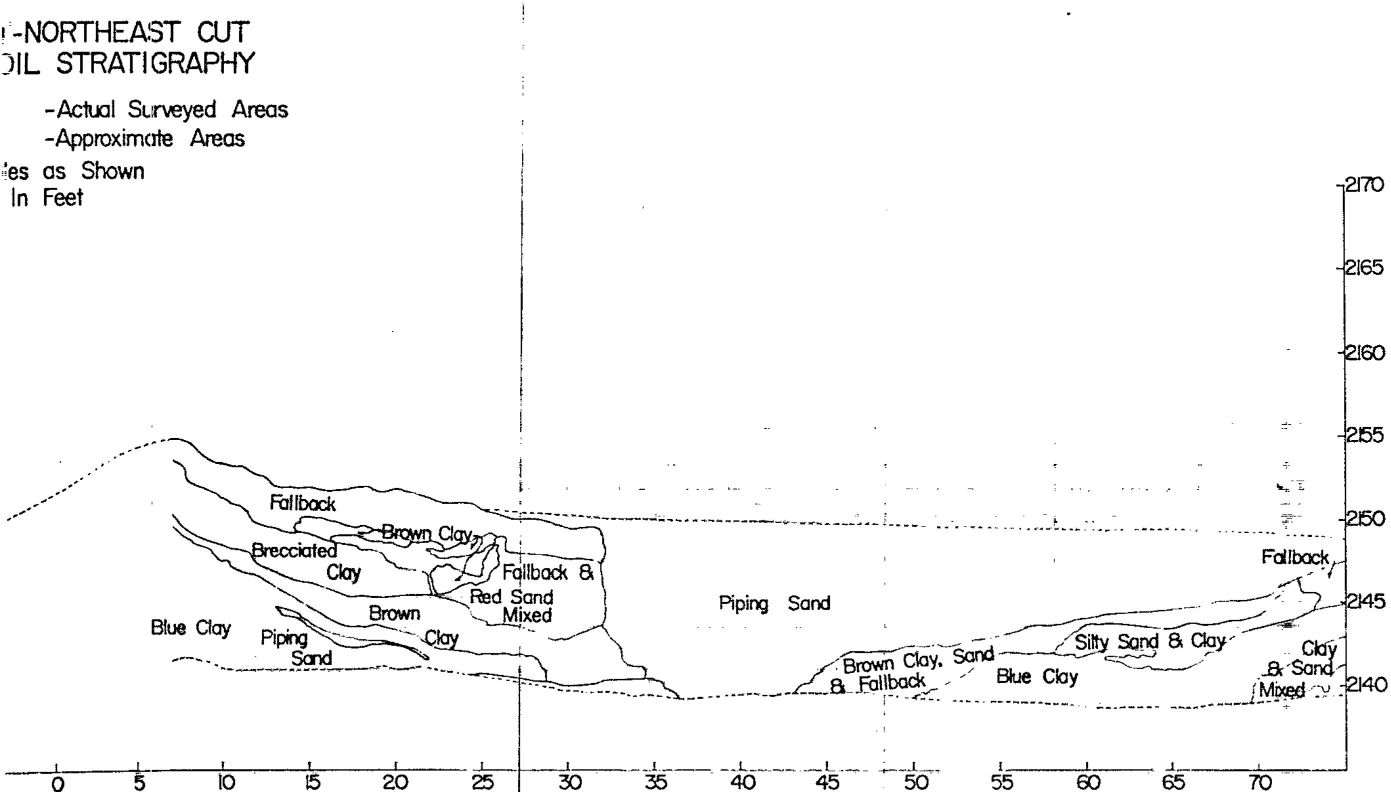


Figure 4/41
The South-West North-East Cut Wall of SNOWBALL Crater
(N70 to S70 ft)

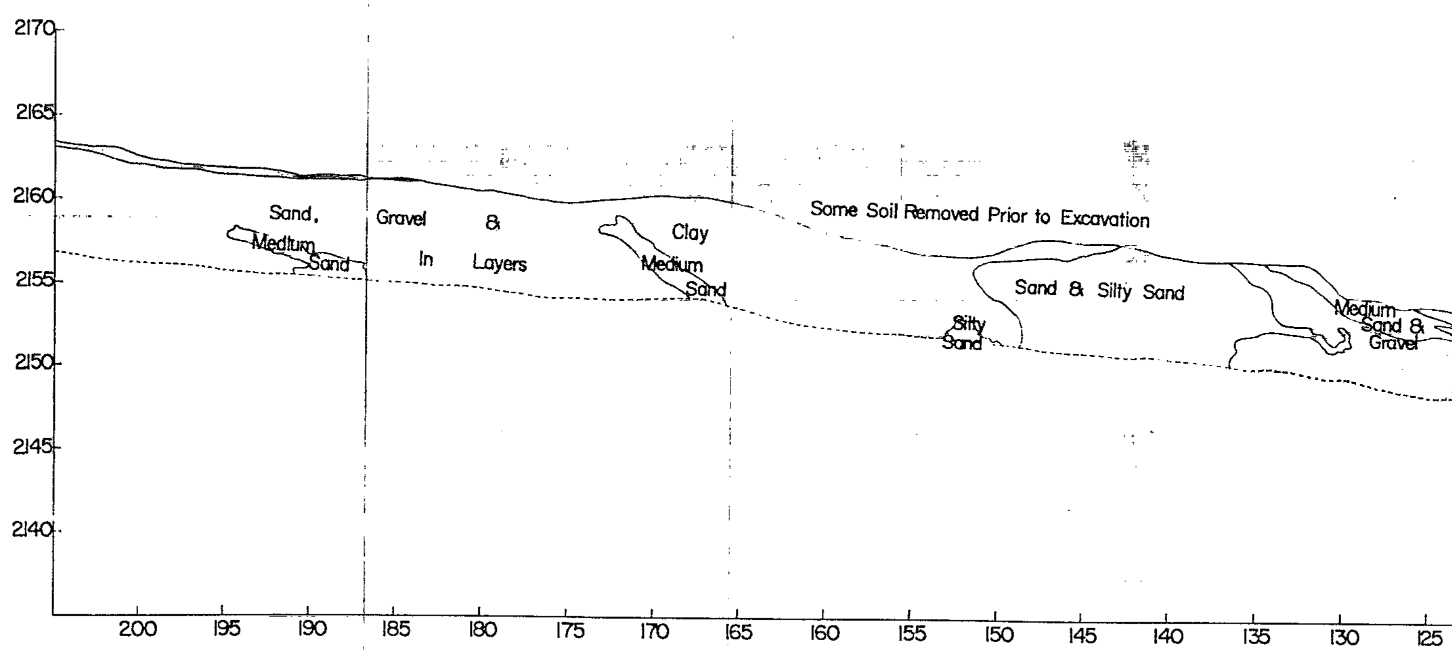
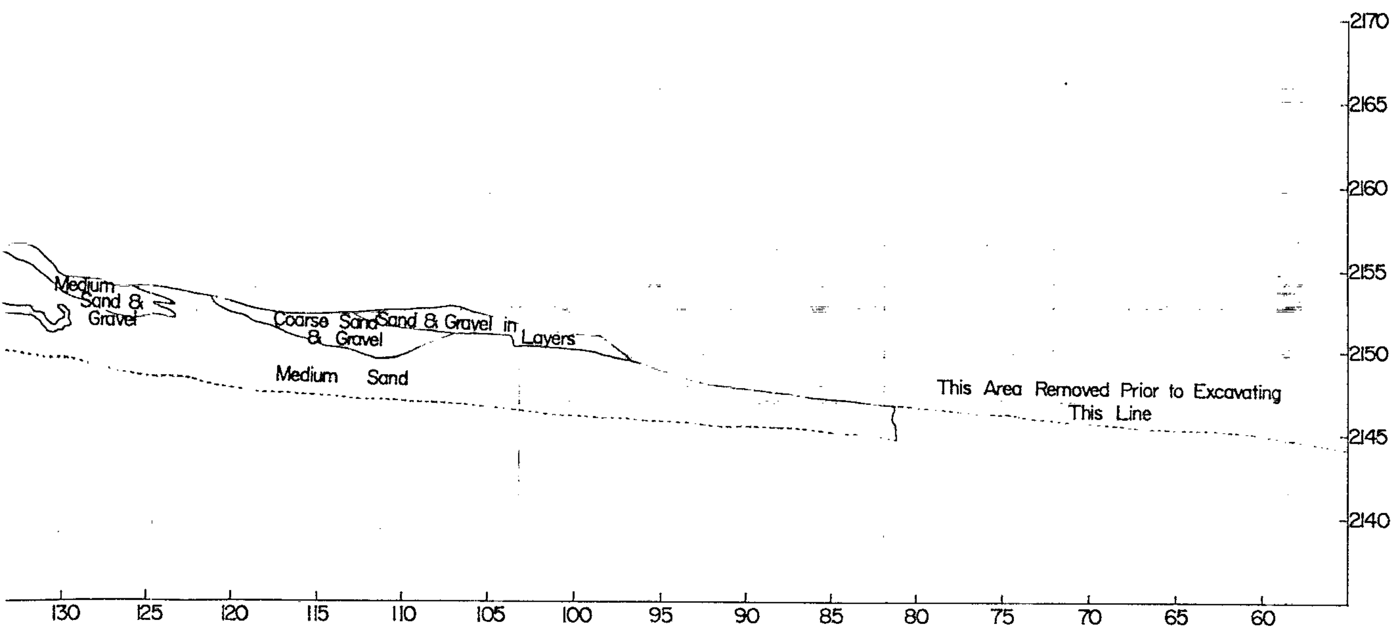


Figure 4/42
The South-West North-East Cut Wall of SNOWBALL Crater
(N200 to 55 ft)

SOUTHWEST NORTHEAST CUT
SHOWING SOIL STRATIGRAPHY

Solid Lines -Actual Surveyed Areas
Dotted Lines -Approximate Areas
Scales as Shown
In Feet



top layers of this section, which is shown as "ejecta" or fallback. At the time of the excavation, the existence of a coherently overturned rim had not been detected, and the material shown as "ejecta" had been cleared down to the pre-shot ground surface at an earlier stage, as part of a different project studying the crater ejecta, as had been undertaken on earlier more canonical craters. It will be shown later that the region shown blank as "ejecta" in this plot of any SNOWBALL excavation, is occupied by the coherently overturned flap detected and excavated in detail on the PRAIRIE FLAT crater.

Beyond the hinge region, the general inward dip of the strata is again noted, and between 135 and 160 ft there is evidence of block faulting, a generally downward movement between opposing normal faults. This is in roughly the same region as the equivalent structure on the North-South line 75 ft West of the sand column line as discussed above. This again confirms that there was a circumferential, block faulted and downwardly displaced structure well beyond the crater "rim".

Farther out, at about 233 ft from GZ, there is another section of the circumferential sand dyke. Although slightly removed from the more common 210-220 ft, the section confirms that there is an essentially circular ring dyke. At the level excavated, the sections of the dyke are sensibly vertical, but it is suggested that they may well be related to a conical thrust fault rather than a normal fault system similar to the block faulted region detected closer to the rim. This is certainly a moot point, but evidence of such a thrust fault system does exist and is demonstrated both structurally and by the sand column markers in many of the craters described in this report.

4.6.5 North Section Excavations, 4 ft, 10 ft, and 11 ft East Of North-South Sand Column Line

These three parallel sections, running north from GZ and parallel to the North-South sand column line are plotted together in Figure 4/43. By so doing, the variation even along closely spaced lines of excavation may be noted. As shall be discussed in the next section, the north side of the SNOWBALL crater was complicated by the fact that it breached the only "anomalous" area of the Watching Hill test site, thus losing the pre-existing horizontally layered lacustrine beds common to the south side, and other craters.

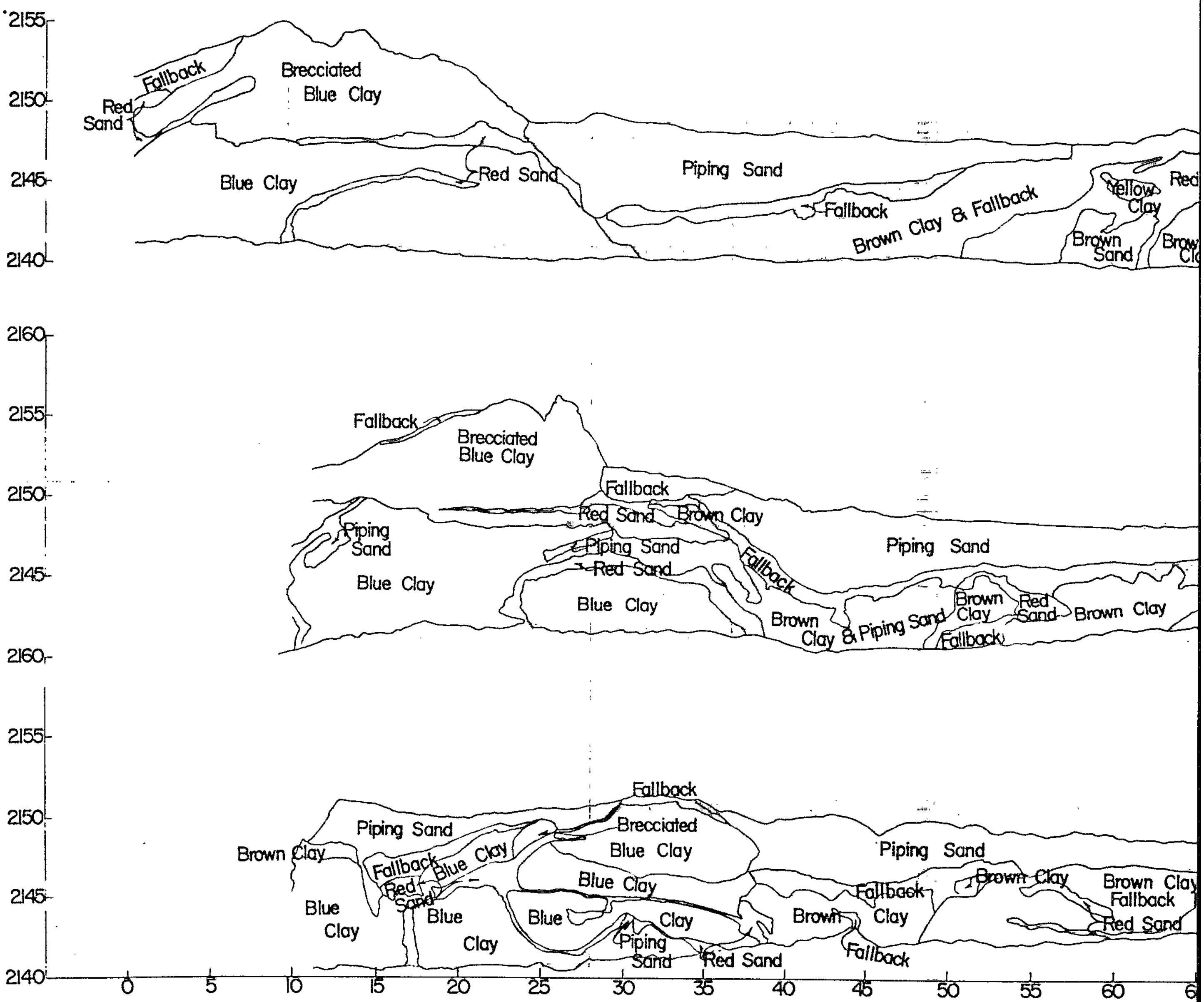
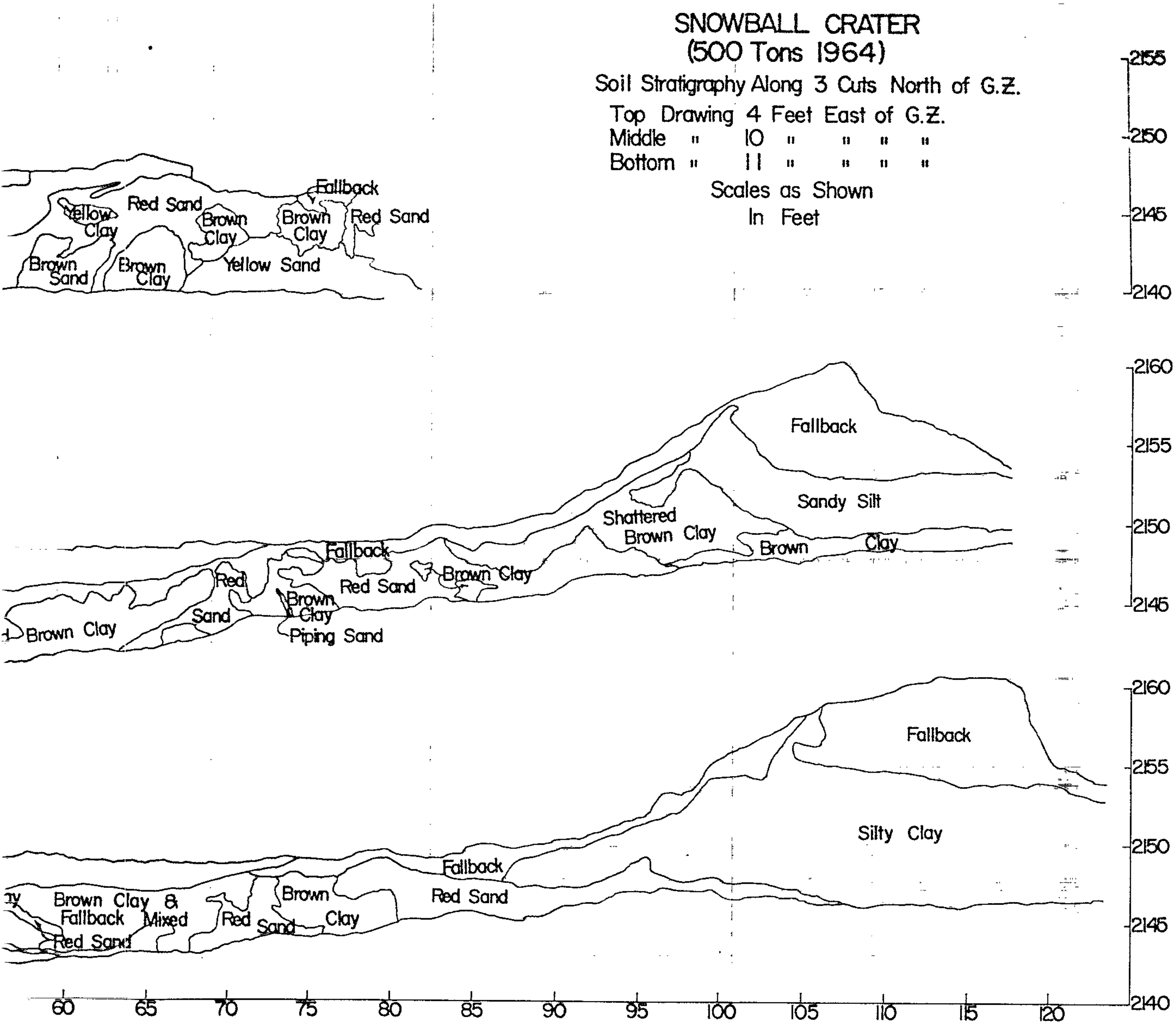


Figure 4/43
North Section Excavation 4 ft, 10 ft and 11 ft East of North-South Sand Column Line of SNOWBALL Crater


SNOWBALL CRATER
(500 Tons 1964)
Soil Stratigraphy Along 3 Cuts North of G.Z.
Top Drawing 4 Feet East of G.Z.
Middle " 10 " " " "
Bottom " 11 " " " "
Scales as Shown
In Feet
2155
2150
2145
2140
Fallback
Yellow Clay
Red Sand
Brown Clay
Brown Clay
Red Sand
Brown Sand
Brown Clay
Yellow Sand
2160
2155
2150
2145
Fallback
Sandy Silt
Shattered Brown Clay
Brown
Clay
Fallback
Red
Red Sand
Brown Clay
Brown Clay
Sand
Brown Clay
Piping Sand
2160
2155
2150
2145
2140
Fallback
Silty Clay
Fallback
Red Sand
Brown Clay & Fallback
Mixed
Red Sand
Brown
Red
Sand
Clay
60
65
70
75
80
85
90
95
100
105
110
115
120

Consider first the section 4 ft east of GZ, so that the GZ is actually 4 ft "West" (ie. towards the observer) at the scale zero. This is a most interesting section, as in this cut the central mound is composed almost entirely of updomed blue clay which does not show evident stratification even though it shows three major intrusions of red piping sand. Note that the top section of the blue clay is marked "brecciated". Actually, shattered would be a better term. In this region the clay was rather hard, as if baked, and finely shattered in a cubic pattern, apparently due to tensile fracturing at the time of maximum uplift. Note the smooth section of the blue clay at the lower level, which was still the consistency of soft cheese. The effect is shown in the photograph of Figure 4/44.

The main sand infilling which covered the crater bottom is clearly shown and overlies, as would be expected, a thin layer of fallback debris. Below this is a concave section of brown clay, which overlies the blue clay in the predetonation stratigraphy, evidence of a synclinal trench around the central mound. Note, however, that this synclinal structure is bounded (at between 50 and 55 ft south of GZ) by a thick anticlinal structure, consisting mainly of a red sand which contains massive "inclusions" of brown sand and blocky brown clay, overlying in the region between 65 and 80 ft west a yellow sand. However, looking back at the central mound several quite large and obvious intrusions of the red sand into the uplifted blue clay are noted. It is observed that the red sand, which was quite distinct in both texture and colour from the main "yellow" piping sand that gave the major deposits, was the main infilling in "dendritic" type hydraulic fractures, and appears to have come from a distinct stratum which underlies the source of the main yellow sand. Thus, although there is clearly an anticlinal ridge, in this case it cannot be identified as a purely structural anticline, as it has been, at least, enhanced by a pseudo-volcanic red sand "eruption" which has encased large blocks of clay and a ridge of yellow sand, which must equally be "pseudo-volcanic" as no such massive stratum of yellow sand existed pre-detonation. It may be noted that the photograph, in Figure 4/33, shows, in the central mound itself, a similar inclusion of large blocks of brown clay in the updoming, and obviously essentially fluid-at-the-time blue clay from

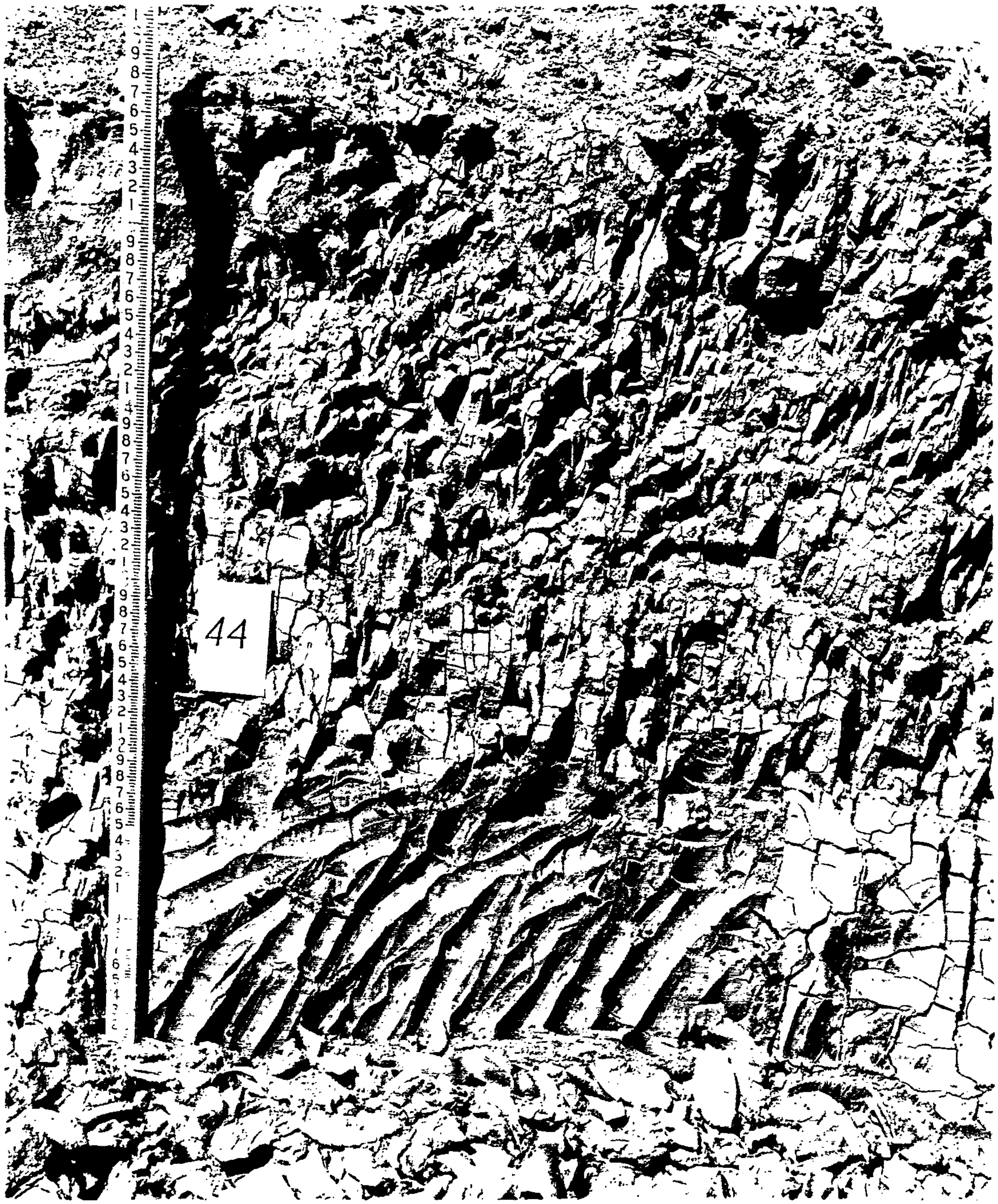


Figure 4/44
Tensile Fractured Clay at Top of SNOWBALL Central Uplift

a greater depth. It is, in fact, quite possible that at the scale of the detonation the blue clay acted in a semi-fluid way, but this must be distinguished from the actually liquid "pseudo magma" of the heavily sand laden water which produced the internal and external pseudo- volcanism.

The two lower sections in Figure 4/43, showing two very slightly separated sections running north at 10 and 11 ft from GZ start 10 ft farther north than the previous section, but extend much farther out, to 125 ft, which takes them beyond the crater's North rim. In the region of the central mound - the northern part of that mound - less evidence of pure upthrust, and more of a complicated mixture of large blocky lumps of the blue clay, separated by intrusions of red sand are seen, in what appear to be hydraulic fractures which were not the source of the main yellow piping sand.

Similarly, under the crater floor (and its cover of yellow sand) the material is mainly in the form of blocky fragments interspersed with various materials, including red sand intrusives. There appears no evidence for the "anticlinal ridge", the confused uplift in the 4 ft cut line, so it is probably incorrect to think that that was evidence of a concentric anticlinal ridge, so much as of a localized dome. This, it will be seen later in PRAIRIE FLAT and DIAL PACK, is quite consistent with the discrete, conical and isolated pseudo-volcanic cones found along ring fractures in the later craters. These were never noticed at SNOWBALL, probably because they were rapidly drowned by the rapid inflow of water and then covered by the yellow sand infill.

Of greater interest is the rim region of the crater. In both sections readers are again warned to ignore the term "fallback", which relates to the assumption at the time that all material found above the pre-shot surface was "fallback" and cleared away. This is the region of the overturned flap. Stratification on the north side of the crater was complex, pre-shot, and only in the section at 10 ft east was an "upturned" structure similar to the hinge regions elsewhere recorded. This is particularly interesting, as in the field it was always considered to be an "upthrust rim", illustrated in Figure 4/36. It was only at a much later stage, after the plotting of the north sand column line for this region, that

that it was realized that this apparent upthrust is, in terms of the pre-shot ground surface, actually downwarped in terms of final displacement. This is clearly demonstrated in Figure 4/27 by sand columns N 13 and N 14, which straddle the feature. There is no doubt that the original strata, at an early stage of formation and before the start of coherent overturning were sharply depressed, and only the end section at the boundary of the true crater started to swing up again as part of the flap formation. The final displacement of the entire section which "appears" upturned is in fact downward warped. It is remarked that this may well be the case in many impact structures presumed to be bounded by "uplifted" rims of similar appearance to the field geologist not blessed with horizontal stratification which may be traced to determine pre-shot elevations well away from the crater.

4.6.6 North-East Cut Wall, Beyond Crater Rim

The section in Figure 4/45, which is an extension to the North-East of the line given earlier for the South-West cut, is limited to a rather thin section between 190 and 300 ft, and was undertaken at a late stage in an attempt to clarify the very confused structures found on the northern half of the crater.

The pattern of the structure (post-shot, but beyond the crater rim) is entirely different from any other section taken on the Watching Hill test site. Normally, in this region close to any of the main craters, one would expect to find strata, uniformly sub-horizontal, but possibly dipping inward at a low angle towards the crater, the "saucer depression" that surrounded all the main craters at Suffield.

However, in the North-East section, a sequence of steeply dipping strata, composed of distinct beds of clay, sand and gravel was seen. It is obvious that represents the pre-shot stratigraphy in the form of successively advancing, rather than merely overlying beds. It was essentially this evidence that resulted in the present author declaring that this Northern region of the SNOWBALL crater intersected a sequence of fore-set beds. More properly, it may be interpreted as a delta deposit at the mouth of a fast flowing stream, entering the lake which, elsewhere, deposited the flat lying beds common to the area. Obviously, as the effect was either seasonal, or certainly periodic,

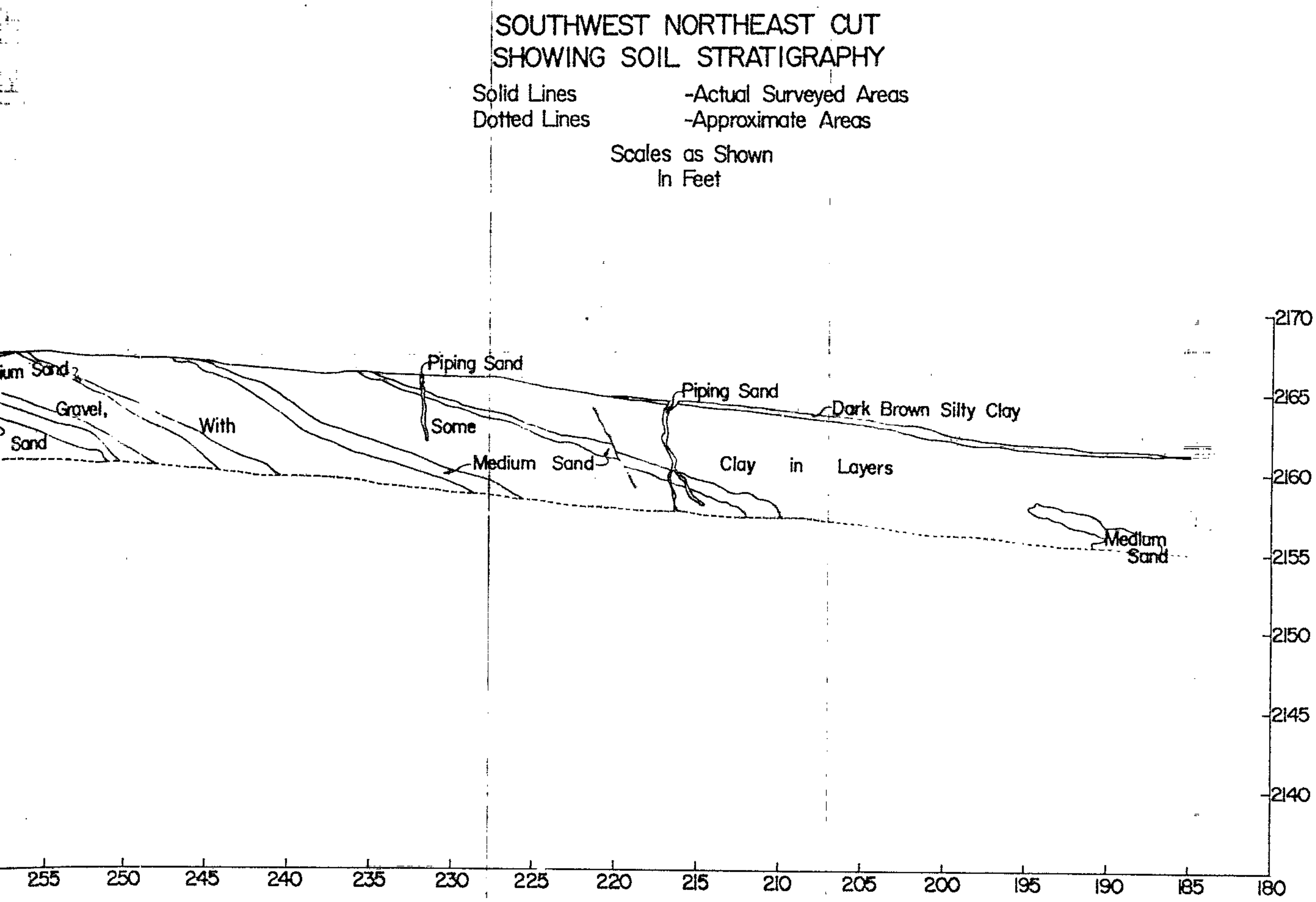
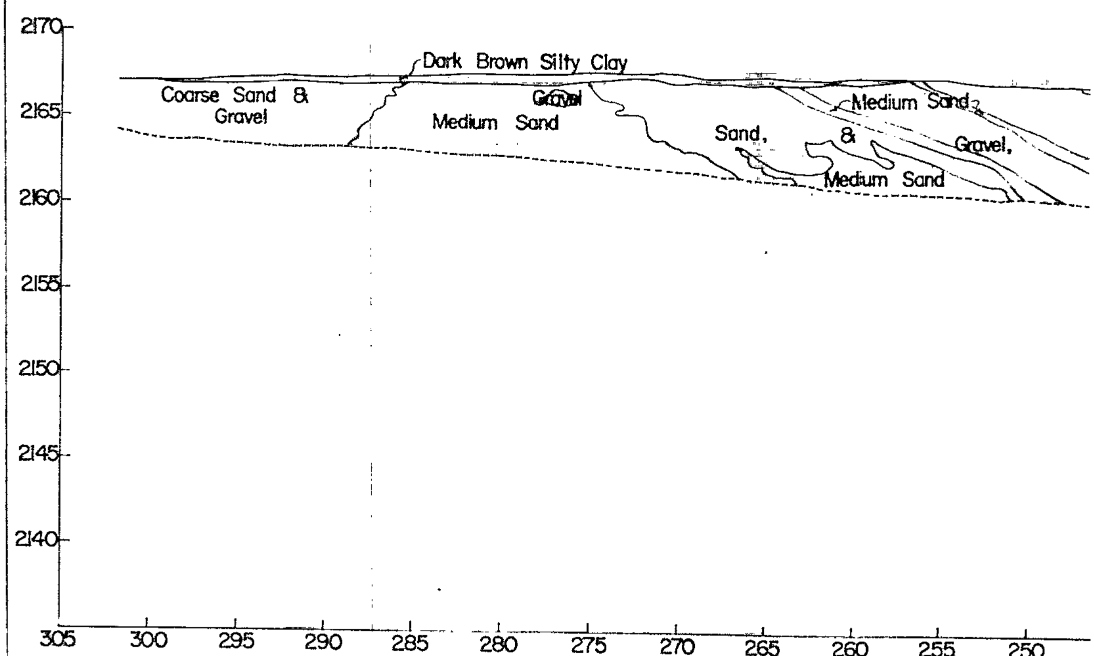


Figure 4/45
North-East Cut Wall Beyond SNOWBALL Crater Rim



Dark Brown Silty Clay
Coarse Sand & Gravel
Gravel
Medium Sand
Sand,
&
Medium Sand
Medium Sand,
Gravel,
2170
2165
2160
2155
2150
2145
2140
305
300
295
290
285
280
275
270
265
260
255
250

the sequence of beds in the delta deposit would parallel the sequence of the horizontally layered lacustrine beds, but "radially" rather than vertically. It is perhaps not surprising that in the early excavations north of GZ considerable misinterpretation (and misunderstanding) among the field workers ensued.

It will be appreciated that the Northern section of the crater was excavated after the field workers had become very familiar with the "easy" stratification found in the major excavations on the south side. Basically, on the North side it was thought that the anomalies were distortions of the originally horizontal bedding. However, as this basic premise was false, it was never quite understood what was being recorded in the field, and it is rather remarkable that, as far as can be determined, no "fudging" occurred.

Looking at the section many years later, it is of interest to note that it is now possible to separate out the effects which were, indeed, attributable to the detonation. In particular, it may be certain that in the region between 210 and 230 ft, the explosion caused "external pseudo-volcanism", now evidenced by two vertical sand pipes, and also a clear example of a small normal fault at about 220 ft. By comparison with other sections, it is reasonably certain that the detonation caused basically similar effects at comparable distances, even though the materials were geometrically different, if geologically similar.

4.6.7 North Section Excavations, 50 ft, 75 ft, 100 ft And 120 ft East Of North-South Sand Column Line (Field Plots 6, 7, 8 & 9)

The section in Figure 4/46, is adjacent and parallel to, but not on the North-South sand column line. It is in fact a composite plot deriving from lines parallel with, but at distances of 50, 75, 100 and 120 ft east of the main North-South sand column line. It was derived from excavations trying to solve the peculiar structures being located on the north side of the crater, to determine the existence of the delta type deposits. The excavations were eventually plotted in composite form, because gross discrepancies were being observed which indicated very large "radial" movements of quite large blocks of material. It appeared, as the composite plots show, that movement had taken place along a slip surface, which was continuous and sloping gently in towards the crater. The bulk movement, however, was in essence radially outward from the crater. The author has in the past interpreted the slip face as a thrust fault. However, study of this section, and comparisons with other sections in the area, now make it appear less likely that the slip face, which exists, or the postulated thrust fault, is a function of the formation of the crater.

The section is best first examined in the region between 265 and 300 ft from GZ, where a fairly thick block of coarse sand and gravel appears to have been displaced radially outward by 30 to 40 ft. It appears to the author that this block moved along a slip face which may be followed at a shallow angle to within about 150 ft from GZ, that is to say under the rim of the crater. The question, however, is whether this slip face was consequent on the formation of the crater, or preceded it. The obvious place to look for an answer to this is the recorded displacements in the sand columns.

The section may be compared profitably with the section showing the sand column displacements for the North-South line (Figures 4/27 and 4/28), on which are superimposed the strata plotted for that line. In that section the proposed thrust slip face can be traced easily by comparison with the break depth of the sand column displacements, where each column shows, out to at least 210 feet, sharp breaks between the upper, inward and downward moving displacement, and the lower, outward and downward displacement. The line of the discontinuities defines a low angle slip plane, which is probably a thrust fault formed by the detonation, but with reverse slippage later. Note, further, that while the direction of movement shown by the sand columns at 240 to 325 ft is consistent with an outward movement of the material above the thrust plane, even as a final state, the extent of the movement recorded is nowhere near the 30 - 40 ft implied by the stratification along the lines up to 120 ft east of the sand column line. There is no obvious solution to this ambiguity. On the other hand, outward radial movements of this order are detected on other Suffield craters. Clearly, evidence from detailed studies in the field are needed to resolve the issue - but not, of course, at Suffield where the craters no longer exist.

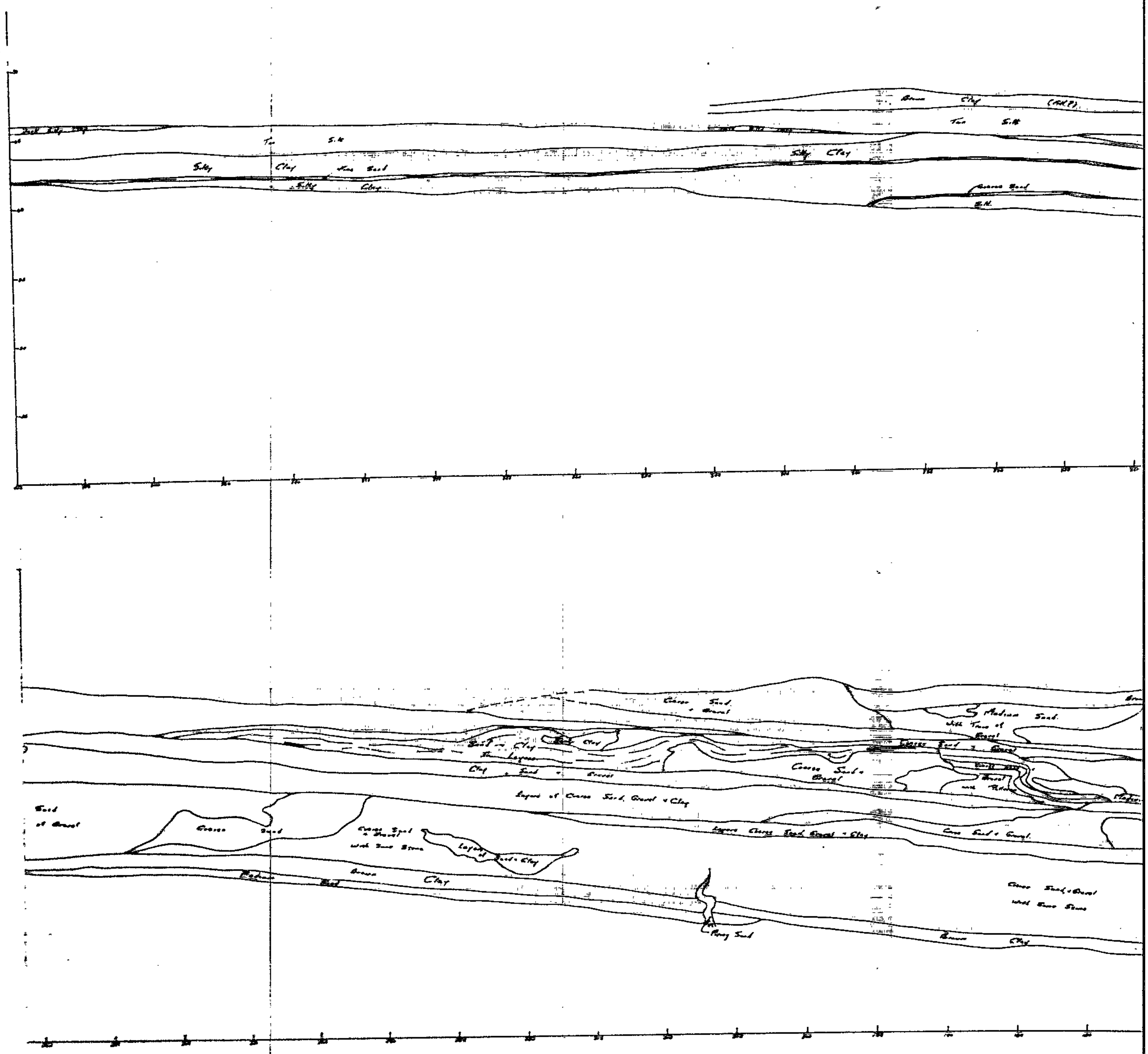
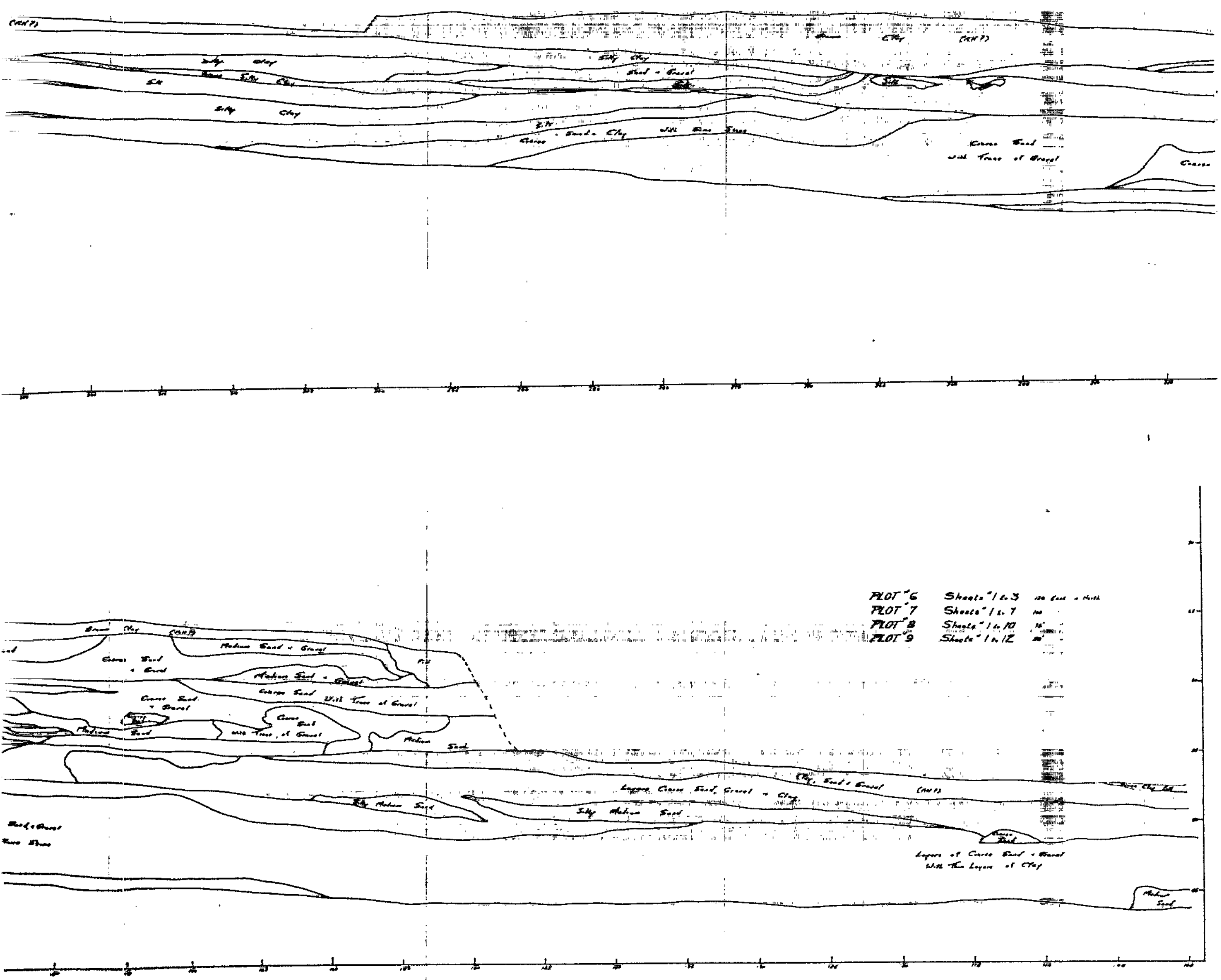


Figure 4/46
Composite Section Based on Excavations Along Lines 50, 75, 100, 120 ft East of North Sand Column Line


PLOT #6 Sheets #1 to 3
PLOT #7 Sheets #1 to 7
PLOT #8 Sheets #1 to 10
PLOT #9 Sheets #1 to 12
Silty Clay
Sand + Gravel
Coarse Sand
Medium Sand + Gravel
Medium Sand
Fill
Layers of Coarse Sand + Gravel
With Thin Layers of Clay

As the gross movement shown in this section is orders of magnitude greater than those shown by the sand column markers, it is probable that a new movement superimposed on an older, and much greater movement is being observed, which may date from the period of the delta deposits. Nevertheless, it is an odd coincidence that the slip face is about where one would expect, on the basis of other crater data, the existence of a thrust fault. Coincidences do happen in the real world. Towards the end of the lengthy excavations of the SNOWBALL crater, a determined attempt was made to produce a stratigraphic section, and this is discussed below.

4.6.8 The South-East North-West Section

This stratigraphic section was excavated and surveyed as almost the final phase of the field study of SNOWBALL, and is taken directly across the crater, through GZ, from beyond the "south" rim to beyond the "north" rim, actually along a line running along the SE to NW diameter. As it was a very late stage excavation, there were advantages and disadvantages involved in the work. It was an advantage to have had considerable experience in plotting stratigraphical sections from field plots but obviously by the time this section was studied a great deal of earlier excavation, along many lines had taken place, and many of these older excavations crossed the line of the present section. Thus, although a single section, advantage was taken of earlier work, and on occasions actual detail taken from small sections of earlier excavations. In most cases, these "earlier excavation" data are shown as dotted lines on this fresh section. Also, as in the other SNOWBALL sections, it must be recalled that the areas marked as "fallout" or "ejecta" must be taken to include probable overturned flaps, removed before they were suspected in connection with other studies.

The final section obtained in this way is shown as three separate Figures 4/47 - 4/49, from SE 220 to 70 ft, from SE 75 ft to NW 75 ft, and from NW 70 to NW 220 ft. Thus the entire section is continuous for over 440 ft, through GZ, and well beyond the rim at each end. The sections will be discussed in the above sequence.

Turning first to the SE 220 to 70 ft section (Figure 4/47), the first

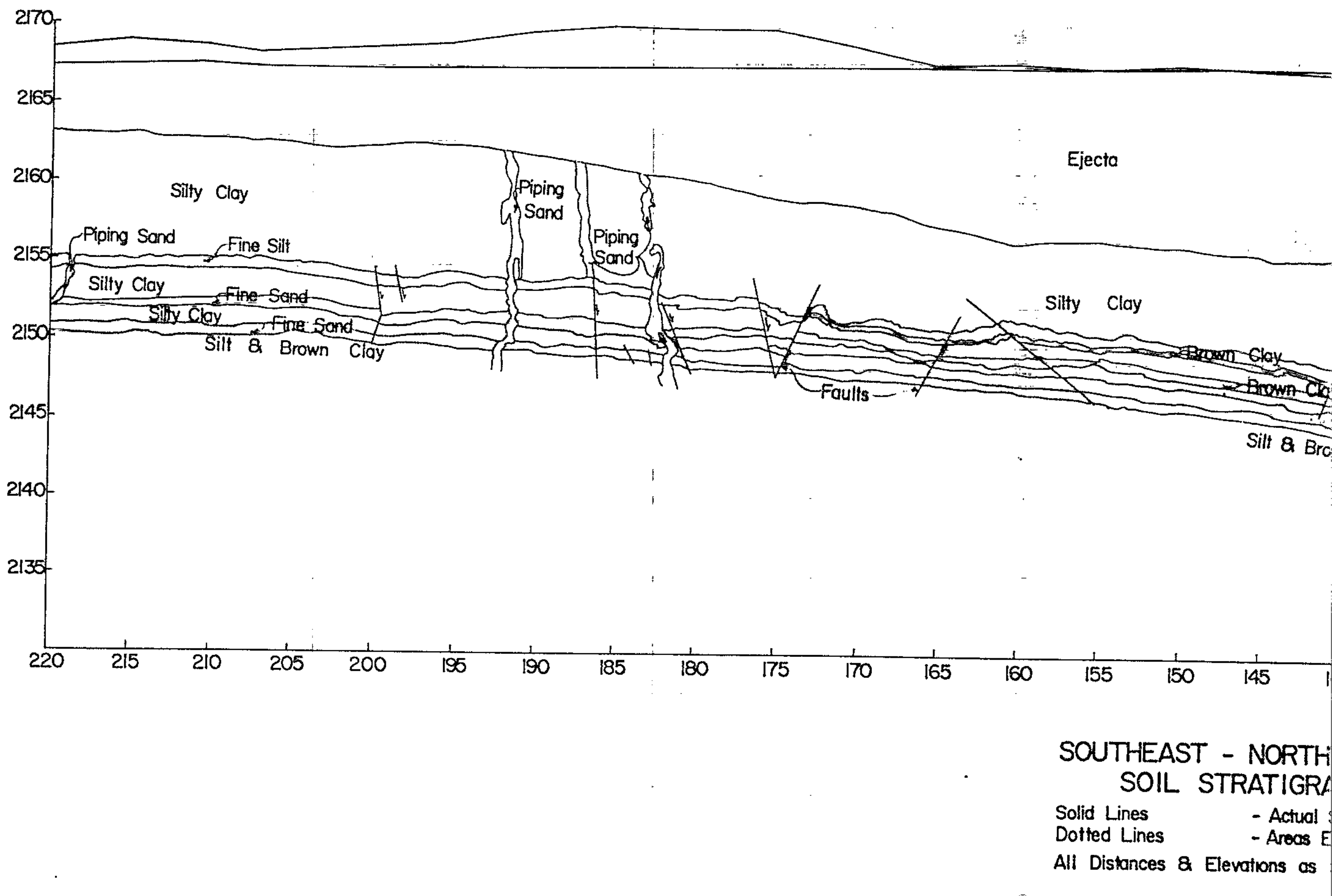
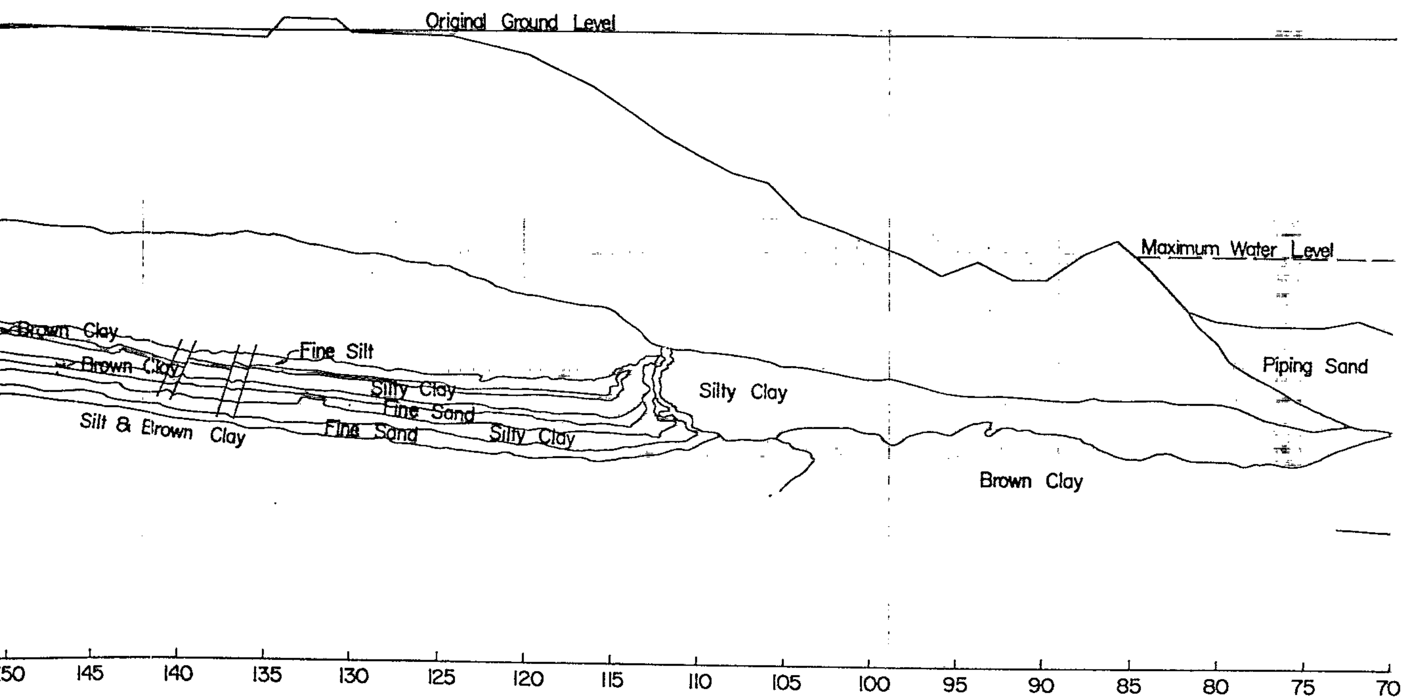


Figure 4/47
The South-East North-West Section Through SNOWBALL Crater
(S220 to 70 ft)



.ST - NORTHWEST CUT
STRATIGRAPHY

- Actual Surveyed Areas
- Areas Excavated Earlier

& Elevations as Shown in Feet

observation is the general shallow angle inward dip of the pre-shot surface, which is confirmed at depth by the similarity dipping fine silt stratum traced as a single entity between 70 and 120 ft. Note the vertical sand pipe at 173 ft, which is at the outer limit of the rim structure. We have, in an earlier section, shown photographically that there is a circumferential fissure apparent on the surface in a corresponding position near the "rim".

The single sand stratum mentioned above between 170 and 120 ft becomes the top member of a suite of strata between 120 and 90 ft, which are concave upward, and which are virtually certainly the lowest section of an overturned flap. With hind sight, it is clear that these strata should have been followed into the area marked "ejecta"; as was successfully done on the later PRAIRIE FLAT crater. Note also that the bottom member appears to be a thick bed of red sand of the type which fills the hydraulic fractures. However, it is thought that the apparent conformity is an illusion, and that this sand has been deposited during and after the crater information. As yet, study of bore hole sections has not revealed the original source of this material.

We turn now to the second section (Figure 4/48), between 75 SE and 75 NW, running through GZ, and the central uplift. In the NW direction, the first structure encountered is a massive ridge of blue clay. This, in its final form, abuts onto the overturned hinge region discussed above. Almost certainly, this is a view of the inner flank of a concentric ridge of uplifted blue clay, as will be shown on later craters in that position. Between 65 ft SE and the rise of the central uplift at 25-30 ft the floor of the crater is covered with the deposit of the yellow "piping sand" (basically "flat" in the nomenclature of impact craters) which was the main effluent in all the pseudo-volcanic vents. It is of interest to see below a thin layer of fallback debris, (centered on the 50 ft SE mark) that there is a thick deposit, presumably itself "pseudo-volcanic" but from a different initial depth. Centered on 25 ft SE, the first rise of the central mound is encountered where the base of the mound in this region is the blue clay, but brown clay has been engulfed, and there is an intrusive pipe of the red sand, which does not quite rise to the surface (a common situation with the red sand).

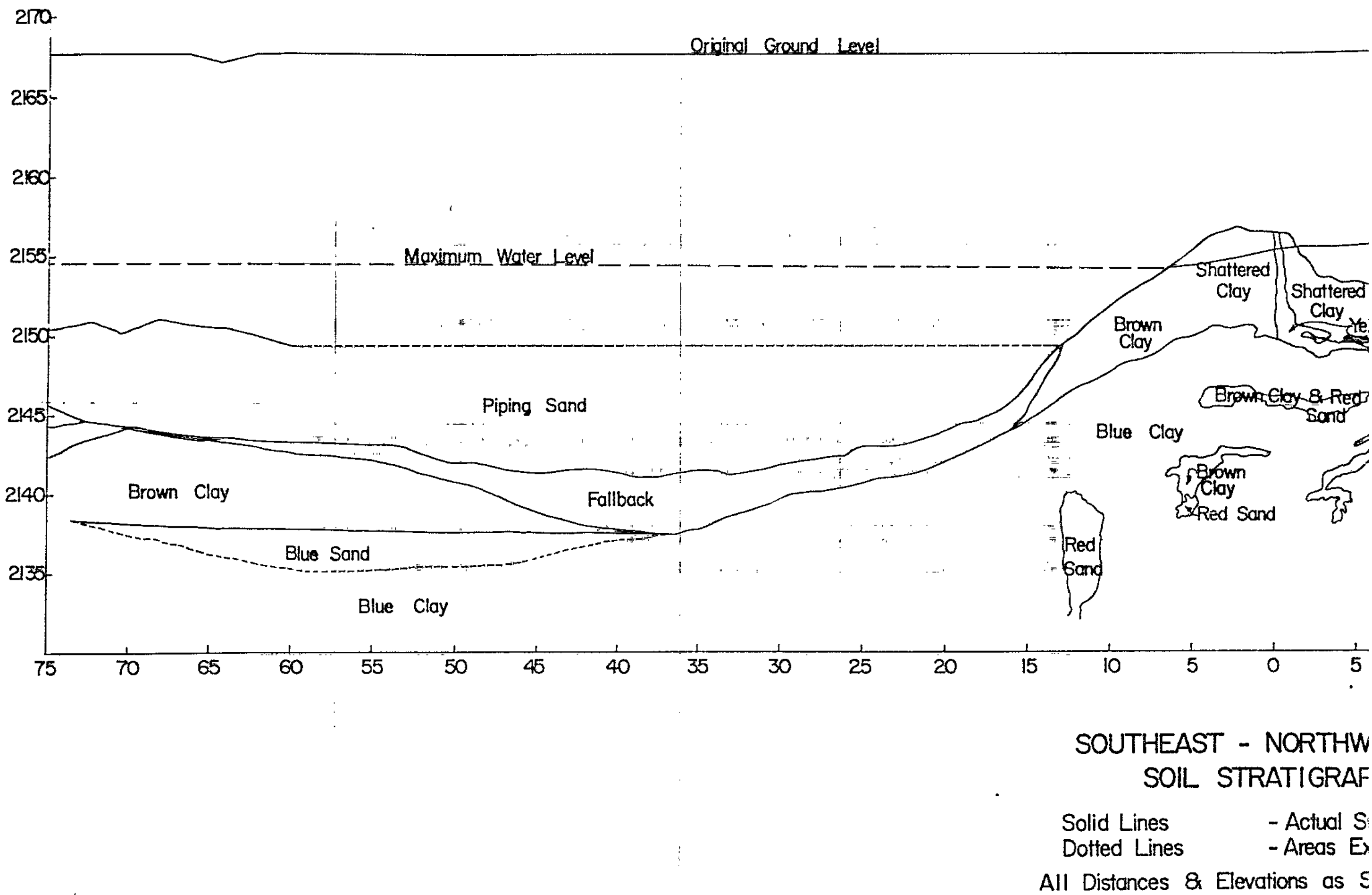
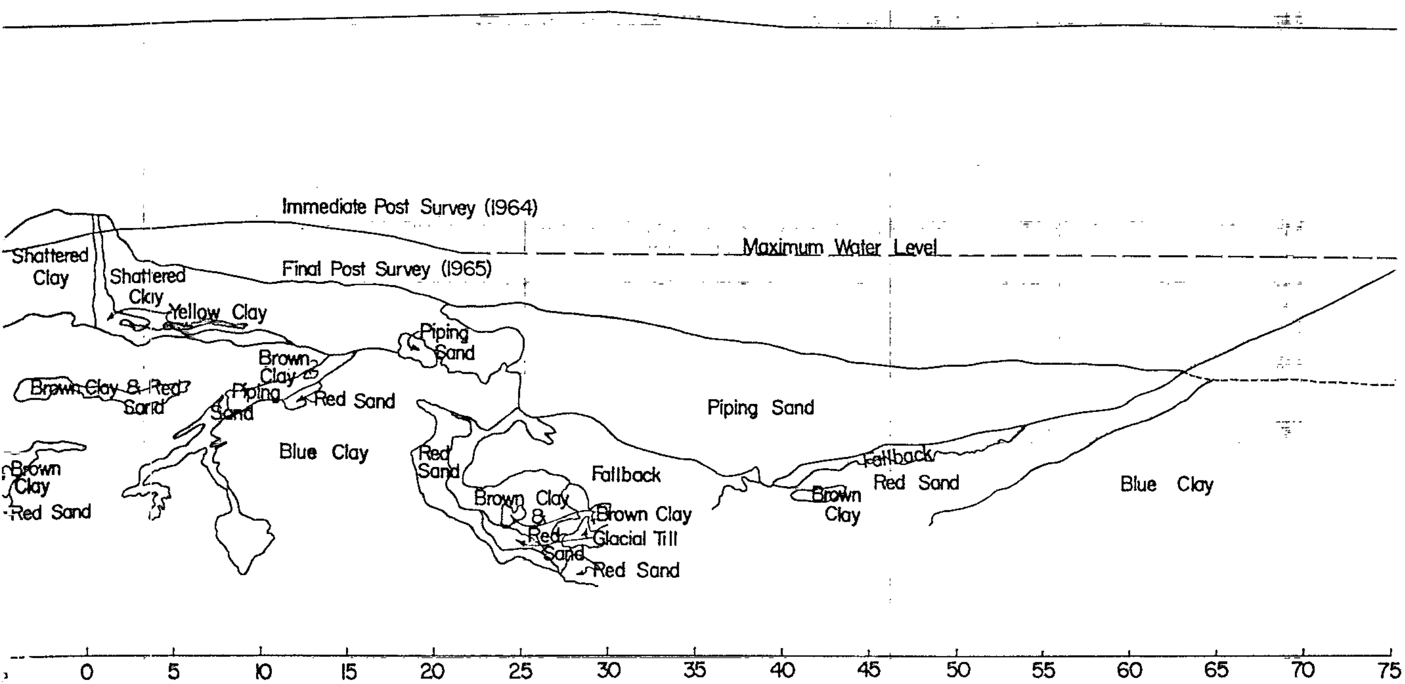


Figure 4/48
The South-East North-West Section Through SNOWBALL Crater
(S75 to N75 ft)



ST - NORTHWEST CUT
STRATIGRAPHY

- Actual Surveyed Areas
- Areas Excavated Earlier

Elevations as Shown in Feet

In the region centered on 5-10 ft SE, a large dome of blue clay is seen, penetrated by a pseudo-volcanic pipe of the yellow "piping sand" which contains small inclusion of brown clay near its top, and a very small pocket of red sand, which shows how obvious the contrast between the two sands appeared in the field. It is noted that the mouth of this pipe is at the location shown in the early post-shot photographs to be the main vent for the inflow of water laden with the yellow sand. The apparent termination in a pseudo-magmatic chamber is probably deceptive, as the pipe probably ran into or out of the section. Still, that is what is recorded.

A peculiarity, not recalled by the author, is visible at a higher level where there appears to be a pipe of "yellow clay", not piping sand, rising vertically to the top of the mound. There is no record of a pseudo-volcanic cone being formed at this point, though it does coincide with the location of one on the 1961 Suffield 100 ton crater. It passes through the tensile fractured blue clay mentioned in another section of the mound. At present, this is something of a mystery. Deep below the top of the mound there is clear evidence of the plastic flowing of the blue clay, which has encased discrete blocks of brown clay and pockets of red sand.

Beyond GZ, between 15 and 75 ft NW, we see a perfectly regular formation of the ring syncline around the mount, with the major infilling of yellow piping sand on top, filling the syncline, and resting on the thin fallback debris layer. This is underlain by a thick bed of brown clay, overlying a thin stratum of blue sand capping the blue clay, which is continuous into the domed central uplift. Thus in this particular section, unusually, the northern structure is more regular than the southern.

We now turn to the third plot of this section (Figure 4/49), running from 70 to 220 ft NW. The first and most obvious thing to remark upon is that this section appears to have missed the confusing "delta deposit" entirely. It appears to be back in the normal horizontal lacustrine sediments which made Watching Hill such a valuable and consistent test site. Of course, care must be taken not to accept the large area shown as "ejecta" at face value. It is certain that it was NOT ejecta, but an overturned flap. Note, however, the naming of a thick "silty clay" deposit which overlies the brown clay

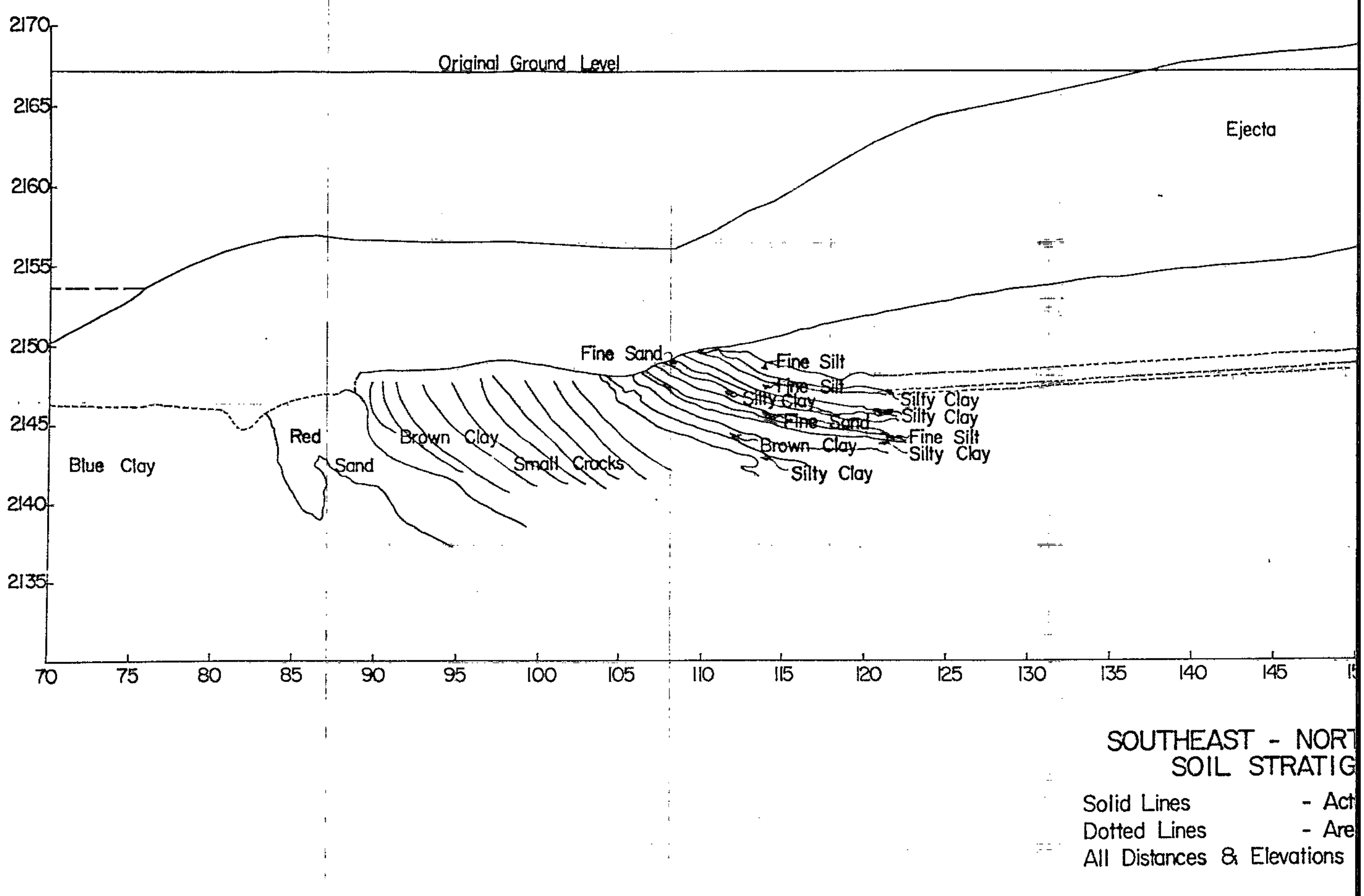
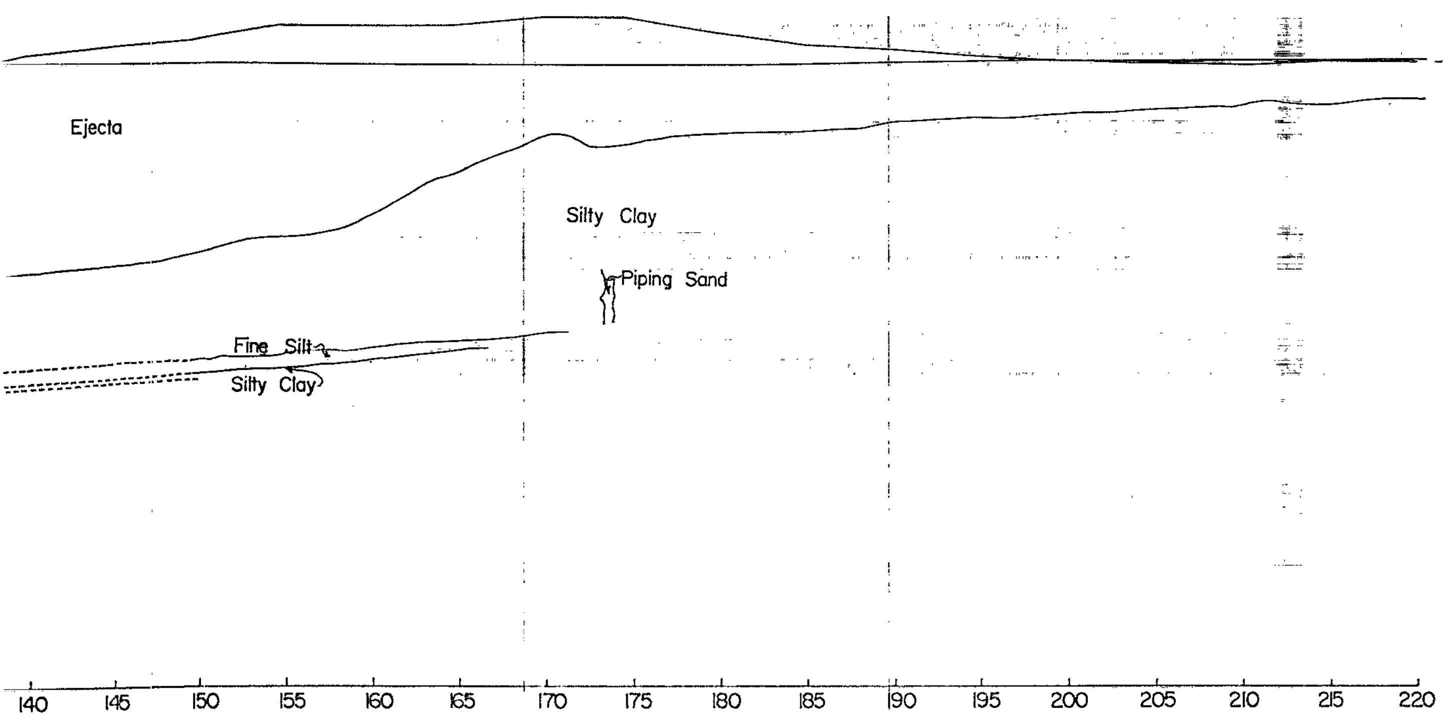


Figure 4/49
The South-East North-West Section Through SNOWBALL Crater
(N70 to 220 ft)



!HEAST - NORTHWEST CUT
SOIL STRATIGRAPHY

ıes -- Actual Surveyed Areas

ines -- Areas Excavated Earlier

ınces & Elevations as Shown in Feet

between 70 and 100 ft NW. At the 110 ft mark the deposit is apparently interrupted by the vertically upturned strata, the "hinge region" of the lip. Whether or not this thick silty clay layer is to be identified with the similarly named, and very thick deposit above the finely layered stratification that is plotted in detail beyond the hinge is a moot point. Superficially, it would appear that they can NOT be the same material, as if so the inner bed between 70 and 110 ft should not be there at all, but be overturned to lie on its outward "extension". The explanation may lie in the notation below the stratified section, that the base is "silt and brown clay". It is possible that the bottom "contact" between 105 and 110 ft is a field plotting, or possibly later a draughting error. If so, the "silty clay" shown between 70 and 110 ft is an upward displacement of the main underlying "silt and brown clay". Perhaps Homer nodded.

Of much greater interest is the fine structure shown in the well mapped stratigraphy between 110 ft NW and the end of the section at 220 ft NW. Between 135 and 175 ft NW, it is seen that the suite of strata are regularly faulted, sometimes by parallel sets of faults, sometimes by opposing pairs of faults outlining block faulting. Note that the two pairs centered near 165 and 175 ft are opposed in character, one with apex down, the other with apex up. At first sight this is surprising, considering the sets as unitary. In fact, closer observation shows that what appear to be triangular block faults are actually bounded by pairs of parallel faults in such close proximity that, as the slopes of the parallel pairs are opposed they are separated by a downward pointing triangle of material. All the faults are "normal faults" in attitude, but despite the detailed arrow markings on the plot, the actual final direction of displacement of adjoining blocks is uncertain. A nice little problem for a structural geologist.

Beyond the main fault zone - which, incidentally, shows fairly regular drag folding as well - there is an area between 180 and 195 ft, where there is a concentration of pipes of the yellow sand which in some areas are marked as bounded by faulting, but in others they look like hydraulic fractures. If not otherwise marked, the author would expect the one set, fault bounded, to be packed with the usual yellow sand, while the

more dendritic ones would be filled with the red sand. That however is not what the draughtsman indicates, presumably under supervision of the excavators and correct. Well, that still looks anomalous to the author.

At 200 ft NW another pair of faults is shown, with the interesting feature that one shows an attitude change. At the farthest limit of the section, just short of 220 ft NW, another small piping sand vent is recorded.

All in all, this SE-NW section is the most detailed of the stratigraphic cross sections of the SNOWBALL crater. While it raises a few new questions, in general it shows the remarkable structural integrity revealed in this major Suffield crater. There is little doubt that the SNOWBALL crater was one of the most completely excavated and recorded, certainly at Suffield but probably anywhere.

The time and money expended has been amply justified by the increase in understanding of complex craters. It has enabled later experimental (and potentially central uplift) craters to be the subject of refined and economical pre-trial planning. The "learning process" and extensive identification of features analogous to those found on presumed impact craters has made possible the asking and experimental answering of highly selective questions when any "impact probable" site comes under field study. Not all the answers are in, nor are all the questions asked, but anyone contemplating field work on newly suspected craters could well start with a review of the SNOWBALL data.

4.7 TOPOGRAPHIC MAPS OF SNOWBALL CRATER

This section is currently limited to a brief note to indicate what is available. Figures 4/50 and 4/51 show pre and post-shot topographic maps, respectively, of the SNOWBALL crater. These were produced by photogrammetric interpretation of aerial photographs, and are derived directly from the WES report Rooke et al (1968). However, the mission was flown by the U.S. Army 4th Aviation Battalion, using a light aircraft mounting a KA39A camera, focal length 6 inches and flight altitudes of 600 ft and 1200 ft above the surface.

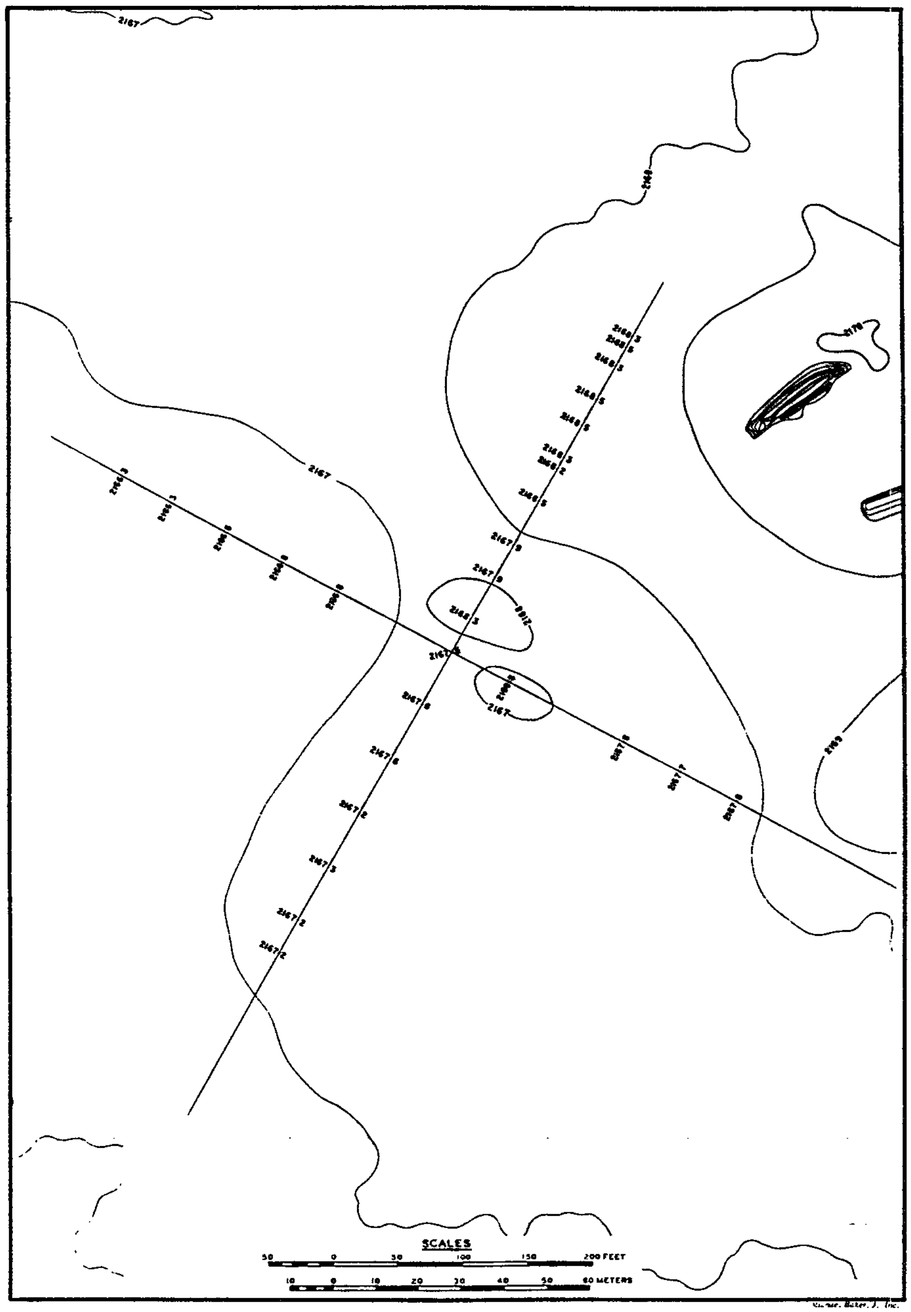


Figure 4/50
Pre-shot Aerial Map of SNOWBALL Crater Area Showing Spot Elevations Along Radials. Elevations and Countours in Feet Above Mean Sea Level (from Rooke et al 1968)

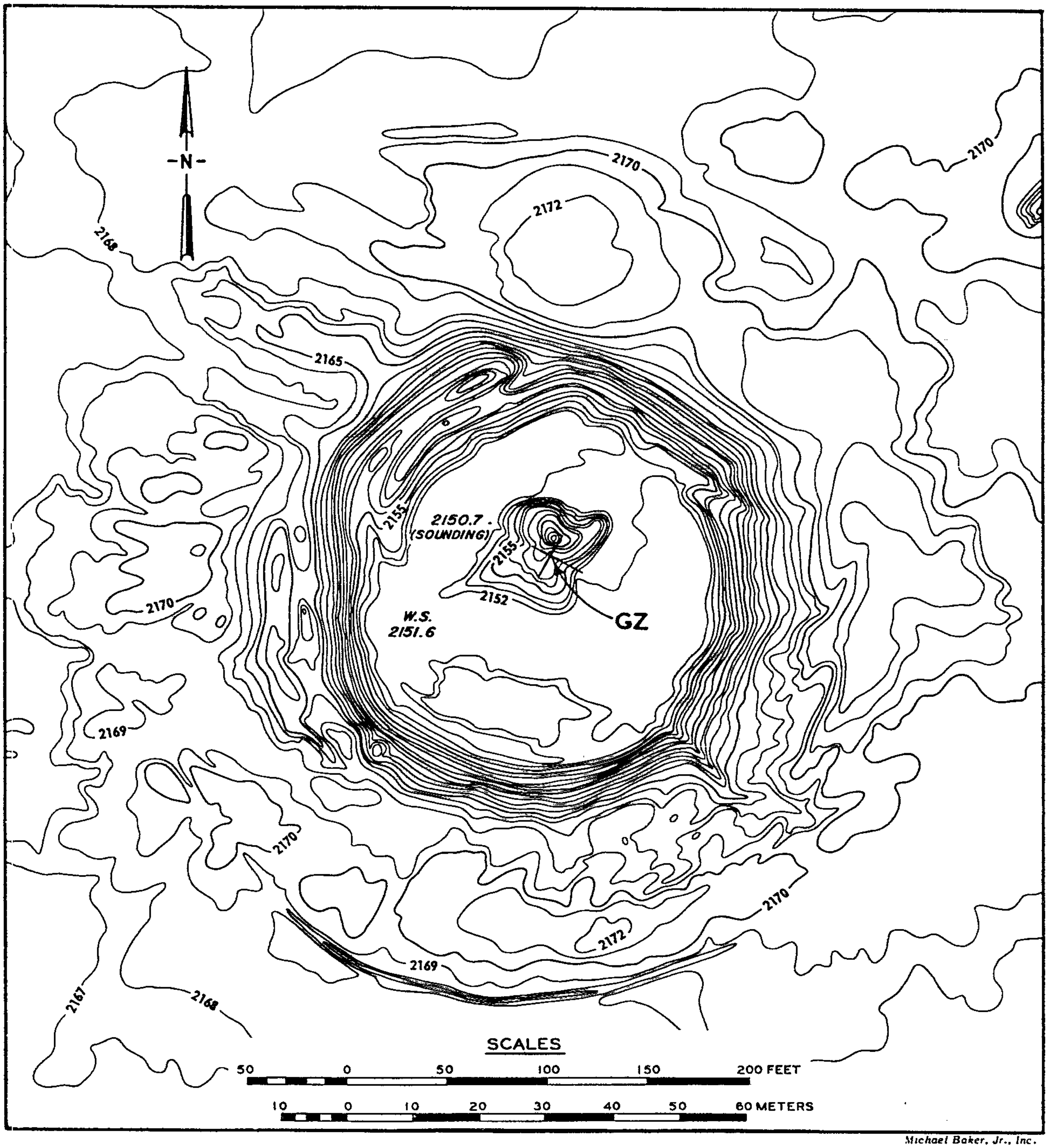


Figure 4/51
Postshot Aerial Map of SNOWBALL Crater Area

The present location of the original photographs, which may be of direct interest to the U.S. Geological Survey, is not known but may possibly be traceable through WES.

4.8 STRONG MOTION SEISMIC DATA FROM SNOWBALL

It has been observed early in this text that the strong motion seismic data from the earlier Suffield trials, up and including the 1961 Suffield 100 ton explosion have been placed in the public domain, and to a large extent analyzed. This does not apply to the SNOWBALL 500 ton trial, or later trials.

However, although the strong motion seismology relating to surface explosion was no longer the prime interest of the present author, the recording project was continued in the later trials. In all cases, the original seismograms have been preserved. In the particular case of SNOWBALL, the seismograms were digitized and published in that form (as well as in analogue form, in the case of the 10,000 ft seismogram, and as a vertical/radial orbit) in a limited distribution report (Jones, 1964).

As no further analysis is currently anticipated, the location of the data is merely recorded, without inclusion in this text.

CHAPTER FIVE

THE 500 TON PRAIRIE FLAT CRATER (9 AUGUST 1968)

5.1 INTRODUCTION

In many ways the PRAIRIE FLAT trial was a turning point for the Suffield crater study group. Canadian funding for the project was effectively terminated, with the notable exception that the team was authorized to become one of the American Project teams, while remaining on the salaried staff of the Canadian Defence Research Board. Funding for the installation of sand columns and the subsequent excavation was provided by DASA, now DNA. As a result, the team, including the present author as the scientist in charge, became subject to the reporting discipline of DASA. Consequently, a detailed presentation of the actual field data was speedily produced (Jones et al, 1970), but as a limited distribution DASA report, which to the present time remains the most complete single presentation of crater data from Suffield, and actually preceded any serious publication of the SNOWBALL data. The SNOWBALL crater was such a revelation that attention was diverted from the routine of reporting planned work, to the investigation of the first artifical "astrobleme" structure, and bringing it to the attention of the wider scientific community. Mea Culpa est.

In view of the existence of the detailed reporting in Jones et al (1970), the discussion in this chapter will concentrate again on those aspects of the crater of planetological interest, essentially restricted to material corresponding to that presented for the 100 ton trials and the 500 ton SNOWBALL. The data used, of course, derive from the cited DASA report by Jones et al, but also from an analytical paper presented at the 8th Lunar Science Conference (Roddy, Ullrich, Sauer and Jones, 1977). The latter paper is of prime significance as it presents data on the actual trajectories of the cratered material, as opposed to residual displacement data. Some additional material drawn from the unpublished archives is also used.

As will be seen, PRAIRIE FLAT was visually strikingly different from not only the conventional bowl-shaped crater, but also from the central uplift SNOWBALL crater.

crater. Detailed analysis of the data however revealed that there were covert similarities between SNOWBALL and PRAIRIE FLAT. Visually, however, PRAIRIE FLAT conformed to the ringed craters on the moon, rather than the "simple" central uplift pattern.

5.2 THE IMMEDIATE POST DETONATION CRATER

The PRAIRIE FLAT crater was produced by the detonation of a 500 ton tangent sphere of TNT, the same configuration as that used for DISTANT PLAIN 6. As has been mentioned, this change of charge configuration, from hemisphere to tangent sphere was, in part, but only in part, an attempt to bring the Suffield craters into scaled conformity to the NTS nuclear craters. As happened in the case of the two cited 100 ton craters, this objective was achieved in terms of overall size, but NOT in terms of crater morphology.

The charge was detonated at 1800 hrs UT2 on the 9 August 1968. It is interesting to note that due to the change in charge configuration, neither the fireball nor the actual shock wave expanded as simple hemispheres. With the tangent sphere configuration, the shock wave from the surface reflected to combine with the directly expanding wave above the ground, to create a cylindrically expanding Mach Stem, though due to the low height of burst the triple point intersection of the shocks rose steeply. The effect on the fireball was not dissimilar, as is shown in Figure 5/1. Note the almost vertical face to the ground surge which rings the base of the fireball. The effects on above surface targets remote from the charge would still be due to an effectively vertical shock front however, with known scaling properties. However, an effect possibly related to the very earliest period of shock wave expansion, will be discussed later in this chapter.

Figure 5/2 shows the immediate post-detonation appearance of the PRAIRIE FLAT crater, in an oblique aerial view. The precise time of this photograph is not available, but comparison with the earlier SNOWBALL photographs would place it within the first ten to fifteen minutes after the detonation.

Clearly, the newly formed crater is effectively dry, but water was now

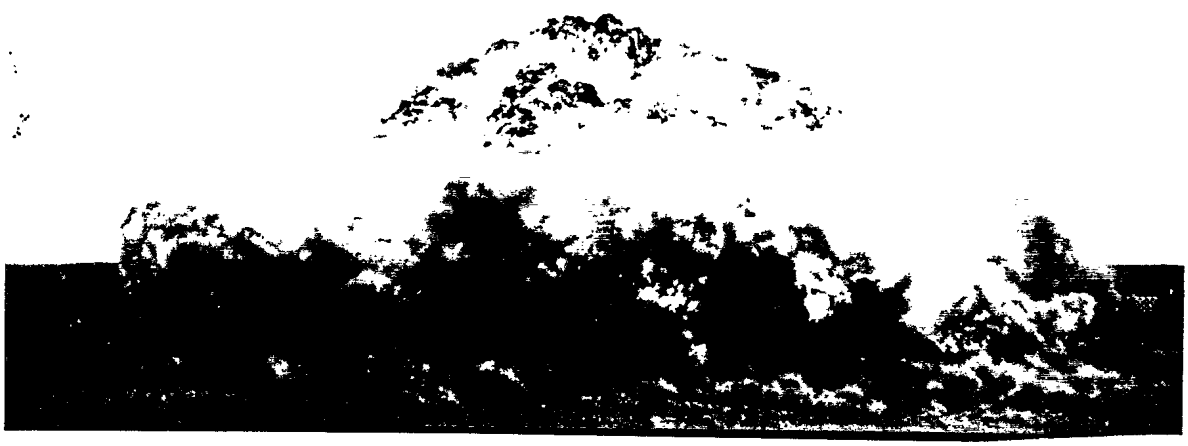


Figure 5/1
Late Stage Expansion of PRAIRIE FLAT Fireball

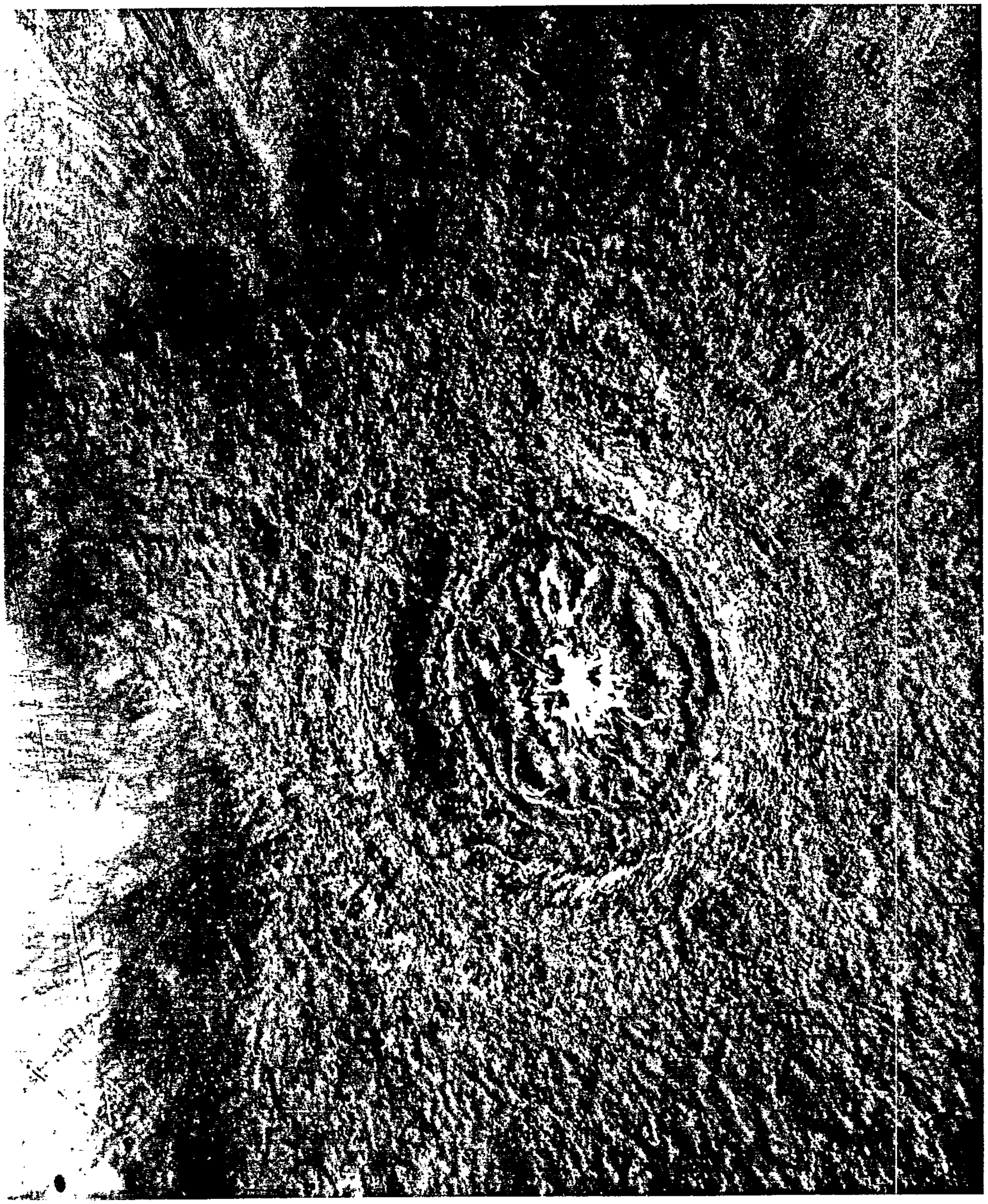


Figure 5/2
Early Post Formation Appearance of PRAIRIE FLAT Crater

starting to flow in the central region, which in this case is a hollow surrounded by an elevated ring.

Again, there is no clear evidence of an elevated rim structure, while the floor of the crater possesses a set of alternating high and low circumferential features. While these are probably anticlinal and synclinal sets, this can obviously not be confirmed from the photograph. Attention is drawn to the circumferential hollow immediately adjoining the crater wall. It will be seen that there is a darker ring, which appears to be made of blocky upthrust from a circumferential fracture centered in this trough. Closer views will be shown later.

At this stage, at least, there is no clearly visible circumferential crack system corresponding to that surrounding SNOWBALL. However, observe that the rim structure, such as it is, on the side away from the crater lip shows a circumferential trough, which (at between nine and ten o'clock in the photograph) appears to be bounded by a fracture system, which itself borders another higher ridge. In fact, in this photograph, counting from GZ, at least four, possibly five circumferential ridges separated by (at least) three circumferential troughs can be seen.

There is no evidence in this photograph of surface eruptions of water external to the crater, nor did any appear later. This is in quite sharp contrast to the external pseudo-vulcanism on SNOWBALL.

However, circumferential cracks did in fact exist under the ejecta blanket, as shown in Figure 5/3. The concentration in the one sector is an artifact of the excavation, of course, not a characteristic of the crater.

It is of interest to compare this Figure 5/3 with the equivalent Figure 3/11, given in Chapter 3 relating to the DISTANT PLAIN 6 trial, in which the 100 ton charge had the same tangent sphere configuration. The pattern of circumferential cracks is similar enough to indicate identity of mechanism of formation, even to the extent of the cracks not developing into open fissures.

This similarity between the two tangent sphere charges is even greater when

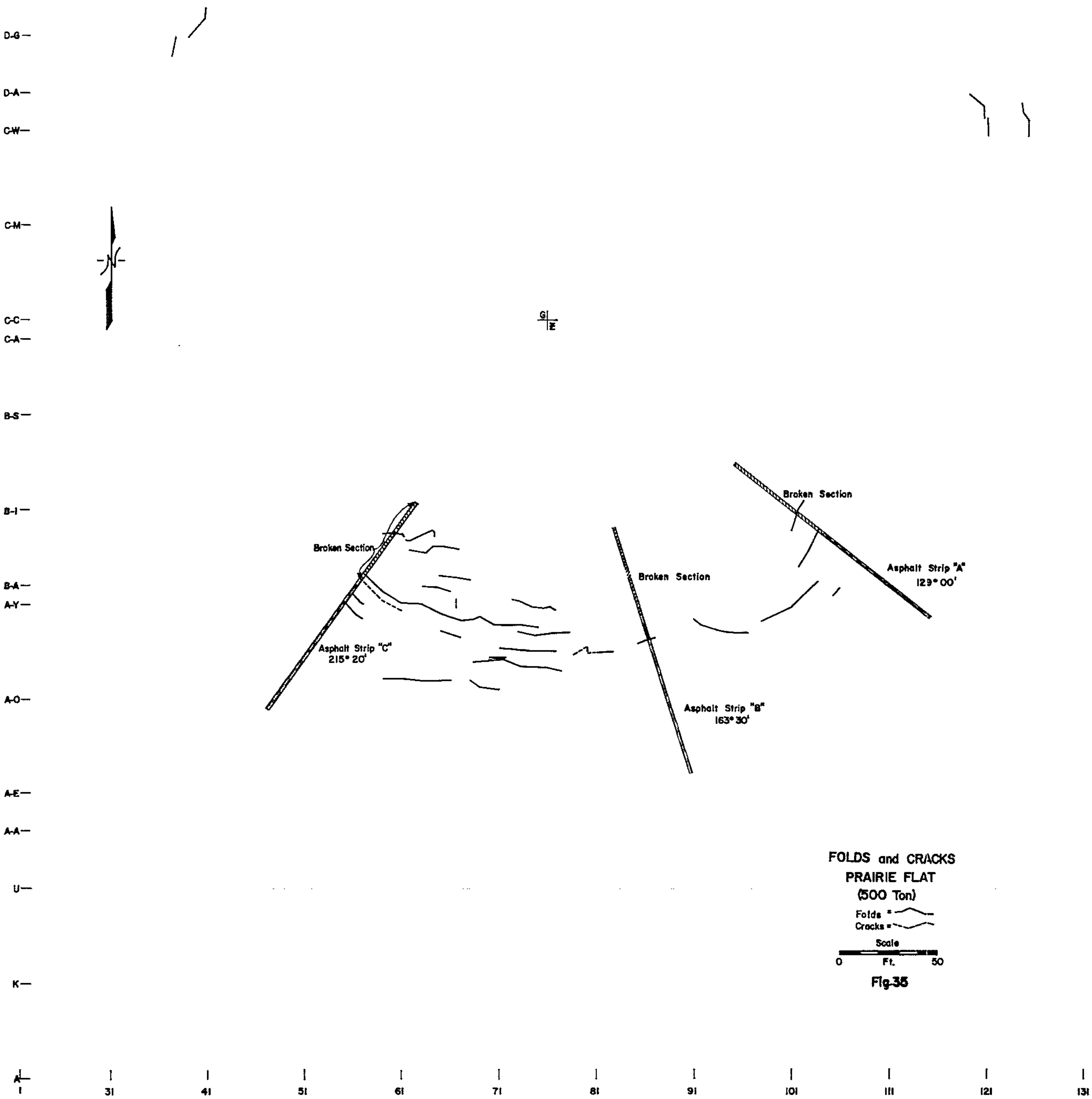


Figure 5/3

Circumferential Folds and Cracks PRAIRIE FLAT Crater viewing the condition of the similar asphalt strips installed on PRAIRIE FLAT, which are shown in Figure 5/4, which may be compared to Figure 3/12 on DISTANT PLAIN 6. Despite the essentially downward movement of the ground, even beyond the rim, the dominant mechanism appears to be a gross radial compaction of at least the upper layers beyond the rim, on both DISTANT PLAIN 6 and PRAIRIE FLAT. In the case of PRAIRIE FLAT the surface zone suffered such compression that the original surface between 75 ft and 190 ft became compressed into a region between 110 ft and 190 ft, so that the inner part suffered at least 30 to 40 ft of radial, outward motion against the "resisting block" of the outlying terrain. At the actual surface, the compaction was in the form of a wrinkling of the surface, shown in Figure 5/4.

Figure 5/5 shows the appearance of the area immediately inside the main crater void, shortly after the detonation and before any significant water flow. Note the absence of any significant elevated rim to this crater. Despite the light covering of true fallback material, the structural nature of the elevated inner ridge is evident. Also, the circumferential fracture pattern, and associated blocky upthrust in the middle of the trough is clearly visible. Figure 5/6 is a similar view of another section of the trough, in which the ring of blocky upthrust clay is more evident.

Soon after these photographs were taken, water started to flow into the outer trough, but from sources nearer the centre of the crater. Figure 5/7, taken an hour or so after the detonation, shows clearly the pattern of water flow originating in the central hollow around GZ, and filling the inner and outer troughs in succession. Figure 5/8 is a view looking across the centre of the crater shortly after water started to flow into the outer trough. The rapidity and scale of this inflow is shown in Figure 5/9 which shows the flow pattern swirling around the blocky upthrusts. As will be seen later, it is possible that by this time there were water sources distributed along this fracture system also, but if so they were relatively late flows. The general overall pattern of development at a slightly later stage is shown in an aerial oblique view in Figure 5/10. It can now be seen that the sources of water in the inner hollow were actually fairly evenly spaced

Figure 5/4
Surface Wave Pattern in Asphalt Strips PRAIRIE FLAT Crater

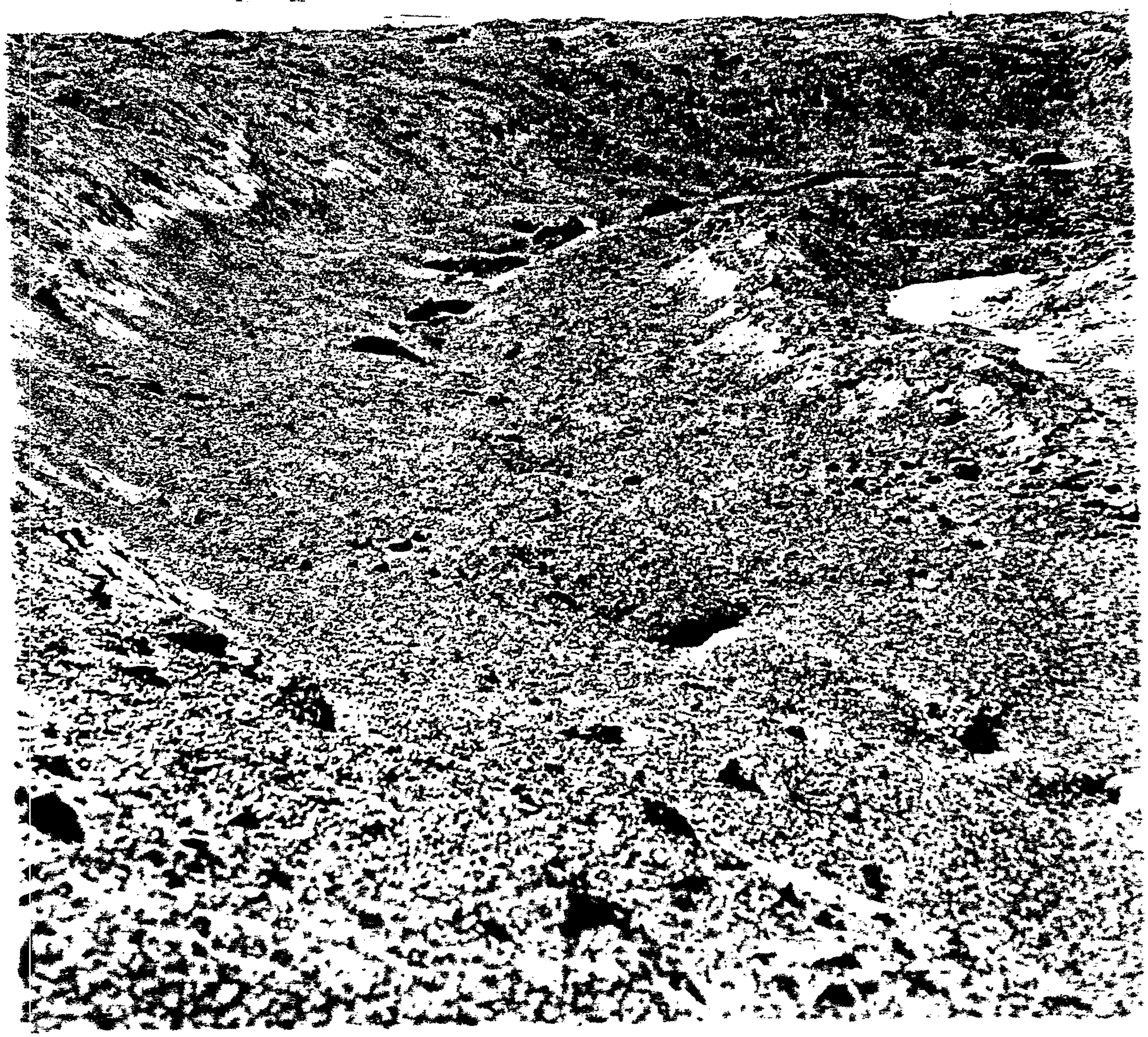


Figure 5/5
Outer Trough and Ridge Inside PRAIRIE FLAT Crater Before Water Entry

Figure 5/6
Another View of Outer Trough and Fracture System

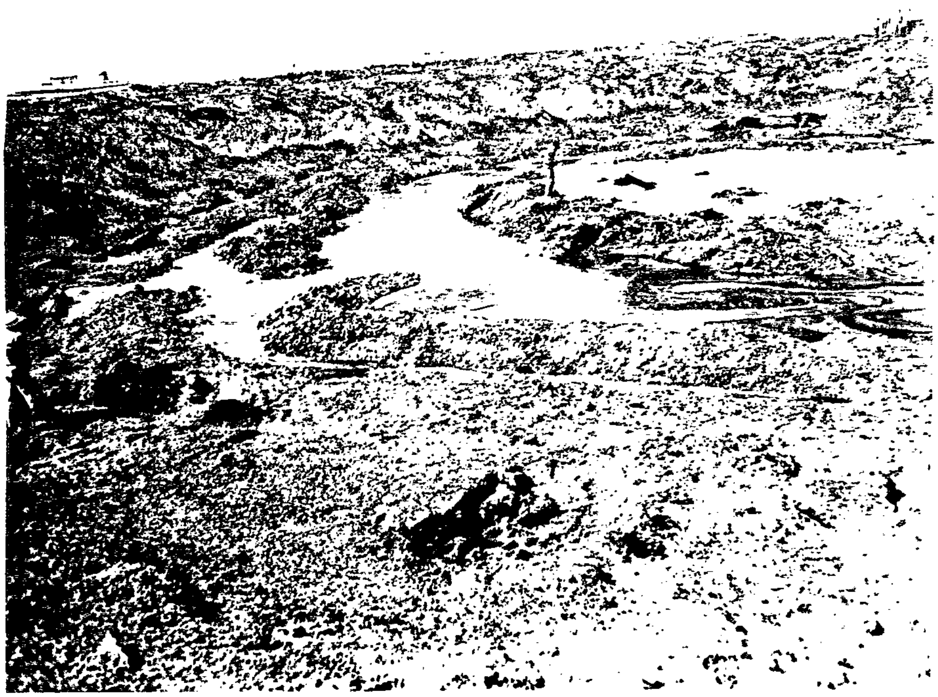


Figure 5/7
Inner Trough Filling by Flow from GZ Area

Figure 5/8

View Across Crater Centre as Filling Progressed

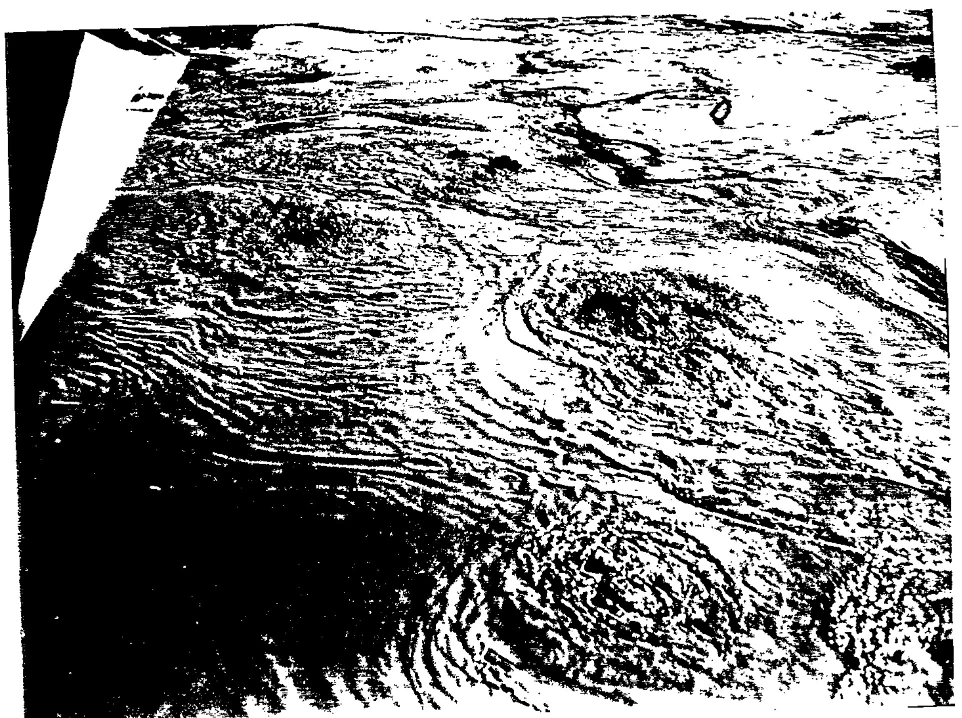


Figure 5/9

Water Swirling Around Blocky Upthrust During Filling

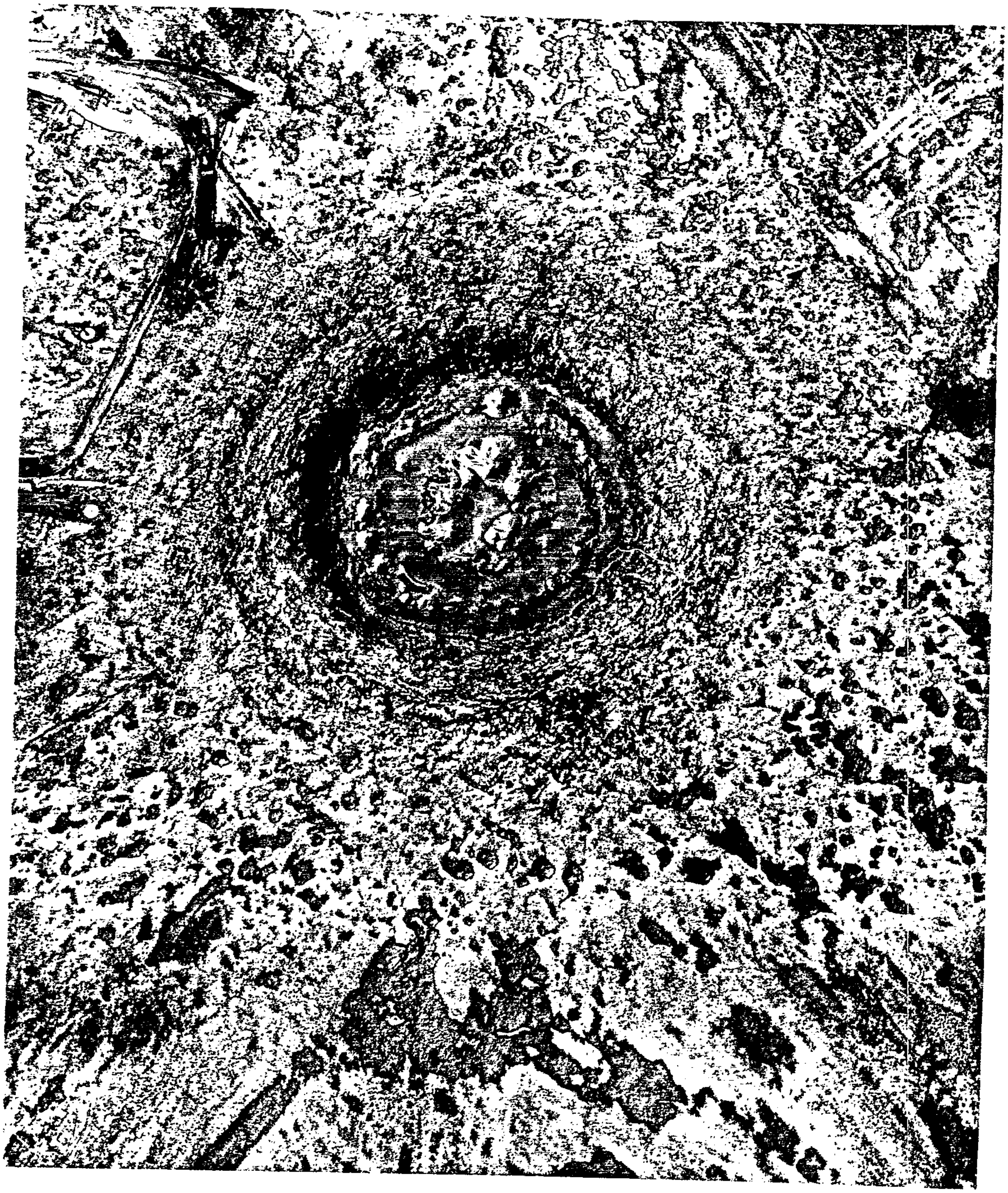


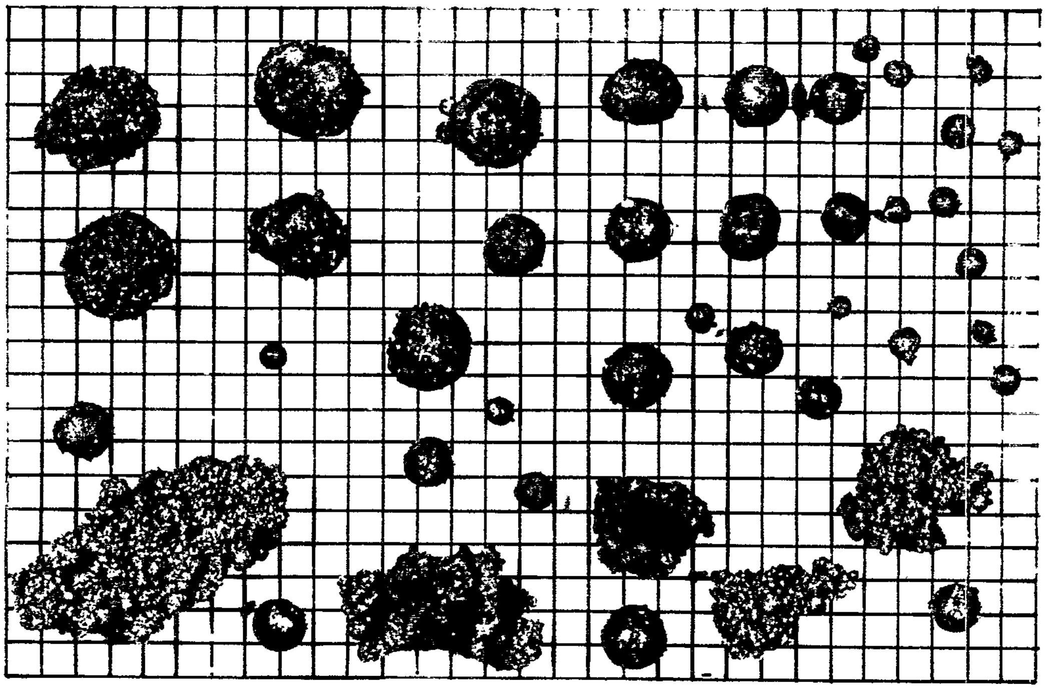
Figure 5/10
Aerial Oblique During Early Pseudo-Volcanism

around the outside of the hollow, against the inner edge of the inner circular ridge. One major pseudo-volcanic peak has also grown on the outer ridge, together with several smaller sources spaced around the ring, which will be discussed again later. Note also that in this photograph the fracture in the middle of the outer trough is clearly visible.

A cursory examination of Figure 5/10 and comparison with the equivalent photograph for SNOWBALL (Figure 4/14), would recognize that the mottled pattern of black patches covering the entire area around the crater consist of pools of water, or at least previously wetted ground. It is, however, emphasized that it would be quite wrong to interpret these pools as evidence of external pseudo-vulcanism similar to that on SNOWBALL. In the particular case of PRAIRIE FLAT, the Watching Hill test site was traversed a few days after the test by a series of thunderstorms with heavy rainfall. What is seen in Figure 5/10 is the residual effect of this rainfall (a comparatively rare phenomenon at the test site, though such localized thunderstorms are common enough on the prairies). As it happened, this pooling of surface water had a beneficial effect on the post trial operations as discussed in the next section. Unfortunately, the heavy rain also had a damaging effect on the collection of discrete ejecta lumps for another project.

5.3 DETECTION OF FUSED MATERIAL NEAR PRAIRIE FLAT

Even during the initial approach, on foot to the crater, comments were made about the unusual "crunchiness" of the ejecta blanket, actually an audible effect associated with footfall. Curiosity led to a brief examination of the surface, and it was noted that there was a fine scattering of material which appeared to be fused by extreme high temperature. This had not been detected on any earlier trial, but an attempt to make a significant collection proved futile due to the lack of contrast and the relative scarcity of the fused material. However, the heavy rainfall mentioned above came to our aid, and a few days after the trial it was noticed that the water pools (shown in Figure 5/10) were covered with a scum of material, which proved to be the previously noted fused material. Much of the material was in the form of fused silica droplets, in the form of hollow spheres, with a bulk density considerably less than one. As a result, the heavy rain had



Grid Spacing 1/10 inch

Figure 5/11
Fused Material Found in the PRAIRIE FLAT Ejecta

in effect collected the material by flotation and concentration in the rain water pools.

The appearance of the material is shown in Figure 5/11, including both the hollow spheres and some other partially fused silt/clay lumps. No such material had been noted on any earlier trials at Suffield (even the tangent sphere DISTANT PLAIN 6 trial). This does not mean that it did not exist, but the author and colleagues were confident that with the very detailed studies of the earlier trial such an effect would not have been missed. However, on the later DIAL PACK crater, produced by a charge duplicating that of PRAIRIE FLAT, this fused material was again evident. It would appear that the material was produced only by the 500 ton tangent sphere configuration, and almost certainly by the fusion of the upper silt layer immediately underlying the charge, being dispersed by the combined effect of the blast wave and the base surge shown in an earlier figure.

Spectroscopic examination of the material confirmed its probable source in the upper silt layer. Physically, the material existed in large quantities in the mm+ range, though the partially fused material could range as high as a few cm. Similar material has been reported by Philby (1933) associated with the Wabar crater in desert sand. On the other hand, it was later demonstrated to the author (at Imperial College, London) that the material was closely similar to the (microscopic scale) fly ash produced by coal-fired power generating stations. It is a moot point whether or not this material is analogous to impactite/tectite material which exists in fields associated with known terrestrial impact structures (for example, the Bosumtwi crater in Ghana). At PRAIRIE FLAT (and later at DIAL PACK) the total quantity of fused material must have been quite large. Unlike the normal tectite, the PRAIRIE FLAT material was "popcorned" into hollow spheres and dumbbells, so light that it would have been easily transported by wind into in extensive "down wind plume". It can only be speculated what a field geologist would have made of this structure if it had been found years later, rather than studied immediately after the known causative surface explosion.

The author's personal collection of this material was lost many years ago in a house fire, and none appears to have been preserved at Suffield. However, a recent search of Dave Roddy's archives in Flagstaff has revealed a substantial quantity from both PRAIRIE FLAT and DIAL PACK, available for any future study that may become necessary.

5.4 CORRELATION OF DYNAMIC TRAJECTORIES AND STRUCTURAL DEFORMATION

In the earlier section, describing the Suffield Marker sand column technique, a caveat was entered to the effect that the "displacement vectors" plotted from the sand column marker data did not represent actual particle trajectories, but merely the initial and final positions of the markers. On PRAIRIE FLAT, these data were supplemented by data obtained by use of velocity gauges installed in an array similar to, and associated with the sand columns. The data obtained have been integrated and published by Roddy, Ullrich, Sauer & Jones (1977), with a remarkable degree of successful correlation. No attempt is made herein to consider the detail of that correlation, as it is available in the public domain. However, it seems appropriate to include the basic interpretive plots from Roddy et at (1977) in this section, in order to make the overall discussion of the Suffield craters in the present text as illuminating as possible.

Figures 5/12 to 5/15 herein are reproduced directly form the cited paper. The figures, with their appropriate titles, are almost self explanatory. In all cases the velocity gauges indicate that the particle motion was in the form of a tilted, prograde ellipse of, generally speaking, from three quarters of a cycle to an almost full cycle, and there is close correlation between the motion derived from the velocity gauges and the initial and final positions of the associated sand column marker cans.

It has been remarked earlier than the dominant seismic surface wave, recorded well beyond the crater rim, also consisted of tilted prograde ellipses, and a typical example (taken in this case from the 1961 Suffield 100 ton trial) is shown in Figure 5/16 taken from Jones (1963). It shows the particle motion in the radial/vertical plane at 12,000 ft from GZ. This has been chosen to demonstrate that the ground motion

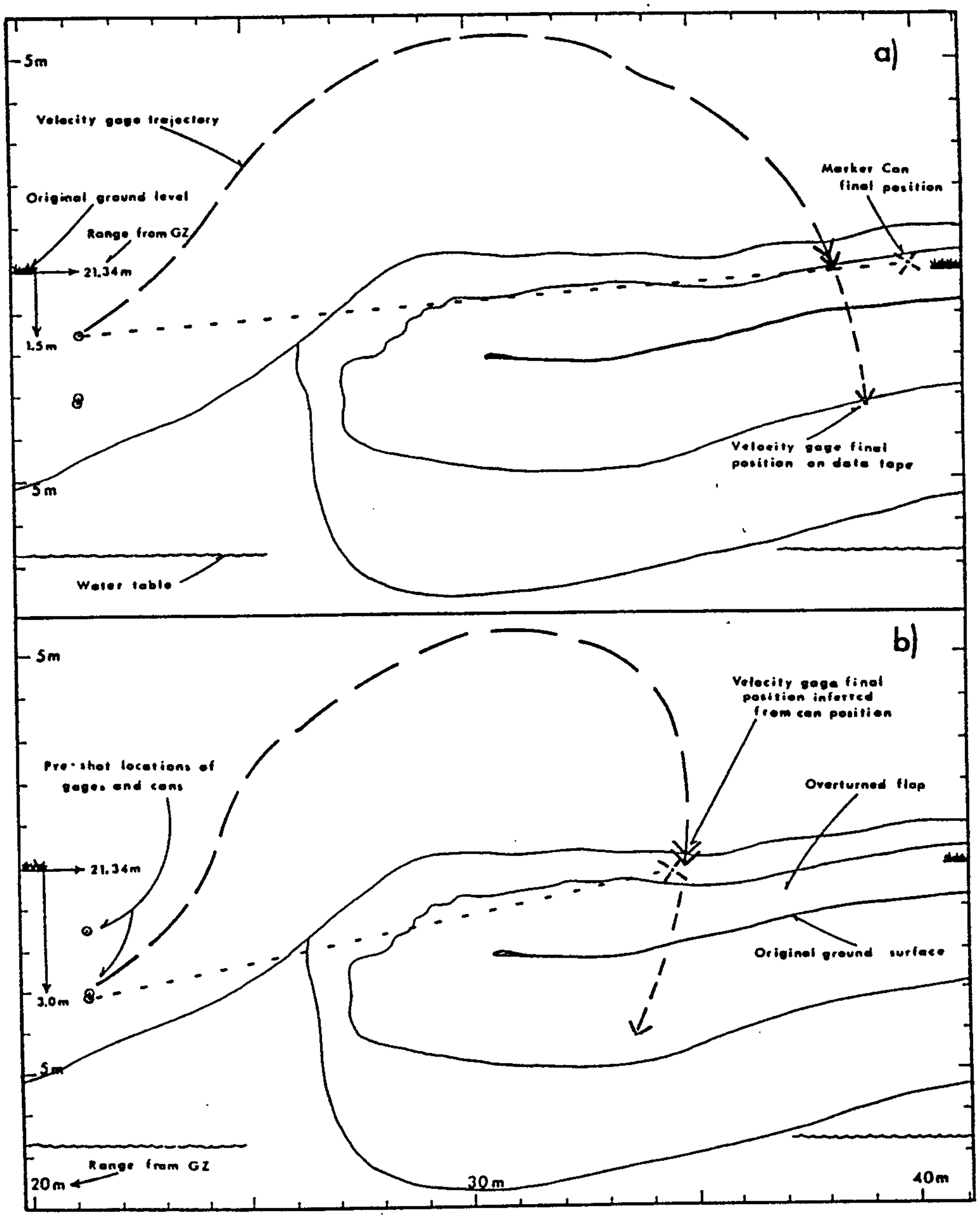


Figure 5/12

Terminal Displacements of Sand Column Marker Cans and Trajectories of Velocity Gauges at the 21.34 m Range and 1.5 and 3.0 m Depths (Roddy et al, 1977)

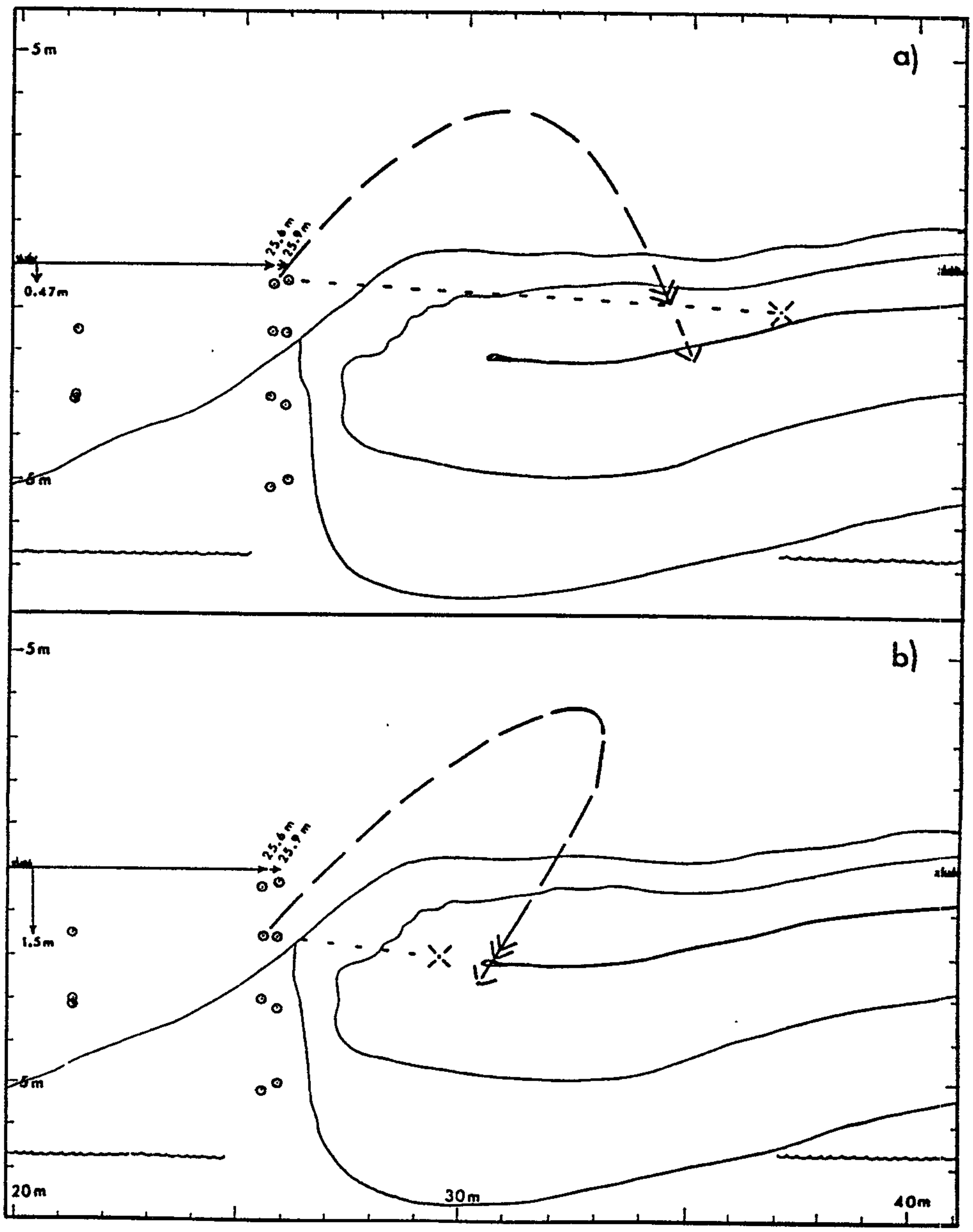


Figure 5/13
Terminal Displacements of Sand Column Marker Cans and Trajectories of Velocity Gauges at the 25.60 m Range and 0.45 and 1.5 m Depths (Roddy et al, 1977)

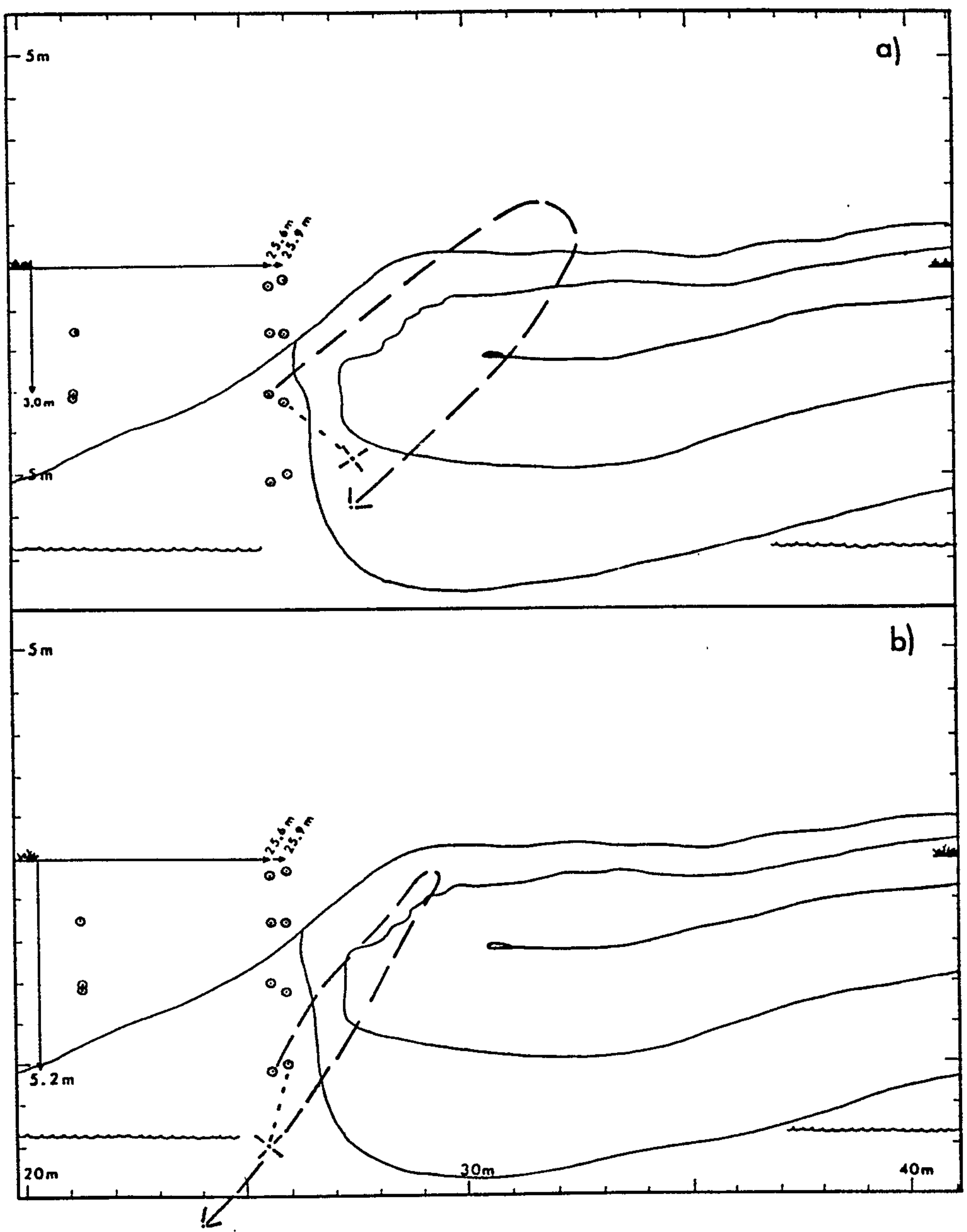


Figure 5/14
Terminal Displacements of Sand Column Marker Cans and Trajectories of Velocity Guages at the 25.60 m Range and 3.0 and 5.0 m Depths (Roddy et al, 1977)

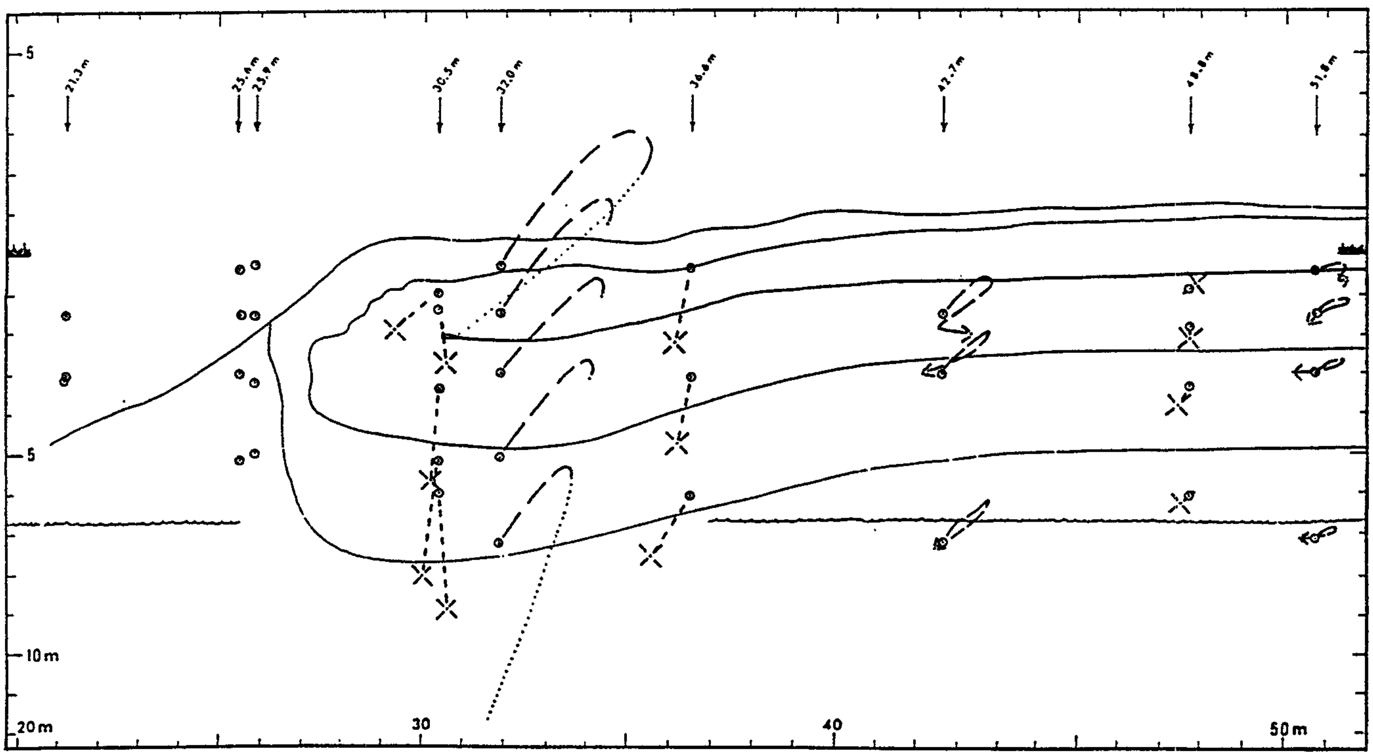


Figure 5/15

Terminal Displacements of Sand Column Marker Cans and Trajectories of Velocity Guages at the Ranges and Depths Shown (Roddy et al, 1977)

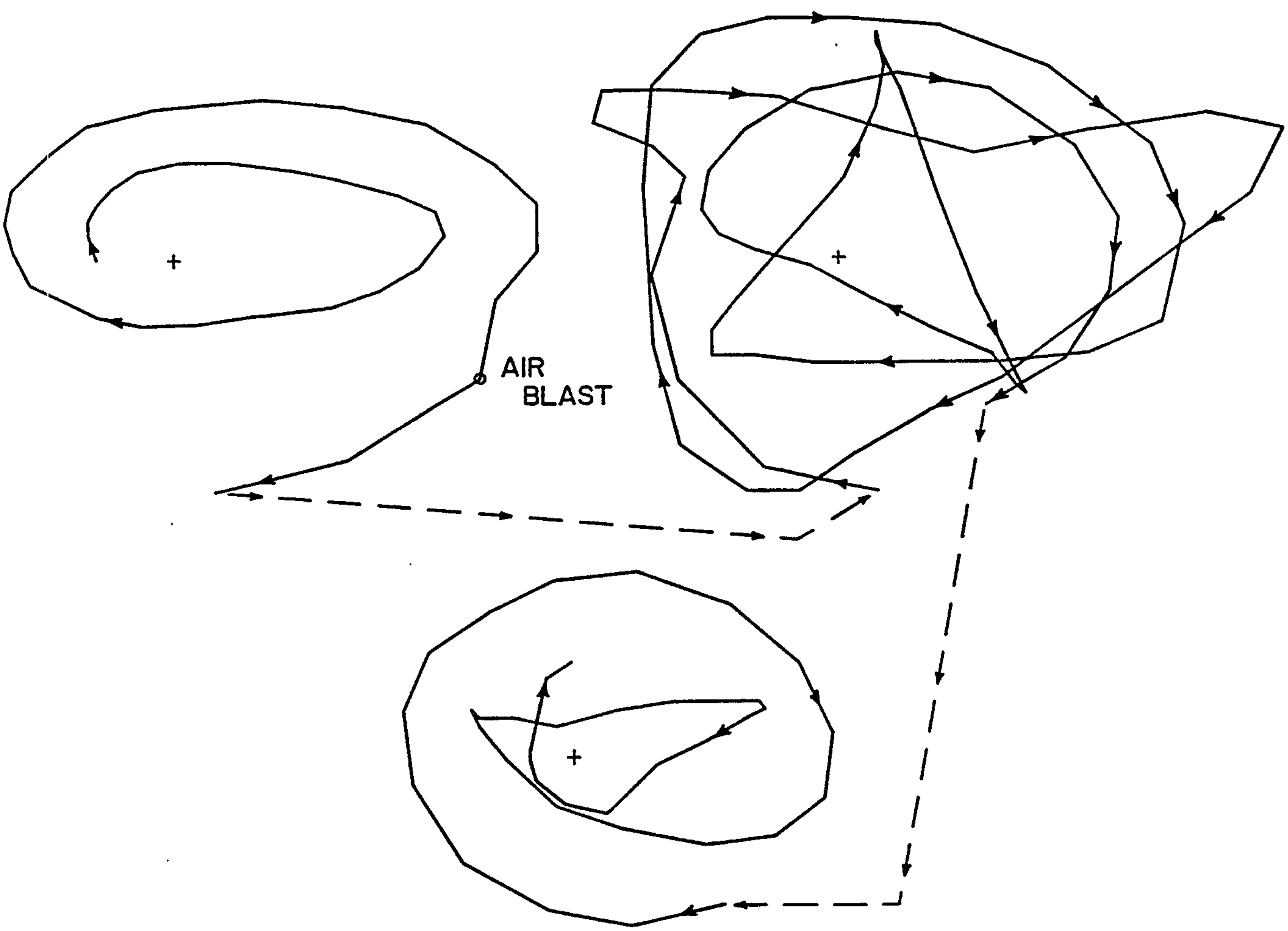


Figure 5/16
Particle Trajectories at 12,000 foot Range from 1961 Suffield 100T Trial

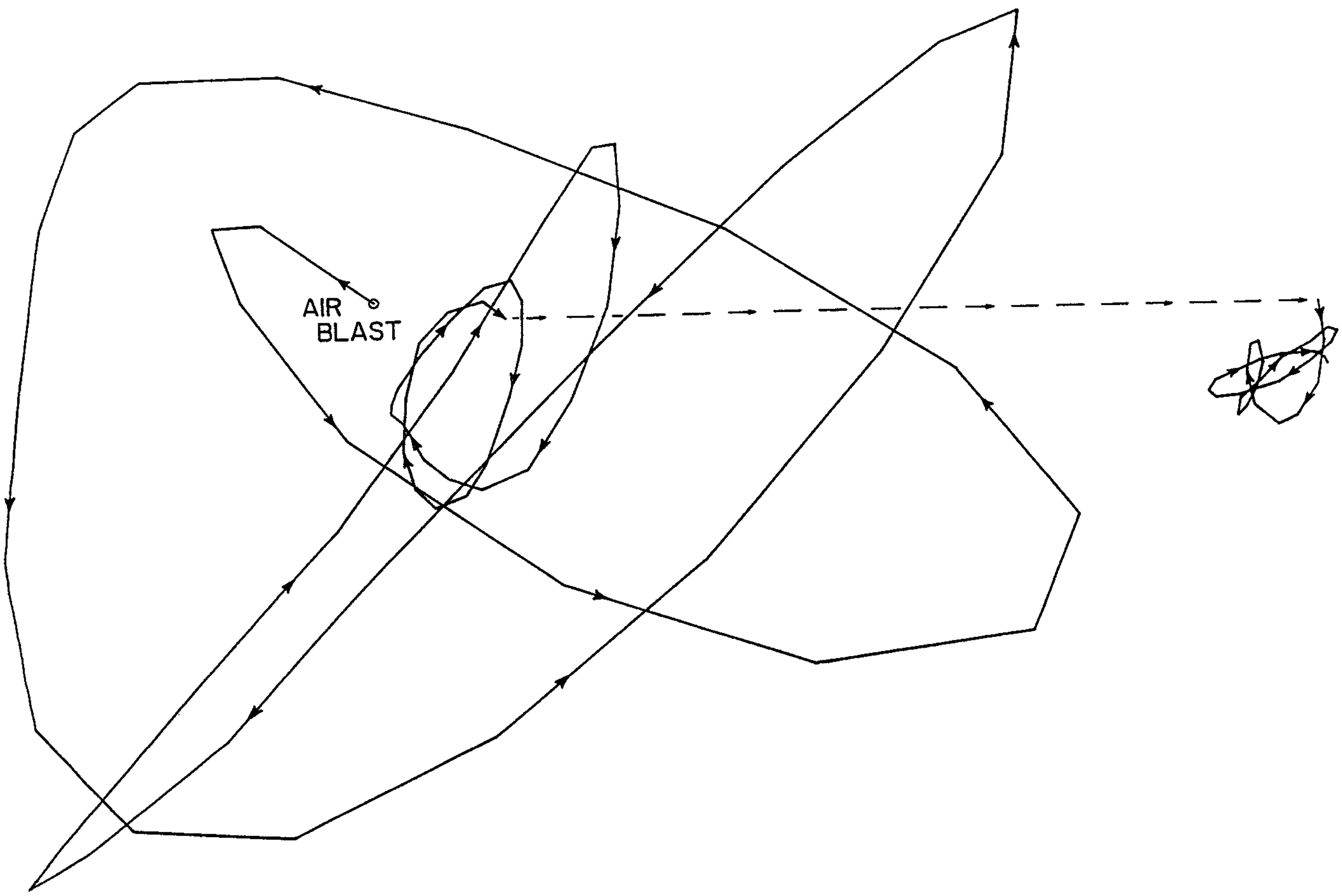


Figure 5/17
Particle Trajectories at 2,000 foot Range from 1961 Suffield 100T Trial

before the arrival of the airblast is at this point a prograde, flat lying, ellipse. However, not too much should be made of this, as the nature of the orbits changes quite sharply at different ranges, and the initial motion is frequently the normal retrograde Rayleigh ellipse. In general, it may be said that the long train of surface waves changes phase repeatedly, and the overall pattern, as might be expected, is a pair of sets of cycles, one prograde tilted elliptic, and the other retrograde tilted elliptic, but it would be quite inappropriate to select particular cycles for correlation with other records without detailed analysis of the particular events, locations and times. The sole purpose, for the moment, is to show that there is no inherent contradiction between the velocity gauge records shown in Figures 5/12 to 5/15, and the surface seismic effects at longer ranges. The closer to the detonation, the fewer the cycles which may be expected, and in particular, the greater the proportion of the seismic wave which is post arrival of the airblast, and coupled.

Figure 5/17, also from Jones (1963) is from the record taken at a much closer range than Figure 5/16, 2000 instead of 12,000 ft. In this case the record starts with the arrival of the airblast at the seismograph, and the initial effect is a large amplitude retrograde tilted ellipse, but after barely one cycle the tilt changes to a forward tilt, virtually at right angles to the initial motion, and then converts into a prograde motion at the new tilt. In this case the prograde forward tilted motion continues almost unchanged until it decays to small amplitude. It has been demonstrated conclusively by Jones (1967) that this seismic effect is **quite independent of any cratering of the ground**. Non-cratering surface explosions of propane-oxygen, for example, produce identical seismic records for a given charge size and range. The question must then be posed, is the particle motion recorded by the velocity gauges, as shown in Figures 5/12 to 5/15 a direct linking to the high pressure blast wave, rather than to any cratering mechanism? Is the crater lip itself formed as a function of an air-coupled large amplitude ground wave, which is large enough to "break" in the plunging mode? This, of course, is a highly controversial suggestion, but it can **not** be rejected out of hand.

Editorial Note

There is an as-yet unresolved mystery about the strong motion seismic recording on PRAIRIE FLAT. Although the pre-trial planning indicates a layout of five Sprengnether seismographs, associated with accelerometers and telluric probes, the author has been unable to find any interpretation reports. The actual seismic recording programme also included long range seismic recording by the University of Alberta. The strong motion plan was a continuation of the programme developed by the author, from 5 lb to 500 tons, but on this particular trial the author merely had overall authority as the Canadian Scientific Coordinator, and in the trial itself the author acted as the U.S. Project Officer for the cratering programme. The author has located the original seismograms in his personal archives, and his recollection is that these were later digitized by Steve Cyganic. In their original forms, the various traces overlap, as was usual, and it was always necessary to separate the traces and digitize before plotting particle trajectories. Inspection of the original seismograms reveal that they are consistent with all the earlier trials, ie. large amplitude air coupled waves, not significantly different from the 100 ton trial records except that the wave periods were, of course, longer at the (scaled) ranges. If no published interpretation can be found, consideration may later have to be given to a fresh assault upon them.

5.5 EXCAVATION OF THE PRAIRIE FLAT CRATER

The excavation of the PRAIRIE FLAT crater was a complex operation, basically divided into three distinct sections. Initial excavation was to examine the volume of material in the ejecta blanket as preserved on the radial asphalt strips, that is above the original ground surface. The second phase consisted of trenching along the sand column line, through the rim structure of the crater. The third phase related to the interior of the crater proper. Some general comments are in order before starting the detailed discussion.

Reference has been made earlier to the possible existence of a coherently overturned flap surrounding the crater. In earlier trials this was not very evident, and where the field evidence showed signs of an overturn, it was not thought to be coherent, but in the form of overturning of blocks of material, and sequential fallout of the ejecta. However, sufficient curiosity had been aroused that on PRAIRIE FLAT the effect was studied in detail during the excavation of the rim structure, by the Suffield crater study team in close association with the U.S. Geological Survey Branch of Astrology, primarily David Roddy. Thus although the mechanism of excavation was that routinely associated with excavating the sand column markers, great care was taken to record the stratigraphy as it was exposed successively during the excavation, and detailed field mapping and photographic coverage was undertaken. PRAIRIE FLAT was the first crater in which this detailed stratigraphic study was undertaken, and it proved conclusively the existence of a phenomenon which had not, so far as is known, been detected on earlier experimental craters **nor on any recognized impact structure**. Overturned rims had, indeed, been recognized on impact structure, but what had not been recognized was the **coherent** nature of the overturned flap, that is to say it was quite definitely **not** due to sequential fallout or simple overturning of individual surface blocks. Subsequently, this coherent overturning was recognized in the data from other craters.

5.6 STRATIGRAPHY OF THE COHERENTLY OVERTURNED FLAP

Figure 5/18 is a composite stratigraphic plot made from the (necessarily piecemeal) excavation data, close to the east sand column line on PRAIRIE FLAT. This is a fold-out derived from Jones et al (1970). The original large scale Mylar based drawings produced at DRES were entrusted to David Roddy, U.S. Geological Survey, Flagstaff, for safe keeping when the author left Suffield, and have recently been re-located in the "Roddy archives" of the Branch of Astrogeology.

Figure 5/19 is a similar plot taken along the south sand column line. In both these sections it is clear that the strata from some 10 to 30 ft below the original surface may be traced continuously through the rim of the crater, to extend as a completely coherent overturned flap out to at least 170 ft from ground zero. Many of the strata were fine, free running sand, sandwiched between but slightly more competent strata of silty clay. As the flap extended from the rim out to 170 ft, these strata were stretched and thinned from thickness of up to a foot to thin filaments of a fractions of an inch. Total structural integrity was maintained in the sand/silty clay sandwich, proving conclusively that the material of the overturned flap had never been part of disintegrated, ejected "fallout" material.

It is, of course, clear that a form of overturned flap may be produced by overturning and sequential fallout of ejecta, and there is little doubt that the "overturned ejecta" noted in field studies of certain impact craters may well be of that pattern. It is even more certain that the mechanism acting at PRAIRIE FLAT - and probably at all the major Suffield craters - was not of this type, but a coherent rolling back and stretching of a continuously competent sandwich of underlying strata, deposited without disruption on the original stratification of the ground subject to the cratering.

Here we merely present the field data without further speculation, which is deferred to a later chapter.

There is one interesting observation which is not clearly shown in the stratigraphic sections as presented in Figures 5/18 and 5/19, simply because these sections are composites made up of very many correlated small sections, so that while an accurate representation of the overall coherence found in the field, they do not show all that was observed. In particular, in excavating the east line, represented in Figure 5/18, it was observed that in one of the excavated regions there was a duplication of the "underlying" strata, to the extent that there was a repetition of the strata in the original posture, that is two, "pre-shot surfaces" associated with the immediately underlying strata were encountered. This caused some confusion in the field, which was only resolved at a late stage when it was realized that in this region a block of the pre-cratered ground between the center of the crater and out to about 120 ft had actually sheared, and moved horizontally outward for about 20 ft. It is probable that this was actually a thrust fault which preceded the coherent overturning which formed the flap. This is similar to the effect noted on earlier trials, and correlates very closely with the data from the 1961

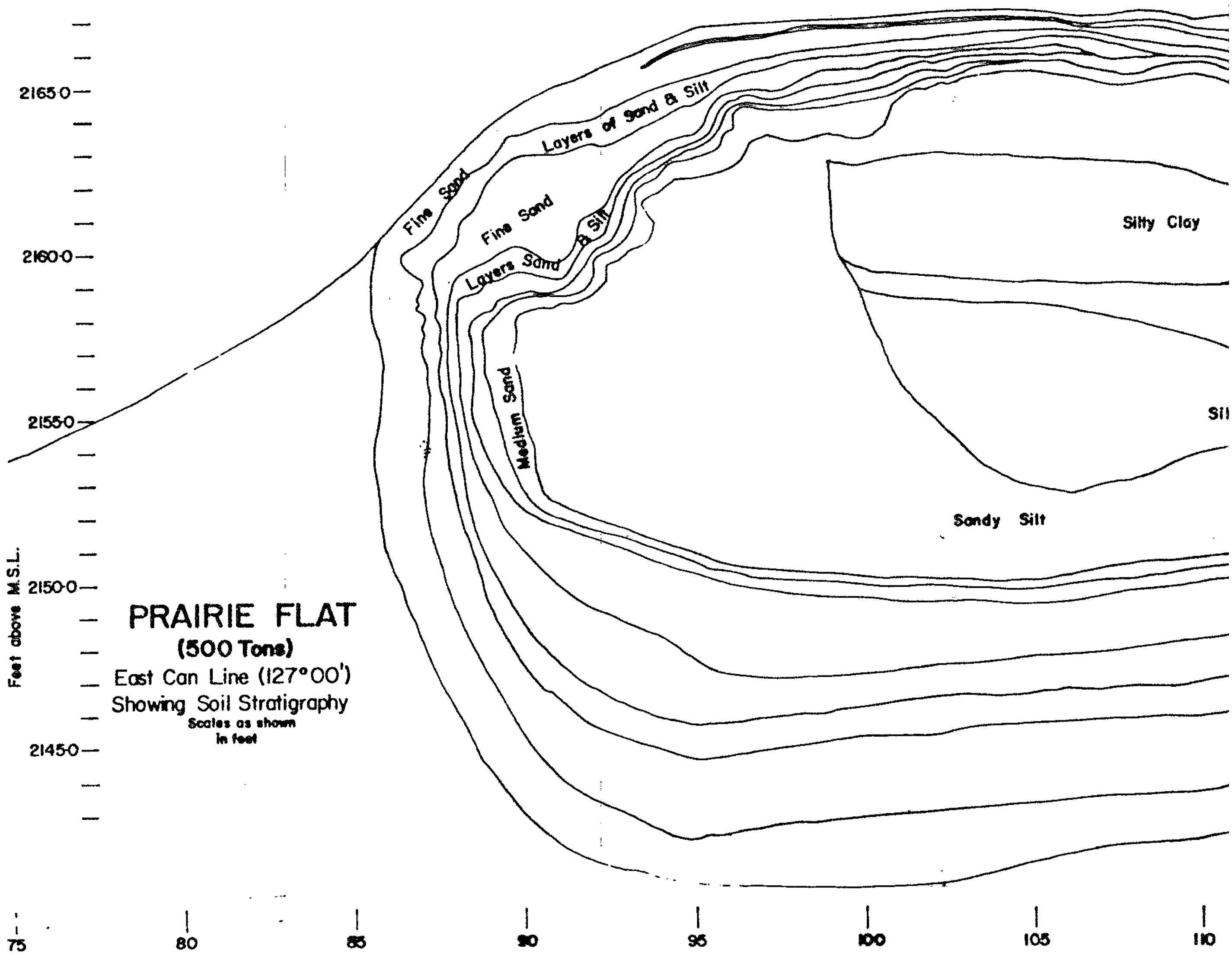
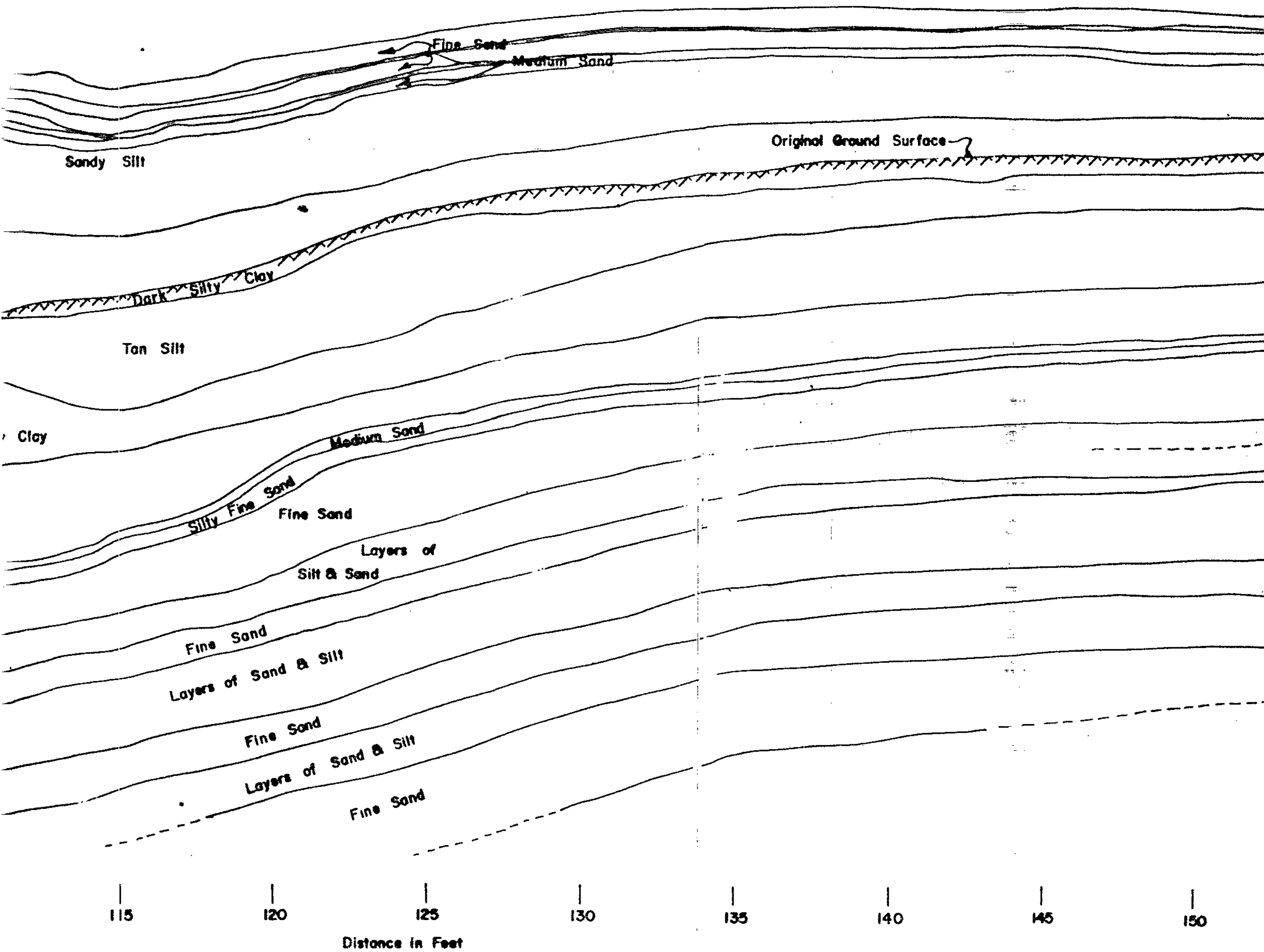
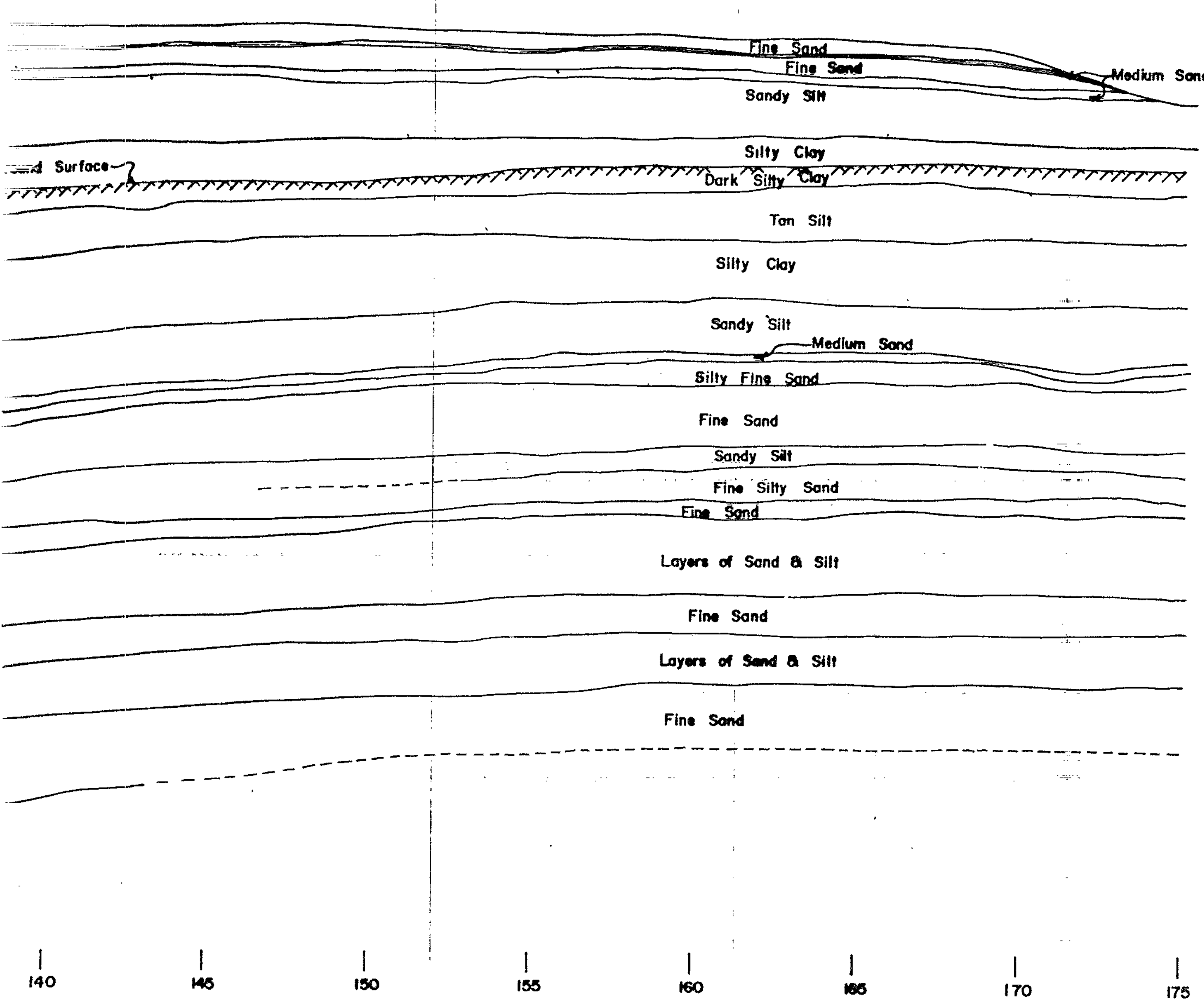


Figure 5/18
East Can Line Showing Soil Stratigraphy from PRAIRIE FLAT


Fine Sand
Medium Sand
Sandy Silt
Original Ground Surface
Dark Silty Clay
Tan Silt
Clay
Medium Sand
Silty Fine Sand
Fine Sand
Layers of
Silt & Sand
Fine Sand
Layers of Sand & Silt
Fine Sand
Layers of Sand & Silt
Fine Sand
115
120
125
130
135
140
145
150
Distance in Feet



Fine Sand
Fine Sand
Medium Sand
Sandy Silt
Silty Clay
Surface
Dark Silty Clay
Tan Silt
Silty Clay
Sandy Silt
Medium Sand
Silty Fine Sand
Fine Sand
Sandy Silt
Fine Silty Sand
Fine Sand
Layers of Sand & Silt
Fine Sand
Layers of Sand & Silt
Fine Sand
140
145
150
155
160
165
170
175

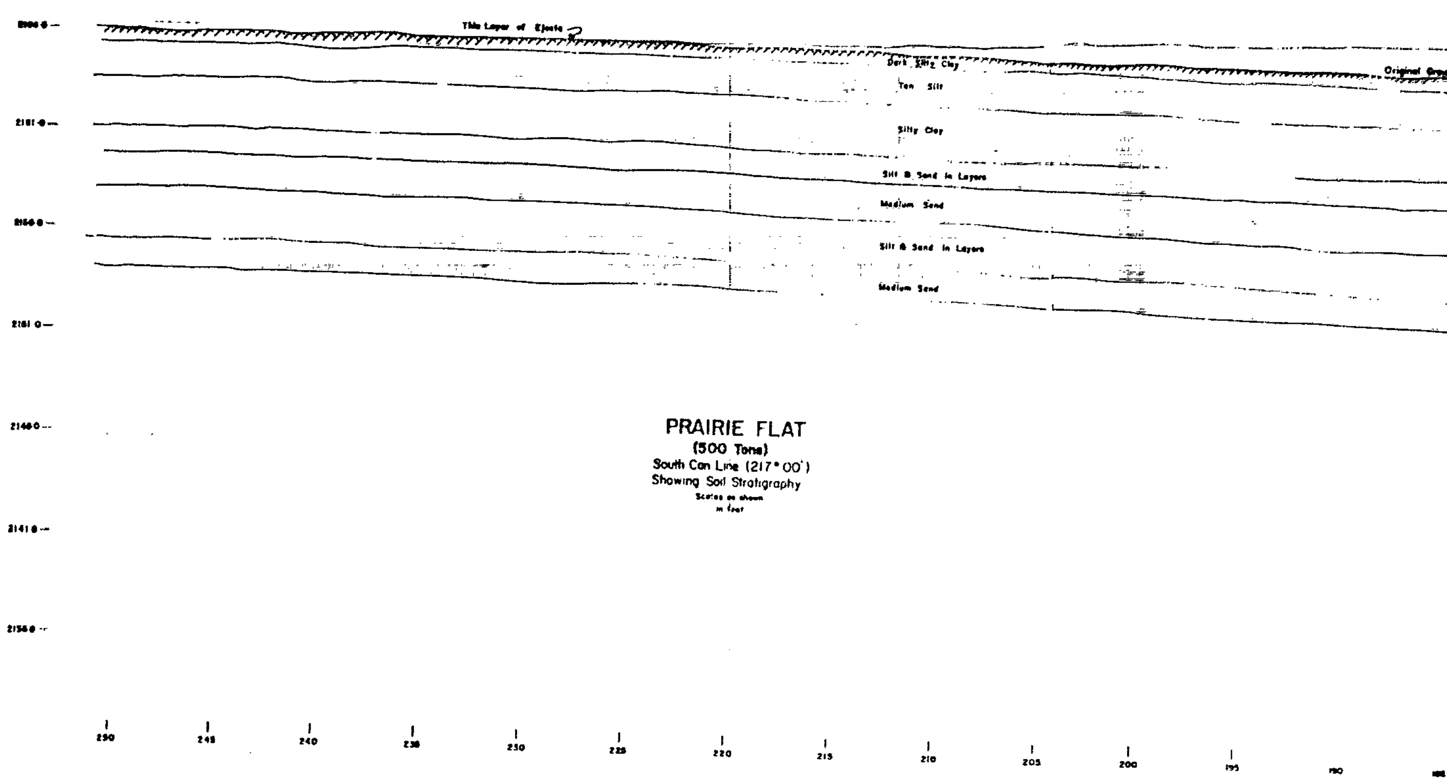
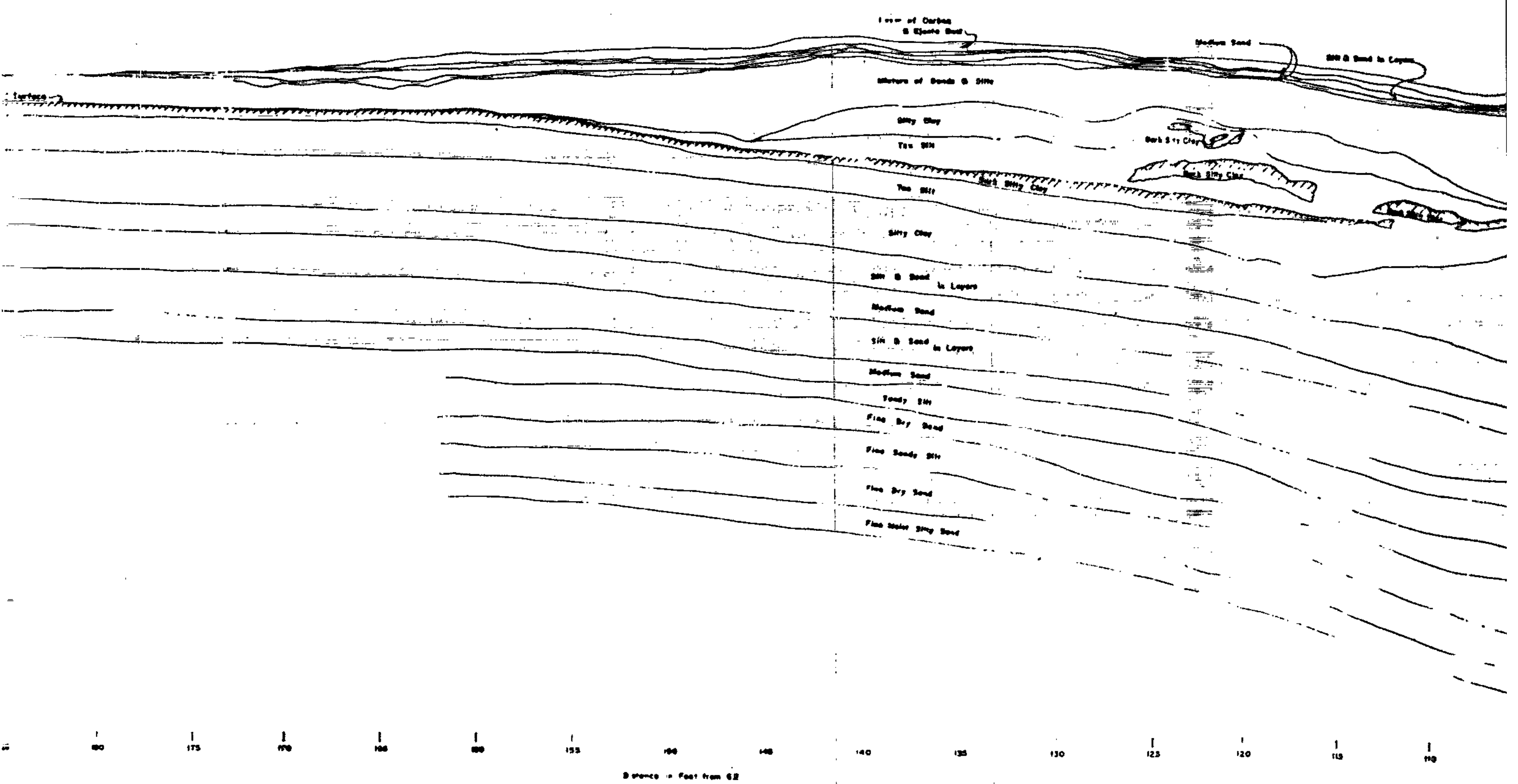
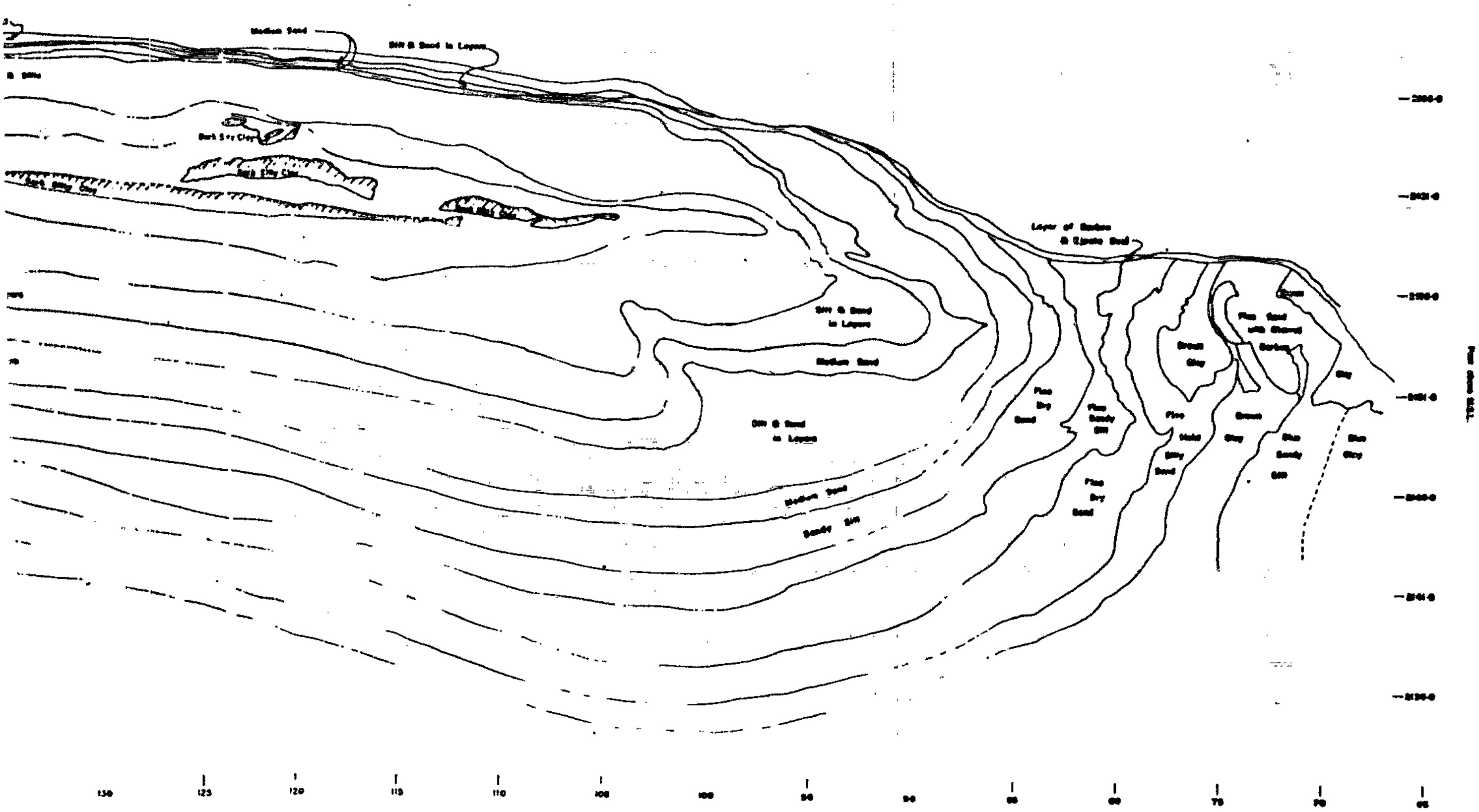


Figure 5/19

South Can Line Showing Soil Stratigraphy from PRAIRIE FLAT


Surface
Medium Sand
Mixture of Sands & Silts
Silty Clay
Tan Silt
Dark Silty Clay
Tan Silt
Silty Clay
Silt & Sand in Layers
Medium Sand
Silt & Sand in Layers
Medium Sand
Sandy Silt
Fine Dry Sand
Fine Sandy Silt
Fine Dry Sand
Fine Moist Silty Sand
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110


Medium Sand
Silt & Sand in Layers
Silt & Sand in Layers
Medium Sand
Silt & Sand in Layers
Medium Sand
Fine Dry Sand
Fine Dry Sand
Brown Clay
Brown Clay
Blue Clay

Suffield 100 ton trial.

While not evident in the stratigraphic sections as plotted, the effect is clearly demonstrated in the sand column data, after plotting. Such an effect is not, of course, obvious in the field during the slow, selective excavation of the sand column markers. These data are discussed below.

5.7 THE SAND COLUMN DATA IN THE RIM REGIONS

Although the actual field work was simultaneous in the collection of the various sets of data, and the excavation was of necessity undertaken a small section at a time, often in successive vertical slices, each recorded separately, there is a sharp distinction in the method of presentation. In the stratigraphic sections, discussed above, the individual slices have been interpreted as a single, composite section, an over-all correct picture which was confidently declared to be the basic structure of the coherently overturned flap.

In contrast, the data from the sand column markers, and the recorded shears in the sand columns themselves, are precise recordings of the actual surveyed positions along the excavated sand column lines, with no smoothing of the data. They thus reveal the fine structure which underlies the stratigraphic sections. In the case of PRAIRIE FLAT there is considerable merit in discussing the data presented separately as a "WES type" plotting of the shears and later using the displacements recording for the marked elements by the Suffield marker. We look first at the pattern of shears revealed by the sand columns.

Figure 5/20 show the pattern revealed by the south line sand columns. Note first that there is an unexpected inward movement connected primarily with column S5 at roughly 90 ft from GZ. However, markers from the same column, barely removed from those which show the inward displacement, indicate an almost equal outward displacement. In fact, the top levels of all the columns are, in effect "smeared" into the area of the ejecta blanket. During the excavation, no notation was made declaring these upper markers to have been found in true ejecta, and there is a pattern to the movement which tends to refute the possibility. Nevertheless, as no explanation can be given for the anomalous final locations of these markers, judgement must be reserved. They may, in fact, record only the final position of markers which had been ejected into ballistic trajectories.

This uncertainty does not extend to the bulk of the markers, which in the diagram are connected by solid lines which represent the actual disposition of the column material as found by excavation. Note that in columns S9 to S3 the upper parts of the columns exhibit quite clearly a shear fracture, or multiple shear fracture system, which extends at a uniform shallow angle. If this angle is continued to intersect with the pre-shot surface, it does so in the vicinity of a rather jumbled collection of markers derived from the inner columns. The precise mechanism involved remains uncertain, but the implication is clear that a thrust fault breached the surface at about 145 ft from GZ.

Turning now to Figure 5/21, which shows the shear patterns in the east sand columns, it is noted that in this case there is no sign of anomalous inward motion, but a general outward motion, with again a clear indication of a thrust fault, at a similar shallow angle. However, in this case the apparent rupture of the surface, by the lowest shear, would occur very much farther out, possibly well beyond 200 ft from GZ. Nevertheless, although it is not so clearly marked on the south line, there is evidence of a similar fracture of the surface close to 145 ft. Referring back to Figure 5/20, some evidence is seen in column S2 of a shear displacement which could indicate an eventual surface fracture at around 180 - 200 ft also. Column S1, which is not plotted in the figure, lay at 250 ft, and was virtually undisturbed from its pre-shot vertical location. The evidence from both sand columns is that a sheaf of sub-parallel shallow angle shears existed, presumably as a system of cone fractures, around the PRAIRIE FLAT crater, and breached the surface, possibly several times, between 145 ft and 200 ft from GZ. It is instructive to look again at Figure 5/3 which shows the crack and fold pattern located under the ejecta. It will be seen that the concentration of crack lines lies in the very region, 150 - 200 ft from GZ, suggested by the above proposed penetration of the surface by the sheaf of thrust faults.

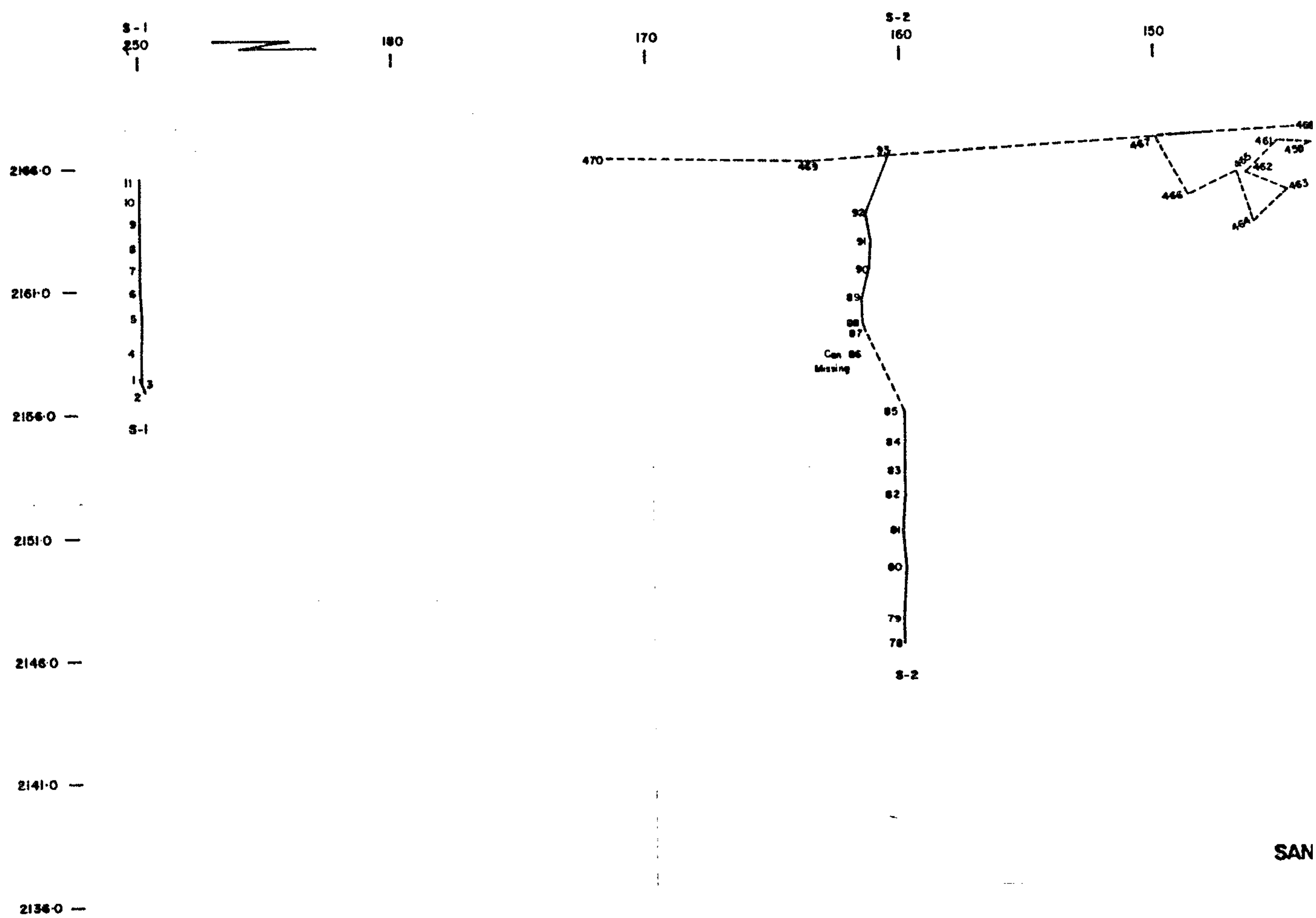
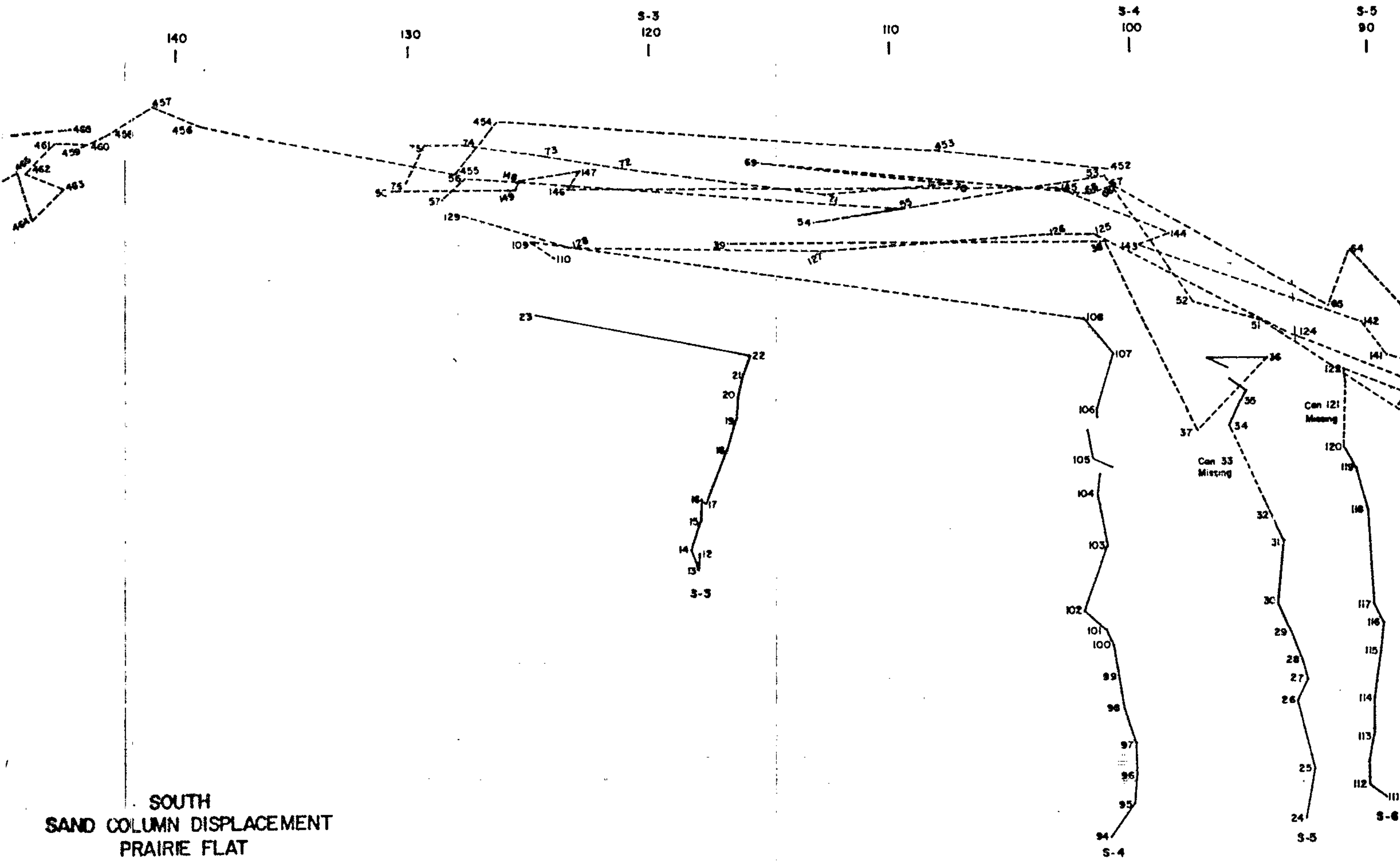
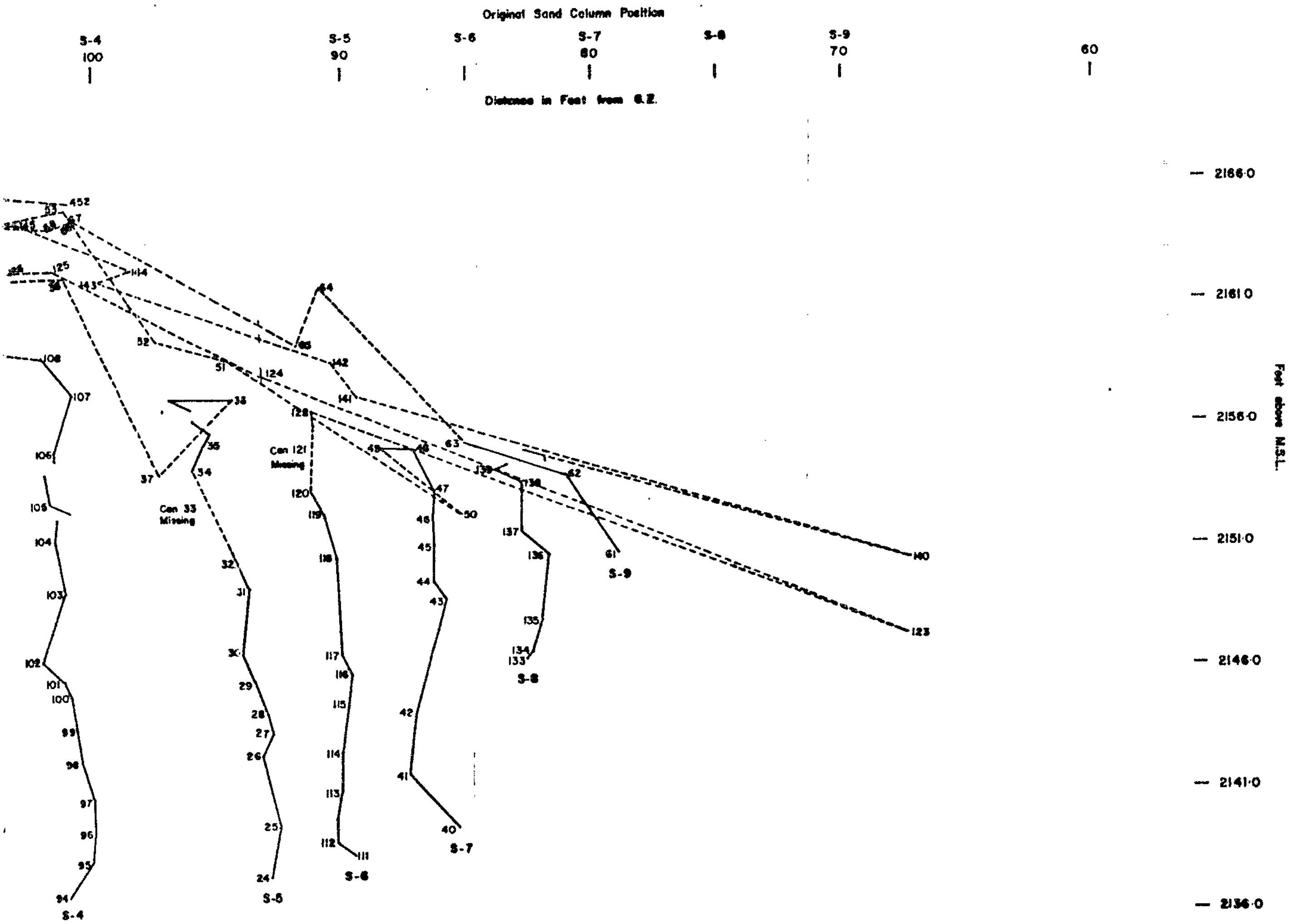


Figure 5/20
South Sand Column Displacements from PRAIRIE FLAT



SOUTH
SAND COLUMN DISPLACEMENT
PRAIRIE FLAT
(500 Tons)
23=Marker Can Number
Scale
0 Ft 5



Original Sand Column Position
S-4
100
S-5
90
S-6
S-7
80
S-8
S-9
70
60
Distance in Feet from G.Z.
2166.0
2161.0
2156.0
2151.0
2146.0
2141.0
2136.0
Feet above M.S.L.
Can 33 Missing
Can 121 Missing
S-4
S-5
S-6
S-7
S-8
S-9

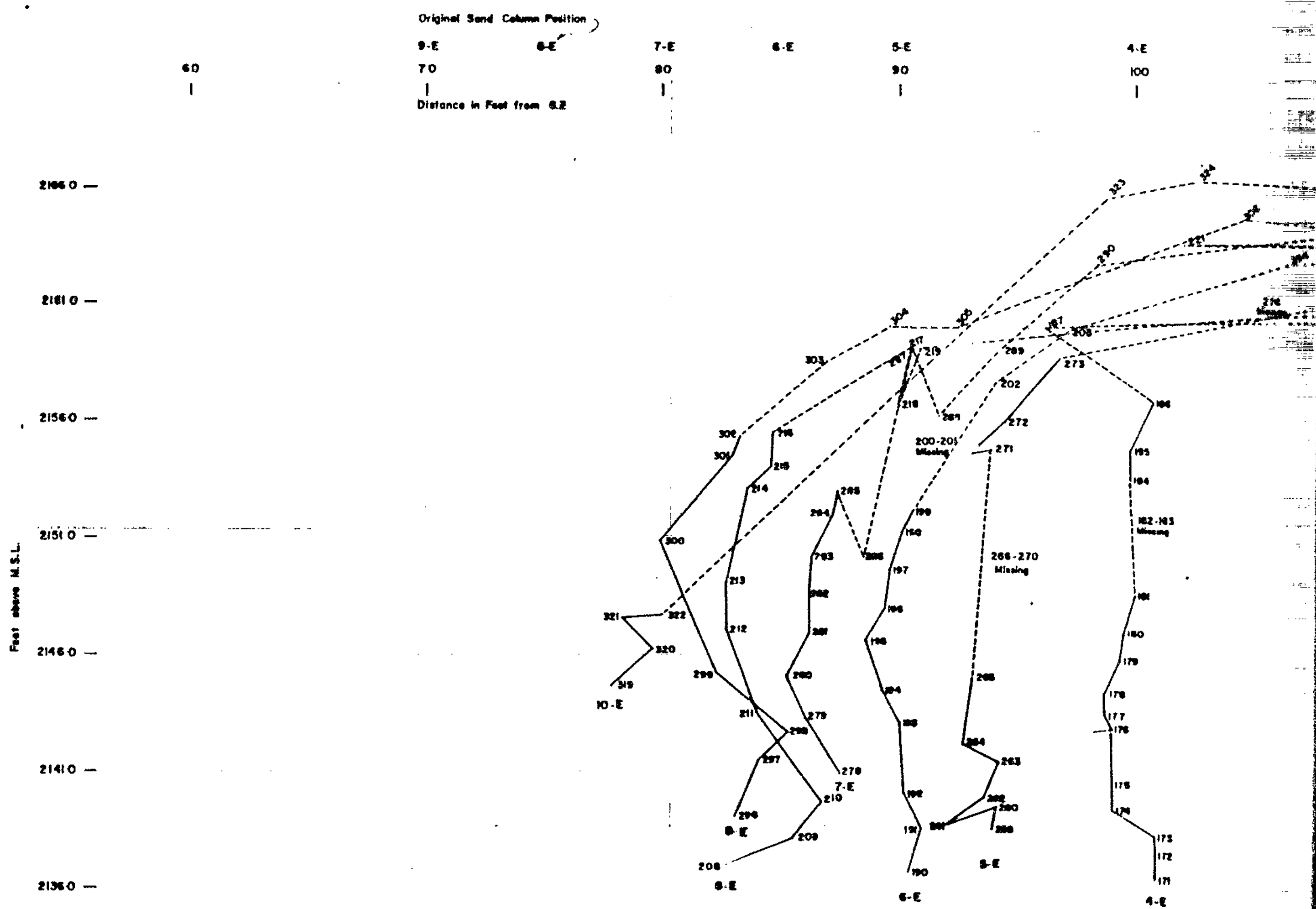
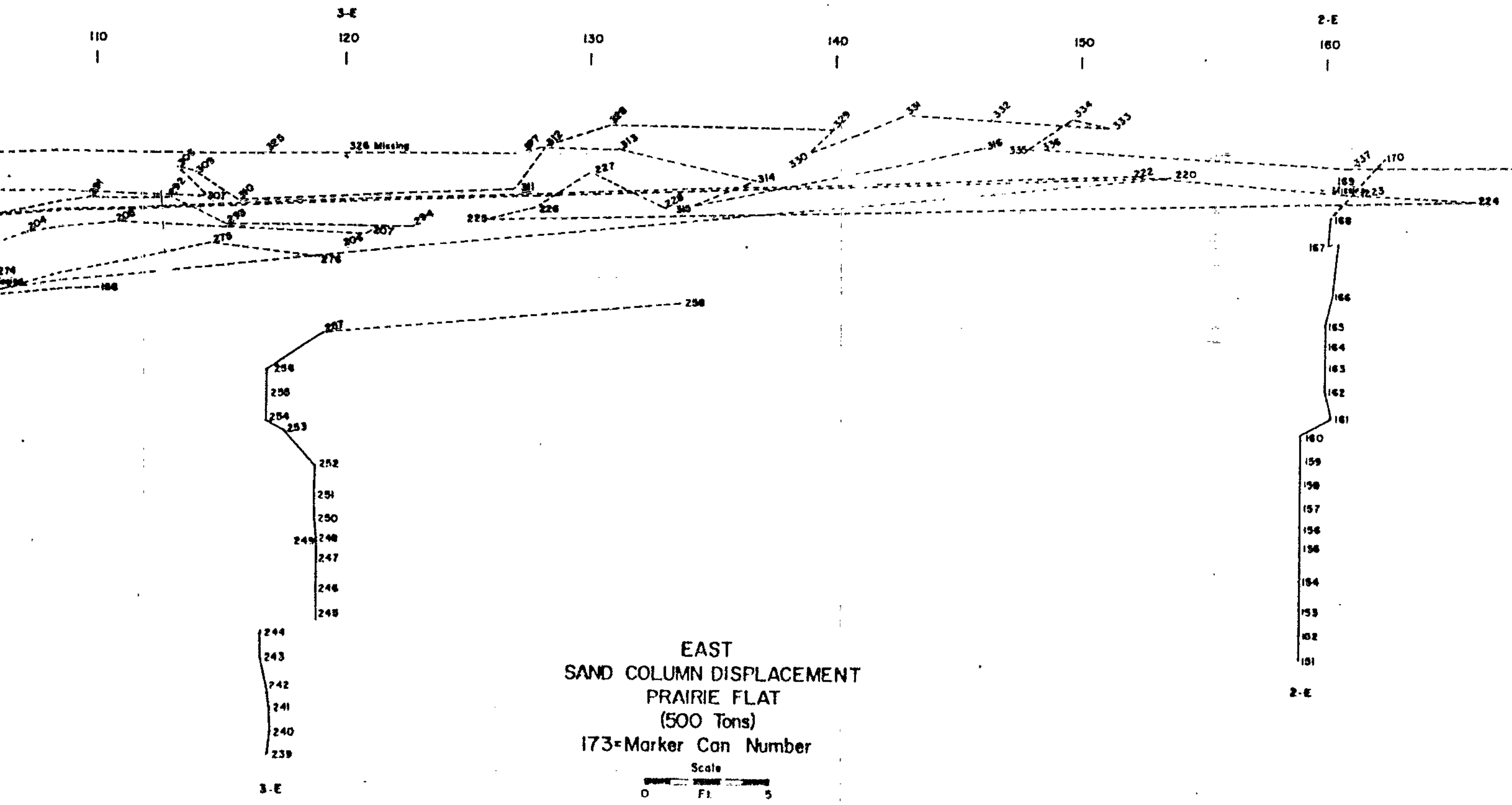
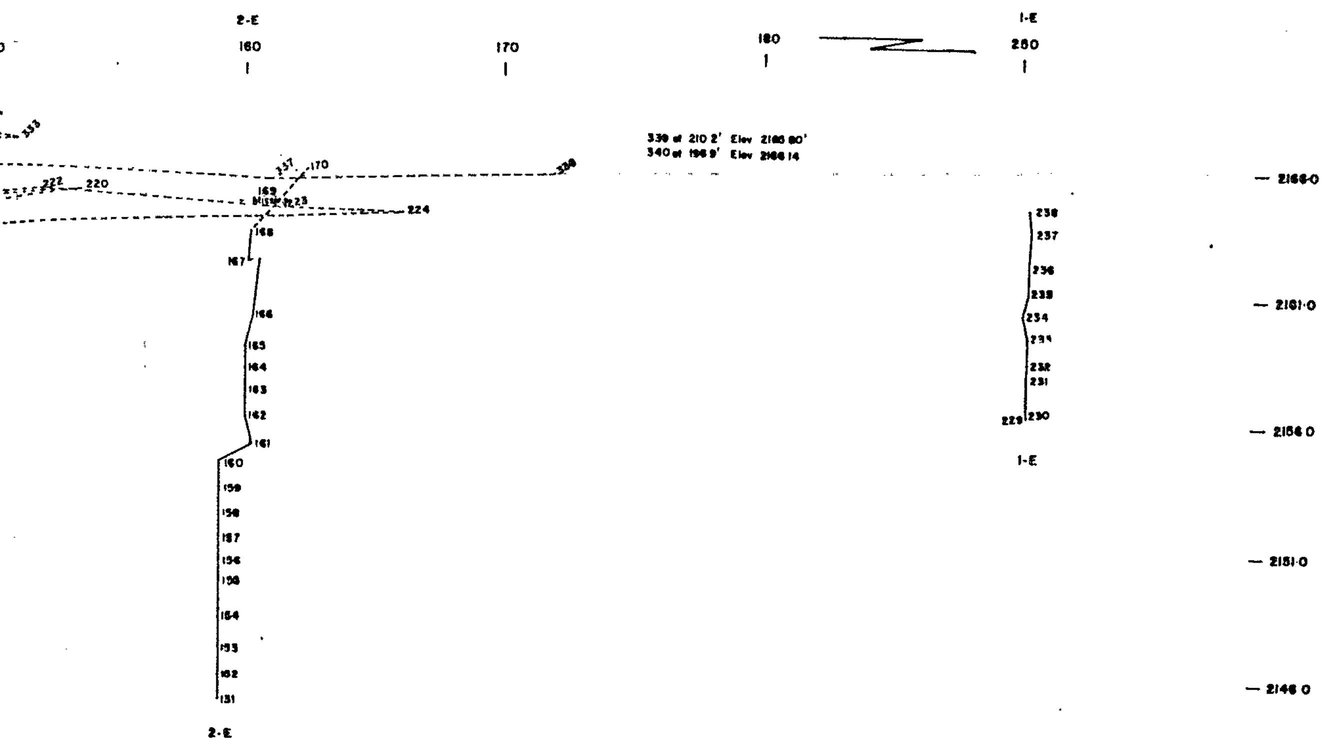


Figure 5/21
East Sand Column Displacements from PRAIRIE FLAT



EAST
SAND COLUMN DISPLACEMENT
PRAIRIE FLAT
(500 Tons)
173=Marker Can Number


2-E
160
170
180
1-E
250
2166.0
2161.0
2156.0
2151.0
2146.0
2141.0
2136.0
1-E
2-E

5.7.1 Displacement Data from Sand Columns and Boeing Ejecta Project

At the time of the PRAIRIE FLAT trial, it was found that the vector displacements recorded by excavation of the markers in the two sand column lines, and the several radial lines of the Boeing project could not be presented by manual drafting. The complexity of the overlapping from the closely spaced columns of markers made even large scale drawings difficult to interpret, and small scale reductions suitable for publication would be meaningless. In terms of manual drafting, the situation is, obviously, unchanged even decades later. However, the orginal numerical data have been preserved in the DASIAC report, WT 2115, and need not be included herein. It is the opinion of the present Suffield staff, in the group which is heir apparant to the Suffield Geophysics team, that these unique original data could be usefully employed in theoretical calculations using modern day computer codes and protocols. Consideration will be given to an in-house project of this type.

5.8 CONTOUR MAP OF PRAIRIE FLAT CRATER

Figure 5/22 is a contour map of PRAIRIE FLAT produced by conventional ground survey. While one would hardly anticipate that such a survey would detect circumferential, but inconspicuous cracking, it is interesting to note that the S-E sector does show a circular feature at about 140 ft from GZ, where such a circumferential crack would be expected.

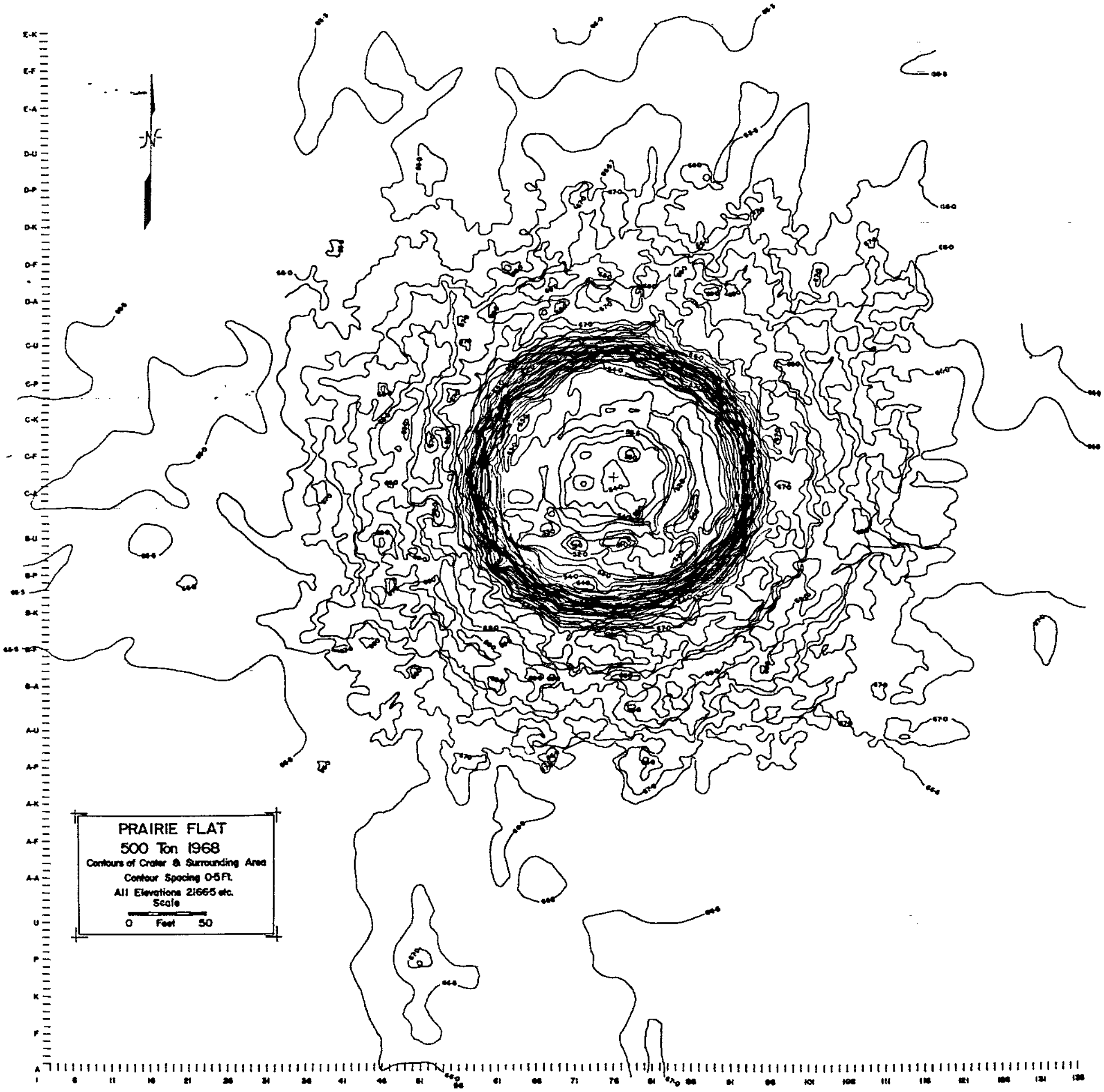


Figure 5/22
Contour Plot of PRAIRIE FLAT Crater and Surrounding Area

CHAPTER SIX

THE 500 TON DIAL PACK CRATER
(23 July 1970)

6.1 INTRODUCTION

The explosive charge used in the DIAL PACK trial was an exact replica of that used in the PRAIRIE FLAT trial, that is to say a 500 ton block built sphere, detonated in a surface tangent configuration on the 23 July 1970 on the Watching Hill test site. No doubt partly because of the replicate nature of the trial, the trial budget was austere, limiting the degree of post-detonation field work.

The present author had left Suffield nearly a year before the trial date and had no responsibility relating to the DIAL PACK crater study programme. Neither, as it happened, did his erstwhile chief field Technical Officer, Claude Diehl, who was with the author in the pre-trial weeks tracking icebergs off the coast of Labrador! As a result of this, and the financial stringency, no sand columns were installed for the DIAL PACK crater study and so no detailed numerical data on ground displacement could be obtained.

Nevertheless, the cooperation which had been developed among Suffield, The Waterways Experiment Station and the U.S. Geological Survey Branch of Astrogeology came to the fore on this trial, and extensive data collection was undertaken by both the American agencies, supported by the Suffield Field staff, which permit the DIAL PACK crater to be compared directly with the earlier Suffield craters, and also with geological structures studied by similar techniques.

As usual, WES rapidly produced a report in their standard format, in this case by Rooke, Meyer and Conway (1972) and Roddy of Branch of Astrogeology contributed an extensive report, which includes comparisons with earlier Suffield craters and with planetary features, to the DIAL PACK Symposium report (Roddy 1971). The DIAL PACK Symposium report, in three volumes, is classified confidential overall, but the Roddy contribution is unclassified.

The study of the DIAL PACK crater was unique in one way, as it was used as an Astronaut training exercise. The author was recalled from Labrador to join with Roddy in acting as briefing and conducting officers for a group of thirteen astronauts, the entire active astronaut team at the time. The astronauts were taken to the crater within five minutes of the detonation, and were able to construct a relatively complete sequence of cratering events from this observation of a fresh crater. Lunar sampling and surface exploration techniques were discussed in terms of the DIAL PACK stratigraphy. The blocky overturned flap and the known original stratigraphy were useful in demonstrating the use of a crater as a "drill hole" for lunar collecting techniques.

It is said that this was the greatest number of astronauts ever collected for a single training exercise, so it is fair to assume that by 1970 the planetological significance of the Suffield central uplift craters had been widely recognized.

A description of the crater itself is now presented, but it is stressed that although present on the trial day, the present author had no technical responsibilities in the crater study, and the material in this chapter is dependent upon the work of Rooke et al and Roddy. It is included because, although the charge replicated that of PRAIRIE FLAT, and the craters were not without close similarity, there were distinct differences as well, and the techniques of study were more directly comparable with those used in studying geological structures than experimental ones. Nevertheless, in applying these geological techniques, much of the interpretation was dependent upon the knowledge gained by actual excavation and displacement tracing on earlier Suffield trials.

6.2 THE SUPERFICIAL CRATER

As anticipated with the replicated conditions, the DIAL PACK crater was superficially very similar to the PRAIRIE FLAT crater, though with some interesting additions. That is to say, the overall dimensions were closely matched, as shown in Table 6/1. It was also a ringed crater, though in the case of DIAL PACK the small inner ring was replaced by a central mound, details of which will be discussed later. Also, the crater started life as a completely dry crater, but again within the first thirty minutes water, laden with sand, started to flow in the crater. Unlike PRAIRIE FLAT, but similar to SNOWBALL, there was also some external flow (pseudo-vulcanism) associated with circumferential and radial fissures. The ejecta blanket was lobed, as was that of PRAIRIE FLAT, the strata under the rim were depressed, sloping inward towards GZ as was the case with both SNOWBALL and PRAIRIE FLAT, and there was a clear, coherently overturned flap in the rim area, though cohesion at points remote from the crater was less than in PRAIRIE FLAT.

The initial ground survey was undertaken by conventional survey techniques by the Suffield field staff, on an east-west line soon after the detonation and before the inflow of water. In the table there are minor differences between the data quoted by Roddy and by WES and this may be due to slight differences in definition of the basic parameters, which is a common problem. Despite the minor differences, it is clear that the two craters are virtually indistinguishable in terms of overall dimensions.

TABLE 6/1

COMPARISON OF SUPERFICAL DATA
DIAL PACK AND PRAIRIE FLAT

	DIAL PACK (ft)	PRAIRIE FLAT (ft)
Apparent Crater Diam (WES)	190	200
Ground Level Diam (Roddy)	200	210
GZ Depth (WES)	8.6	12
Max Depth (WES)	13.1	15
Depth (Roddy) (from Grd Level)	12	12
Depth From Rim (Roddy)	16	15
True Crater Diam (WES)	310	308

WES always maintain that the best parameter to use in scaling craters is the True Crater diameter, defined in terms of the "rupture zone" found by excavation and particularly with the aid of the sand column technique. Regrettably, this parameter is not normally available for planetary structures. As has been pointed out earlier, the estimation of original energy yield for planetary structure scaling is fraught with uncertainties, and should be used with great care, if at all.

Figure 6/1 is a view of the complete charge, as replicated for PRAIRIE FLAT and DIAL PACK. Figure 6/2 is an oblique aerial view of the DIAL PACK crater, while Figure 6/3 is a vertical view of DIAL PACK with superimposed contours, a photograph used in Rooke et al (1972). However Roddy (1971) notes "a detailed topographic map has been made by the Geological Survey, Flagstaff, for the Waterways Experiment Station" and this no doubt is the original source of Figure 6/3. Oddly enough, it does not appear to have been used by Roddy in his Symposium paper, though he does use several other examples. It is shown here because it illustrates clearly one of the ways in which DIAL PACK differs from PRAIRIE FLAT, and all earlier Suffield craters. This is the existence of a profusion of **radial** ridges on the inner floor of the crater, much more evident than the circumferential anticlinal-synclinal ridging, though in fact these also existed in DIAL PACK. The radial ridges were also structural, as proved by excavation and consisted of sets of synclinal and anticlinal folds radial to GZ. The author is not aware that such radial ridging exists on any known impact structure on earth. However, in mature impact structures they could easily be missed, if not suspected, due to late stage sedimentation covering the structures. Radial geophysical studies would find circumferential structures as part of routine interpretation, but such surveys could well fail to detect the radial ridging. The more serious question that needs to be answered is whether or not these radial ridges correspond to radial cracking, inside the crater floor and possibly extending beyond the rim as sources of internal and external pseudo-vulcanism, as noted for the circumferential ridging inside PRAIRIE FLAT, and the radial effects on SNOWBALL.

Figure 6/4 after Roddy, is a topographic map, at small scale in the figure but available at full scale from the U.S. Geological Survey. It is included mainly to show

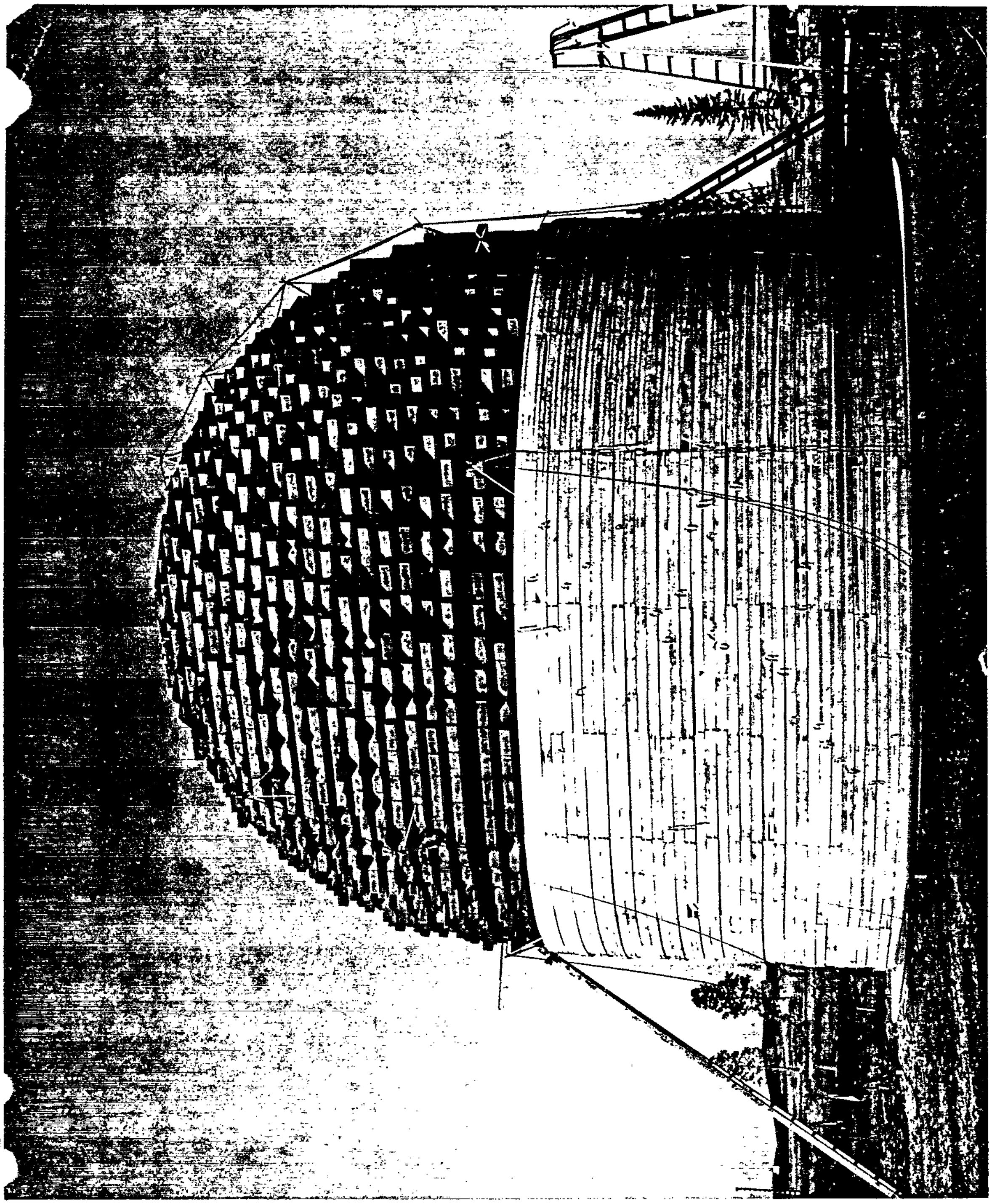


Figure 6/1
500 Ton Surface Tangent Charge, Replicated PRAIRIE FLAT and DIAL PACK

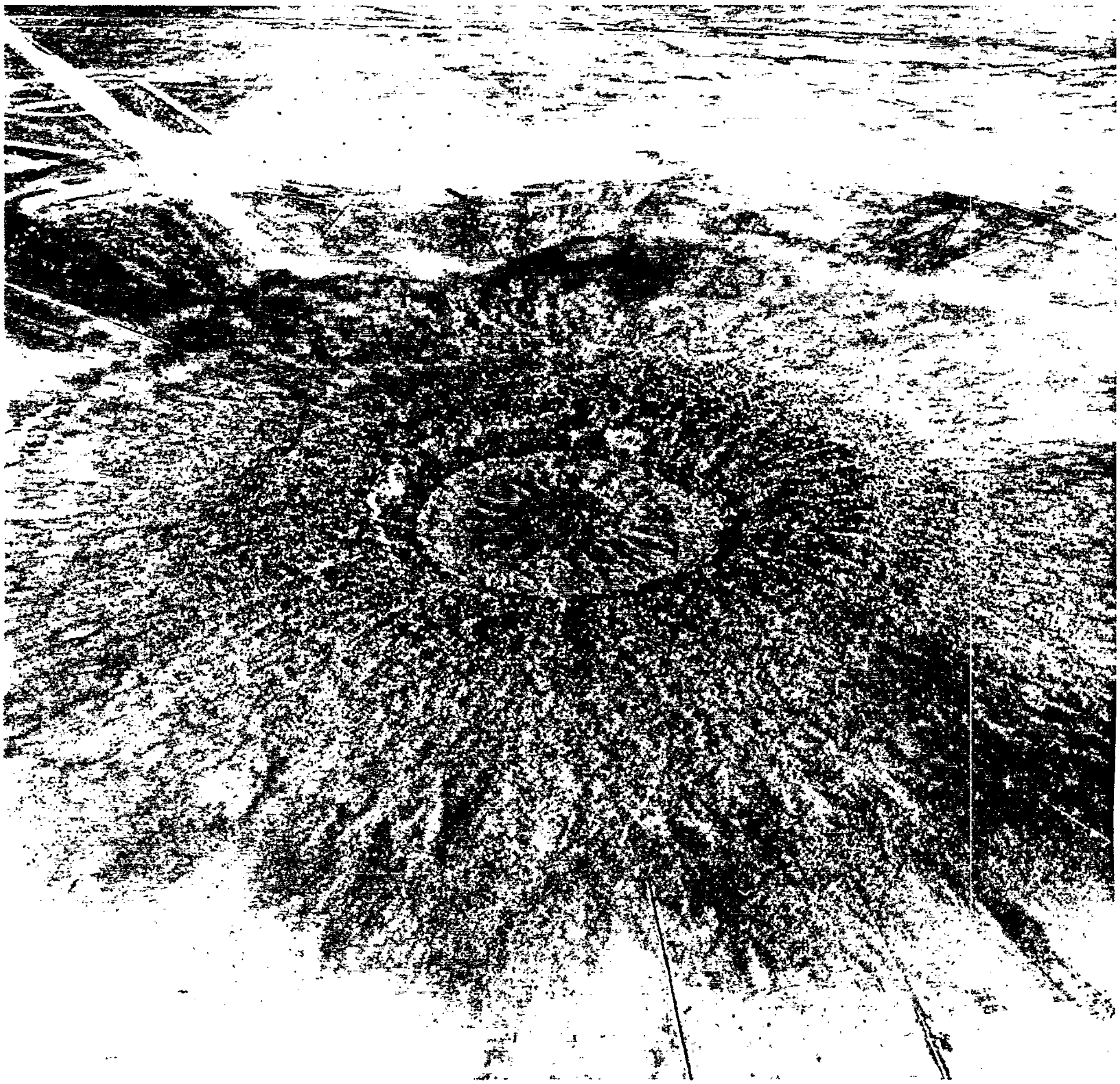


Figure 6/2
Oblique Aerial View of DIAL PACK Apparent Crater

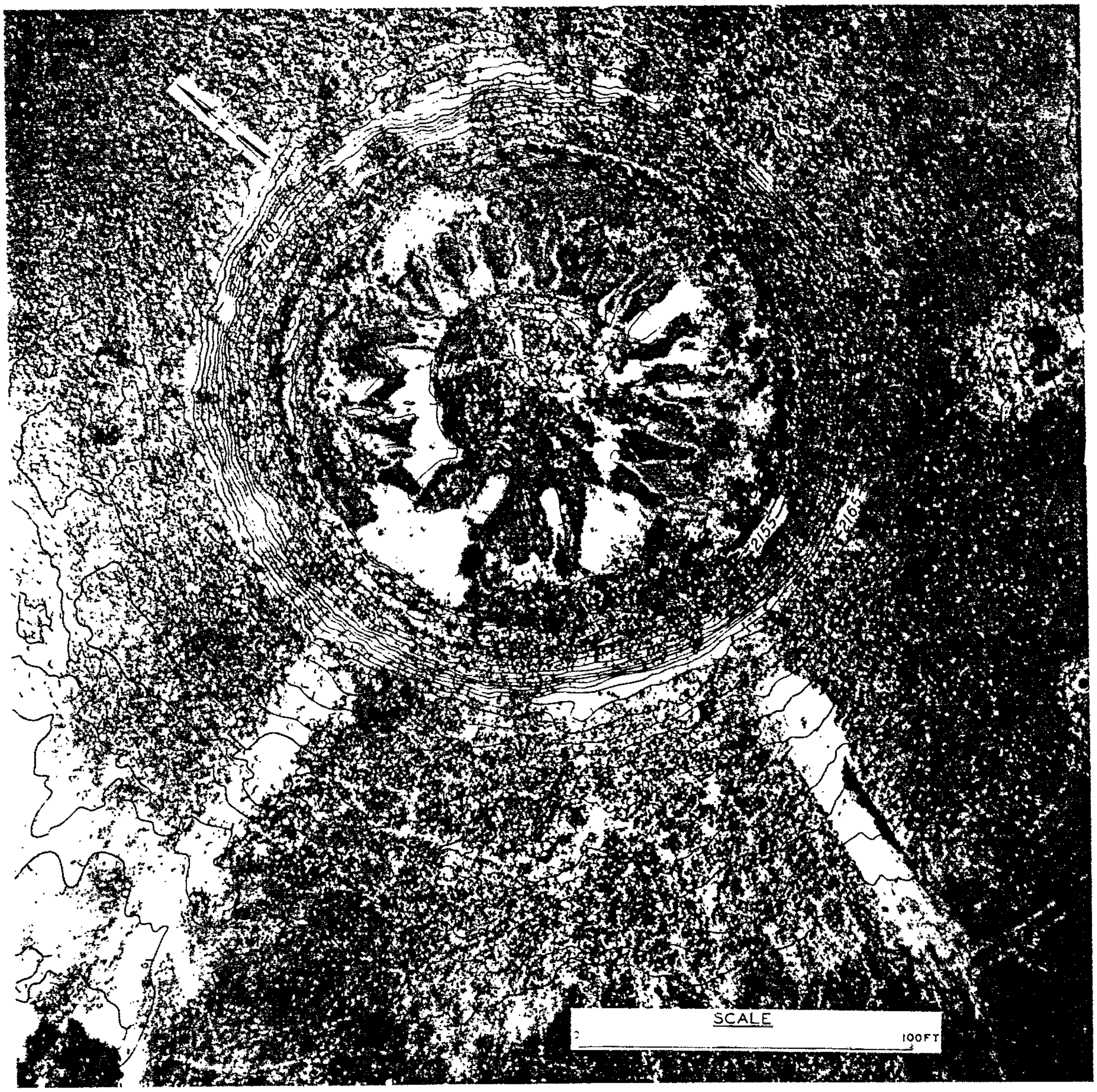


Figure 6/3
Vertical Aerial View of DIAL PACK Apparent Crater with Superimposed Countours
(after Rooke et al, 1972)

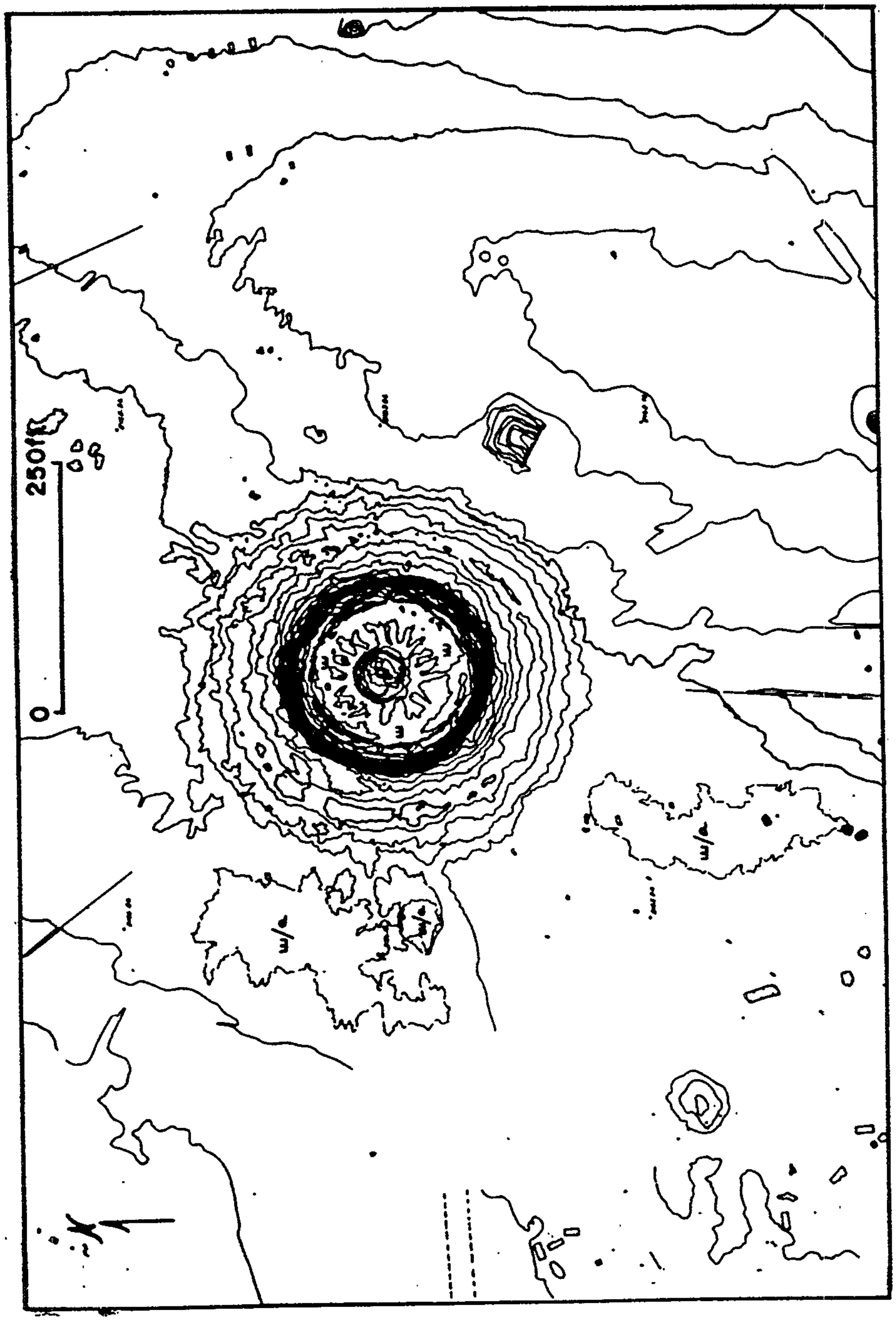


Figure 6/4

Topographic Map of DIAL PACK Crater with Contour Interval of 1 foot; and Label w/a = water/aluminum Deposition from Rim Fracture, and W indicates Lake in Crater (after Roddy, 1971) the external provinces of flooding and sand deposition, which correspond to the provinces shown earlier for the SNOWBALL crater. It is seen that the DIAL PACK crater is transitional between the PRAIRIE FLAT crater and the SNOWBALL crater, with the central uplift more pronounced than in PRAIRIE FLAT but less dominant than in SNOWBALL, while the ringed structure internal to the crater is more evident than in SNOWBALL but not as dominant as in PRAIRIE FLAT. The structural hierarchy appears to be in the sequence PRAIRIE FLAT, DIAL PACK, SNOWBALL, but at present there is not a full enough understanding to predict where a 500 ton crater will fall in the hierarchy.

The DIAL PACK crater also matched the PRAIRIE FLAT crater in the production of fused material, in the form of hollow spheres and distortions of that form. Roddy has shown that the fusion occurred at temperatures in excess of 1,100°C and probably nearer 1,500°C, both at DIAL PACK and PRAIRIE FLAT. No purpose would be served by illustrating the DIAL PACK material, as it was identical in appearance to that from PRAIRIE FLAT shown in Figure 5/11. Roddy points out that Duke et al (1970) have shown that the Apollo Lunar Sample 10084-79 contains material which at least visually is indistinguishable from the PRAIRIE FLAT and DIAL PACK material.

Rooke et al state they found, during excavation to define the true crater, evidence of a 4 ft high ridge of **overthrust** material approximately 118 ft south of GZ, that is under the rim structure, between the 95 ft radius apparent crater and the 155 ft true crater. This is in the location of thrust faulting mentioned in this region of earlier craters (but not the deeper thrust faults shown by the sand columns). Unfortunately the location is not more closely defined.

Figure 6/5 is a DRES photograph taken inside the DIAL PACK crater, looking across the central mound, which is some 45-50 ft in diameter. Note that although there is a small vent at the top of the mound, the main flow of water appears to have come from the trough surrounding the mound. No particular mapping of the vents appears to have been done, but as the U.S. Geological Survey files are said to contain some 1,500 photographs of this crater much more work is possible on archival material.

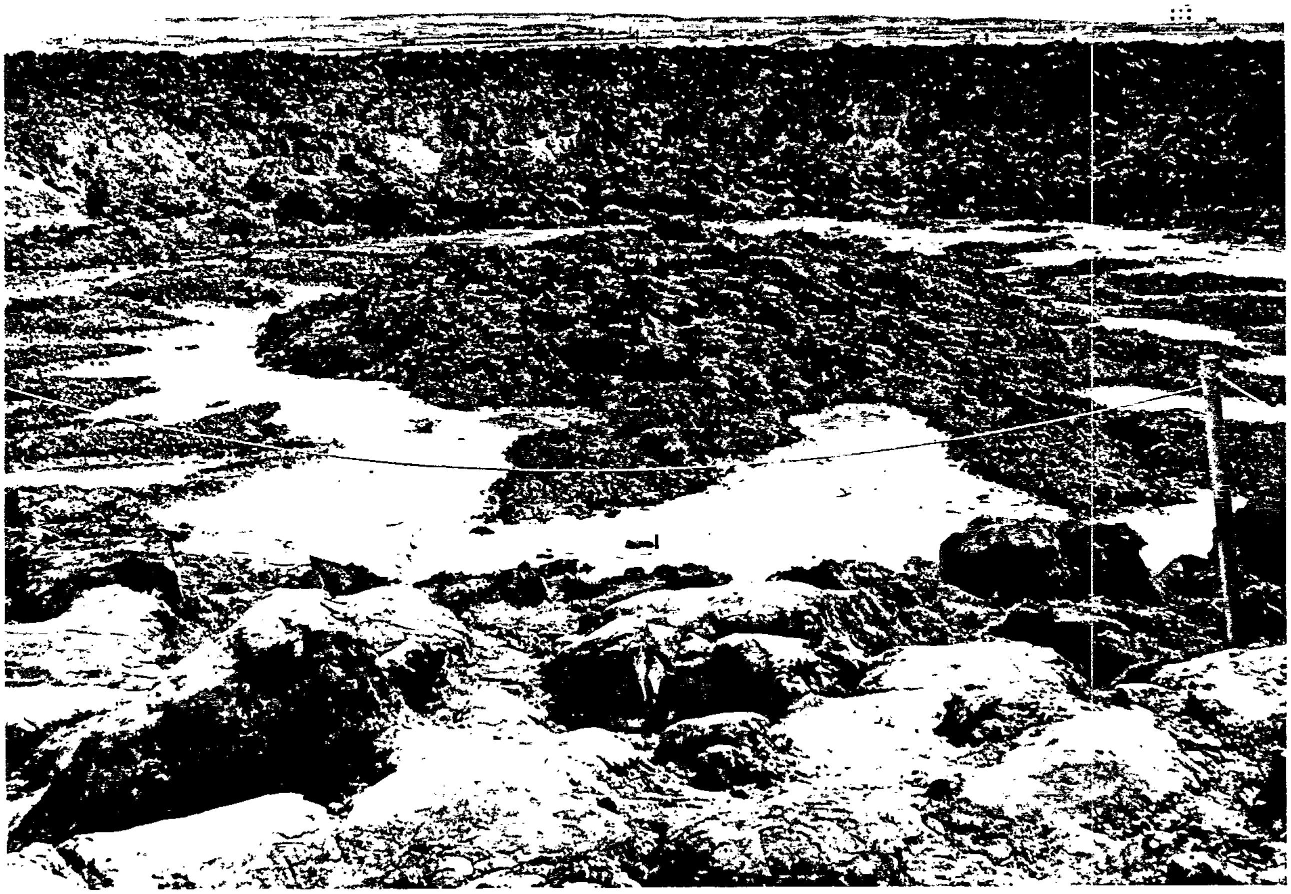


Figure 6/5
Interior of DIAL PACK Crater Looking Across Central Mound

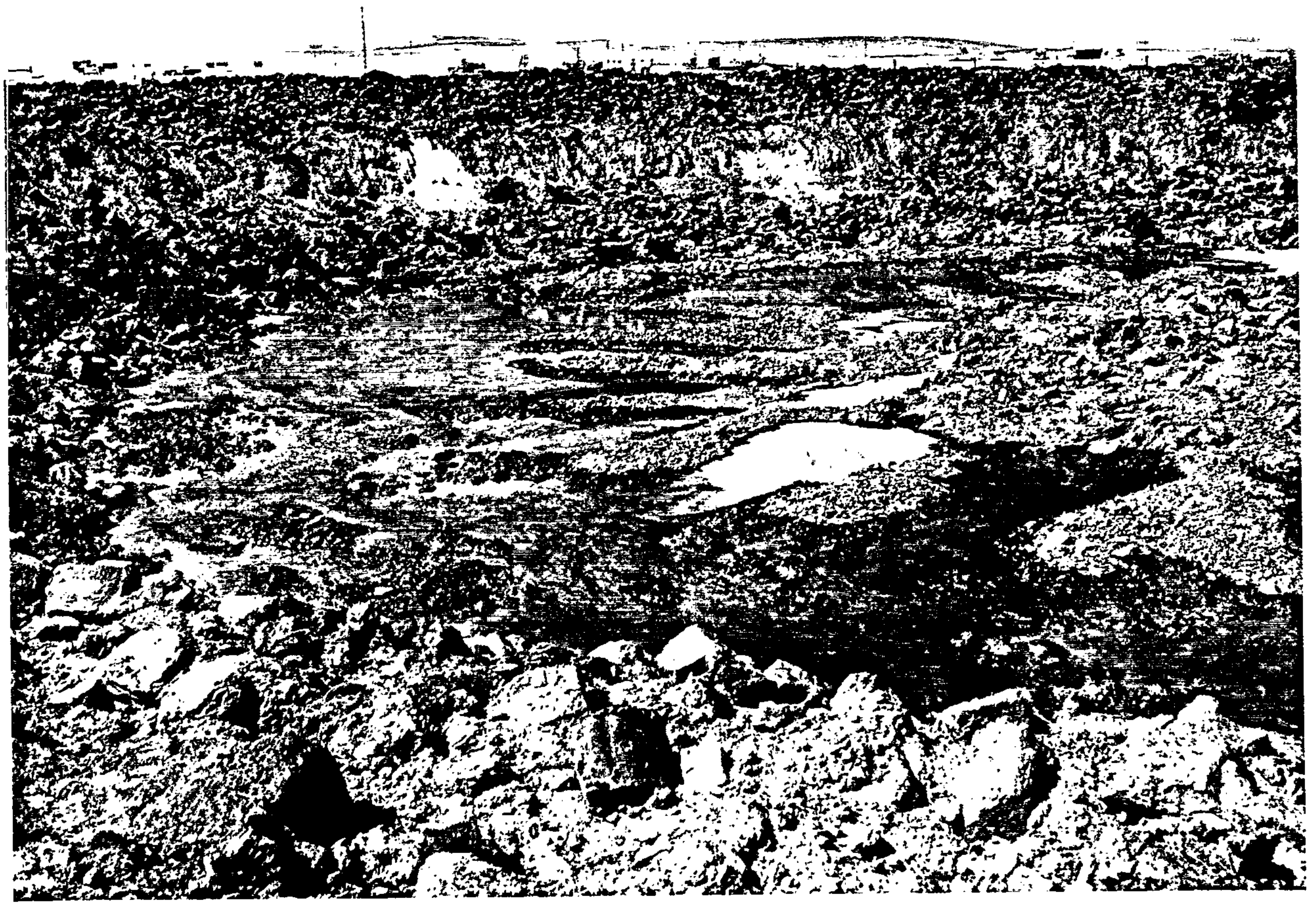


Figure 6/6
Outer Trench of DIAL PACK Showing Radial Ridges

Figure 6/7
DIAL PACK Central Area After Water Flow Ended

Figure 6/6 is a view at ground level across the outer trough of DIALPACK, when the ingress of water was almost stopped. It shows clearly the radial ridging, a feature not previously observed at Suffield. Note in particular the pseudo-volcanic cone, by this time quiescent, which is situated between two of the ridges. This may well indicate that the bottom of the inter-ridge trough contains a fracture system similar to the fracture in the circumferential trough of PRAIRIE FLAT (Figure 5/5). This may well indicate that the radial cracking on Snowball was not random, but controlled by a consistent structural formation.

A possible confirmation of the above is shown in Figure 6/7, of the central area of DIALPACK after the water flow ended. It will be seen that the traces of earlier flow leaving the central mound is evenly spaced along radial lines, and these tend to be directed in between the radial ridges external to the mound.

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CHAPTER SEVEN

STRUCTURAL ANALOGUES IN IMPACT STRUCTURES

7.1 INTRODUCTION

It will be appreciated that at the time of the Suffield trials man was at the dawn of the period of planetary exploration, despite centuries of telescopic study. In essence, the only extra terrestrial body whose surface morphology could be studied by optical means was the Moon. It was known that other planets had attendant satellites, but neither these nor their parent planet could be studied beyond the barest outlines. While it was obvious that the Moon was abundantly supplied with craters, it was by no means accepted that these craters were impact, rather than endogenous structures similar to volcanic caldera which were well observed on earth, if in limited numbers. Some structures on earth were enigmatic, and in general terms crypto-explosive, but barely a handful of these were considered to be impact craters. This is hardly to be wondered at when it is less than 200 years since even the reality of meteorites was accepted by the scientific establishment. Stones falling from heaven were classed as primitive myths. In geology, the doctrine of uniformitarianism had become a faith, and the theory of Catastrophe a heresy. It was held that all structures on earth could be explained by uniform action of processes, infinitely slow on the human time scale, but fairly rapid when viewed from the standpoint of geological time, especially as the accepted age of the earth was pushed back from the canonical 4004 BC to, initially 500,000,000 and then to the uncertain thousands of millions of years. It is an odd reflection that it was maintained that the lunar craters could NOT be impact craters, because the earth showed "no sign" of a similar bombardment.

Of course, proponents of the impact hypothesis, such as C.S. Beals, countered that the doctrine of uniformitarian geology itself precluded the obvious surface manifestation of ancient impact scars (vide eg, Beals & Halliday 1967) due to the continuous re-working of the terrestrial lithosphere.

It is not contended that the Suffield craters were a dominant factor in the awakening of the geological and astronomical community to the importance of the impact mechanism. The Suffield experiments merely coincided with a relatively sudden outpouring of papers by many scientists relating both terrestrial features and lunar craters to hypothesized impact origins. A selection of such papers from the decade concerned are listed in the general bibliography. The importance of the Suffield craters lies in the fact that they formed a set of well studied craters from known explosive events, which clearly demonstrated that the complex structures commonly used to counter the impact hypothesis could in fact be produced by surface explosions. In the remainder of this chapter some selected comparisons are made, primarily in connection with structures which had been denied acceptance as impact structures.

7.2 THE EAGLE BUTTE STRUCTURE IN ALBERTA

The Eagle Butte structure in the Cypress Hills of Alberta is of particular interest to the author. It was probably the first geological structure which was re-interpreted as a result of the Suffield crater studies. This anomalous structure lies at the head of the Eagle Butte valley, west of Elkwater and some 100 miles east by south of Suffield. It was first recorded, as far as can be traced by Dyer (1926), but was interpreted as being a "slump structure".

The historical development of this interpretation is well covered by Williams & Dyer (1930) and in extended detail by Russell & Landes (1940). As it exists today, it is a sub-circular structure about 10 km in diameter in Tp 8 & 9, range 4, west of the 4th meridian, to the north of Eagle Butte itself. The surface manifestation is sufficiently "crateriform" to have attracted the author's attention on his frequent trips along the Eagle Butte road, as the road cuts through the "rim" of the structure, and passes alongside what appeared to be a central uplift. However, study of the cited references made this interpretation appear improbable.

During the early stages of the excavation of the SNOWBALL crater, however, the discovery of the vertical sand dykes (such as Figure 4/34) recalled to the author that both Williams & Dyer and Russell & Landes had made reference to "vertical sandstone dykes" somewhere in the general vicinity of Thelma and Manyberries, quite close to the Eagle Butte structure. As by this stage the Dominion Observatory Ottawa had staff on site at Suffield, the author prevailed upon Mike Dence to have a look at the Eagle Butte structure. Although the reputed sandstone dykes were not located, Dence after a limited field study confirmed the author's opinion that the structure was almost certainly an impact crater. The photographs taken by Dence on that trip are included in the relevant addendum to this report. It is interesting to note that while the Eagle Butte structure is not included in the listing of probable impact craters in Beals & Halliday (1967), it is listed by Dence (1972) as a possible with a diameter of 10 km, and by Robertson & Grieve (1975) as a "probable", and suggest an age of 30-40 million years BP.

Without reference to "slumping" Robertson and Grieve, in the cited paper, note that "Previously, high angle thrust faults producing repetitions and cutouts have been inferred to account for these structures" (ie. Eagle Butte and two other similar Prairie structures).

In the preparation of the correlated effects discussed in the earlier chapters of this report, it became apparent that the remembered details of Eagle Butte were quite closely matched by several features recorded at Suffield. Despite the fact that Eagle Butte is now, as shown above, accepted as an impact site it is worth reviewing the analogies that are now recognizable, in terms of the Suffield data and the data of Williams & Dyer and Russell & Landes, recalling in doing so that the cited authors interpreted the structure as a slump feature, in a period before "impact theory" became respectable.

Clearly, in discussing the structure the above authors restricted their comments on the structure to the "inside" of the structure itself, and at no time relate the sandstone dykes to the structure. As their discussion is based on the slump hypothesis, it is interesting to note that they record thrust faulting in a location essentially under the "rim" of the structure considered as an impact crater. The location is in a (then) working mine, in which the coal seam is some 6 ft thick. Quoting Russell & Landes:

"On the working face of the mine the writer observed typical thrust faults, the direction of which indicates movement from the south".

Note that this is, in effect, radially outward from the center of the Eagle Butte structure, that is ground zero if it is an impact structure. Later Russell & Landes comment, "There is distinct evidence of thrusting movements in the coal mine. Thrust faulting, however, is not the explanation (ie. of the structure) for the overthrust beds are much below their normal position, not above it, as thrusting would require...the remaining possibility is large scale slumping..."

The above picture may now be compared with, for example, the data from SNOWBALL. Not only is there thrust faulting recognized in approximately the equivalent position, but at SNOWBALL the survey shows that the beds are significantly lower than the "normal", that is pre-detonation position, due to the very large "saucer" depression which surrounded the crater proper. Thus, one would record overthrust beds, lower rather than higher than the undisturbed level.

Far more interesting than this isolated observation is the question of the sandstone dykes. It is emphasized that the earlier workers never made any connection between these dykes and the Eagle Butte structure, and discuss them in isolation. The fullest discussion is in Williams & Dyer, and appears so relevant that extensive quotation is required. Some minor omissions and paraphrasing exist.

Williams & Dyer (1930)

Sandstone intrusives cut the Bearpaw formation from top to bottom, in an area of SE Alberta south of the Cypress Hills.

At the first locality a small irregular dyke cuts a lignite seam at the top of the Pale Beds, and also the overlying Bearpaw shale. The sand of the dyke is so similar to the sand of the Pale Beds, which outcrop nearby, that it seems certain that the sand from the lower formation has been forced into the overlying shale in the form of dykes.

At the second locality, numerous light grey sandstone dykes occur...cutting dark grey Bearpaw shale. They are generally under 1 ft thick, stand nearly vertical, and run in various directions, cutting one another in a complicated manner....The third location is at the base of the Fox Hills section on Willow Creek below Thelma (Ed note..ie. immediately south of the Eagle Butte structure).

In a 140 ft cutbank...about 100 ft of the Bearpaw shale is exposed below about 30 ft of Fox Hills sandstone. Several vertical dykes about 6 inches thick cut the Bearpaw shale, but terminate sharply at the base of the Fox Hills sandstone. Nearby, nearly vertical dykes of small size converge upward and widen out abruptly into a mass of sandstone about 40 ft in diameter and about 40 ft high. This is bevelled off...but the intrusive probably extended originally to the base of the Fox Hills sandstone. The convergence of the feeding dykelets from below, their irregular penetration of the Bearpaw shale, and the lack of connection...with the overlying Fox Hills sandstone leads to the conclusion that the intrusion was from below. For about a one mile down Willow Creek, small sandstone dykes cut Bearpaw shale, to an horizon about 200 ft below the top of the formation.

...it is logical to assume that they have cut the Bearpaw shale from the bottom to the top...The time of deposition is limited to the short interval between the deposition of the Bearpaw Shale and the near-shore Fox Hills sandstone...similar sandstone dykes are known, and those of similar character are recognized as being intrusions from below and **resemble dykes formed by gushing springs following earthquakes** at Calabria (1793), New Madrid (1811-13), Valparaiso (1822) and Sonora (1887).

The emphasis given above is by the present author. Clearly, Williams and Dyer considered the case for intrusion from below, by gushing springs following upon a catastrophic event well proven by their field analysis.

Their description, quite clearly, is of an event directly comparable in all the main characteristics with the "pseudo-volcanism" on the Suffield craters, but with the added interest that the materials involved are identical, and similarly water deposited, rather than volcanic intrusions. Thus it would appear that an impact large enough to create the Eagle Butte structure, in the comparable prairie stratigraphy, is **directly modelled** by the Suffield 500 ton detonations.

One is tempted to leave it at that, but unfortunately Russell & Landes seem to reject the arguments of Williams & Dyer. In doing so, they base their argument on a factor which has, oddly enough, caused controversy on the Suffield trials. Again, it is necessary to quote the earlier workers.

After a discussion of the provenance and characteristics of the dykes essentially similar to that of Williams & Dyer, they urge rejection of the hypothesis of formation from below on several grounds.

Russell & Landes:

"Against this view (ie. of penetration from below) the writer would urge the following observation":

i. The dykes are confined to a single type of sediment, the non-plastic Bearpaw and Eastend formation. They terminate on reaching the plastic or sandy sediments. **Such restricted distribution seems inexplicable by the forced up from below hypothesis** (Ed Note. The emphasis is editorial. We know that on the Suffield trials the dyke material unequivocally did penetrate from below, did form surface deposits, and did not penetrate the strata as sills).

ii. The material of the dykes is not very similar to the sediments of the Oldman formation, which are predominantly plastic clays which might be expected to form a semi-fluid mass capable of being forced up. Instead the dykes consist of highly siliceous non-plastic materials (Ed Note: The underlying strata at the Suffield sites are plastic blue clay, nevertheless, the dykes were pure sand, derived presumably from relatively thin, water bearing strata).

iii. The base of the dykes that are exposed to the bottom terminate in a wedge shape, and do not show derivation from the underlying sediment.

iv. Some of the dykes, if derived from below **would have to be forced through hundreds of feet of sediment, over 800 ft in the case of the dyke on Willow Creek.**

The above emphasis is by the present author. It is of interest to note that this objection is precisely that made at Suffield to deny the transport of material from considerable depth at DISTANT PLAIN 6 (and other) locations.

Russell & Landes then proceed to suggest that the dykes are actually fissure fillings from above and the side, introduced in late Tertiary times.

The present author concedes that the third objection, the wedge shaped termination of the base of the dykes, can not be countered at this time. No photographic evidence of the basal formation of the Suffield dykes has yet been located in the archives. However, all three of the other objections are clearly shown to be false by the Suffield data, where it is quite certain that the dyke material filled the fissures from below, and in some cases may actually have created the fissures. As to the fourth objection, the apparent great depth of the dyke penetration, attention has already been drawn to a similar controversy at DISTANT PLAIN 6 and PRAIRIE FLAT...**That question must still remain open.**

The relative positioning of the dykes on Eagle Butte and the Suffield trials must also be considered. Williams & Dyer's third location, showing a clustering of the dykes, is at the base of the Fox Hills section on Willow Creek below Thelma. It is observed that this location, treating Eagle Butte as an impact crater, is between five and ten km from the rim of the crater, possibly closer if one allows for the present distorted circularity of the structure. That is to say, roughly twice the radius of the crater rim from the Ground Zero of the impact. This places the cluster of dykes almost exactly in the same relative position as the dykes excavated on the SNOWBALL crater.

The other locations on Eagle Butte are marginally further away, but it is clear that they would be well within the zone of surface fracturing of the Suffield crater.

Of course, the time of formation of the dykes is critical, as we know that at the Suffield trials the dykes were formed during the first week after formation of the craters. The time scaling involved in a larger scale geological structure is uncertain, but it is fair to assume that if the causes are similar, then the dykes at Eagle Butte should have been formed in a relatively short time of perhaps a few years.

As the correlation of the dykes to the structure was not made by the earlier workers, this time relationship was obviously not considered, and there is gross uncertainty about the age of both the dykes and the structure itself. Russell & Landes, of course, considering the process of dyke formation to be purely a discrete geological process, place the formation time between that of the deposition of the Bearpaw shale and the Fox Hills sandstone, at the start of the Laramide revolution, roughly the three quarter point of the Cretaceous.

The age of the Eagle Butte structure is itself unknown, but Robertson & Grive suggest that it is some 30-40 million BP, but do not explain that suggestion.

The present author has no specific information to counter the above estimates of age, but is of the opinion that the Eagle Butte crater - as it may now be called - is not as old as assumed by Robertson & Grieve, and that the sand dykes are roughly contemporaneous, following almost immediately, in terms of geological time, the formation of the crater. The existing crater structure lies in the Eagle Butte Valley, probably a Pleistocene erosion channel, in an area which before the erosion by ice and by meltwater had a cover of at least several hundred feet of upper Cretaceous rock. It appears unlikely that a 30-40 million year old crater in that location should emerge from the erosion still exhibiting a crateriform surface morphology.

It is suggested, without specifying an actual age, that the Eagle Butte crater is comparatively young, and that the sandstone dykes in the area were emplaced rapidly, soon after and as direct consequence of the impact. No doubt, a detailed study of the crater with the more modern understanding of impacts would resolved the issue.

Russell & Landes also makes one - almost a throw away - comment about the Eagle Butte structure which appears relevant. Discussing exposures at a point roughly on the south rim of the structure "The north western peak of Eagle Butte is underlain by Whitemud beds, undoubtedly in place and at an elevation of about 4,260 ft". Immediately north of this point is a deep coulee, and on the north side of this Whitemud beds, obviously disturbed, occurring at an elevation of 4,100 ft. Closer examination of the north slope of the coulee reveals small outcrops of Whitemud beds, **in one case completely overturned.**

Note that this overturned bed occurs exactly where, on the Suffield trials, overturned flaps becomes evident.

An interesting paper by Sawatzky (1976) also lists Eagle Butte Structure as a "probable" impact site, and discusses it in conjunction with four other structures in the "Williston Basin". The discussion is mainly in terms of well drilling logs, and the electric-log section of the Eagle Butte structure clearly shows that the central uplift is structural. The paper also contains a structural contour map of the Eagle Butte crater, on the base Fish Scales horizon. The contour map shows circular contours out to some 10 km from the central uplift high, that is out to beyond the areas known to contain the sandstone dykes. The data also indicate "considerable faulting and repetition of section". Sawatzky also points out the significance of such structures as potential repositories for commercial quantities of hydrocarbon accumulation. Of the five structures discussed, two have resulted in commercial production of oil while others including Eagle Butte show interesting oil and gas levels. The age is suggested as "possibly Tertiary".

7.3 A DISCUSSION OF OTHER IMPACT STRUCTURES AND PUBLICATIONS

A variety of other structures have, over the years, been compared with the Suffield craters. Although some time has been given to considering the Eagle Butte crater, it does not appear necessary to include equally detailed discussion of many other sites, as much of the material is already in the public domain. Particular attention is drawn to the book **Impact and Explosion Cratering - Planetary and Terrestrial Implications** (Pergamon Press 1976) which is essentially the proceedings of a symposium on planetary cratering mechanics held at Flagstaff, edited by Roddy, Pepin and Merrill. The book contains some 66 papers, of which 17 make direct use of or reference to the

Suffield Craters. Many of the other papers are of relevance to the interpretation of Suffield craters even though no direct reference to them is made. These, incidentally, include the above quoted paper by Sawatzky on the structures in the Williston Basin.

Attention is also drawn to the discussion in Jones (1976) a limited distribution report which is in the public domain. This is now essentially a period piece reflecting the then-current speculations, but its detailed study of SNOWBALL is to some extent a precursor to the present text. The paper lists 71 references to papers and reports which appeared relevant at the time of writing.

In the following, discussion is limited to some structures which still appear relevant, and to "open" papers directly making use of Suffield crater data.

Early releases intended to draw attention to the planetary significance of the Suffield craters were made by Jones (1964) and by Roddy, Jones & Diehl (1969), and in introductory remarks by Jones in Hope's translation of Sukhanov (1968), all of which released certain photographs of SNOWBALL and PRAIRIE FLAT, but have little relevance today.

Of greater interest is a comparison of the SNOWBALL crater with the Great Ashanti, or Bosumtwi crater in Ghana, by Jones (1965), the main feature of which is the overlay repeated herein as Figure 7/1 of the SNOWBALL fracture pattern on the drainage pattern around the Bosumtwi crater. This correlation is discussed in the previously cited review Jones (1976), as well as in the cited reference. No additional comment appears necessary today.

As has been indicated earlier, the excavation of the SNOWBALL crater resulted in cooperation by the U.S. Geological Survey Branch of Astrogeology, in the form of on site work by David Roddy. At the time Roddy was preparing a doctoral dissertation on the Flynn Creek central uplift structure in Tennesee. While this structure was already being recognized as an impact crater, the recent experimental evidence for the creation of central uplift structures by surface explosions was of paramount importance. As a result, Roddy visited and worked on the SNOWBALL crater in direct

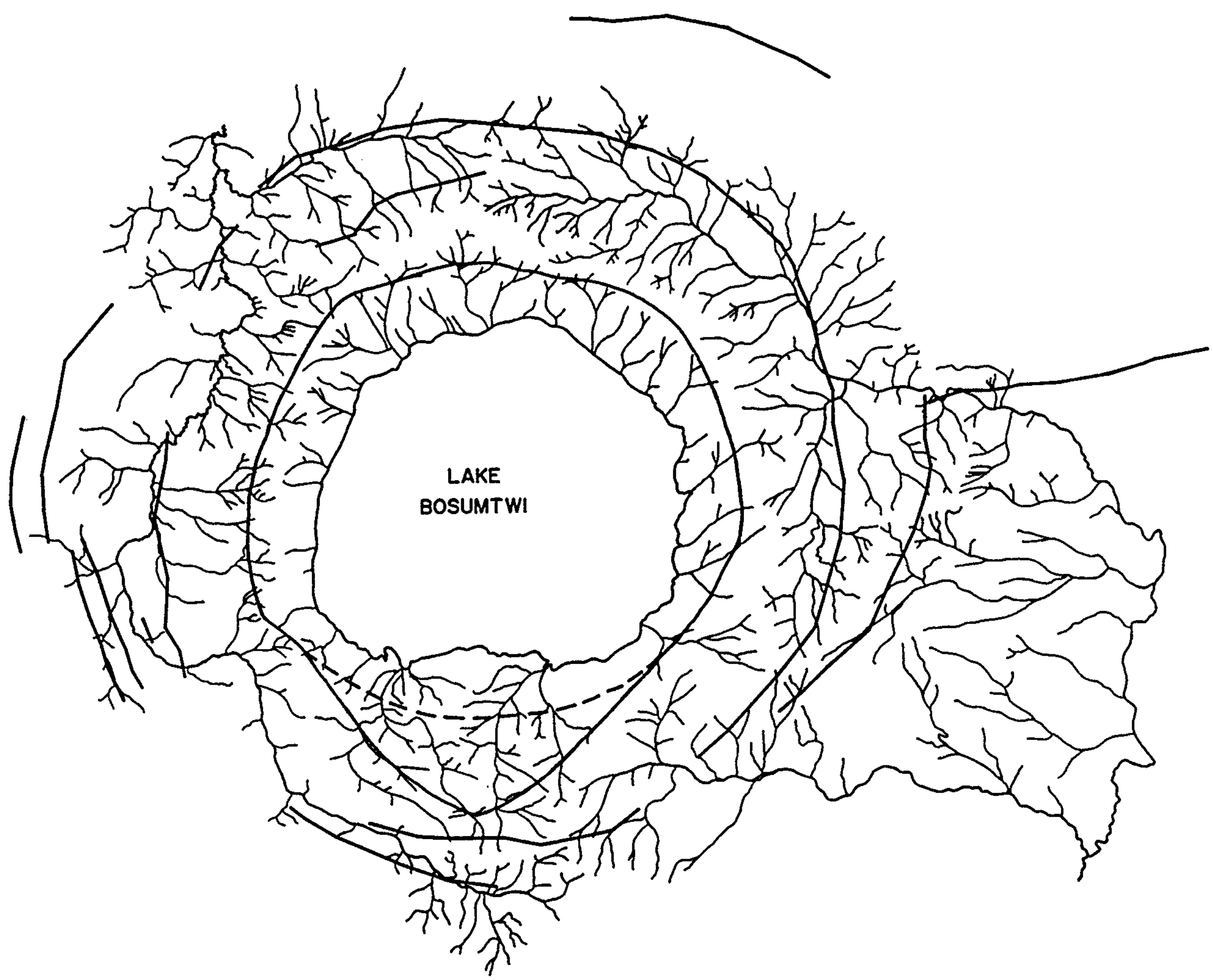

Figure 7/1
SNOWBALL Fracture Pattern and Bosumtwi Drainage System

relationship to his Flynn Creek studies. Thereafter, he represented the U.S. Geological Survey Branch of Astrogeology at all the later Suffield explosions. While his geological analysis of the ejecta blankets were of primary concern, he was closely associated with the Suffield crater study team, and was supported by the Suffield staff in the actual field work. This resulted in a spate of papers, of which Roddy (1966 a & b), Roddy (1968 a & b & c), Roddy (1970), Roddy (1976), Roddy (1977 a & b) and Roddy, Ullrich & Jones (1977) are all of direct relevance to the present text. In addition, Roddy (1967) is a summary of the Suffield experimental cratering studies. Some other papers are listed in the bibliography, having been cited elsewhere in this text. The cooperation between Roddy and the present author continues.

Close cooperation also existed between the author and Prof. N.J. Price, who was instrumental in bringing the Suffield craters to the attention of a wide audience, and also in drawing the author's attention to a variety of significant effects which might otherwise have been missed. Two early papers, Price (1975) and Price, Norman & Chukwe-Ike (1977) attracted attention to some of the wider implications, while use was made of Suffield data in the ICSU Committee report on Nuclear Waste Disposal (Price, Fyfe et al 1984). At a later stage, part of Chapter 4 of the book Price & Cosgrove (1990) depended upon the results of the Suffield crater studies.

Particular attention is drawn to Seeger (1968) and Black (1964), which relate to the Versailles crater in Kentucky and the Jeptha Knob structure, also in Kentucky. The present author was escorted to each of these by the cited authors, and they proved to be of considerable interest, despite the fact that neither was visually impressive. The principal interest lies in the fact that these structures are remarkably small on the terrestrial scale for central uplift structures, being only a few thousand feet in "lip" diameter. They contain not only clear central uplift structures, but also circumferential folds and faults, quite similar in location and morphology to those found on SNOWBALL, PRAIRIE FLAT and DISTANT PLAIN 6. It is also of particular interest that the underlying rock in each case is essentially a carbonate rock, which is considered capable of producing high pressure gas flows under impact conditions. It does appear that some form of endogenous fluidised material (gaseous or liquid) is a common factor in the production of central uplift type craters. The "fluid" may be water, as in the case of the Suffield craters and Eagle Butte, gas as in the relatively small Versailles and Jeptha Knob, or liquid "melt", either directly formed by the impact or resulting from lithostatic stress release by the formation of the crater void, as may apply in large scale Terrestrial (and possibly Lunar) craters. This remains a speculative, unproven hypothesis at the present time. It is perhaps of interest to note that the apparent need for some form of fluid injection has been cited as a reason for treating some central uplift structures as due to cometary impact rather than the impact of a solid object. Crooke (1967) went even further and suggests that at the Gosse's Bluff ringed structure in Australia the impact was not merely that of a comet, but that cosmic ice, or the vapour there from was actually injected.

In the years since the Suffield experiments, information on the surface structures of extra terrestrial bodies has become voluminous, and technology of mapping now in use at the U.S. Geological Survey Astrogeology Branch makes the surface based technology used at Suffield appear quite elementary (though probably considerably cheaper!). It would be of considerable value to have a study of the Suffield craters produced using the modern interpretive technology so that a direct comparison could be made between the Suffield central uplift craters and some of the extraterrestrial structures.

However, even in the 60's some interesting comparisons could be made. A paper by Shotts (1968) is directly relevant as it deals with pseudo-volcanism in the vicinity of the Copernicus crater. The objective of the paper is to consider the possibility that the large number of "aligned" small craters visible in the region of the ejecta blanket may have been produced by the release of volatiles. Shotts uses the basic mapping of Copernicus published by Shoemaker (1962) but discusses the data from a different viewpoint. It appears that in the case of Copernicus, at least at the stage of mapping then available, the majority of "alignments" of small craters consisting of three or more structures were radial to the main crater, inside the ejecta blanket. However, a considerable number, including some of the longest chains were circumferential. The majority of the aligned craters appear to occupy rifts, rills, or clear depressions...presumably corresponding to the crack pattern found near the Suffield craters. Shott suggests that the aligned craters were formed largely by exudation of volatiles along crustal cracks, and most of them must have formed within a short time after the impact. This conforms to the present author's comments on the experimental craters and some of the terrestrial impact craters, provided only that the term Volatiles is extended to read "Fluid", and allowance is made for the possibility that the normal "fluid" is endogenous rather than an exotic injection.

It may be deduced directly from the experimental data that in the case of a large terrestrial impact there is a probability that there will be a post-impact intrusion of dykes of material essentially different from the country rocks intruded, with probable fractionation of the fluidised material. Whether or not such intrusives would result in significant mineralization of provinces adjacent to a large impact is a moot point, but this is at least a strong possibility.

Attention is now drawn to one of the largest, and most controversial structures on earth, the Vredefort complex in Southern Africa. Even today, when the reality of impact structures on earth is well accepted, there is a school of thought, particularly among South African geologists, which denies an impact origin for Vredefort. For example, du Toit (1966) claims that the structure is due to purely tectonic forces, excluding "the fantastic view of meteorite impact proposed by Daly".

Figure 7/2 is map of the structure, derived from the maps of the South African Geological Survey. The central dome is some 50 km in diameter (or larger, depending how one terminates the mound), while the general circularity extends out to at least 150 km from the center. Comparison of Figure 7/2 with the earlier photography and mapping of the Suffield craters will be sufficient to explain the present author's conviction that the structure is an impact structure, or astrobleme to use Dietz's term.

The probable impact origin of the structure has been emphasized by, among others, Dietz (1960, 1961, 1962 & 1963) and by Hargraves (1961 and elsewhere). Grieve (1982) discusses the existence of Shatter cones in the complex, the majority of which indicated a single, central origin for the pressure wave, despite a few anomalies pointed out by Simpson (1981). Grieve reiterates his view that the Vredefort complex has an impact origin.

During a private visit to South Africa in 1993 the present author took the opportunity to visit the structure, traversing the structure along two more or less radial lines, with the map of Figure 7/2 in hand. Obviously, no detailed study could be undertaken during a short visit, but the obvious similarity of the structure to the known morphology of central uplift craters appeared quite striking. Particular attention is drawn to the central granitic dome and the internal trough abutting onto the coherently overturned rim structure. The very large external cyncline is NOT well matched by the Suffield data, but is not inconsistent and attention is drawn to the location of the "Western Ultra Deeps" bounding the ridge of the Far West Rand. This is, approximately, in the relative position of the main fracture pattern circumscribing the SNOWBALL crater. Note also the generally circularly symmetric positioning of the Upper Witwatersrand and the Gatsrand ridge.

An interesting, but possibly quite irrelevant observation was made near the small town of Vredefort itself. Despite the fact that the impact origin of the main structure is usually denied in the area, a sign draws attention to a small lake as being a "Meteorite Lake". While it certainly is NOT a meteorite crater, it was noted that this small lake corresponds in position to that of the main vent in the central uplift at SNOWBALL. The actual lake is in the granitic rock, and is bounded by sub-vertical granite walls. If the rock had been carbonate, the lake would approximate to a Cenote, or sink hole, but actually appears to occupy a void in a complex fracture system. Oddly enough, alongside the steep rim of the lake there is a sedimentary deposit which contains a variety of shells. Unfortunately, it did not prove possible to obtain any information on

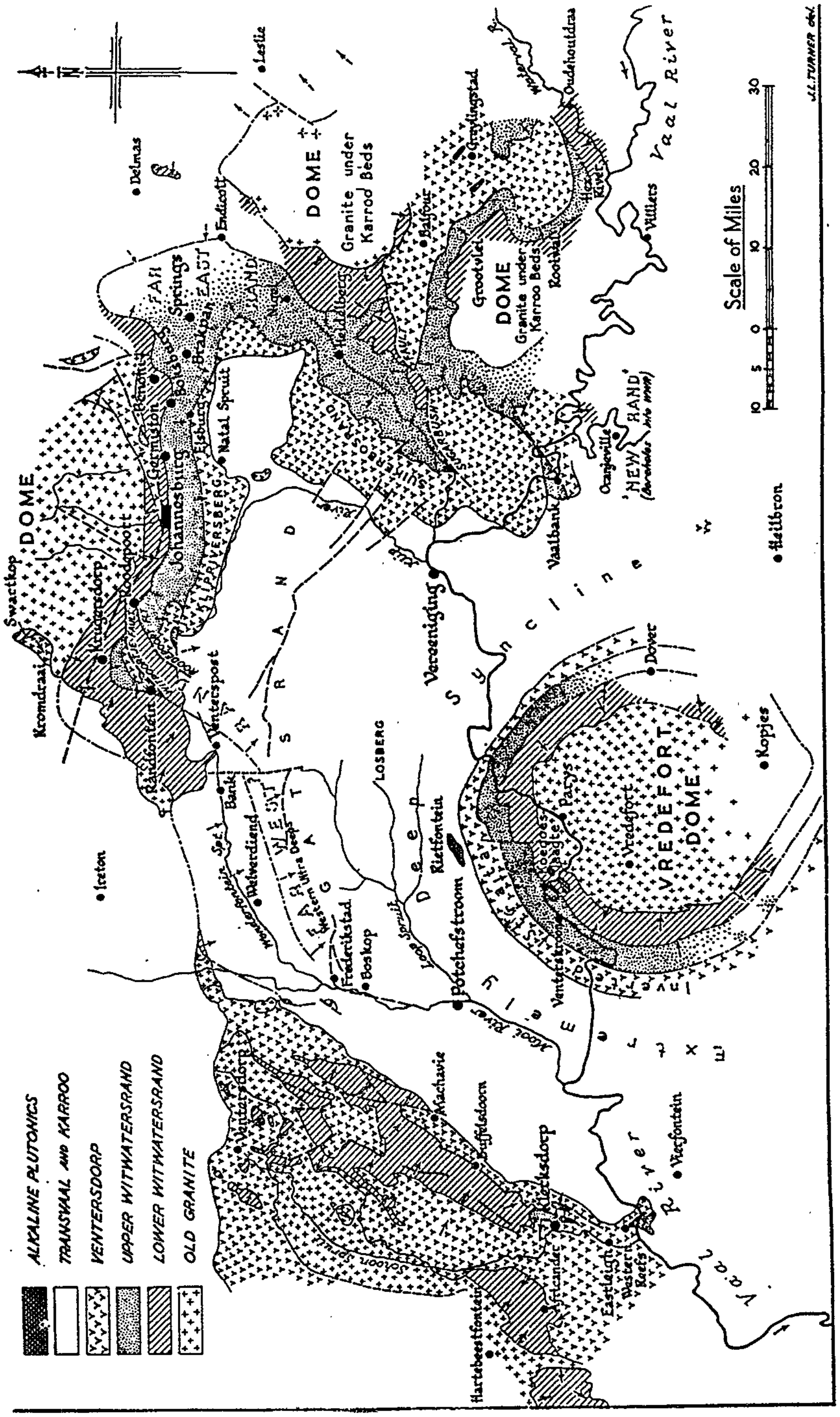

Figure 7/2

Map of the Vredefort Structure in South Africa a geological study of this feature. The location was intriguing, but not too much should be made of that.

Photographs taken during the author's traverse are appended to this report without further comment (Addendum to Chapter 7).

The theory of the impact origin of Vredefort is confirmed not only by the occurrence of shatter cones, but also by discovery of both Stishovite and Coesite in the rocks of the central uplift, as reported by Martini (1978).

A rather similar situation exists in Canada where a significant ore body is associated with a proposed impact structure. This is the Sudbury Nickel and copper ore body, which Dietz (1964) interpreted as based upon an impact crater, originally some 30 miles in apparent diameter, formed by an impacting bolide some two miles in diameter. However, the size of the hypothetical bolide is dependent upon assumptions about its composition and original velocity. Dietz appears to think in terms of a sulfide body which struck at, relatively speaking, a low velocity. Dietz reports the finding of shatter cones at Sudbury, and states that Hargraves concurs in this, and that they were similar but smaller in scale than those discovered at the Vredefort complex (Hargraves, 1961). At a later date Bevan French (1972) reviews the existence of small scale shock metamorphism in a variety of minerals and locations at Sudbury, confirming the probability that it is an impact structure.

The Suffield Geophysics section was involved in a variety of high explosive trials away from Suffield, including the Stagecoach Trials at the Nevada test site, certain American HE trials on hard rock, some of which produced shatter cones (reported by Roddy), the Ripple Rock demolition, and the single off-station explosion in the DISTANT PLAIN series, DISTANT PLAIN 4, also known as the Blowdown Trial, at the 50 ton level in a northern forest at Hinton, Alberta. All such trials have been reported in a variety of technical notes, but are not directly relevant to the study of impact structures other than for the production of shatter cones, which do NOT occur at the Suffield craters due to the nature of the cratered material.

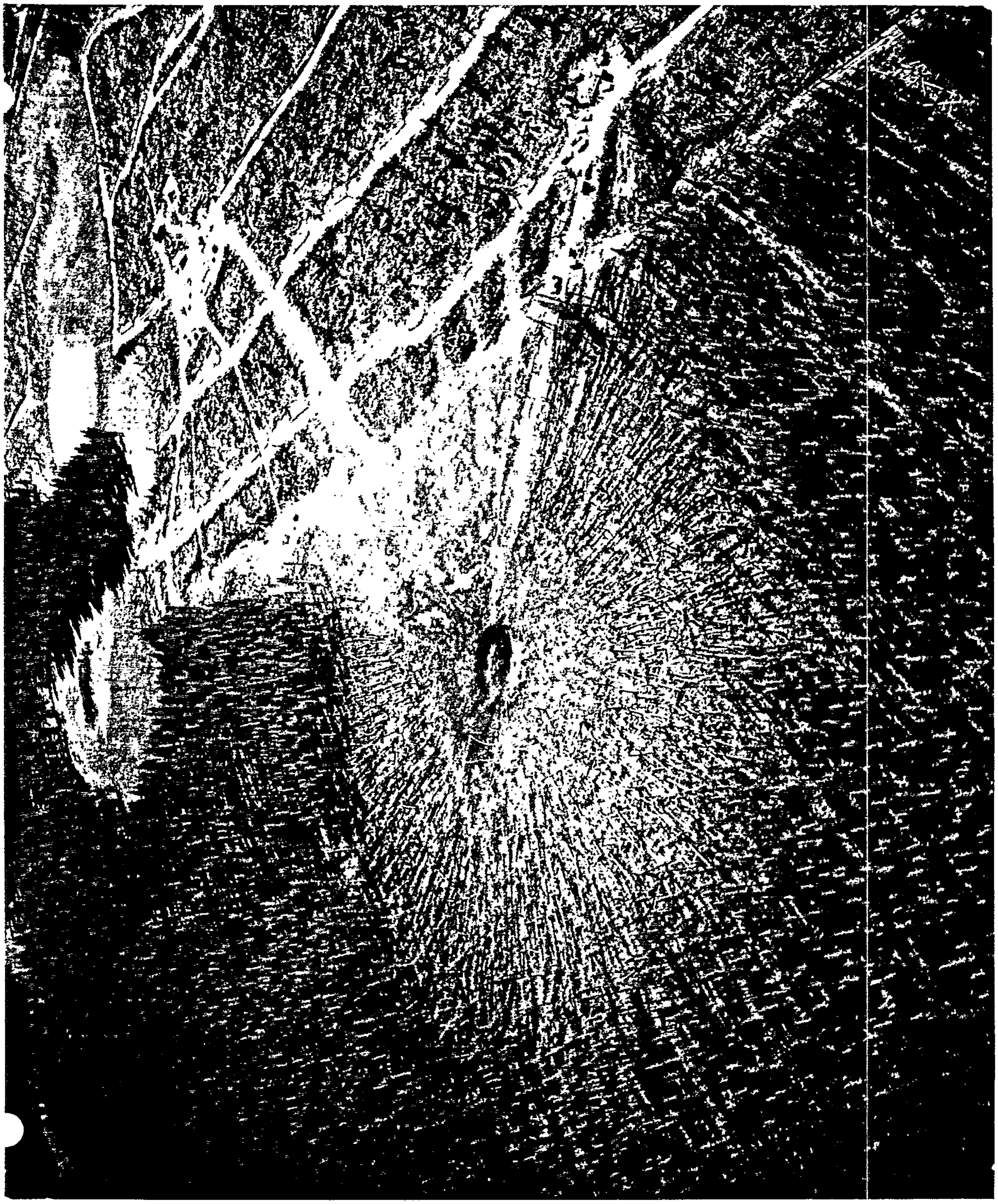

Figure 7/3
Aerial Oblique of DISTANT PLAIN 4, (50 Ton Blowdown)

The Blowdown DISTANT PLAIN 4 trial, however, at the 50 ton level, while it produced a rather uninteresting crater (Figure 7/3) is of significance in the study of impacts due to the similarity of the forest blowdown to that produced by the Tunguska event in Siberia. For the present purpose, it suffices to say that the comparative photograph has been placed in the public domain by Jones (1977 a & b) and additional material is contained in the relevant addendum of archival material associated with the present publication.

7.4 CONCLUDING REMARKS

In summary, it may be said that the Suffield craters exhibit a hierarchy in their morphological features, which parallel those found on much larger planetary structures, and whose existence on craters of known explosive origin support the hypothesis that the planetary structures are the result of meteoritic impact.

Essentially, the dominant features in the hierarchy include:

At the 20 ton level, basically dry, bowl shaped, elevated rim structures, some of which exhibit thrust faulting both below the rim and rarely deeper thrusts which breach the surface at about twice the radial distance from the center to the rim. No evidence of coherent overturning of the ejecta was noted at this scale, but some of the craters exhibit circumferential ring folding external to the crater.

At the 100 ton level, though there are variations depending upon the precise charge configuration, the craters are essentially similar to each other and exhibit:

a) entry of sand laden water into the crater void within 30 minutes of formation.

b) structural central uplifts, which may occasionally be masked later by pseudo-volcanic cones.

c) distinct evidence of thrust faulting under the rim.

d) some evidence, but not always conclusive, of a coherently overturned ejecta blanket on the rim. Certainly, there was overturning of the strata, but the coherence of the overturning was merely probable, not certain.

e) there was a tendency, certain in one case, for the formation of a sharply folded anticline immediately below the rim. All the crater rims were elevated at this scale, similar to that found at the 20 ton scale.

f) in one of the three 100 ton craters, there was conclusive evidence of circumferential "ring" ridges and, in all cases, of circumferential and radial fissuring, though the fissures remained sealed and there was no evidence of external pseudo-volcanism.

At the 500 ton level, all the craters were complex, and there was gross similarity among them. However, there were also quite distinct differences in the final morphology even though all morphologies appeared to relate to similar causes. In fact, the 500 ton craters themselves form an illuminating sub-hierarchy, though in a logical sequence from the 20 ton and 100 ton craters.

In Type A (shown by PRAIRIE FLAT) a ringed structure was formed, in which the internal and external rings, though obviously at quite different final levels, consisted of synclinal-anticlinal concentric folds. Inside the crater, the rings locate series of pseudo-volcanic cones, which appear to relate to en-echelon fractures in the ridges, or a concentric ring fracture in the intervening trough. This "pseudo-magma" was sufficient in quantity to convert the original inner ring into a "volcanic" dome simulating a central uplift, though this would not be obviously structural in the sense of uplifted and folded strata, as seen on the 100 ton trials and on other 500 ton trials. There is no elevated rim structure, but a general shallow depression of the surrounding strata. There is evidence of external circumferential and radial fissuring of the ground, but these fissures do not open and do not become locating structures for pseudo-volcanism, which was absent external to PRAIRIE FLAT, at least as a major feature. Thrust faults are evident high under the rim, but there is also evidence from the numerical sand column data of deeper thrust faults. The evidence from the surface is minimal, if there at all, but the sand columns indicate a potential breaching at twice the rim radial distance.

Type B (shown by DIAL PACK) is again a clearly "ringed" structure, internally and externally. However, in this case the small inner ring at the center of the crater is replaced by a broad shallow structural dome. Pseudo-volcanism internal to the crater follows the broad pattern seen in Type A, but is somewhat confused by the existence of a set of radial ridges and hollows which cross the circumferential ridges. These radial ridges exhibit the same synclinal-anticlinal folding structure. However, in the author's experience this radial ridging is unique to DIAL PACK, and so far as has been traced has not been reported in connection with any planetary structure. However, as was the case at DIAL PACK, such structures may be hidden by volcanic (or pseudo-volcanic) deposits, and also by later sedimentary deposits. In planetary structures, not amenable to excavation, such a ridging could well be missed if not specifically looked for by non-central geophysical sectioning.

Again, there is no elevated rim, but a general shallow depression of the surrounding strata. However, there is evidence of circumferential and radial cracking of the ground, and in this Type B crater this is associated with some external pseudo-volcanism. In this case, however, possibly due to the relative sealed fissures, this is in the form of a shallow, wide spread seepage of sand laden water, more akin to "flood basalts" than to volcanic peaks. While there is no direct evidence of thrust faulting breaching the surface, the pseudo-volcanic provinces are located roughly where they would be expected, at about twice the rim distance from the center. Thus Type B appears to be slightly developed version of Type A, with a greater tendency towards a central uplift and some slight evidence of a tendency for fissures to open external to the crater.

However, the Type A, PRAIRIE FLAT crater was that in which the existence of coherent overturning of an ejecta flap - using the term ejecta loosely - was confirmed. In this case, it was possible to trace complete suites of strata from the original position, through a rim structure and then outwards for hundreds of feet. The suite of strata were progressively thinned, but retained total integrity to the outer limits of the "ejecta" blanket. The field evidence in PRAIRIE FLAT, the Type A crater, is incontrovertible, but it is believed that such coherent overturned flaps existed on ALL the Suffield craters of 100 ton and 500 ton origin, though it was only on PRAIRIE FLAT that the particular suite of strata, with free running sand sandwiched between silt-clay layers could be traced with complete ease.

The final type of 500 ton crater at Suffield, Type C, was actually the first example of a seriously complex crater found at Suffield, the 1964 SNOWBALL crater. Visually, this crater was different from the Type A & B, as it had a large structural central uplift, and a seriously depressed shallow bowl surrounding the crater proper. However, after looking at Types A & B it is recognized that this is only a final stage, which in its completed form included inward slumping from the region of circumferential fracturing, even to the extent of producing internal terracing on the crater walls. The internal pseudo-vulcanism conformed in pattern to that in Types A & B, but owing to it being the first occurrence, and the general masking of the crater floor with the pseudo-volcanic sand, the ring structure was not apparent to observers, but determined later by excavation. Thus the location of the pseudo-volcanic peaks, as observed, was limited to the base of the central uplift and the bottom of the crater walls. In fact, it is virtually certain that they also existed along the crests of inner ringed structures.

External to the crater, there were open circumferential fissures which were detectable all around the crater but were more evident on the south side of the crater, which was also the side where the inner crater walls were most clearly terraced. There was one case of clearly paired circumferential cracks, but several others were observed both nearer the crater rim and farther out. The major cracks, being relatively wide open, did not produce pseudo-volcanic cones, but did produce "flood deposits". Elsewhere, external to the crater, along rather more tightly closed radial and circumferential fissures there were spectacular examples of "Volcanic mountains" with numerous active calderas.

Some of the suffield craters, at all scales, were associated with clearly lobed ejecta blankets, not unlike those associated with lunar craters.

On two craters only, PRAIRIE FLAT and DIAL PACK, which have been distinguished structurally as Types A & B, there was a common feature not met with in any other Suffield crater, and this was the production of large quantities of fused, "popcorned" material deriving from the surface layers. As these two craters were formed by replicate charges, in the tangent sphere configuration, it is probably a peculiarity of the initial profile of the shock/detonation wave interaction with the ground immediately below the charge.

It is noted that the "wet" condition of some of the 100 ton, and all the 500 ton craters is a completely ephemeral stage. At the Suffield scales, the craters dried out completely within a matter of weeks, leaving the craters masked internally with a pseudo-volcanic, but actually sedimentary deposit quite thick enough to mask the internal structural form of the craters, which, prior to excavation, ended up with flat floors and mere dimples of central uplifts.

Finally, it is remarked that there were numerous examples found during excavation of sand filled fissures, of erratic form clearly due to a form of hydraulic fracturing. These existed in the central uplift (associated with pseudo-volcanism) and beyond the crater rim, where in general they did not breach the surface. However, there were also much more regular, and visually vertical, hard packed columns of sand sections of apparently circumferential dykes, which simulate closely in location and appearance the sandstone dykes reported in association with some presumed impact structures, but also closely similar to those reported from other catastrophic events such as major earthquakes.

Thus it may be concluded that the majority of structural features found associated with controversial, but probably impact structures on the planets can be found in association with craters of precisely known origin in near surface explosions. At the Suffield site the conditions of the cratered material are such that shock metamorphism and shatter cones are not found, nor could they be expected. Such features, however, have been confirmed in association with high explosive surface detonations on hard rock on other sites, while the blowdown effect of an accepted bolide on forest has also been confirmed by high explosive detonation near the surface. At Suffield itself, obviously, due to the nature of the terrain and experiments, this "atmospheric" effect only existed in the effect on exposed military targets, not considered in this publication, and the production of air coupled surface waves as the dominant seismic effect.

It has been shown in the foregoing chapters that the Suffield craters, produced by charges ranging from 20 tons TNT to 500 tons TNT contained structural features which were analogous to those found in many naturally occurring, probably impact origin, terrestrial structures. Also, the Suffield craters were visually similar to many lunar structures (and later, structures on other planetary bodies). The question, however, is whether or not the above factual, experimental observations may be taken to indicate that the Suffield craters were not merely analogues, but actually models of the processes by which such structures were produced at the greatly increased scale of the planetary craters.

It was an observed fact that much larger craters than those at Suffield, produced by nuclear detonations, did not in general conform to the analogous pattern, but attempts at Suffield to vary the detonation conditions to make the craters conform to the known nuclear pattern were only partially, if at all successful. Some of the scaled parameters could be adjusted in conformity with the nuclear craters, but the morphology at Suffield retained its complex pattern of central uplift, ring and radial structures, and pseudo-volcanism, and at the largest scale a general saucer-like depression of the ground beyond the main crater void.

It is a cliché of geological studies that laboratory scale models using terrestrial rocks but rarely produce any meaningful result unless the terrestrial rocks are replaced by some other material, simply because true modelling requires scaling of the physical strength of the rocks, and generally speaking, both the model and the full scale structure are, normally, in the same unscaled terrestrial gravitational field, while the time factor between the natural structure and the model is often of the order of millions of years to minutes. All these objections apply to the scaling of crater forming processes, except possibly a reduction in the time factor scaling between an impact and a reasonably large explosion.

The classic study of the use of models to study geological structures is that of M. King Hubbert (1937). This is a lucid investigation of the problem based upon the simplest formulation based upon dimensional analysis. While King Hubbert discusses in some detail the mechanistic techniques which allow actual physical modelling to be undertaken for many processes without undue distortion, perhaps his greatest contribution lies elsewhere, in the field of "conceptual models" applied to very large scale, or very long time scale situations. In such cases strict dynamical similarity may be defined, in conceptual terms, even when the attaining of such similarity in a laboratory model are prohibited on purely practical grounds of time, or conflicting demands upon the model material. King Hubbert does actually consider, in this way, the case of an impacting meteorite, among many other problems relating to the mental visualization of "whole earth" phenomena. Reducing his conclusion to its basic form, he points out that in the case of a moderate sized, normal velocity meteorite impacting on rock, the target material for a laboratory scaled model would require to be of the consistency of soft clay, but loaded with a high density material such as lead oxide. The effect of the impact would be, in the model, a splash rather than a shattering. That is, on the conceptual model scale, hard rock would at the full scale behave rather like mud at the small scale.

No purpose would be served here in a detailed expansion of the theory of dynamical scaling, which is by no means an esoteric subject. Sufficient has been said to allow the author to venture at least a conceptual explanation of the observed differences between Suffield and large scale planetary structures.

Essentially, both the nuclear and the conventional Suffield charges took place in the same terrestrial, gravitational and even geometrical environment. The most significant, but not necessarily the only difference, lies in the nature of the cratered material. Most of the known nuclear craters which have been studied in detail were formed in rocks, ranging from basalt to relatively weak, but indurated desert alluvium, quite dry to the relevant depth, and incapable **at the scale concerned** of producing fluid material. Stratification, where it existed, tended to be generally of similar strong rocks in thick strata. Thus it may be seen, even at this stage, that the "target" material will not change much in going from the nuclear material to the scale of a meteorite crater of typical terrestrial "small" scale, such as the Barringer Crater.

Contrast this with the Suffield situation. To begin with, the explosion tends to be of lower initial energy density, even though at a few charge radii the blast wave will be almost exactly geometrically scaled to the nuclear (they are travelling in the same medium, under similar conditions). On the other hand, the target material for cratering differs in many ways. First of all, the strength of the material is very much less - of the order of the soft clay suggested by King Hubbert as needed for dynamical similarity. Secondly, the stratification is extremely small scale compared with the significant stratification of the earths crust involved in a major impact. Thirdly, at quite moderate depth, comparable to the crater depth, the Suffield target was saturated with water. Above the saturated level, there was connate water in material highly compressible at the experimental scale. In the case of very large scale impacts, it is a moot point whether the effects of the water at the Suffield experiments would simulate the effects of gases or liquids subsequent to the impact.

It has been shown that in the case of a relatively small impact, creating a 10 km crater in material virtually identical with the materials at the Suffield test site, except for an increase in the stratification scale, the structure created is directly modelled by the 500 ton craters at Suffield, even to the existence at both the "model" scale and the "full" scale of dykes of sandstone material - actually stone by now at Eagle Butte, but compacted sand at Suffield.

It is suggested that a nuclear device of the order of Kilotons or megatons, detonated on the surface in Alberta would produce enlarged versions of the Suffield craters, modelling even more closely larger scale impact events. One needs also to consider the implications of detonations at major cities and delta regions of the world...but preferably only as conceptual models.

APPENDIX A

SITE LOCATION PLOTS FOR SUFFIELD TRIALS

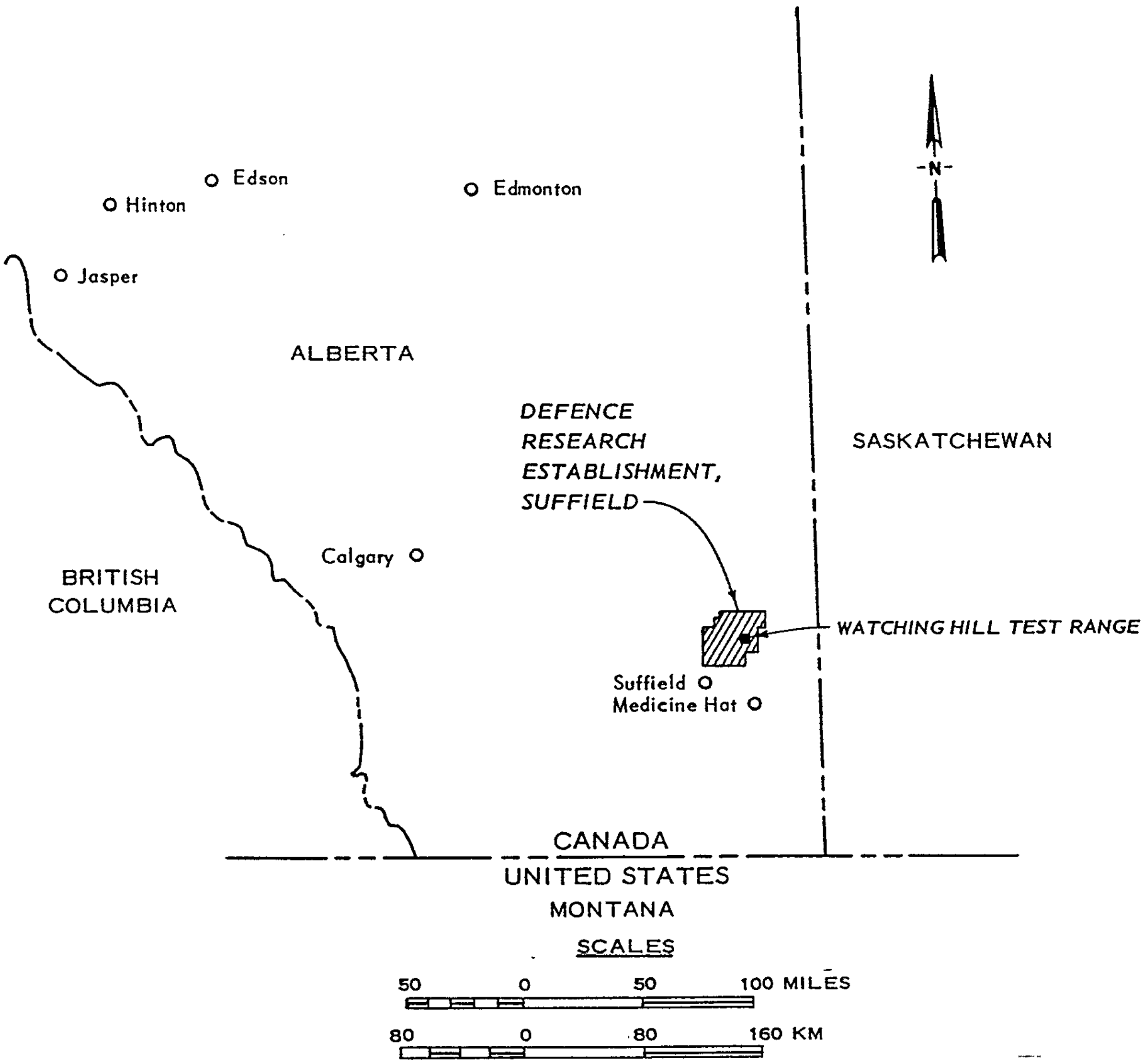

Figure A/1

Location of the Defence Research Establishment Suffield in Alberta

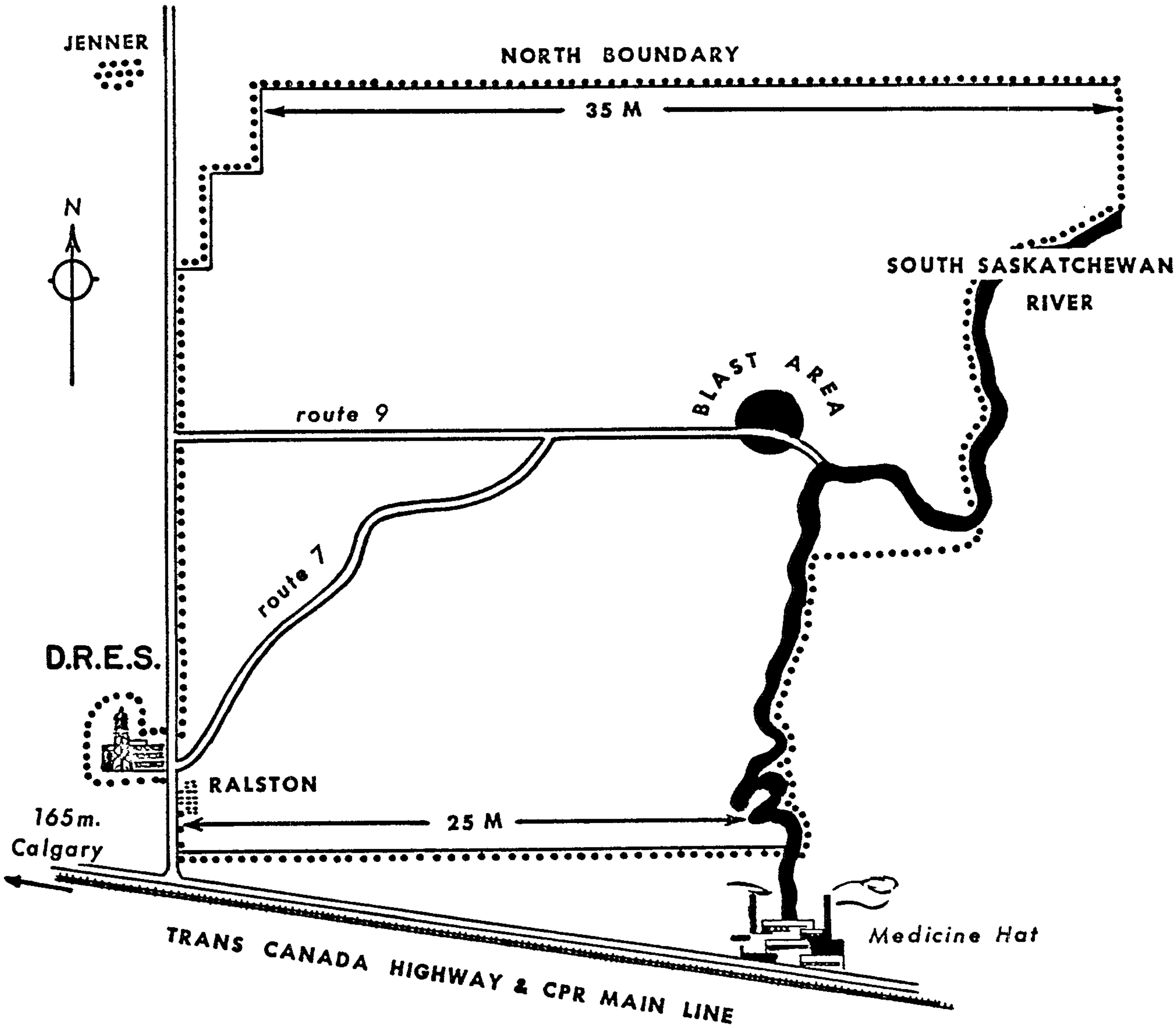

Figure A/2
Defence Research Establishment Suffield Range Area

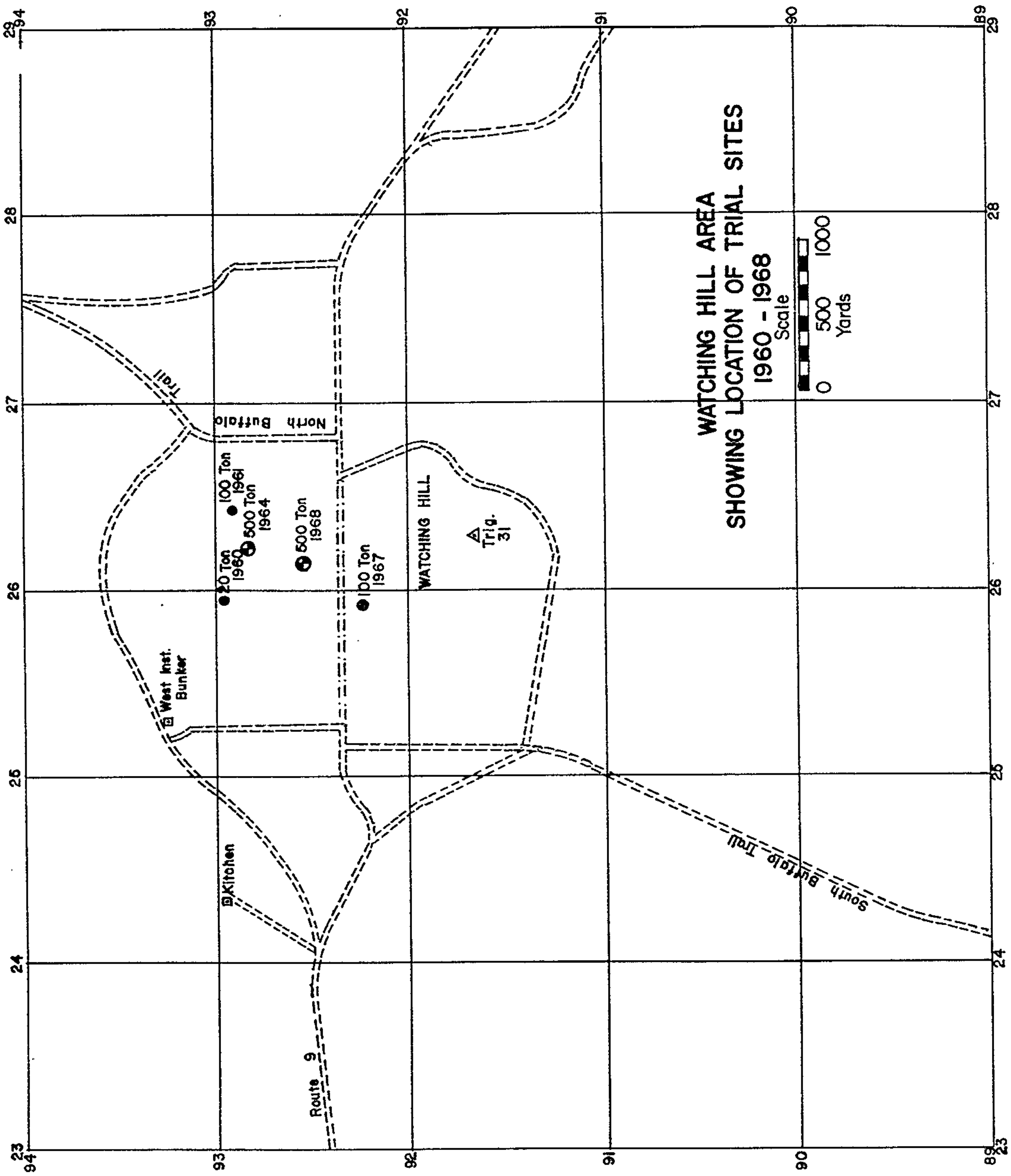

Figure A/3

WATCHING HILL Area Showing Location of Trial Sites (1960-1968)

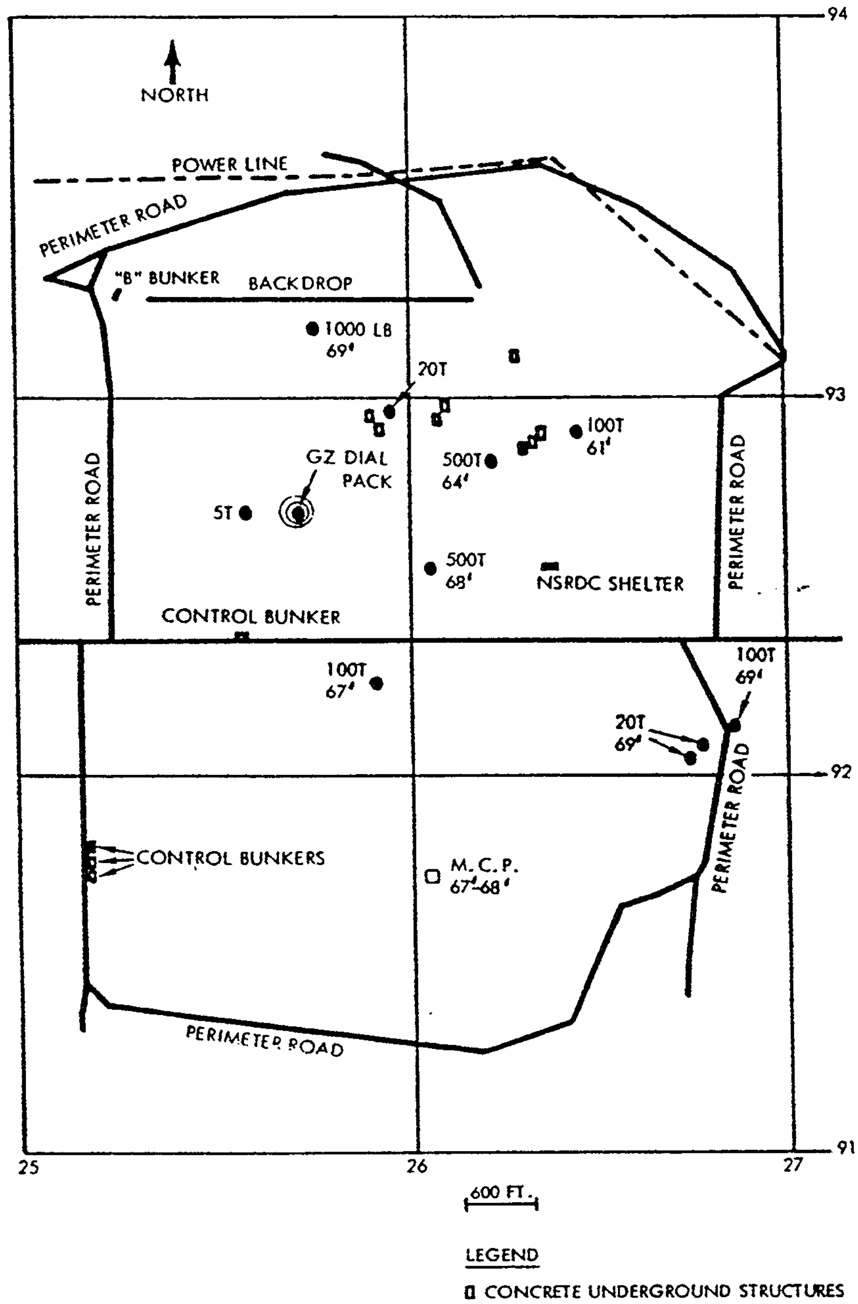

Figure A/4

Location of DIAL PACK Ground Zero

APPENDIX B
GEOLOGICAL SURVEY OF CANADA MAPS OF THE SUFFIELD TEST SITES

(See Back Cover Pocket)

1. Surficial Geology of Part of Defence Research Establishment Suffield (Drowning Ford and Watching Hill Areas) by J.S. Scott, Figure 18, (1970).

2. Drowning Ford Area: Figures 3, 7, 8, and 9, (1970).

3. Drowning Ford Area: Figures 6 and 10, (1970).

4. Watching Hill Area Shot Point Locations: Figure 2, (1970).

Maps are courtesy of the Geological Survey of Canada as appearing in GSC Paper 69-13, "A Shallow Seismic Survey, Elastic Constants Studies and Surficial Geology of Part of Defence Research Establishment Suffield (DRES), Suffield, Alberta", 1970.

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APPENDIX C

CONTENTS OF ADDENDA

PART 1 - ADDENDUM TO EACH CHAPTER

Addendum to Chapter Two (20 ton craters)

Five B&W 4x5 Negatives relating to FE535

0 ton crater Watching Hill

Sixteen colour transparencies, not mounted, relating to DISTANT PLAIN 3

20 ton crater, matching DRES File 7152

Fourteen B&W negatives 4x5, DRES File 7152, most with contact prints.

Addendum to Chapter Three (100 ton craters)

Section A relating to 1961 Suff 100

Six 4x5 negatives and prints

Three 35 mm mounted transparencies

Multilith negative of horizontal marker section Five B&W 4x5 negatives and contact prints file 5879 DRES

Section B relating to DISTANT PLAIN 6

100 ton crater

Eleven colour prints, known origin, showing DP 6 crater and excavation

Six B&W 4x5 negatives and contact prints of DP 6 crater

Two hundred and twenty five colour transparencies, 35 mm, of DP 6

Of these, about half of them are duplicates, one of each pair marked Official Use Only, the other unclassified

Six large B&W prints of aerial vertical photographs of DP 6

Section C relating to ANFO 3

35 mm transparencies (DRES/Diehl origin, unclassified)

Addendum to Chapter Four (SNOWBALL 500 ton)

Addendum 4A

Early post detonation photography

Thirty one B&W 4x5 negatives, with contact prints and some enlargements showing crater at early stages

Twenty B&W 4x5 negatives with contact prints and some enlargements showing early excavation

All above from DRES Files 6700, 6703, 6713 and 6721, but held by Jones for some thirty years

Five Hackman negatives and prints

One composite phot neg of SNOWBALL

Five additional 4x5 B&W DRES negatives and contact prints

One large negative duplicate of 6701/5

Aerial photo of SNOWBALL crater

Two additional Hackman negatives

Six colour aerial 4x5 negatives, probably DRES photos of SNOWBALL

Addendum 4B

Mainly a record of the SNOWBALL excavation of sand columns

Thirty six unmounted 70 mm colour photographs of early excavation

Twenty two B&W 4x5 negatives and contact prints of the excavated sand columns N1 to N14

Twelve B&W 4x5 negatives and contact prints of excavated columns South Line

Thirty B&W 4x5 negatives and contact prints, some enlargements, of excavation of central mound and the North-South excavation wall

Twenty nine B&W 4x5 negatives and contact prints of excavation of N-S line 50 ft East of GZ

Four B&W 4x5 of North rim excavation with contact prints

Thirty one B&W 4x5 negatives and contact prints, some enlargements of an excavated line scaled SE and SW away from sand column line to show stratigraphy. **NOTE THIS SET WHICH IS OF GREAT SIGNIFICANCE.**

Five B&W 4x5 similar to above but on a NW wall from central mound

Seven B&W 4x5 miscellaneous photos of central mound and crater interior.

Addendum 4C

Mainly DANA PARKER Photography

One hundred and eight 70 mm B&W negatives and contact prints COPIED FROM originals by DANA PARKER archived at ERIM (Source data and correspondence is included in Addendum)

Thirty three enlarged prints from above Parker negatives (additional to those used in Chapter Four of text)

Eight Aerial Vertical stereo photos taken by U.S. Army 4th Aviation Bat. and provided by Waterways Experiment Station through Army Standardization Group Ottawa. OFFICIAL USE ONLY.

Addendum 4D

Fifty one B&W negatives and prints relating to the Figures in SR 281. These are "used" supplements to the sets in the earlier Addendum 4 sections, mainly DRES negatives plus Hackman negatives. **These are among the more significant archival records.**

Forty four 35 mm colour transparencies most of which are paired with earlier B&W negatives in the archives.

Addendum to Chapter Five (PRAIRIE FLAT)

Addendum 5A

Twenty three B&W 4x5 negatives and contact prints

Three 70 mm B&W negatives and prints

Three 4x5 colour negatives with B&W prints

Several large prints from negatives

Twenty seven 35 mm transparencies

Fourteen 70 mm B&W negatives of the detonation, with prints

Addendum 5B

Twenty six multilith negatives and prints used in figures for POR 2115 (also some used in main text)

Addendum to Chapter Six (DIAL PACK)

Reprint of Unclassified RODDY report on DIAL PACK. Refer to Chapter Six for the location of DIAL PACK archives.

Addendum to Chapter Seven

Nineteen 35 mm colour transparencies of Eagle Butte, after Dence

Thirteen 35 mm colour transparencies of the Pretoria Salt Pan

Twenty Six 35 mm colour transparencies of the Vredefort Structure

Twenty one B&W 4x5 negatives and prints of the BLOWDOWN site DP 4

Two Polaroid prints of Blowdown

One 4x5 colour aerial of Blowdown

PART 2 - LOCATION OF OTHER ARCHIVES

(a) Author's Archives

The archival material collated in Addenda 2, 3A, 3B, 3C, 4A, 4B, 4C, 4D, 5A, 5B and 7 all derive from the authors personal collection. In addition, the author's collection contains some additional material in formats unsuitable for inclusion as Addenda. These include six containers of 70 mm B&W film taken by the RCAF before and after the SNOWBALL detonation, originally classified Confidential but declassified 2 April 1984. It is thought unlikely that this collection of several hundred frames will be found relevant to crater studies, but may be relevant in other ways and should be preserved. There are also three large folios of original field records relating to the sand column excavations of SNOWBALL, and some very large scale drawings of the plotted sand column data, but these are also available in reduced scale prints and multilith negatives. **Note** that similar plots produced at DRES are now held by Roddy, in Flagstaff, relating to PRAIRIE FLAT (See later for Roddy archives).

(b) DRES Archives

The DRES Photographic Section holds partial, but considerable collections of still photography of most of the Suffield Trials. Also, they retain a virtually complete collection of the high speed cine coverage of the majority of the trials. The DRES Library holds complete collections of the Suffield reports on the trials, and a large collection of related reports from other participating agencies. While not "Original data", they provide a most valuable resource fro anybody wishing to undertake research on the Suffield trials, or blast research in general.

Other than for the above two collections, original data is now scarce at DRES. This arose due to the great uncertainty that existed in the early 70's, during a period of transition from SES to DRES, and the demise of the Defence Research Board. Lamentable, but inevitable in the Cromwellian climate of the times. The then management of DRES was generous in making collections available to past staff (the author and John M. Dewey in particular), even to the extent of stripping relevant items from the DRES photographic collection. Even cabinets full of field survey data were dispatched to the author in Ottawa. Regrettably, other than for the material described in (a) above, the present location of this additional material is unknown, due to a move of the relevant group to new buildings after the author's retirement. However, this is probably small loss as the author took what he considered most valuable with him on retirement, and it is now doubtful that anyone is left who could interpret the abandoned material.

(c) John M. Dewey Archives

The extent of this archive, held in Victoria, B.C., is unknown, but the material refers almost exclusively to air blast phenomena and is understood to be the subject of a current contract.

(d) University of Michigan

The University participated in trials at DRES, and the residual legatee of the data appears to be ERIM, and details have been given in Addendum **4C** with relevant correspondence. It is probable that the copy negatives in **4C** constitute the bulk of the ERIM archives relevant to Suffield, but it is known that some highly relevant data were included in reports not currently available to the author. Permission to copy the Dana Parker negatives, given to the author, is most gratefully recognized.

(e) U.S. Army Waterways Experiment Station

WES were involved at virtually all the Suffield trials relevant to cratering, cooperating with and helping to train the DRES crater study group. Reference has been made in the text to this cooperation, and in particular to the reports issued for each of the major cratering trials.

These reports are short, in a standard format, and give the basic parameters for the superfical craters in a form which allows comparison both among the Suffield Trials and with other, very extensive data on other craters produced by both nuclear and conventional explosives. WES also coordinated, for the earlier trials, aerial photographic coverage, which was later continued in cooperation with the U.S. Branch of Astrogeology. Thus it is certain that WES will have retained some archival data over and above the elements actually published in their reports. However, in the period of primary interest, that is after 1961, the original data are probably held by the U.S. Geological Survey Branch of Astrogeology, whose archives are discussed below.

(f) U.S. Geological Survey Branch of Astrogeology

There is little doubt that the above unit, at Flagstaff, Arizona, holds the world's largest archives dealing with craters produced by large conventional, nuclear, and impact events, the latter both on earth and all the yet-examined planetary bodies. The Branch also in all probability has the most sophisticated mapping technology currently available.

However, for the present purpose attention is drawn to a sub-set which we may term the Roddy Archives, without prejudice to precise "ownership", as they are currently held by Roddy. These archives contain data from nuclear trials, terrestrial impact craters, craters produced by conventional HE and ANFO explosives on a variety of geological provinces, some studied using variations of the sand column technique.

In particular, Roddy participated in all major Suffield trials after SNOWBALL (ie. from 1964 onward), concentrating on three areas - photogeologic mapping, ground study of the ejecta blanket, and stratigraphy of the rim structures. On site support was provided almost exclusively by the Suffield Field Staff and the Suffield Geophysics Section. Consequently Roddy currently holds original records relating to SNOWBALL, PRAIRIE FLAT, DIAL PACK and DISTANT PLAIN 6 in some considerable photographic coverage, mainly in the form of 35 mm colour slides, but also original aerial photogrammetry. In the particular case of DIAL PACK, the Roddy archives are the most complete and significant currently available. They are said to contain over 1,500 photographs of the DIAL PACK crater and an ample supply of the fused material found on DIAL PACK and PRAIRIE FLAT. In the case of PRAIRIE FLAT Roddy holds some original data provided by the present author for safe keeping when he left Suffield. These include, at least, large scale Mylar drawings on the stratigraphic data obtained on rim excavation of PRAIRIE FLAT.

Roddy has published Suffield data extensively, but much remains to be done, particularly in comparing the Suffield craters with impact structures and with large scale (Thousand of tons ANFO) explosions on other test sites, primarily the White Sands Proving Ground, New Mexico.

Discussions are on-going and eventually the Roddy data may be catalogued at least to a limited, consistent format. In such a catalogue the Suffield Craters would form a significant sub-set, and every cooperation should be offered to this end by other agencies who made use of the Suffield trials.

(g) Boeing Aircraft Company Ejecta Studies

Much data was collected by and for the Boeing Company by the Suffield staff, mainly in connection with the ejecta pattern. While some of the raw data have been preserved and published in post-trial records, no complete studies are currently located. It appears that neither the author nor current DRES staff have the necessary company contacts for effective enquiries, and this may require liaison through DNA.

(h) The Bell Telephone Archives

Remarks made under (g) above apply with equal force to the BTL data. Bell were among the earliest participants at Suffield, and were the primary users of the first series of 5 ton charges. Generally, the data collected by BTL were specific to "applied experimentation" on structural damage to military targets, and not relevant to the present study. However, it is known that much data collection was undertaken on missile distribution, which may have significance in impact structure studies. Again, neither the author nor DRES staff have current company contacts so liaison via DNA would be required.

(i) The Seismic Archives - Author's Collection

Although not specific to the craters, the author's collection includes two partitioned containers holding the original Sprengnether records from ALL the trials at

Suffield, plus those from Operation Stagecoach NTS, and the Piapot Creek diversion. These will be deposited at DRES.

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APPENDIX D
BIBLIOGRAPHY

Author's Note

This publication deals with a specific series of crater-forming blast trials at Suffield. As such, it is a time capsule, viewed some three decades after the event. It is therefore appropriate that the Bibliography reflects primarily the events described, together with those other publications which were directly influential in the interpretation made in the immediate aftermath of the trials, and a few later publications which actually made significant use of the Suffield data.

Since the end of the Suffield program, there has been a vast increase in the knowledge relating to impact structures within the planetary system, a virtually unkown field at the time of the Suffield trials. Obviously, there have been hundreds, probably thousands of publications both in this new field and relating to other, large scale, explosive trials. No attempt would be proper to include these later publications. It is understood that the (U.S.A.) DNA maintain an unclassified, computer based bibliography covering the entire field of crater studies. Recourse may be made to that bibliography by serious workers in the field.

The format used in the present bibliography is, in essence, the one advocated by Sir Harold Jeffreys, itself a slight modification of the Royal Society system. It is the system introduced by the author at Suffield to replace the then existing system of numbered references. The primary advantages are that prominence is given to the authors and date, and the editorial system is much simplified by avoiding the need to re-number all references when a reference is added or deleted.

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Several hundred high explosive trials have been held at the then Suffield Experimental Station, now the Defence Research Establishment, Suffield, near Medicine Hat, Alberta, Canada. The majority of the trials were fairly small in scale, from a few pounds to a few tons of TNT. There was, however, a variety of trials at larger scale, ranging from 20 tons TNT to 500 tons TNT. The craters produced by these larger trials were strikingly similar to features on the surface of the earth and with lunar features. At the time of the trials no comparable features had been found elsewhere, but with the advent of the interplanetary space probes it has since become evident that the features are common to all planetary bodies with solid surfaces. It has therefore appeared desirable to prepare a unified text, giving comparable data where available on the series of craters produced at Suffield which were analogous to the planetary features. The present publication is intended to serve that purpose, and place the material in the public domain.

Herein, effort is concentrated upon those craters which demonstrated a morphology essentially analogous to the terrestrial structures previously called crypto-explosive, but now generally accepted as the scars of meteorite impact. In the past they have been denied such an origin in part because experimental craters did not normally exhibit the complex morphology of the typical crypto-explosive structures. This morphology normally included central uplift structures, overturned ejecta blankets, and systems of circumferential synclines, anticlines and fractures, radial fractures and associated volcanic type features such as dykes and extrusive flows of liquid material.

High Explosive surface detonations at Suffield produced craters which exhibited all the above features, and provided precise information on the pattern of displacement and fractures associated with them. Thus the data become a significant element in the present identification of such planetary features as being the result of impact.

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