The Importance of Sediment Studies in Western Lakes as a Key to Basin Management

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(Abstract)

Geological studies in lakes provide a tool by which environmental evolution can be investigated from evidence existing in the sedimentary column. Interpretations of environmental history can be made spanning thousands of years, hundreds of years, and in some cases only tens of years, depending upon the type of information sought and the precision desired. Geological studies can also be used in lakes to investigate the larger and more stable circulatory and boundary phenomena and they are a key factor in resolving problems related to sediment erosion - transportation - and deposition. Sediment geochemistry studies can play a major role in defining the chemical characteristics of lake systems since most chemically reactive species are significantly influenced in their lacustrine cycles by interactions with sediments. Finally, because of the relatively slow rates of change of "sediment systems", geological investigations can provide an essentially synoptic expression of lacustrine conditions with a single sampling program.

The number of examples where comprehensive "limnogeological" approaches have been used in Western Canada are very few. Studies of the mainstem lakes of the Okanagan Valley are reviewed to illustrate the value of geological studies in the research and data provision area of environmental management. A few more specialized limnogeological studies conducted in Western Canada are also described, and limited

reference is made to the extensive geological work on the Laurentian Great Lakes. The suggestion is made that limnogeological studies can often define the real problems which exist in lake systems, and can provide a frame-work for the integration of results produced by more specialized follow-up research. As such, therefore, geological studies should be at the forefront of many management concerns with lakes, or basin - lake systems.

INTRODUCTION

The ideas discussed in this paper are really not new but represent an attempt to promote an understanding of the value of geological studies as they apply to lakes, and to generate an awareness of the significance of such information to lake management.

The following quotation from David G. Frey (1969, p.595), concerning evidence for eutrophication provides an effective opening for this discussion:

"There is really no need to apologize for the amount of information in sediments; it is tremendous, although still largely unappreciated. Some lines of investigation are already quite highly developed and are yielding exciting results. Others are barely perceived, much less explored. To a considerable extent it is not yet fashionable to study recent sediments. However, even the relatively few studies that have been conducted make it clear that paleolimnology will have a real impact on our eventual over-all understanding of eutrophication and its effects on lake ecosystems."

The significance of "palaeostudies" has long been appreciated within the geological community and fortunately there has been some broadening in appreciation by the wider scientific community since David Frey made his remarks. The "lay brotherhood", however, remains largely unaware of the value of such work.

The present paper will expand upon this idea through a selection of examples to show how geological studies can provide different types of evidence:

1) On the evolutionary trends in lakes and as a tool to determine age and also the quality of the ecosystem within and around a lake;
2) On the characteristics of sediment geochemistry and the significance of rates of sedimentation on geochemical budgets;
3) On the sediment record as a reflection of the energy regime within a lake, (circulatory pehenomena and wave activity).

It has been difficult to provide sufficient illustrative examples from lakes in Western Canada alone, and reference to Laurentian Great Lake studies has therefore been included to provide a better balance.

The studies described below include work that has been published and is referenced accordingly, work that is essentially complete but has not yet been published in detail, and research that is presently in progress at the Canada Centre for Inland Waters (CCIW) but which is not yet complete.

EVOLUTIONARY TRENDS IN LAKES

The sedimentary record of a lake is a manifestation of almost all of the inter-related cycles that make up the dynamics of a lacustrine system. As such, the sediments of a lake retain evidence of currently active cycles within the lake as well as cycles that have been operative throughout the lake's evolution. Application of geological principles of stratigraphy, sedimentation and geochemistry can elucidate the long term trends in the evolution of both lakes and basin-lake systems. The examples below have been selected to illustrate the use of geological investigations to identify long term (one century) changes produced in the flora of the Okanagan Valley through the influence of human settlement in the area, and the subsequent alterations occasioned by these changes on the trophic state of each of the mainstem lakes of that Valley.

Pollen Distributions in the Sediments of the Okanagan Mainstem Lakes

Anderson (1972) has investigated in detail the distributions of pollen in core samples taken from Wood, Kalamalka, Okanagan, Skaha and the Osoyoos Lakes of the Okanagan Valley, B.C. (Fig. 1). An abbreviated pollen profile from Osoyoos Lake (Fig. 2) illustrates the general trend in nearly all of the lakes. Total pollen concentration is high at the base, declines to minimum values at 23 cm. and increases to higher values towards the surface. Spruce, pine, hemlock, and grass decline sharply at 28 cm. while poplar, alder, willow and sagebrush increase to significant peaks at 26 cm.

Investigations into the history of land settlement in the Okanagan Valley (Ormsby, 1931) reveal a number of key events to which

The pollen record may be correlated. Cattle were first trailed into the valley from the south about 1860 and cattle ranching was the most important industry until the early 1890's; so much so, that overgrazing depleted much of the rangeland. Experimental evidence from such areas subjected to overgrazing not only show decreases in the availability of forage bunch grass but reveal significant increases in sagebrush (Tisdale, 1947). Sagebrush has a low palatability value and its dominance at the decline in grass pollen is taken to signify extremely overgrazed conditions about 1890.

By 1892 many ranchers were finding cattle-raising unprofitable and, consequently, turned to wheat growing, dairying and fruit farming. This caused a pronounced change in the flora on the lower valley benches and floodplains through cutting, burning and clearing, the effects of which are apparent in the pollen diagram. Peaks in poplar, alder, willow and weedy herbs (Tubuliflorae and Chenopodiaceae) represent a younger flora which quickly immigrated onto the newly disturbed and burned-over areas. Clearing, land-breaking and faulty application of irrigation-water accelerated surface run-off bringing about a sharp increase in the sedimentation rate in Osoyoos Lake. The minimum point in the total concentration curve would denote such a fruit land boom and poor land management during the years 1890 to 1900. However, a decline in the boom occurred between 1911 and 1920, the War years, when fewer trees were planted. Sediment influx was presumably reduced at this time, hence the higher pollen numbers between 10 and 15 cm. Not until 1927 did extensive clearing and fruit farming take place around Osoyoos Lake which may possibly explain lower pollen values at 8 cm. By the early 1950's final stabilization had begun. With increasingly efficient water application through adoption of the sprinkler system, downslope seepage and soil erosion were checked and higher yields and better markets obtained. Higher pollen numbers near the surface of the diagram may signify this trend towards better land management.

Carbon Content of the Sediments from the Okanagan Mainstem Lakes

The carbon content of a given sediment sample is a measure of the carbon deposited minus the carbon remobilized back into the water. Hence, a given concentration of carbon in a sediment is a product of a large number of factors including:

1. Quantity of carbon deposited;
2. Gross sedimentation rate;
3. Decomposition rate of organic matter in the sediment environment;
4. Form of carbon deposited.

Accordingly, high organic carbon content sediments can be produced in a wide range of limnic environments, and organic carbon content of sediments does not necessarily parallel the state of eutrophication of a lake, although a qualitative relationship commonly exist (Kemp 1969).

Fig. 3 is a presentation of profiles of carbon content of sediment cores collected from the deepest part of each of the Okanagan mainstem lakes. These data were collected by A.L.W. Kemp of CCIW. The solid line represents the content of inorganic carbon plotted from the Y-axis, while the broken line represents the content of total carbon plotted from Y-axis. Accordingly, the space between the broken and the solid lines delineates the organic carbon profile of the sediment cores. The depths estimated by Anderson (1972) for an age of one hundred years in each sediment core have been plotted on fig. 3.

In each of the cores an increase of carbon content at the surface appears evident. However, in Okanagan, Osoyoos and Wood Lakes the rate of increase of total carbon content of the sediments appears to have increased at a time essentially synchronous with Anderson's (op. cit.) estimated time of man's first significant influence on the valley. In Skaha Lake, no significant increase in total carbon concentration in the sediments is manifested until about 25 years ago, when a sharp increase in carbon accumulation rate became apparent. Kalamalka Lake, a deep oligotrophic lake near Vernon, precipitates large quantities of calcium carbonate each summer, and an examination of fig. 3 suggests that a relatively minor increase in the rate of carbonate accumulation has occurred in this lake over the last few years.

It can be seen, therefore, that the lakes of the Okanagan Valley most affected in trophic state by long terms changes (i.e. those changes operative for the duration of man's influence) are in the areas of most intensive rural development (Wood, Osoyoos, and Okanagan Lakes). The lake most affected by urban developments over the past 25 years is Skaha Lake, and it seems probable that sewage effluent from Penticton over that period contributed materially to the rapid increase in accumulation rate illustrated in Fig. 3. It is of interest to note, however, that no long term increase in accumulation rate is manifested in Skaha Lake, only a short term increase. From these observations it can be postulated that rural activities have been the prime factor of responsibility for alterations in trophic state of Wood, Okanagan, and Osoyoos Lakes, but urban activities (Penticton) have been the prime cause of water quality deterioration in Skaha Lake.

CHEMICAL CYCLES IN LAKES

Most chemically reactive species are significantly influenced in their lacustrine cycles by interaction with sediments. Detailed sediment geochemistry studies, therefore, can play a major role in defining the chemical characteristics of lake systems, and can accurately quantify the "sediment retention" factor which is crucial to any sophisticated attempt at lake modelling. However, this evidence may not be clearly presented, and it may be altered to an apparently paradoxical state through the lake's response to changing environmental conditions. An example of such a paradox may be seen in the tendency of many lakes characterized by high phosphate loading to contain sediment of lower phosphate concentration than certain lakes of lower phosphate loading. The proper use of geological principles of sedimentation and a thorough knowledge of geochemistry can expose such paradoxes, however, and provide a detailed exposition of major chemical processes in lakes. The examples below have been chosen to demonstrate the use of geological investigations in studying chemical cycles in lakes in the Okanagan Valley of B.C. Research is continuing on these cycles at the time of writing (November 1972) and the results presented in these discussions are preliminary in nature.

Phosphorus Retention in Sediments of the Okanagan Mainstem Lakes

Crucial to an understanding of each of the phosphorus cycles in the Okanagan mainstem lakes , is detailed knowledge of the quantity of phosphate retained in the sediments of each lake on an annual basis. Furthermore, knowledge of the diaganetic cycles affecting phosphorus in the sediments of each of these lakes will add greatly in assessing the real significance of the sediment phosphorus "sink" in the nutrient cycles of each lake.

Using the sedimentation rate data for the Okanagan mainstem lakes calculated by Anderson (1972), and combining these data with measurements of sediment density, water content, and phosphorus content, a direct calculation can be made of the total retention of phosphorus in each lake on an annual basis over the last 100 years (table 1). These last data are potent tools for lake investigations. The direct measurement of phosphorus retention allows for a much more detailed description of nutrient movements in each lake than is possible when sediment retention remains an estimated rather than a measured parameter. At the time of writing (November 1972) work is currently in progress at CCIW to integrate the sediment nutrient data with measurements taken of the physics and chemistry of the water masses in each lake.

Additional work is also underway to characterize the forms of phosphorus retained in the sediments with the view to adding a new dimension to lake modelling studies: a consideration of sedimentary

Table 1: Retention of Phosphorus in the Sediments of the Okanagan Mainstem Lakes:

LAKE:	DEPTH TO MAN'S INFLUENCE: (CM.) (After Anderson, 1972)	RATE OF SEDIMENTATION: (MM.)	AVERAGE ANNUAL NET ACCUMULATION OVER 100 YRS. IN KG.: (WHOLE LAKE)	AVERAGE P CONTENT OF SEDIMENT TO DEPTH OF MAN'S INFLUENCE: (PPM)	AVERAGE ANNUAL NET RETENTION OF P IN SEDIMENTS: (KG.)
Wood	20	2.0	2.23×10^6	735	1.64×10^3
Kalamalka	29	2.9	1.07×10^7	607	6.50×10^3
Okanagan	10	1.0	6.39×10^7	1200	7.67×10^4
Skaha	21	2.1	1.15×10^7	1370	1.58×10^4
Osoyoos*	28	2.8	1.11×10^7	851	1.18×10^4

* Values for Osoyoos Lake based on a core taken in the south basin only.

diagenetic budgets of phosphorus in each lake. Extensive work in soil chemistry (Chang and Jackson, 1957; Williams et al., 1967) has revealed the major modes of combination of phosphorus in soils. The application of similar lines of investigation to lake sediments has indicated that the phosphorus of sediments predominantly consists of three forms (Williams et al., 1971a,b).

These forms are apatite ($Ca_{10}(PO_4)_6X_2$, where X= OH,F), sorbed forms of inorganic phosphate consisting of orthophosphate ions associated predominantly with iron compounds, and organic esters of phosphoric acid. The behaviour of each of these three major forms of phosphorus in sediments varies from lake to lake,and on the basis of this variation, an assessment can be made of the fate of phosphorus after deposition in the surface layers.

Organic phosphorus appears to decline uniformly with depth in lake sediments (Williams, personal comm.) . The decline in organic phosphorus parallels the decline of organic carbon, and the released orthophosphate can either remain in situ in sorbed form, be converted to apatite, or migrate vertically. In Skaha Lake the mineralized organic phosphorus appears to be converted largely to apatite in situ. There exists, therefore, within the sediments an efficient mechanism preventing the regeneration into the water of phosphorus released from organic modes of combination. The identification of this mechanism is of value to lake management planning for Skaha Lake, as it may be seen that this lake might possibly clean itself of biologically reactive P if inputs can be markedly reduced. This would presumably result in a reversal of the eutrophication of this lake.

Calcium Carbonate Precipitation in Kalamalka Lake

Kalamalka Lake, a deep, oligotrophic lake in the Vernon Creek drainage of the Okanagan Valley, supports an annual cycle of calcium carbonate precipitation unique in the Okanagan mainstem lakes. Secchi disc visibility in Kalamalka Lake in April 1971, when carbonate precipitation was not occurring, exceeded 16 meters. By August of the same year Secchi disc visibility had dropped to less than 6 meters because of turbidity in the water produced by the precipitation of micro-crystalline calcium carbonate. At the time of writing (November 1972) detailed investigations of this carbonate cycle are proceeding but certain preliminary facts can be presented at this time.

Each spring, with the formation of the thermocline the water of the epilimnion of Kalamalka Lake releases micro-crystalline calcite that accumulates on terraces sited around the shores of the lake. The structure of these terraces resembles that of a tropical marine carbonate reef, with a "reef flat" of lower relief bounded by a steep "reef slope". The break occurs at a depth of 13 meters. It is probable that this depth approximates the mean depth of the summer thermocline, integrated over recent geologic time. The calcium carbonate composition of the terrace deposit is extremely high, averaging about 85%. Surface sediments taken from the deep areas of Kalamalka lake contain calcium carbonate concentrations that are approximately inversely proportional to water depth (Fig. 4). It seems probable that this fact reflects the incomplete dissolution of the carbonate that passes through the hypolimnion during sedimentation. Using Anderson's (1972) sedimentation rate of 2.9 mm. of dry sediment per year in the deep part of Kalamalka Lake, and the calcium carbonate content of Kalamalka Lake sediments, it can be estimated that a minimum of 4.07×10^6 kg. of calcium carbonate has accumulated in the sediments of this lake annually over the past century.

The most extraordinary feature of Kalamalka Lake is its excellent water quality, and basin development will reflect the desirability of preserving this feature. Accordingly, an understanding of the details of the calcium carbonate cycle of this lake and its effect on other biologically significant cycles assumes importance. A number of authors have considered the limnology of marl lakes (Schelske, 1962; Brunskill and Ludlam, 1969; Brunskill, 1969) and these authors are in agreement that the precipitation of calcium carbonate in a lake significantly affects the biogeochemical cycles of such a lake. Research is currently underway at CCIW to determine the relationships of the calcium carbonate cycle of Kalamalka Lake to the major cycles of the lake's physics, chemistry, and biology. Preliminary results suggest that the carbonate is precipitated in direct response to changes in thermal structure, and that this precipitation of calcite may be accompanied by a coprecipitation of certain heavy metals (including iron) with significant effects on the lake biota.

ENERGY REGIMES IN LAKES

The movement of unconsolidated material by currents and wave action is an obviously important process in the lacustrine environment. Such processes dominate the substrate formation of the benthic littoral zone and determine the spatial distributions of many toxic and nutrient chemical species in a lake. Short term physical measurements of currents and heat profiles in lakes are often reduced in their value by the confusion of minor processes that integrate to determine a lake's dynamics. However, investigations of distributions of sediment parameters can also be used to investigate and differentiate the larger and more stable circulatory and boundary pehnomena related to the lake basin overall. Studies performed on Lake Ontario and Petit Lac, Switzerland, that have provided valuable information on the energy of these lakes are discussed below.

Mercury in the Great Lakes

The application of tracer techniques in studying the dispersal of sediments relative to energy regimes operating in aqueous systems is well known (Coakley and Nelson, 1972), though these techniques suffer from many limitations. In many instances sediment dispersal can be resolved by utilizing some sediment component of natural origin, for example, through the study of heavy mineral assemblages and geochemical anomalies by exploration techniques related to known zones of mineralization. In recent years it has become apparent that industrial pollutants in concentrations far exceeding natural background levels may also be utilized as point source tracers responding to and defining net sediment movement in the lacustrine environment. An example of such a tracer technique has been demonstrated with regard to mercury in the sediments of the Great Lakes (Thomas, 1972a and 1972b).

Mercury in the sediments of the Great Lakes is associated with the fine particle size fraction (clay and silt) and is hence an indicator of the dispersal of the suspended load. The association of the mercury with the fine material is a limitation in that total sediment mercury concentration varies with the grain size of the host material. This effect must be compensated for by a grain size correction before the true mercury dispersal patterns can be clearly identified. Thomas (1972a and 1972b) produced a correction based upon the concentration of chemically determined quartz which showed an excellent inverse correlation with the clay size material determined by settling techniques. The distribution of quartz corrected mercury in the topmost 3 cms. of sediment in Lake Ontario is shown in Fig. 5. In this figure it can be seen that the mercury is derived from the Niagara River with high concentrations extending anticlockwise in the western basin (Niagara Basin) of the lake. In addition, a zone of high concentration extends from the Niagara River eastwards along the southern shore of the lake and ultimately dispersing into the Rochester or eastern basin.

These data (Fig. 5) would suggest that the net mass circulation of the lake forms an anticlockwise gyre in the western basin with a further eastward flowing water mass along the southern shore east of the Niagara River. This interpretation is entirely corroborated by the theoretical models of Simons and Jordan (1971), Scott et al. (1972) and also by surface current data presented in the I.J.C. Report (1969).

Where direct measurements of mass water movements are not available it may be seen that a fairly precise knowledge of net water movements can be derived from detailed geological investigations provided that a suitable natural or indistrial tracer can be identified. Without such a tracer recourse must be made to the sediment grain size properties.

Ferromanganese Concretions in Lake Ontario

Although tracer materials indicate dispersal patterns they do not provide evidence leading to an understanding of the energy levels occurring at the sediment-water interface. Such energy levels may be inferred from sediment particle size or from the occurrence of specific sediment components. An example in Lake Ontario of such a component is the occurrence and possible distribution of ferromanganese concretions. The occurrence of such concretions has been reported from many Canadian Lakes, for example by Kindle (1932 and 1936), Harriss and Troup (1969) and Cronan and Thomas (1972). Many modes of formation for manganese modules have been suggested though the variations relate to the source of the primary chemical constituents, Mn and Fe. In all cases (both marine and fresh water) certain environmental conditions are a prerequisite. The two important factors are given below:

(1) Nodules are only found in regions of slow or no sediment deposition. Higher deposition rates decrease the time of exposure at the sediment water interface and reduce the possibility of formation. Additionally, continual sedimentation and burial, with a decreasing redox potential with depth, would result in the solubilization of existing concretions.

A lack of sedimentation in a lake implies a medium energy regime sufficient to prevent settling of sediment, yet insufficient to bring about the breakage of concretions due to particle attrition. Mass water flow over the region will also bring about continuous replenishment of the iron and manganese (in solution) necessary to continue the growth of the nodules. (This supposes that precipitation from the overlying waters is the major source of the iron and manganese from the underlying sediments.)

A good example of the occurrence of ferro-manganese concretions has been described from Lake Ontario by Cronan and Thomas (op. cit.). The distribution of this deposit is shown in Fig. 6.

In Lake Ontario the concretions occur in water depths ranging from approximately 30 meters to 60 meters and occur predominantly in the form of a ferromanganese coated sand. This sand is of a lag origin, well sorted at the surface, and overlying glacial clays from which it is derived by winnowing of the finer sediment particles. This deposit thus exists under moderately eroding, or certainly non-depositing, sedimentary conditions and thus defines the existence of a large medium energy zone in the lake.

(2) The precipitation of iron and mangenese is dependent on Eh and pH conditions. Under known pH conditions it is thus possible to define the redox potential occurring at the sediment-water interface. Further, variation in the Fe/Mn composition of the concretions can be attributed to selective fractionation of the iron and manganese during precipitation under varying conditions of Eh or pH. The variation of the Fe/Mn ratio in concretions relative to the spatial variation of sediment Eh has been demonstrated by Cronan and Thomas (op. cit.). These data have been further confirmed by solubility experiments on Lake Ontario concretions carried out by Nriagu (1972).

The unique circumstances under which ferromanganese concretions form give a significant insight into the physical and chemical conditions occurring in a lake. This insight may be inverted as it is possible with even a rudimentary knowledge of a lake system to predict suitable areas for the location of such deposits.

Particle Size Studies on Petit Lac, Switzerland

Over the years many authors have debated the environmental sensitivity of grain size distributuion properties (Mason and Folk, 1958; Friedman, 1961, Moiola and Weiser, 1968). These studies were directed towards differentiating major environmental sediment types, for examples, beach, river and dune sands. Other studies have been made in an endeavour to ascertain the sensitivity of grain size parameters for differentiating sediments within a single environmental system (Folk and Ward, 1957; Duane, 1964; Hubert, 1964; Davis, 1970, Cronan, 1971; Thomas et al, 1972a; 1972b).

Folk and Ward (1957) working with coarse river sediments concluded that the sediment properties could be defined by the variable mixing of a sand and gravel population. Spencer (1963) in theoretical observations of grain size distribution data of earlier authors, and noting the dearth of sediment material in the coarse silt size range (Hough, 1942; Pettijohn, 1957; Wolff, 1964), concluded that all sediments could be described by the mixing of three or less modal populations consisting of gravel, sand and clay. This hypothesis has been utilized successfully to account for the variations in sediment texture in a number of aqueous environments both marine (Cronan, 1971; Davis, 1970; Jones, 1971) and lacustrine (Thomas et al,1972a; 1972b). With the acceptance of the above hypothesis it becomes relatively simple to define particle size distribution in terms of energy dispersion in an aqueous system.

Within the context of this paper it is not feasible to enter into a discussion of the entire range of sedimentological environmental studies, but rather to cite an example in which an effort has been made to define sediment energy regimes within a lacustrine situation. Few such examples exist, though from the existing literature there appears to be a remarkable similarity between the marine and lacustrine environments. This is not surprising since a sediment distribution pattern involving erosion, transport and deposition is the direct result of the interaction of environmental energy and the hydraulic properties of the sediment particle. Since the latter variable is essentially constant then sediment particle distribution in its simplest form is an energy dependent function.

As a specific example the authors have selected the studies undertaken on the Petit Lac (Fig.7), or Western Lake Geneva (Vernet and Thomas, 1972) due to the fact that this lake (an Alpine front lake) shows similarities to those occurring in Western Canada. However, it should be noted that the sediment characteristics of Lake Geneva are in agreement with the data recorded in the Laurentian Great Lakes (Thomas et al, 1972a and 1972b). The particle size discussion presented below is limited to those aspects of the sedimentology of the Petit Lac which are applicable to the definition of the energy regimes in the system.

From the analyses of the total range of grain sizes occurring in a sediment sample, four statistical parameters defining the grain size distribution are derived as follows:

(1) Mean grain size - the arithmetic mean of the grain size distribution.

(2) Standard Deviation - the spread of grain size values around the mean.

(3) Skewness - the degree of asymmetry from a normal distribution curve. Positive skewness signifies dominant coarse material tailing in the finer particle sizes, where negative skewness defines the inverse, dominant fine material with tailing of the distribution curve towards the coarse material.

(4) Kurtosis - defines the degree of <u>peakedness</u> of the distribution curve relative to a normal distribtuion. Positive kurtosis devotes a sharp peaked curve whereas negative kurtosis defines a flattened curve.

The sediments of the Petit Lac may be defined as being composed of mixtures of two end member size populations in the sand and clay ranges.

The size characteristics vary relative to the proportions of these two populations, with the degree of mixing controlled by the net energy available at the sediment-water interface. High energy shallow waters are characterized by the coarse sand population whereas deep water sediments, under low energy conditions, are characterized by the clay size material. Between these two extremes the energy gradient results in mixed populations with a sympathetic variation in the mean grain size (Vernet and Thomas, 1972).

Variations in skewness and kurtosis have proved valuable in providing some spacial concepts in the distribution of energy within the Petit Lac. Each end member population shows a grain size distribution with specific and characteristic symmetry. Both have positive kurtosis but display signs of skewness. The sand population is positively skewed, whereas the clay population is negatively skewed. Mixtures of these populations show gradational variations in the numerical values for both skewness and kurtosis as shown in Fig. 8. These can be related to net energy conditions in the lake. To this end Fig. 8 has been subdivided into zones A to F representing a continuous energy gradient from high energy (Zone A) to low energy (Zone F). The distribution of these energy zones in the Petit Lac is shown in Fig 9., which conforms remarkably to inshore-offshore energy gradients from shallow to deep water conditions. Similar energy patterns have been observed in Lakes Ontario and Huron (Thomas et al. 1972a, 1972b). All the lakes demonstrate a bathymetrical or depth controlled dissipation of wind generated initial energy. A different situation has been observed under shallow water conditions in Lake Erie, in which energy distribution is a function of mean wind direction and fetch, (Thomas, unpublished data). Under these conditions the sediment characteristics remain energy controlled, but do not demonstrate bathymetrical response. Rather they respond in progressive manner, becoming coarser in a downwind direction relative to the mean wind direction over the lake.

This discussion has illustrated the inter-relationship of energy to sediment characteristics. Sediments are, however, dynamic constituents in the lacustrine environment, and (particularly in the near-shore environment) undergo movement relative to major movements of the overlying water masses. This is not discussed in detail here but it can be stated that the directions of such movement can be inferred from the grain size characteristics. Good examples of such studies in lakes exist: i.e. in Lake Ontario,(Lewis and Sly 1971), and Lake Winnipeg,(Veldman 1969) and Kushnir 1971).

SUMMARY

A number of widely differing examples of lacustrine-geological studies have been considered, some from published data and many from studies currently underway. The difficulty in providing adequate examples from Western Canada is a matter of immediate concern; and highlights the need for the involvement of geologists in Western Canadian lake studies.

The authors have attempted to show that useful data may be generated from such geological studies, and that it may be related to a number of aspects which, for convenience, have been considered as related to evolutionary trends, chemical cycles and energy regimes. There are, in fact, many other aspects where geological studies can assist the role of basin management but limitations of space have precluded their inclusion in this discussion.

The authors contend that geological studies, such as just described, have four significant levels of contribution to the "information package" necessary for management decisions.

(1) As a primary tool in assessing how the various processes within a given lake system interrelate. This also includes the provision of basic data from which frameworks can be assembled for the detailed study of various significant processes.

As an example let us say that lake "X" has never been studied, and it is important to develop an understanding of its mass circulation. The integration of geologic data with point data of a physical nature (current meter data, drift data, etc.) offers

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a much more potent level of information than if purely short-term physical circulation studies are carried out.

(2) As a specialist tool in its own right, i.e. to provide data which can be obtained by no other means. The discussion on sediment - phosphorus relationships is an excellent example of this.

(3) As a means of "follow-up" after man-induced changes in a system. The geological tool is at an advantage again because of its ability to integrate and "net" the effect of minor fluctuations.

(4) As a means of providing meaningful synoptic data, without the necessity of a massive and instantaneous data collection.

Within the context of the preceding discussions, the authors contend that geological studies offer significant information at relatively low cost to basin management teams and should receive more attention when considering the development of environmental understanding of lake systems.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. J. D. H. Williams of the Canada Centre for Inland Waters and to Dr. T. W. Anderson of the Geological Survey of Canada for their assistance in preparing this paper. Further thanks are expressed to Dr. R. A. Vollenweider, Chief, Lakes Research Division, to Mr. J. P. Bruce, Director, Canada Centre for Inland Waters, and to Dr. A. T. Prince, Director-General, Inland Waters Directorate for reviewing the paper and for their helpful comments.

Finally, thanks are due to the Okanagan Basin Study Group and in particular to Mr. A. M. Thomson, Study Director, for encouragement and support during the collection of certain of the data presented in this paper.

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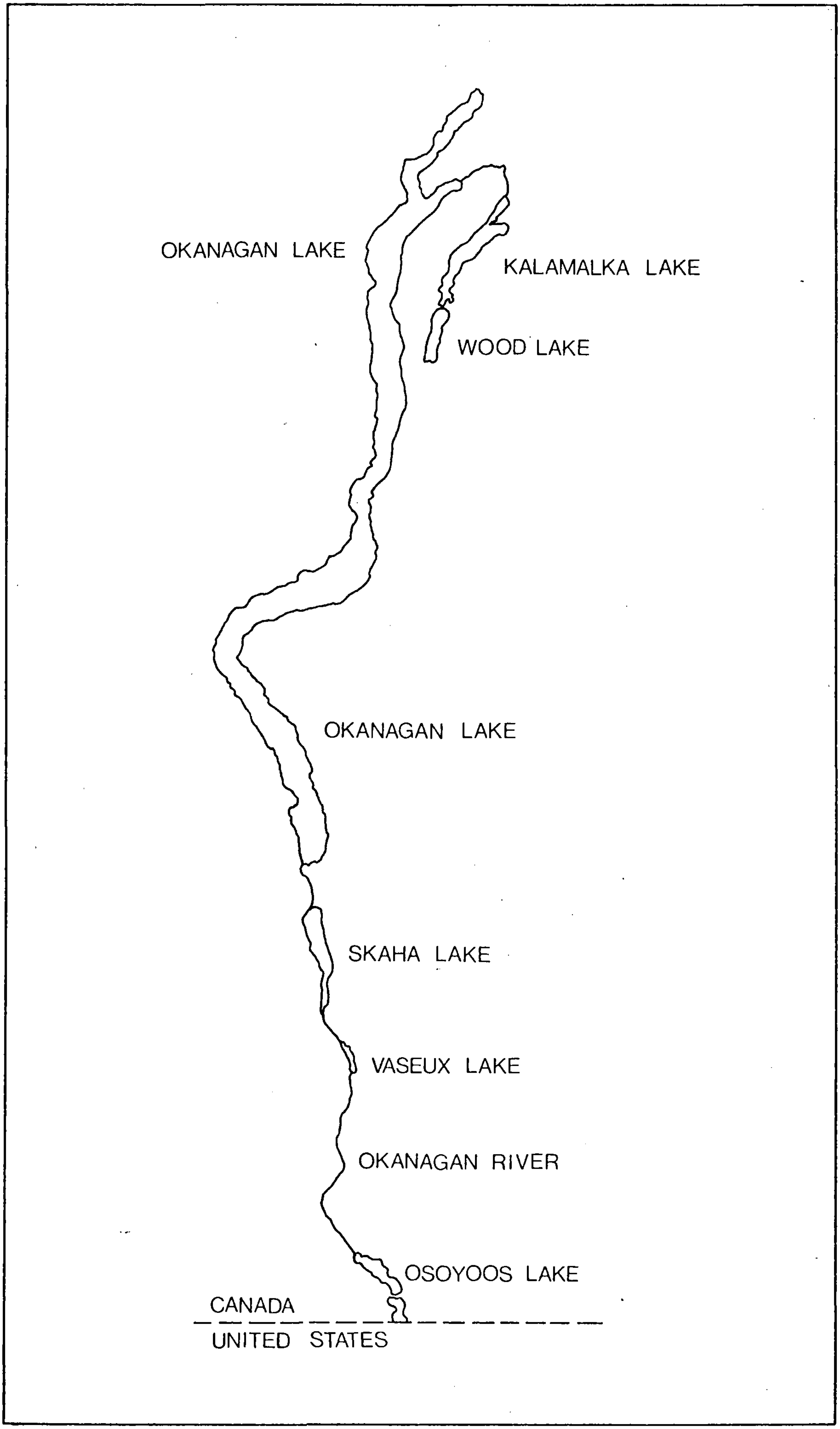
LIST OF TEXT FIGURES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KALAMALKA LAKE
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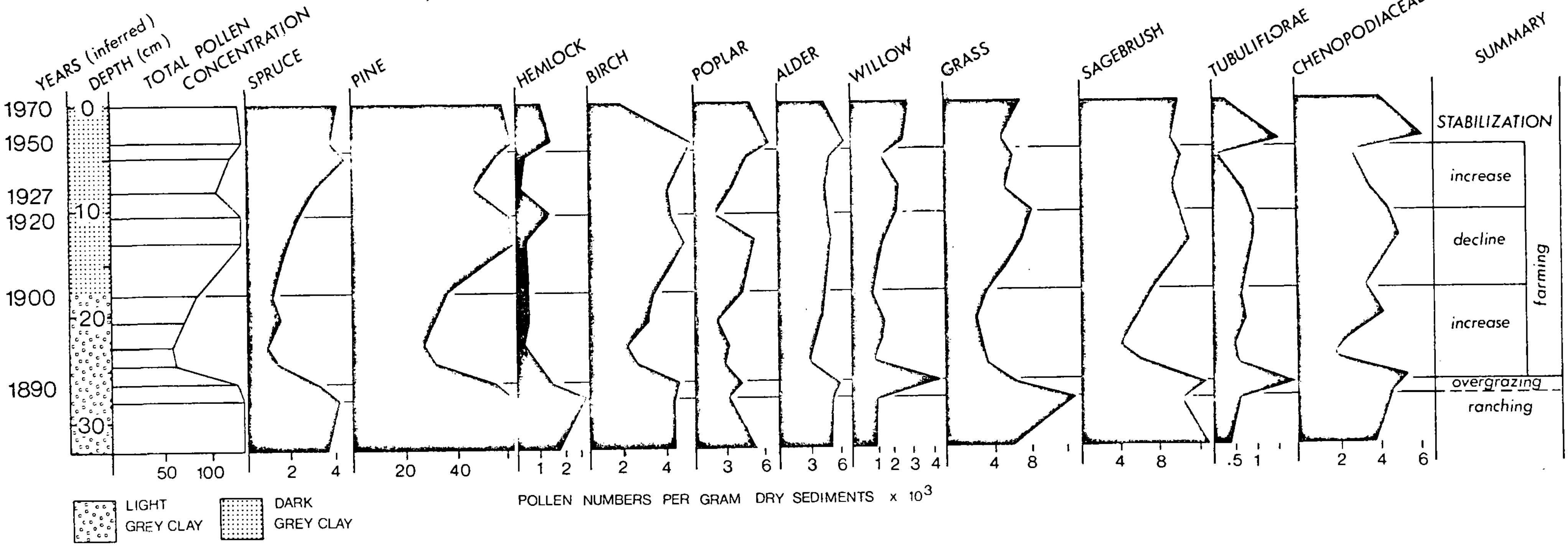
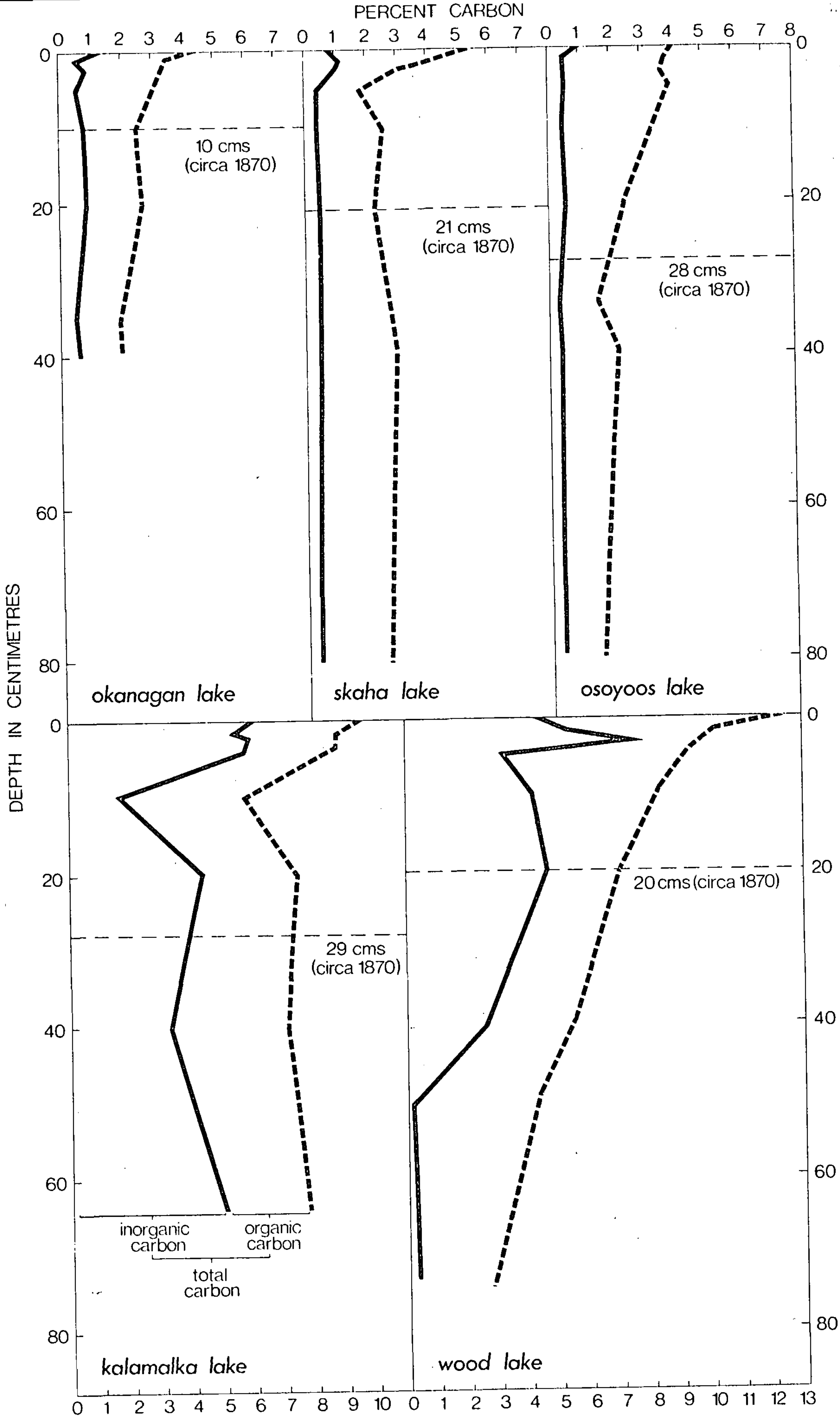
VASEUX LAKE
OKANAGAN RIVER
OSOYOOS LAKE
CANADA
UNITED STATES

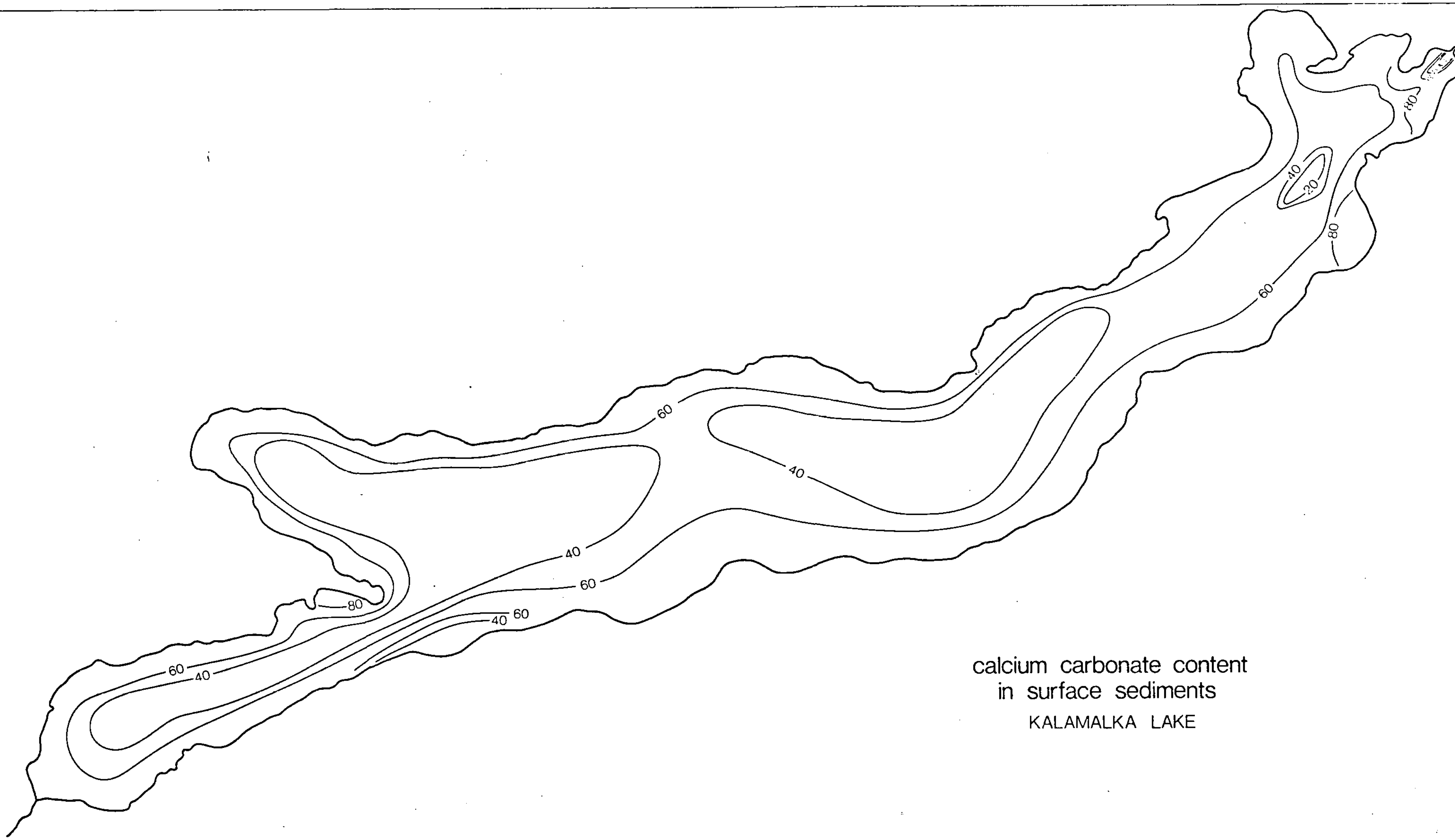
OSOYOOS LAKE, B.C.





profiles of carbon content of cores from the okanagan mainstem lakes

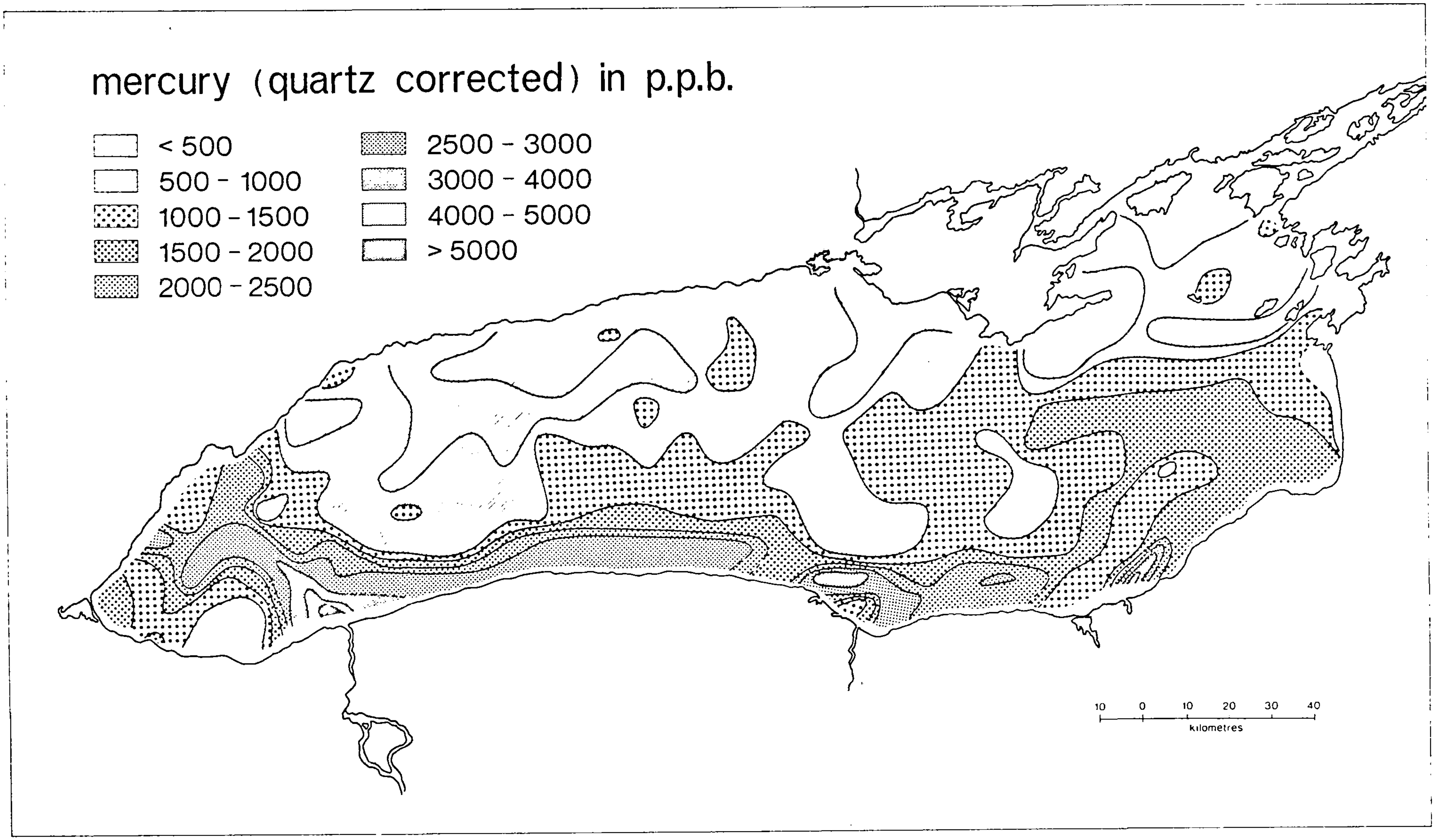
carbon data from Dr. A.L.W. Kemp C.C.I.W



calcium carbonate content
in surface sediments
KALAMALKA LAKE

contour interval - 20% $CaCO_3$ by weight

B.E. St John Task 121


mercury (quartz corrected) in p.p.b.
< 500
500 - 1000
1000 - 1500
1500 - 2000
2000 - 2500
2500 - 3000
3000 - 4000
4000 - 5000
> 5000
10 0 10 20 30 40
kilometres

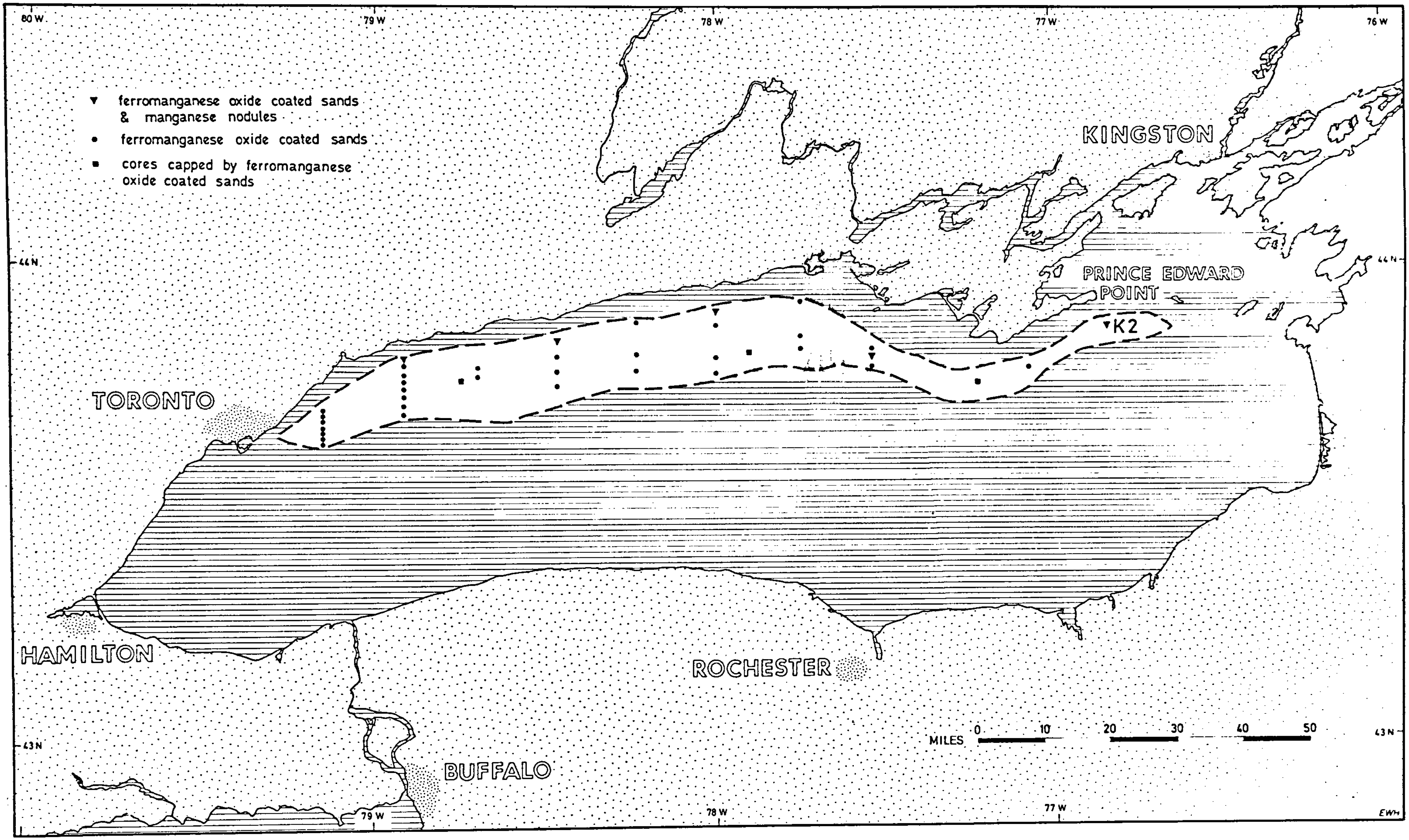
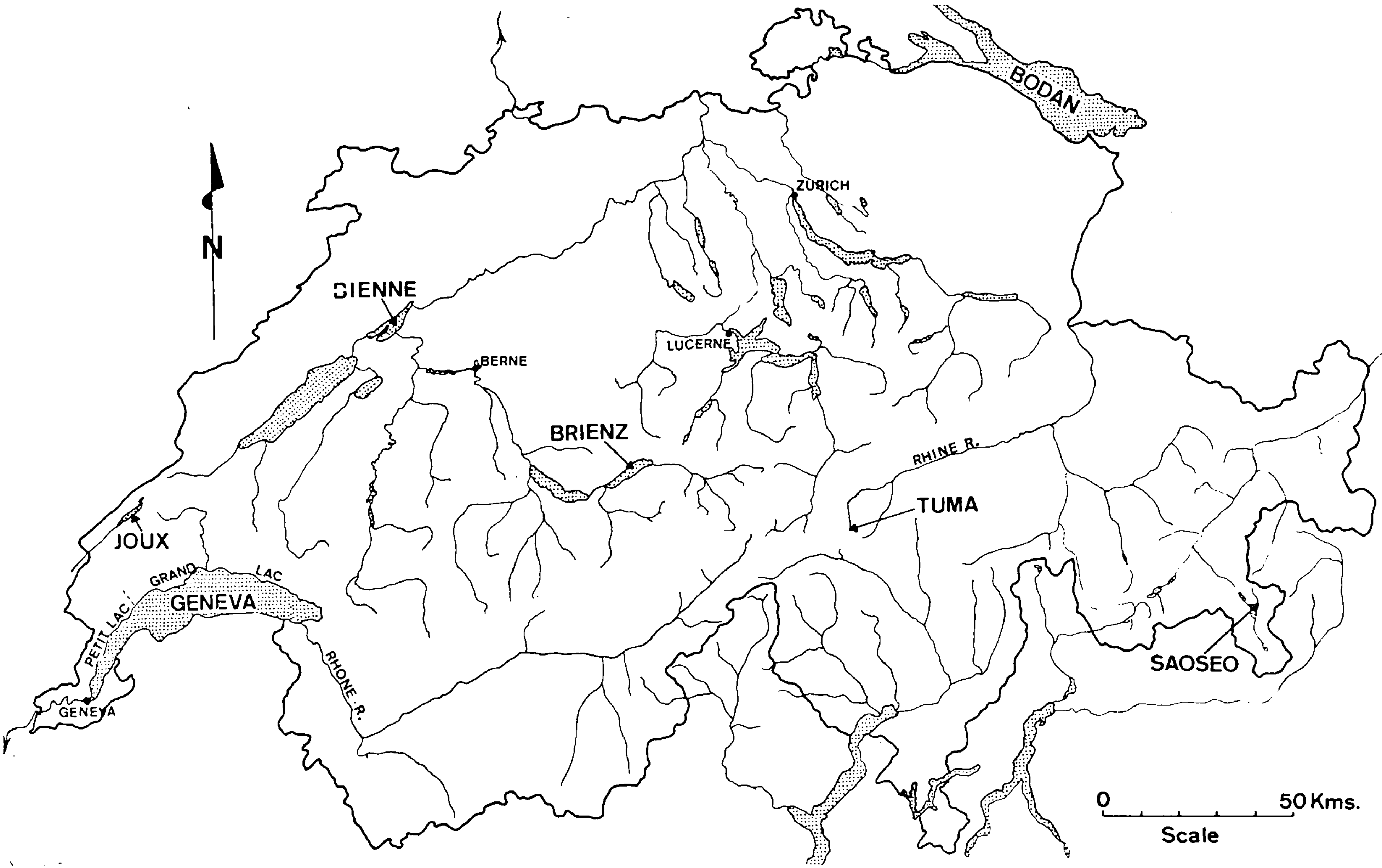
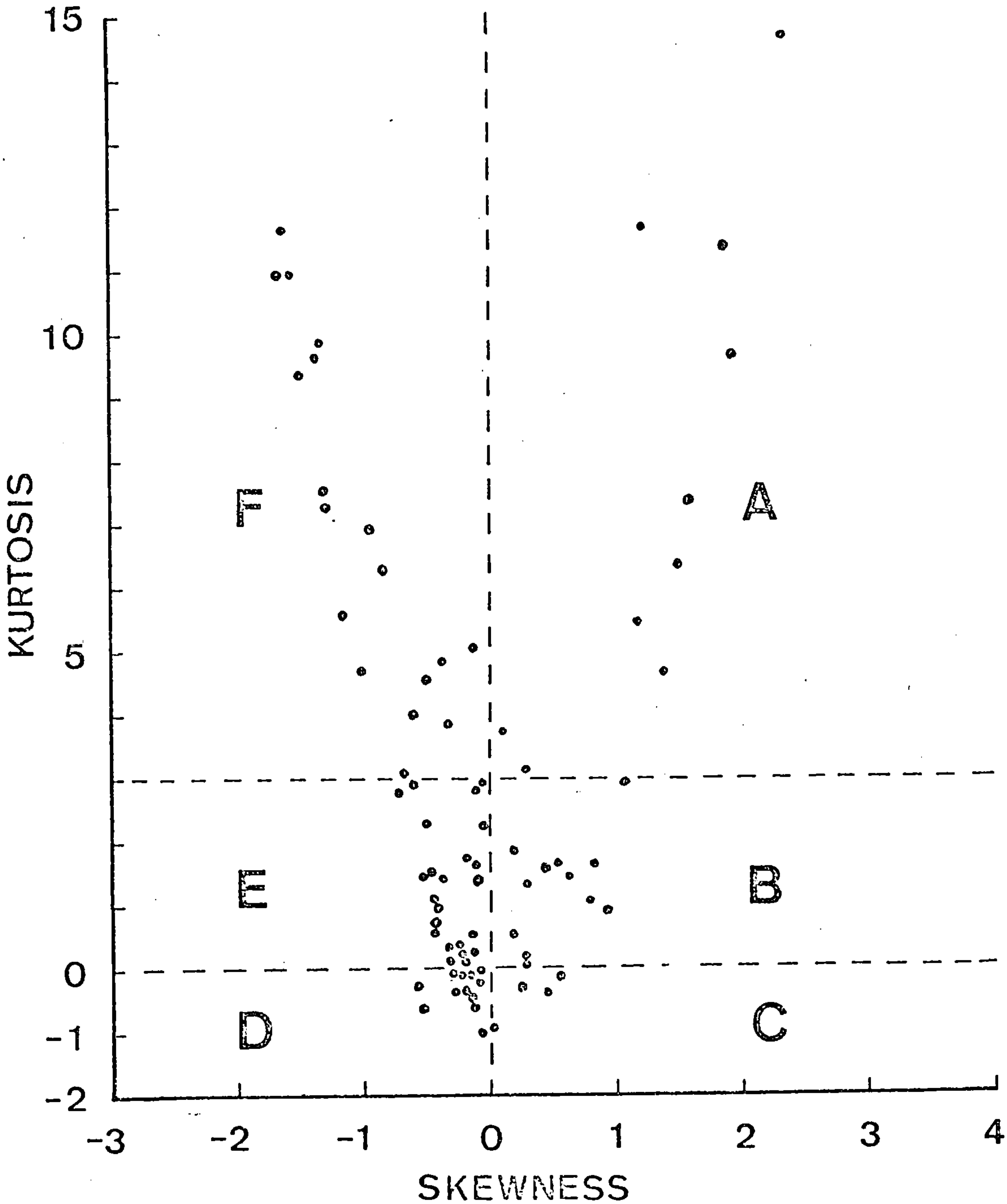

80 W
79 W
78 W
77 W
76 W
44 N
43 N
ferromanganese oxide coated sands & manganese nodules
ferromanganese oxide coated sands
cores capped by ferromanganese oxide coated sands
KINGSTON
PRINCE EDWARD POINT
K2
TORONTO
HAMILTON
ROCHESTER
BUFFALO
MILES
0
10
20
30
40
50
EWH

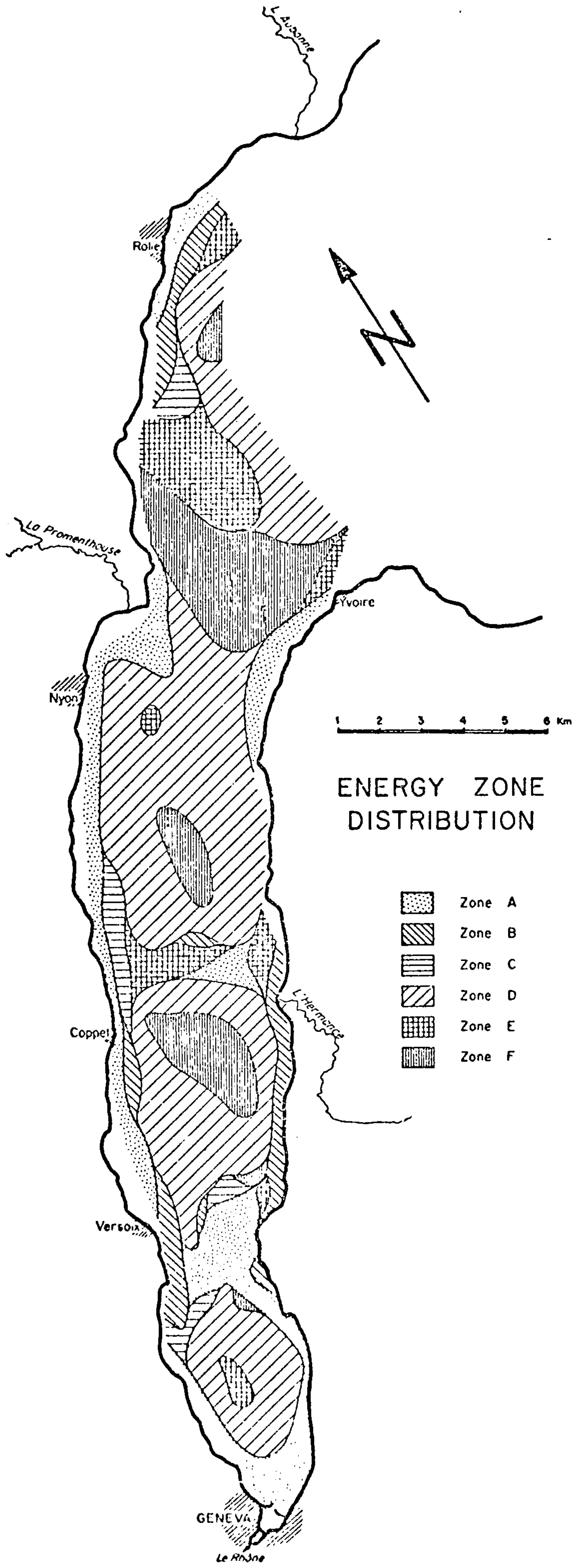
Fig. 6



N
BODAN
ZURICH
DIENNE
BERNE
LUCERNE
BRIENZ
RHINE R.
TUMA
JOUX
GRAND
LAC
GENEVA
PETIT LAC
GENEVA
RHONE R.
SAOSEO
0
50 Kms.
Scale



15
10
5
0
-1
-2
KURTOSIS
F
A
E
B
D
C
-3
-2
-1
0
1
2
3
4
SKEWNESS



L'Aubonne
Rolle
La Promenthouse
Yvoire
Nyon
1 2 3 4 5 6 Km
ENERGY ZONE
DISTRIBUTION
Zone A
Zone B
Zone C
Zone D
Zone E
Zone F
L'Hermance
Coppet
Versoix
GENEVA
Le Rhône