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MAGNETIC AND SEISMIC REFLECTION SURVEYS OF LAKE SUPERIOR

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MAGNETIC AND SEISMIC REFLECTION SURVEYS OF LAKE SUPERIOR

BY

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PREFACE

Since 1969, personnel of the University of Wisconsin Sea Grant Program have been engaged in an exploration survey of the potentially copper-bearing rocks beneath Lake Superior, chiefly off the Keweenaw Peninsula. This investigation -- including geochemical, sedimentological, and geophysical studies -- was initiated to assess the copper potential as well as develop new methods for locating similar underwater lode deposits elsewhere in the Great Lakes. Further impetus has been given to the copper survey as a result of losses in American copper sources overseas, increased industrial demand for copper, and, of no less importance, the need to revitalize the industrial employment base in the Upper Peninsula. As the geophysical mapping of the lake floor and rocks beneath is fundamental to commercial involvement, Mr. Brzozowy's investigation, particularly his findings on fault patterns, is of immediate interest to the industrial sector. Accordingly, I have requested that Mr. Brzozowy's report be published for wider circulation.

Comments and observations regarding this study are solicited.

Professor J. Robert Moore
Coordinator
Sea Grant Minerals Program

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ABSTRACT

Precambrian rocks of Keweenawan age form a large syncline in the Lake Superior region. The north limb of this syncline is exposed in northeastern Minnesota, along the northern and eastern shores of the lake, and on islands within the lake. The south limb of the syncline is exposed in northern Wisconsin and on the Keweenaw Peninsula of Michigan.

The structure north and east of the Keweenaw Peninsula was studied. Approximately 1,000 track miles of magnetic and seismic data were collected. The magnetic data consist of total magnetic intensity profiles; the seismic data consist of continuous reflection profiles.

An isochron contour map of unconsolidated sediments was constructed; thickness of these sediments ranges from 0 to 400 feet. A map of bedrock topography was constructed. The trend of the bedrock surface parallels the bathymetry of Lake Superior and the elevation of this surface deepens towards the axis of the Lake Superior syncline. The patterns of unconsolidated sediments and bedrock topography are a result of glacial erosion and deposition.

A total magnetic intensity map was constructed. The magnetic anomaly pattern, that correlates with the rock units on the Keweenaw Peninsula, extends eastward to Manitou Island. To the southeast of Manitou Island, this anomaly pattern curves to the southeast following the strike of the Keweenawan lavas, and decreases in amplitude. This amplitude decrease may be explained by burial of the Keweenawan lavas by late Keweenawan or Paleozoic sediments.

Magnetic and seismic profiles were studied in detail. Southwest of Eagle Harbor, Michigan, a magnetic anomaly correlates with a north-south trending normal fault. The Keweenaw fault was located offshore between Manitou Island and Keweenaw Point. Relative magnetic maxima and minima correlate with known geology in this area. In the Stannard Rock area, no evidence of faulting was observed on the seismic profiles. This lack of evidence may, however, be due to the limitations of the seismic system.

From the offshore area between Keweenaw Point and Manitou Island, the Keweenaw fault may curve to the southeast and pass to the southwest of Stannard Rock. Instead of following the above path, the Keweenaw fault may extend eastward and join an east-west trending fault located to the south of Caribou Island.

These magnetic and seismic data provide no evidence to substantiate the existence of the proposed north-south trending fault that extends from Ashburton Bay to Big Bay. The seismic data provide no evidence to substantiate the existence of the east-west trending fault located to the south of Caribou Island, however, a change in the magnetic anomaly pattern between Manitou Island and Stannard Rock may provide evidence for the existence of this east-west fault.

INTRODUCTION

The Lake Superior region has been the subject of geophysical investigations for the past 15 to 20 years. The continuous seismic profiling studies completed by the University of Wisconsin-Madison Geophysical & Polar Research Center and the aeromagnetic and gravity surveys completed in the area provided regional geophysical coverage of the Lake Superior area. The results of these surveys showed the need for more detailed coverage in the offshore Keweenaw Peninsula area in order to more accurately evaluate the regional structure of the area.

From August 26 to September 2 of 1971, I was involved in a geophysical survey of Lake Superior in an area located to the north and southeast of the Keweenaw Peninsula. The purpose of this survey was to study the structure of the area and to assess the potential of copper deposits in the waters surrounding the Keweenaw copper producing district. Approximately 1,000 track miles of data were gathered. The data consisted of continuous air gun seismic profiles, sono-buoy refraction profiles, continuous magnetometer profiles, high resolution profiles, and some 200 grab and dredge samples of the lake bottom. The lines along which the data were gathered and the limits of the study are illustrated in Plate I. This paper is primarily concerned with the results of the air gun seismic and magnetic data and their relation to the structural framework of the study area and the Lake Superior region.

GEOLOGICAL SETTING

Structural Features of the Lake Superior Region

The major structural features that border the Lake Superior basin include the Michigan basin, the Wisconsin arch, the mid-continent gravity high, and the Keweenaw, Douglas, and Lake Owen faults. Within Lake Superior proper, the major structural features include the Lake Superior syncline, the Keweenaw fault, the Isle Royale fault, and some faults in the eastern part of the lake that were located by the use of geophysical methods (Fig. 1).

The Precambrian rocks of Keweenawan age form a large syncline which encloses most of the Lake Superior basin. The location of the syncline axis (Fig. 1) was deduced from the attitude of exposed Keweenawan rocks from within and around the Lake Superior basin. The north limb of the syncline is exposed in northern Wisconsin, along the northwestern and northeastern shores of Lake Superior, and on islands within the lake. In the northeastern portion of Minnesota and on Isle Royale (Fig. 1), Keweenawan rocks have a dip of 10° to 30° to the southeast. On the north shore of the Lake and on Isle St. Ignace, Keweenawan rocks have a dip to the south. On Michipicoten Island, dips of 17° to 44° to the south were recorded for Keweenawan rocks (Halls, 1966, pp. 15, 21). The north limb of the syncline bends to the southeast somewhere to the east of

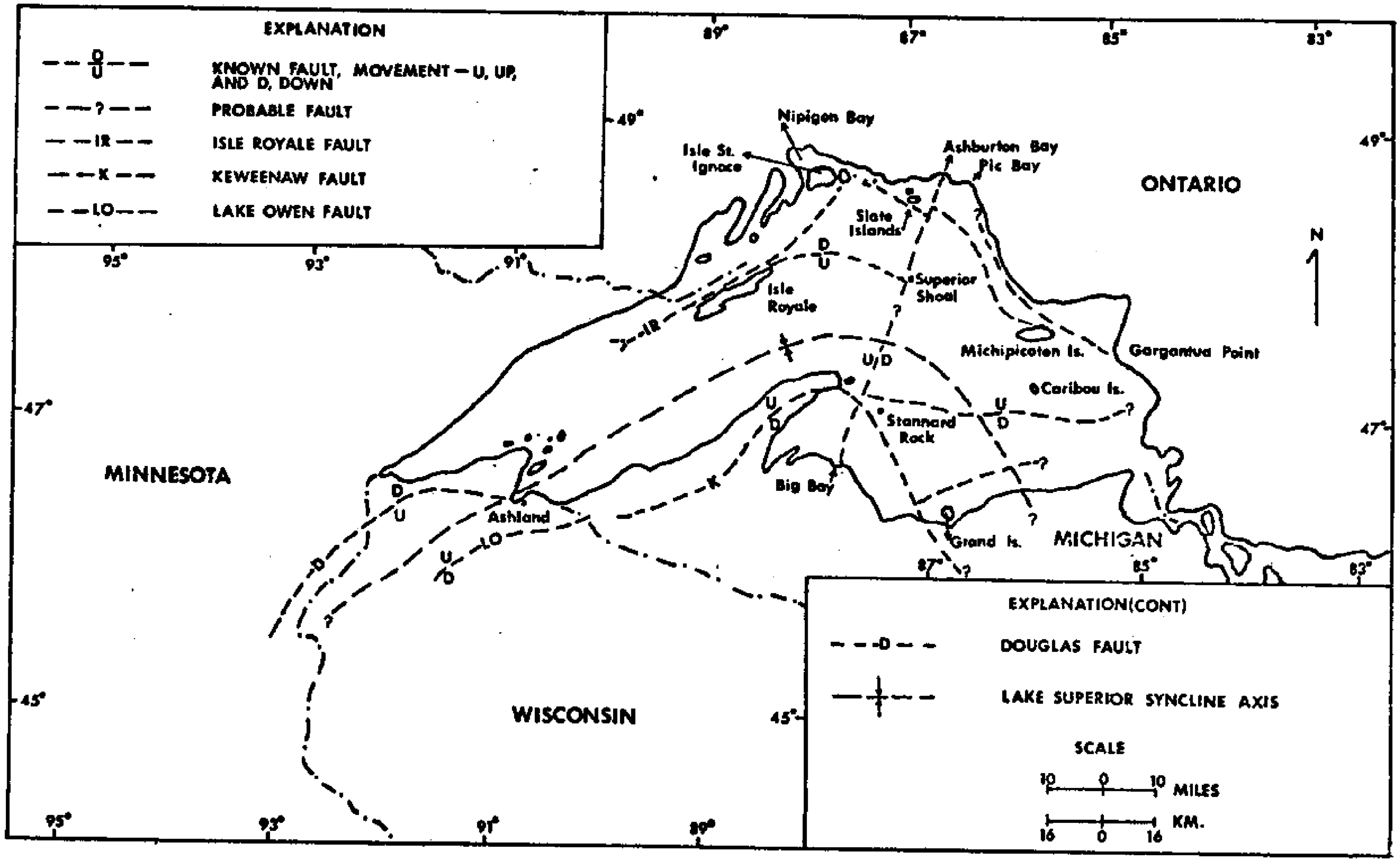

Figure 1. Structure map of the Lake Superior region. Modified from Halls (1966), Hinze and others (1966), and Wold and Ostenso (1966).

Michipicoten Island. Evidence for this bending is seen in the southwest dip direction of the Keweenawan volcanics on the eastern shore of Lake Superior (Halls, 1966, p. 21).

The south limb of the syncline is exposed in northern Wisconsin and on the Keweenaw Peninsula (Fig. 1). On the Keweenaw Peninsula, dips as high as 70° to the northwest have been recorded. The inland extension of the Lake Superior syncline is exposed near Ashland, Wisconsin. In this area, rocks on the north limb of the syncline have a dip of 40° to 60° to the southeast; the rocks on the south limb have a dip of 30° to 60° to the northwest. "Although structure contours clearly show closure of the syncline south of Duluth, gravity, aeromagnetic and borehole data suggest that the Keweenawan rocks continue southward in a narrow trough for a distance of some 500 miles into Kansas (Halls, 1966, p.3)."

The mid-continent gravity high is one of the most prominent gravitational features in the United States. According to Thiel (1956, p. 1080), local gravitational changes along this high, which extends into Kansas, reach 150 milligals. The gravity high has been correlated by Thiel (1956) to Keweenawan volcanic rocks and gabbro that outcrop in northern Wisconsin and Minnesota. The gravity lows which border the east and west flanks of the high have been attributed to sediments. Coons and others (1967, p. 2384) state that in areas where no clastic sediments are present in the outcrop area, gravity lows are not found adjacent to the gravity high. Cohen and Meyer (1966, p. 142) suggest that these gravity lows may be underlain at depth by a material of basic composition and high density.

The Douglas fault (Fig. 1), located on the north limb of the syncline in northern Wisconsin, is a reverse fault and forms the contact between the older middle Keweenawan volcanics on its upthrown block to the southeast and the younger Upper Bayfield group sediments to the northwest. The Lake Owen fault, located on the south limb of the syncline, is a reverse fault with its upthrown block to the northeast (Halls, 1966, p. 10). The Lake Owen fault, (Fig. 1), is a possible westward extension of the Keweenaw fault. Both faults, however, are obscured in the Mellen, Wisconsin, area by a gabbro intrusion and cross faults (Wold and Ostenso, 1966, p. 69).

The Keweenaw fault is a high angle, reverse fault, which is located along the Keweenaw Peninsula. The fault has a strike approximately parallel to the strike of the Lake Superior syncline axis, and its downthrown block is to the south (Halls, 1966, p.6). One possible lakeward extension of the Keweenaw fault (Fig. 1), has been postulated to extend eastward into Lake Superior, bend sharply to the southeast, and intersect the eastern Upper Peninsula of Michigan to the west of Grand Island (Hinze and others, 1966, p. 105).

The existence of the Isle Royale fault, originally postulated on geological grounds by Van Hise and Leith (1911), was confirmed by the aeromagnetic data of Wold and Ostenso (1966, p. 82). The Isle Royale fault has a strike approximately parallel to the strike of the Lake Superior syncline axis and is located to the north of Isle Royale (Fig. 1). This fault, with its downthrown block to the north, extends in a westerly direction to about longitude 90°10'W and in an easterly direction to approximately longitude 88°30'W where it biforcates. One branch trends northeasterly towards Isle St. Ignace, while the other branch trends in an easterly direction until it is terminated near Superior Shoal by a north-south fault (Fig. 1) that extends from Ashburton Bay to Big Bay (Wold and Ostenso, 1966, p. 83; Hinze and others, 1966, p. 105).

On the basis of aeromagnetic data, Hinze and others (1966, p. 105) suggest the existence of several faults in the eastern portion of the lake. One such possible fault has a northwest strike and extends from the north shore of Michipicoten Island to the vicinity of the Slate Islands (Fig. 1). Near Slate Islands, this fault is offset by the same north-south fault that terminates the Isle Royale fault. To the northwest of this north-south fault, an extension of the fault from Michipicoten Island has a northwest strike and extends towards Nipigon Bay (Fig. 1). A second postulated fault extends northwesterly from Gargantua Point to Pic Bay. A third fault (a second possible extension of the Keweenaw fault), which is located to the south of Caribou Island, has also been postulated. A fourth fault that trends east-west has been located about 10 to 15 miles to the north of Grand Island (Fig. 1).

The north-south trending bottom topography (Fig. 7) of eastern Lake Superior is in sharp contrast to the northeast-southwest trending bottom topography of the western portion of the lake. The magnetic data of Hinze and others (1966) offer no direct explanation for the north-south, sublacustarine topographic features in the eastern portion of the lake. Hinze and others (1966) suggest that the strike of the eastern Lake Superior structural basin is approximately north-south and that "possibly a structural alignment controlling the topography lies in a parallel direction."

General Geology of the Lake Superior Region

Northeastern Shore

The northeastern shore of Lake Superior from Schrieber, Ontario to Sault Ste. Marie is composed mainly of Archean age rocks with exposures of Keweenawan age lavas and sediments in isolated localities (Fig. 2). According to Van Hise and Leith (1911, p. 392), the thickest accumulations of Keweenawan basic volcanics and interflow sediments occur on Mamaise Point, where they are about 15,000 feet thick. The strike of these rocks at this location is

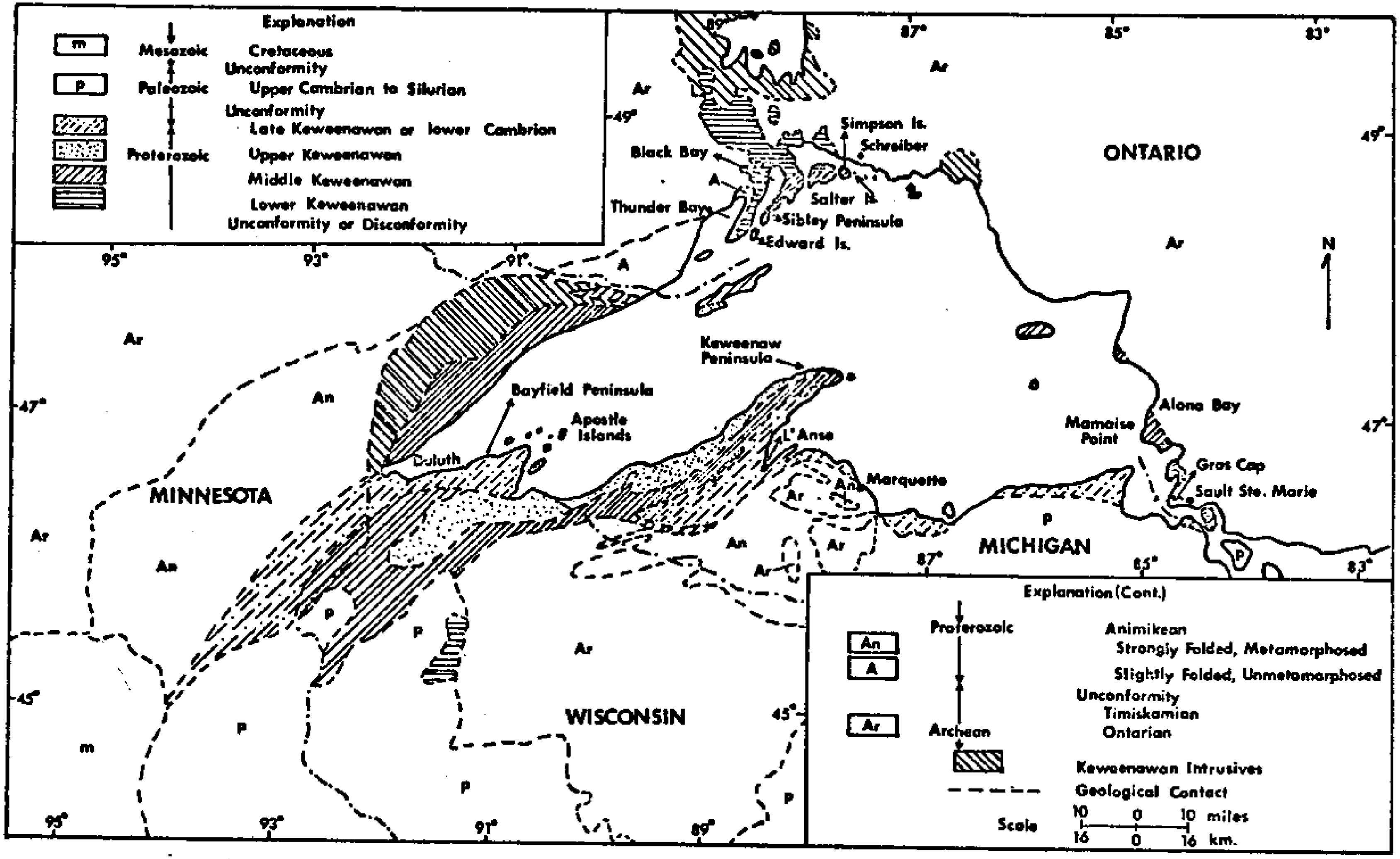

Figure 2. General geologic map of the Lake Superior region. Modified from Halls (1966, p. 4).

approximately north-south, and the dip ranges from 20° to 30° to the west. Minor exposures of middle Keweenawan rocks occur at Gangantua Point (Fig. 1), Alona Bay, and Gros Cap. At these locations, the Keweenawan rocks are erosional remnants approximately 3,000 feet thick. Within eastern Lake Superior proper, exposures of Keweenawan volcanic rocks are confined to Michipicoten Island, Superior Shoal, and Stannard Rock (Halls, 1966, p. 20).

Michipicoten Island is composed of middle Keweenawan acidic and basic flows estimated by Annels (1970, p. 7) to be 11,500 feet thick. Rocks on the island have an east-west strike and the dip of the strata is to the south. At the northwestern end of the island, the strike changes to a northwesterly-southeasterly direction, and the dip direction is to the southeast. According to Burwash (1905, p. 43), this change in strike may be due to a south-plunging anticline with its apex and eastern limb exposed and its western limb concealed beneath Lake Superior. Middle Keweenawan conglomerates also occur on Isle Royale.

According to Parker (1964, p. 19, 21), samples of bedrock dredged from Stannard Rock and Superior Shoal indicate that the floor of Lake Superior may be composed of middle Keweenawan lavas at these locations. Irving (1883, p. 139) describes the rocks of Stannard Rock as "non-quartziferous porphyry and, thus, belonging to the Keweenawan series." DuBois (1962, p. 20) suggests that eastern Lake Superior is underlain by Keweenawan rocks. Coleman (1899, p. 143) reported a sequence of Lake Superior group sandstone on Caribou Island. The small islands between Gargantua Point (Fig. 1) and Alona Bay (Fig. 2) are composed of undifferentiated, late Keweenawan sediments (Halls, 1966, p. 21).

Northwestern Shore

The northwestern shore of Lake Superior from Duluth, Minnesota, to Schrieber, Ontario, is composed mainly of Archean and Animikean age rocks, although all three divisions of the Keweenawan are also found in the area (Fig. 2). The lower Keweenawan sedimentary sequence attains its maximum thickness near Thunder Bay, Ontario, where it is known as the Sibley series. Middle Keweenawan lavas are known as the North Shore volcanic group along The Minnesota coast and as the Osler series in the Thunder Bay district (Halls, 1966, p. 15). Upper Keweenawan rocks outcrop on Isle Royale.

The northeastern Minnesota shore of Lake Superior is composed mainly of the middle Keweenawan Duluth complex and North Shore Volcanic group, which have a northeast strike; the dip of these strata is about 10° to 20° to the southeast. To the north of the middle Keweenawan rocks in this area, Archean rocks are exposed; to the west, Animikean rocks are found. From the Minnesota-Canada border to the west shore of Thunder Bay, Animikean rocks are intruded by middle Keweenawan diabase dikes. To the north of these Animikean rocks, Archean rocks are exposed (Halls, 1966, p. 15).

The north shore of Thunder Bay is composed of Archean rocks; the Sibley Peninsula is composed mainly of the lower Keweenawan Sibley series and minor amounts of Animikean sediments. The peninsula to the east of Black Bay is composed mainly of middle Keweenawan volcanics, which have a northeast strike; the dip of these rocks is to the southeast. Minor amounts of lower Keweenawan sediments are exposed in the northern portion of this peninsula (Halls, 1966, p. 15). Edward Island is composed of rocks of the Osler series, which have a northeast strike and the dip of these rocks is to the southeast. St. Ignace (Fig. 1), Simpson, and Salter Islands are composed of middle Keweenawan volcanics, which have an east-west strike and a southerly dip (Halls, 1966, p. 15).

Isle Royale is composed of middle Keweenawan volcanics and upper Keweenawan sediments. The strike of these rocks is northeast, and they dip to the southeast. Lane (1898) estimated the middle Keweenawan on Isle Royale to be at least 6,400 feet thick. He also correlated the Greenstone Ridge flow on Isle Royale with the Greenstone flow on the Keweenaw Peninsula and correlated the Isle Royale volcanic sequence with part of the Portage Lake lava series on the Keweenaw Peninsula. The upper Keweenawan rocks on Isle Royale are about 3,500 feet thick and consist of a conglomerate similar to the Copper Harbor formation of the Upper Peninsula of Michigan and a sandstone which conceivably might be the Freda or one of the sandstones of the Copper Harbor formation (Halls, 1966, p. 19).

Southern Shore

The southern shore of Lake Superior includes the area from Duluth, Minnesota, to Sault Ste. Marie. The area from Duluth, Minnesota to the Wisconsin-Michigan border is underlain by the following: the late Keweenawan or lower Cambrian Lower Bayfield group, which outcrops south of Duluth; the late Keweenawan or lower Cambrian Upper Bayfield group, which comprises the Bayfield Peninsula and Apostle Islands; the middle Keweenawan volcanics; and upper Keweenawan sediments of the Oronto group, which consists of the Copper Harbor conglomerate, the Nonesuch shale, and the Freda formation. The Oronto group is exposed near Ashland, Wisconsin, (Halls, 1966, p. 10).

The area from L'Anse, Michigan, to Marquette, Michigan, is composed mainly of Archean and Animikean rocks intruded by pre-Keweenawan diabase dikes. The flat-lying Jacobsville sandstone of late Keweenawan or lower Cambrian age occurs in narrow outcrops along the Lake Superior shore in this area (Halls, 1966, p. 10).

From Marquette, Michigan, to Sault Ste. Marie, the geology consists of "off-lapping Cambrian, Orodovician, and Silurian sediments" which overlie the non-marine Jacobsville sandstone (Patenaude, 1964, p. 3). The Jacobsville sandstone occurs in narrow outcrops along most of the lake shore in this area. Patenaude (1964) suggests that regional aeromagnetic surveys of the eastern Upper Michigan area indicate that Keweenawan volcanics constitute some of the Precambrian basement beneath the overlying Jacobsville sandstone and Paleozoic sediments. Bacon(1957), on the basis of gravity data, suggests that Keweenawan rocks may persist southward from the eastern end of Lake Superior through the Lower Peninsula of Michigan.

The Keweenaw Peninsula has a Keweenawan sequence consisting of the middle Keweenawan Portage Lake lava series which are overlain to the north by a sequence of upper Keweenawan sediments of the Oronto group, which from oldest to youngest are the Copper Harbor conglomerate, the Nonesuch shale, and the Freda formation (Fig. 3). Southwest of Calumet, Michigan, the Keweenawan strata have a northeast strike and they dip to the northeast. Northeast of Calumet, Michigan, the strata have an east-west strike and northerly dip. The dips of the units within the Keweenawan sequence range from 0° to 70°, with a decrease in dip toward the top of the succession (Halls, 1966, p. 7). The southern boundary of the Portage Lake lava series is the Keweenaw fault. South of the Keweenaw fault, the flat-lying Jacobsville sandstone is exposed. Halls (1966, p. 6) suggests that the total thickness of the Portage Lake lavas is between 20,000 and 30,000 feet, however, only the upper 10,000 to 15,000 feet of the Portage Lake lavas are exposed on the Keweenaw Peninsula. The rest of the lava, according to Halls (1966, p. 6) is on the footwall of the Keweenaw fault covered by the Jacobsville sandstone.

According to VanHise and Leith (1911, p. 387), the Portage Lake lava series ranges in composition from basalt to andesite and is interbedded with thin conglomerate and sandstone layers, which may have a thickness of over 600 feet. Cornwall and Wright (1954) recognize over 300 flows in the exposed portion of the Portage Lake lavas. The most prominent flow in the Portage Lake lavas, the Greenstone flow, is traceable from the eastern end of the Keweenaw Peninsula to Houghton, Michigan (Halls, 1966, p. 8).

Butler and Burbank (1929, p. 21) state that the Keweenawan flows decrease in thickness away from the center of the Lake Superior basin. Bent-pipe amydgules in the lava, according to Hotchkiss (1923, p. 671) and Butler and Burbank (1929, p. 26), indicate that flowage of the lavas occurred outward from the center of the Lake Superior basin; however, current bedding and imbricate structure within the interflow sediments suggest that sediment derivation was from a southerly source (White and Wright, 1960; Hamblin and Horner, 1961).

The Copper Harbor conglomerate lies conformably on the Portage Lake lavas and is composed of "Rudely stratified pebble to boulder conglomerates with generally lesser amounts of sandstone and volcanics and a little tuffaceous material. The boulders and pebbles

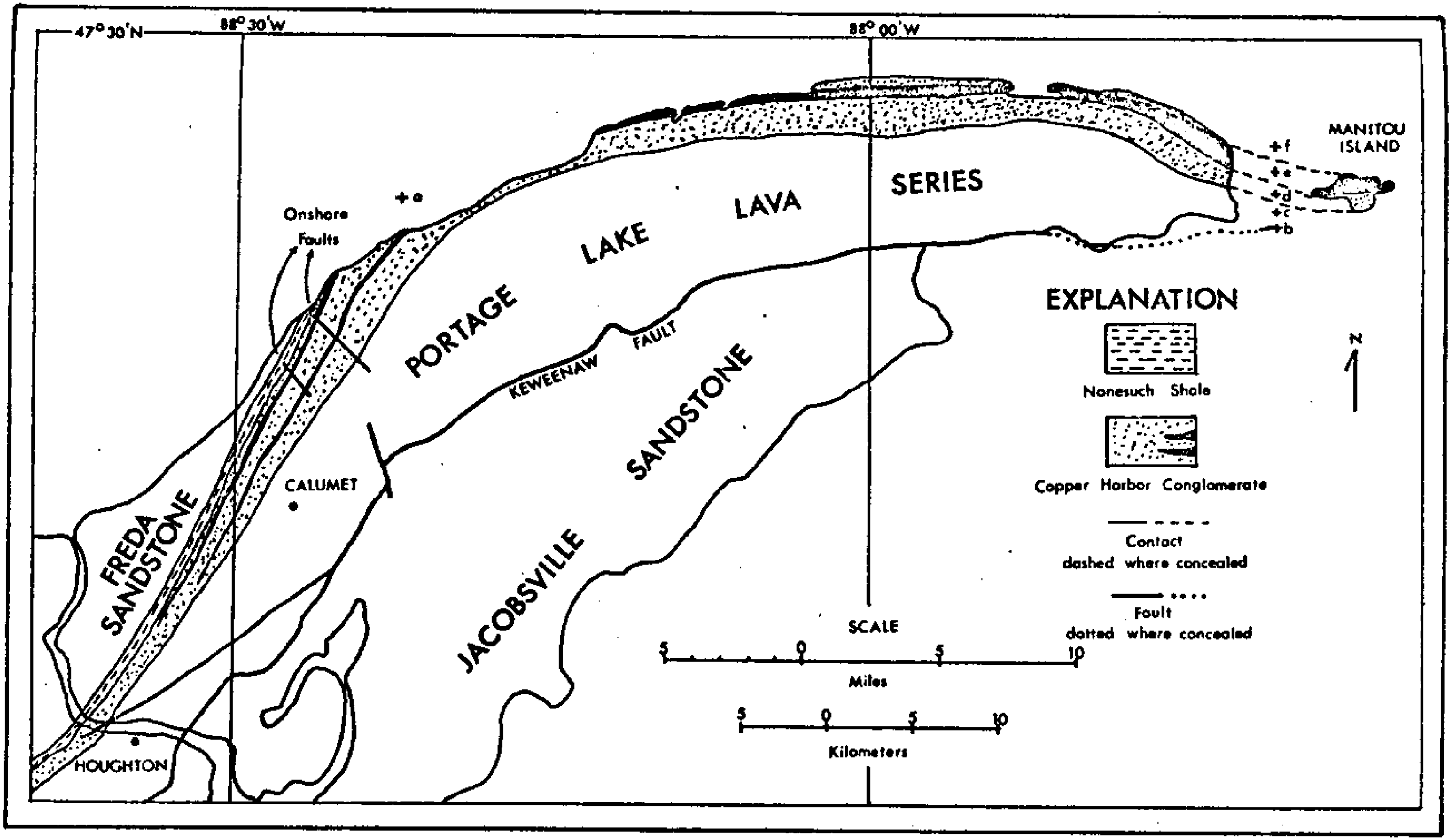

Figure 3. General geologic map of the Keweenaw Peninsula. Point a. marks an offshore normal fault and magnetic anomaly; point b. marks the offshore location of the Keweenaw fault. Points c. and e. mark magnetic maxima; points d. and f. mark magnetic minima. Modified from White (1972, p. F4).

consist primarily of rhyolite and granophyre; basalt and andesite fragments are generally subordinate (Halls, 1966, p. 8)." Lenses and more persistent layers of red, arkosic sandstone are also present within the Copper Harbor conglomerate (Halls, 1966, p. 8). Cornwall (1954c) reports thicknesses of up to 400 feet for these individual sandstone units, and that crossbedding within the sandstone shows that these sediments were transported from a southerly or southeasterly source (White and Wright, 1960; Hamblin and Horner, 1961).

Basic volcanics also occur within the Copper Harbor conglomerate. These volcanics reach their greatest development on the eastern end of the Keweenaw Peninsula (Irving, 1883).

The Copper Harbor conglomerate has a fairly uniform thickness of 4,000 to 5,000 feet on the Keweenaw Peninsula except near Houghton, Michigan, where it thins to about 2,000 feet. The contact of the Copper Harbor conglomerate with the overlying Nonesuch shale is abrupt (Halls, 1966, p. 9).

The Nonesuch shale is composed of fine-grained siltstones and retains a constant thickness of about 600 feet along the Keweenaw Peninsula. The Nonesuch shale thins to about 250 feet north of Mellen, Wisconsin, (White and Wright, 1954), and grades upward into the Freda formation (Halls, 1966, p. 9). The Freda formation, consisting of red, micaceous silty shale and interbedded arkosic sandstones, is about 5,000 feet thick on the Keweenaw Peninsula (Halls, 1966, p. 9).

The Jacobsville sandstone is a primarily quartzose, fine-to medium-grained, red and gray sandstone of late Keweenawan or lower Cambrian age. Its maximum thickness is estimated by Bacon (1964, p. 57) as 10,000 feet. According to Hamblin (1961), current bedding within the Jacobsville sandstone indicates a northerly direction of sediment transport.

The Geology of Manitou Island (Fig. 3) consists of the Copper Harbor conglomerate, which has an east-west strike and northerly dip. Slight deviations of the strike and dip from this general trend are observed on the eastern and northern tips of the island (Cornwall and Wright, 1955).

Within Lake Superior, in the offshore Keweenaw Peninsula area, a series of glacial, late-glacial lacustarine, and post-glacial sediments are found to overlie the sandstone bedrock identified by Farrand (1969, p. 36) as "probably Jacobsville sandstone." Zumberge and Gast (1961) identified bedrock in this area as a "sandstone of the Lake Superior group." Between Isle Royale and the Keweenaw Peninsula, bedrock was found to be overlain by 144 feet of glacial and lacustarine sediments (Zumberge and Gast, 1961).

Farrand (1969, p. 36, 37) states that a red clayey or silty till and well sorted brown sand immediately overlie bedrock in the offshore area to the north of the Keweenaw Peninsula. He dates these sediments as "not older than the end of the last glaciation in North America." Zumberge and Gast (1961) correlate the red till with the Valders of the Lake Superior region. Overlying the red till is a late-glacial sequence of red and gray varved clays. This varved clay sequence is, in turn, overlain by a post-glacial, homogeneous gray clay. In near shore areas, the varved clays are also overlain by a brown sandy sediment (Farrand, 1969).

PREVIOUS GEOPHYSICAL INVESTIGATIONS

Seismic Surveys

Interpretation of the data obtained from the 1963 Lake Superior seismic experiment shows that the crustal structure of the Lake Superior region is not uniform and simple. Within the crust, an upper refractor that has a seismic velocity of 6.67 km/sec underlies a section of Keweenawan sediments and volcanics estimated by Smith and others (1966, p. 181) to have a thickness of 4 to 6 km. This upper refractor is an undulating surface, which reaches a maximum depth, not greater than 15 km, to the east and west of the Keweenaw Peninsula (Berry and West, 1966, p. 161). The upper mantle velocity (Pn) is estimated by Berry and West (1966) to be approximately 8.1 km/sec and is estimated to be 8.3 km/sec by Smith and others (1964). The structure of the Moho is considered by Berry and West (1966, p. 180) to be basin-like and east-dipping at a depth of about 35 km at the western end of the lake and at a depth of about 60 km at the eastern end of the lake. Smith and others (1966, p. 181) estimate the depth of the Moho to be at least 55 km at the eastern end of the lake and to be about 20 km to the west.

The first continuous seismic profiling study within the lake was conducted by Zumberge and Gast (1961) and consisted of about 250 miles of traverses. The University of Wisconsin-Madison Geophysical and Polar Research Center conducted a continuous seismic profiling study in western Lake Superior in 1965, during which about 900 miles of profile were gathered. The results of this survey showed the maximum depth of penetration to be 0.25 second with horizons deeper than 0.1 second commonly observed (Wold and Ostenso, 1966, p. 72). The University of Wisconsin-Madison Geophysical & Polar Research Center also conducted continuous seismic profiling studies within the remainder of the lake during the summers of 1966 and 1967. The results of these surveys have not yet been published.

Bacon (1964), using seismic reflection data, determined that the thickness of the Jacobsville sandstone is about 10,000 feet and that the throw of the Keweenaw fault is approximately 10,000 feet. Bacon and others (1968, p. 14) made vertical velocity, density, and porosity determinations in the Jacobsville sandstone.

Magnetic Surveys

Balsley and others (1962; 1963a-k) completed an aeromagnetic survey of Keweenaw and Houghton Counties, Michigan. Wold and Ostenso (1966) and Hinze and others (1966) completed a regional aeromagnetic survey of the Lake Superior area. The aeromagnetic data of Wold and Ostenso (1966) indicate the location of the Lake Superior syncline axis, the Isle Royale, Keweenaw, Douglas, and Lake Owen faults, and the Gunflint, Gogebic, and Marquette iron ranges. The magnetic pattern west of longitude 91°W has been attributed to mafic rocks in the upper part of the middle Keweenawan lava series by Wold and Ostenso (1966). The aeromagnetic data of Hinze and others (1966) was interpreted to indicate the presence of the previously discussed faults in eastern Lake Superior. Hinze and others (1966) attribute the source of the magnetic anomaly pattern on the Keweenaw Peninsula and in the Stannard Rock area to be middle Keweenawan basic volcanics.

Patenaude (1964) completed an aeromagnetic survey of the eastern Upper Peninsula of Michigan. He suggests that Keweenawan volcanics constitute part of the Precambrian basement in eastern Upper Michigan and that the Keweenaw fault continues from the Keweenaw Peninsula to eastern Upper Michigan.

Gravity Surveys

Gravity surveys were completed in northern Wisconsin and northern Minnesota by Thiel (1956) and on the Keweenaw Peninsula by Bacon (1957). Weber and Goodacre (1966), using underwater gravity observations, have completed a Bouguer anomaly map of Lake Superior. This Bouguer map was compiled using the data of Bacon (1957) and the underwater gravity observations completed by the Dominion Observatory and the University of Wisconsin in 1964.

The relative Bouguer gravity highs that extend from the Keweenaw Peninsula southeastward to the Lower Peninsula of Michigan and those highs that extend northeastward into Lake Superior can be attributed to the presence of Keweenawan volcanics in eastern Lake Superior.

Paleomagnetic Studies

Studies of the magnetic susceptibility and remnant magnetization of the Keweenawan rocks in the Lake Superior area have been made by Mooney and Bleifuss (1953), Jahren (1965), Bath (1960), and DuBois (1962).

According to Mooney and Bleifuss (1953), the susceptibility values of individual Keweenawan formations differ significantly but also overlap. The susceptibility of the Keweenawan formations ranges from 0.0005 to 0.005 c.g.s. units and, according to Jahren (1965), is unrelated to the remnant magnetization.

According to Bath (1960), the induced magnetization alone cannot account for the large amplitude magnetic anomalies observed over the Keweenawan lavas. The ratio of remnant to induced magnetization, the Konigsberger ratio, is greater than 1 for most of the Keweenawan volcanics. According to Jahren (1965), the azimuth and dip of the remnant magnetization for Keweenawan rocks are 290° to 291° and 38° to 47° respectively and are 284° to 294° and 0° to 44° respectively, according to DuBois (1962).

GEOPHYSICAL METHODS EMPLOYED

Seismic Reflection Method

Equipment Description and Procedure

The continuous seismic reflection data were gathered using a Bolt Model 600B air gun as an energy source. The air gun was fired every 4-8 seconds by a Bolt Model FC firing control. Air was supplied to the gun by a Rix Model K-20 compressor at approximately 1,200 p.s.i. (Fig. 4).

The Bolt air gun stores high pressure air in two chambers, an upper control chamber, and a lower control chamber. In the rest position, between firings, the two chambers are sealed by a triggering piston and a firing piston mounted on a common shank, forming a shuttle. High pressure air is supplied to the upper control chamber and seeps into the lower control chamber through an orifice in the shank of the shuttle. The gun is then sealed because the area of the triggering piston is greater than that of the firing piston, and a downward holding force exists. The gun is fired by actuating the solenoid with an electrical firing pulse from the firing control box (Fig. 4). Upon firing, a burst of high pressure air is suddenly delivered to the bottom side of the triggering piston, thereby upsetting the force balance. The shuttle valve assembly opens at high velocity, reaches maximum stroke, and returns to its sealed position, all in a period of about ten milliseconds. During the time that the shuttle valve is open, most of the high pressure air in the lower control chamber is suddenly vented in to the water (United Geophysical Corporation, 1968, p. 22).

The air gun was towed approximately 100 feet behind the ship at a depth of about 30 feet (Fig. 6). Ten and 40 cubic inch chambers were alternately used on the air gun during the survey. A bubble suppressor was used with the 40 cubic inch chamber to minimize the effects of the bubble pulse on the final records.

When air is released into the water, an expanding gas bubble is formed. After about 200 milliseconds, bubble expansion stops and contraction begins, at first slowly and then with increasing speed. Bubble contraction stops after about 400 milliseconds. From this time onward, bubble expansion begins again. This cycle may be repeated several times, though with decreasing energy and intensity.

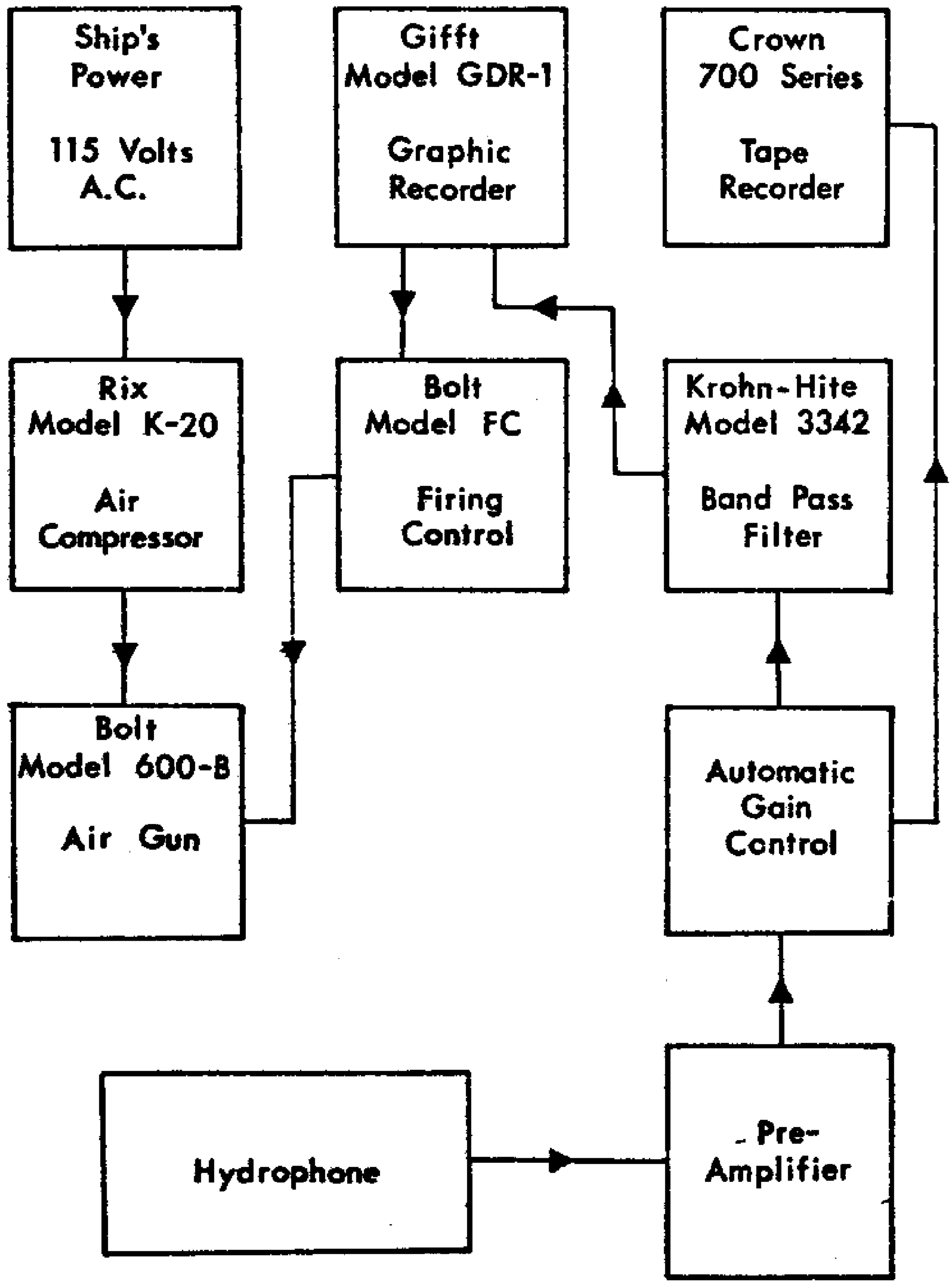

Figure 4. Schematic diagram of seismic equipment set up.

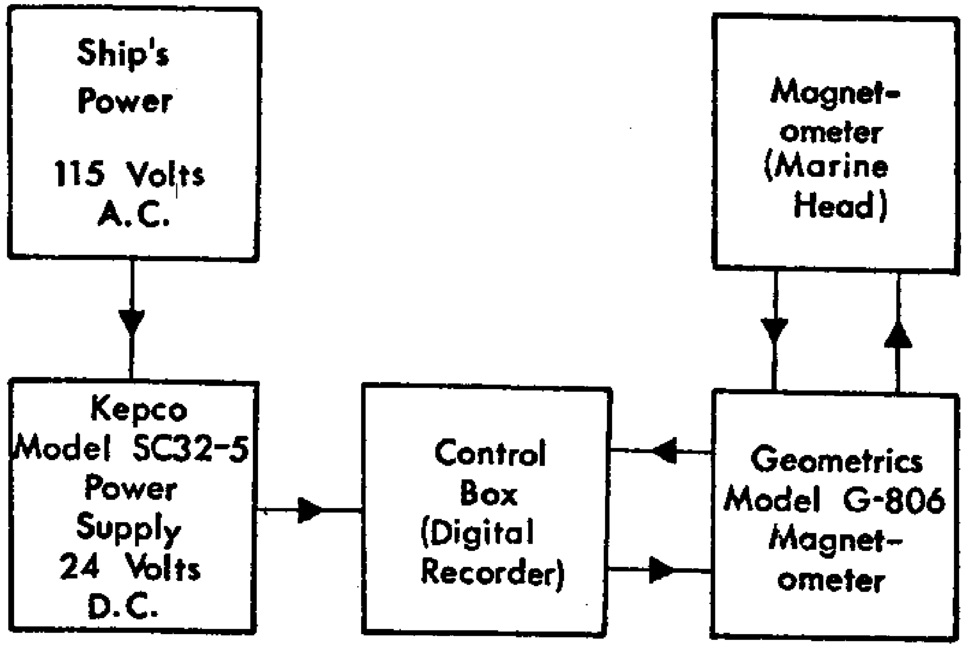

Figure 5. Schematic diagram of magnetic equipment set up.

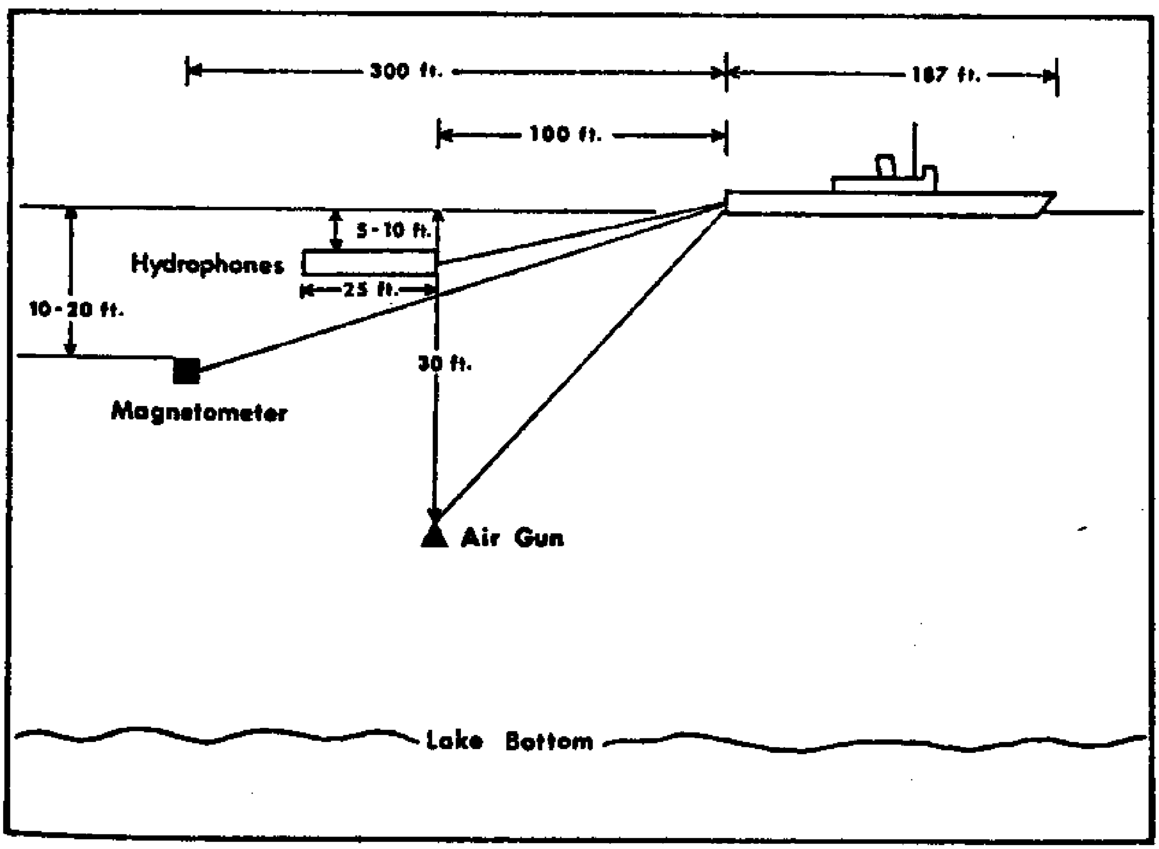

Figure 6. Towing configuration of geophysical equipment.

This phenomenon is called bubble oscillation, and the pressure pulses radiated during times of minimum bubble radius are called bubble pulses (United Geophysical Corporation, 1968, p. 10).

Multiple reflections occur when acoustic energy is reflected away from a horizon towards the air-water interface. At this interface, energy is reflected back towards the horizon. After being reflected from the horizon for a second time, the energy is picked up again by the hydrophones and recorded later than the original event. Multiple reflections and bubble pulse reflections interfere with reflections from deep horizons and are, therefore, undesirable.

The acoustic energy reflected from the lake bottom and sub-bottom was picked up by a hydrophone array that was towed about 100 feet behind the ship at a depth of approximately 10 feet (Fig. 6). This hydrophone array was made in the University of Wisconsin-Milwaukee geophysics laboratory and consisted of 50 Aquadyne, AQ-1 pressure sensitive elements, which were connected in parallel. These elements were mounted in a 1-inch diameter, plastic tube filled with hydraulic jack oil. The elements converted acoustic signals reflected from the lake bottom and sub-bottom into electrical signal, which were then transmitted to the ship and recorded.

Aboard the ship, various pieces of equipment were used to receive and record seismic data. Electrical signals from the hydrophone array were sent through a pre-amplifier and an automatic gain control, both of which were made in the University of Wisconsin-Milwaukee geophysics laboratory. After passing through the automatic gain control, the electrical signal was recorded in an unfiltered form by a 4-track, analog, Crown 700 series magnetic tape recorder. These same electrical signals were also filtered by a Krohn-Hite, Model 3342 band pass filter before they were recorded on a Gifft, Model GDR-1, graphic, wet paper recorder (Fig. 4). The frequency of recorded signal ranged from 40 to 600 Hz and this range was varied slightly from record to record. The record from the recorder resembles a geologic cross-section. The vertical scale on these records is represented by the two-way travel time in milliseconds of the seismic reflections.

Data Reduction

The magnetic tape recordings of the seismic data were replayed through Krohn-Hite filters Models 310-C, 3342, and 350A, which were connected in series. The pass band range of the filtered data was 40 to 650 Hz; this range was varied slightly from record to record. The filtered data were then recorded on a Honeywell Model 1856 Visicorder of the fiber optics type. Signal-to-noise ratio was improved on the seismic data and in most cases a clearer record than the original was obtained.

The seismic records were then visually interpreted by laying tracing paper over the filtered records and tracing the real events, which were visually separated from multiple and bubble pulse reflections. The sediment-bedrock interface was noted. Two way travel time in milliseconds of seismic reflections through the sedimentary layer (hereafter called time thickness) was measured and then plotted on a base map. Points of equal time thickness were then contoured to form an isochron map of the unconsolidated sediments overlying bedrock (Plate II). A bathymetric map of portions of Lake Superior compiled by Ristic (1964) was used as a guide while contouring the isochron map.

A seismic velocity of 5,000 feet/sec was assumed for the unconsolidated sediments (Wold and Ostenso, 1966, p. 22). Using this velocity, time thickness was then converted to feet (Table 1). Using the thickness of the sediments in feet and the bathymetric chart constructed by Ristic (1964), a map of bedrock topography was constructed (Plate III). The depth of the water and thickness of the sediment layer were subtracted from the elevation of the International Great Lakes low water datum (1955). The resultant elevations were contoured at 100 foot intervals.

During interpretation, errors may have been introduced by not picking the actual sediment-bedrock interface. The assumption of a particular seismic velocity for the unconsolidated sediments may be in error if lateral and vertical velocity variations exist in the unconsolidated sediments. A vertical velocity function ($V = 5000 + .6\ h$) was assumed for the unconsolidated sediments. At $h = 400$ feet, the seismic velocity of the unconsolidated sediments is 5,240 ft/sec. with this velocity, the thickness of the sedimentary layer was calculated and observed to be 13 feet greater than the thickness obtained when a seismic velocity of 5,000 ft/sec was used.

Magnetic Method

Equipment Descriptions and Procedure

The magnetic data were gathered using a Geometrics Model G-806 proton precession magnetometer with marine sensor. The sensor was towed approximately 300 feet behind the ship at a depth of 10 to 20 feet (Fig. 6). The magnetometer was mounted in a control box fitted with digital and analog recorders. Power was supplied to the magnetometer via a Kepco Model Sc 32-5 power supply (Fig. 5).

The magnetometer operates on the principle of nuclear magnetic resonance to produce a measurement of the scalar magnitude of the total magnetic intensity field. The magnetometer has a range of 20,000 to 100,000 gammas with an accuracy of ±0.5 gamma. Readings of the magnetic field were recorded every 6 seconds in areas of relatively flat gradient and every 2 seconds when areas of high gradient were encountered. The digital recorder counted the precession signal from the magnetometer and converted it to a visual display. The digital data were then fed into the analog converter,

Table 1.

Equivalence of thickness in milliseconds to thickness in feet for unconsolidated sediments

Two-way travel time in milliseconds (t)	Thickness (h) in feet (meters)
10	25 (7.5 m)
20	50 (15.0 m)
40	100 (30.0 m)
80	200 (60.0 m)
120	300 (90.0 m)
160	400 (120.0 m)

Note: The thickness values in feet for the unconsolidated sediments were obtained by using the following:

$$h = \frac{t \text{ sec}}{2} (5{,}000 \text{ ft/sec})$$

which had outputs of 50 and 500 gammas full scale when the magnetometer operated at ±0.5 gamma sensitivity and outputs of 100 and 1,000 gammas full scale when the magnetometer was operating at ±1 gamma sensitivity. The outputs from the analog converter were recorded on paper record tapes aboard ship.

Data Reduction

The magnetic data were analyzed, by hand, from the paper analog record tapes. Data points were selected at 1 minute intervals in low gradient areas and every 15 seconds in high gradient areas. Profiles of these data were plotted along the ship's track lines (Plate IV) using the track lines as a base representing 60,000 gammas. Magnetic readings greater than 60,000 gammas were plotted relative to the top and left of the track lines (Plate IV). These profiles were used as a guide when the total magnetic intensity map (Plate V) was contoured at an interval of 100 gammas.

The total magnetic intensity map was prepared using the data gathered during the 1971 Lake Superior survey and the data gathered by Balsley and others (1962; 1963 a-k). The data of Balsley and others consisted of total intensity aeromagnetic data, gathered with a flux-gate magnetometer, at an elevation of 500 feet above the ground. Since the flux-gate magnetometer is capable only of noting relative changes in the earth's magnetic field, these data are, therefore, only relative.

By matching individual contour lines from the edge of the author's survey area to contour lines on the edge of the survey area of Balsley and others (1962; 1963 a-k), the author was able to establish that the zero value obtained with the flux-gate magnetometer corresponds to a value of 58,200 gammas.

Navigation

Radar and sightings from known landmarks were used to determine the positions of the track lines. Positioning accuracy was about ±0.5 mile (0.8 km) when the ship was out of sight of land and approximately ±0.25 mile (0.4 km) nearer to shore.

Navigational errors may have influenced data accuracy if track lines were incorrectly positioned. Where time marks were not closely spaced on the track lines, interpolation of the position of a data point on the track line by assuming a constant ship velocity may lead to error.

DISCUSSION OF GEOPHYSICAL DATA

Seismic Data

Sediment thickness contours (Plate II) generally parallel bathymetry (Fig. 7). To the west of Manitou Island, sediment

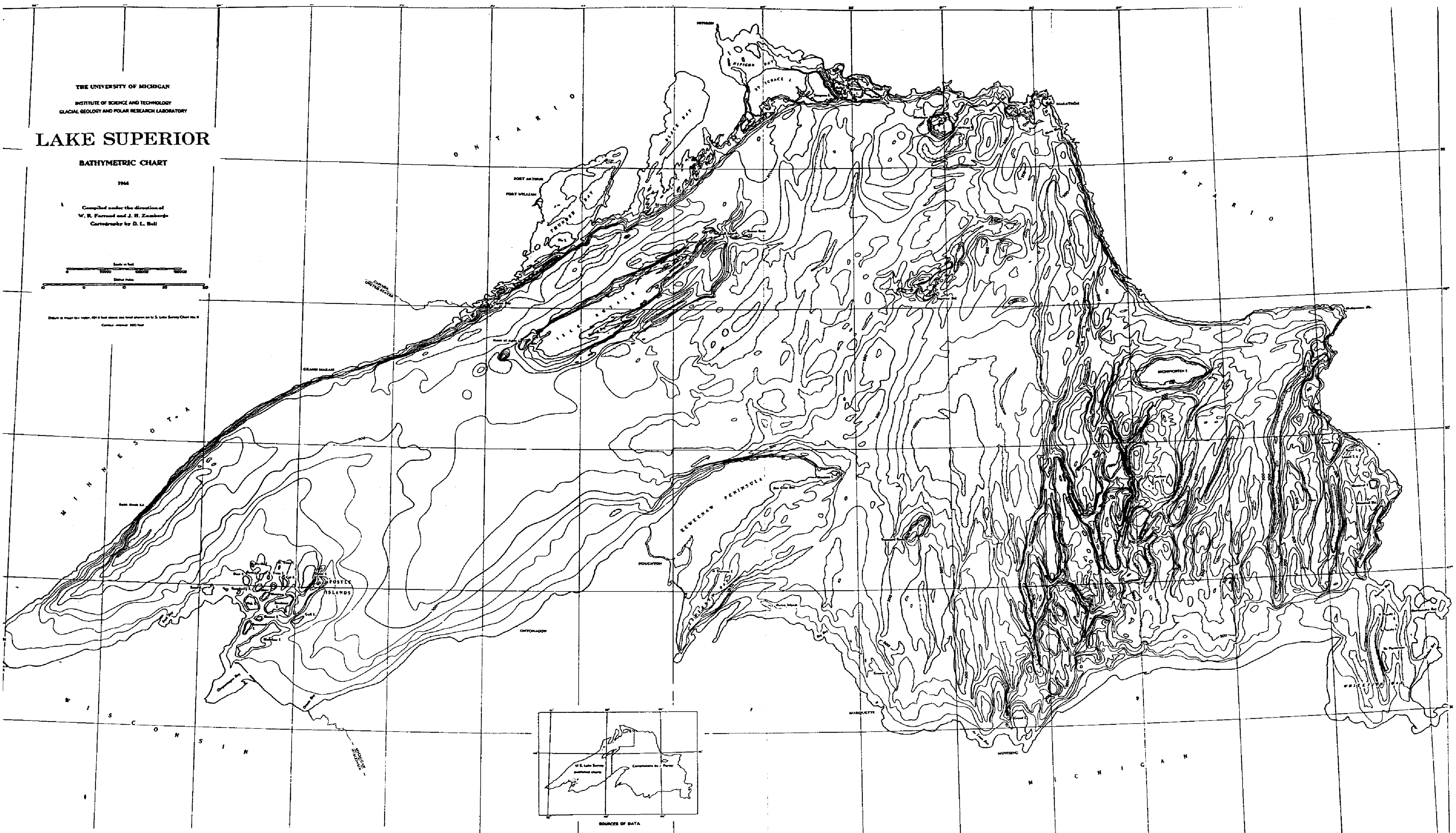

Figure 7. Bathymetric chart of Lake Superior from Farrand and Zumberge (1966)

thickness contours parallel the northeast-southwest trending bathymetry of western Lake Superior. To the southeast of Manitou Island, the sediment thickness contours parallel the north-south trending bathymetry of eastern Lake Superior.

The thickness of unconsolidated sediments (Plate II, Table 1) within the study area ranges from 0 to 160 ms.; thicknesses of 10 to 80 ms. predominate. Sediment accumulations less than 10 ms. and greater than 80 ms. are of relatively small areal extent.

Accumulations of unconsolidated sediments less than 10 ms. thick are observed in the following areas: 1.) near point a.(Plate II) in a narrow, northeast-southwest trending trough; and 2.) near point b. (Plate II) in a small north trending patch.

Accumulations of unconsolidated sediments greater than 80 ms. thick are found in the following areas: 1.) near point c. (Plate II) in a U-shaped band; 2.) near points d. and e. (Plate II) in narrow, east-west trending bands; 3.) near point f. (Plate II) in a narrow, east-west trending trough; 4.) near point g. (Plate II) in a broad, northeast-southwest trending trough; and 5.) at point h. (Plate II) in a narrow, northeast-southwest trending trough.

Patterns of bedrock topography (Plate III) closely parallel bathymetry suggesting a bedrock control of bathymetry (Plate II, Fig. 7). North of the Keweenaw Peninsula, the elevation of the bedrock surface deepens towards the Lake Superior syncline axis. Geologically, the nature of the bedrock surface underlying the unconsolidated sediments varies within the study area (Plate II, Fig. 3).

North of the Keweenaw Peninsula, to the east of longitude 88°30'W the Freda sandstone, the Nonesuch shale, and the Copper Harbor conglomerate comprise the bedrock surface; to the west of longitude 88°30'W, the Freda sandstone comprises the bedrock surface. Farther north of the study area, the Freda sandstone, the Nonesuch shale, and the Copper Harbor conglomerate are probably overlain by the Jacobsville sandstone (Zumberge and Gast, 1961) or by a sandstone of the Lake Superior group (Farrand, 1969, p. 36). Between Manitou Island and Keweenaw Point, the bedrock surface is composed of, from south to north, the Jacobsville sandstone, the Portage Lake Lava series, and the Copper Harbor conglomerate. To the southeast of Manitou Island, Keweenawan lavas are probably overlain by a thick sedimentary cover (Hinze and others, 1966, p. 106).

The patterns of unconsolidated sediments (Plate II) are due to glacial erosion and deposition. Parker (1964, p. 3) states that advances and retreats of continental glaciers came from a northeasterly direction and that the rate of glacial erosion was controlled by the type of rock that the glaciers passed over.

Parker (1964, p. 38) suggests that ice coming from the northeast was diverted around Superior Shoal (Fig. 1) forming two lobes. One lobe of ice moved around Superior Shoal in a southerly direction into eastern Lake Superior, while another ice lobe moved in a southwesterly direction towards the area between the Keweenaw Peninsula and Isle Royale. Parker (1964, p. 38) also states that "since bedrock structure between the Keweenaw Peninsula and Isle Royale appears to be discontinuous, it is believed that the retreat of the glaciers in this part of the basin was slow and irregular and that many small recessional moraines were deposited."

The patterns of unconsolidated sediments and bedrock topography which are observed to the north of Copper Harbor (Plates II & III), can be explained by the existence of the Chippewa-Keweenaw interlobate moraine. This moraine, according to Parker (1964, p. 38), trends in a northeasterly direction from the eastern end of the Keweenaw Peninsula to Superior Shoal and "was deposited on bedrock which had been partly protected from erosion by diversion of the glacier around Superior Shoal." Hinze and others (1966, p. 105) suggest the existence of two faults, a north-south trending fault that extends from Ashburton Bay to Big Bay (Fig. 1), and an east-west trending fault located to the south of Caribou Island (Fig. 1). The previously discussed seismic data provide no evidence to substantiate the existence of either of these faults. These faults, however, may not have been observed due to shallow penetration of the seismic energy.

Magnetic Data

Factors Influencing Magnetic Anomaly Character

The factors influencing the amplitude of a magnetic anomaly are the type and susceptibility (k) of the rock, the Konigsberger Ratio (Q) (Table 2.), the depths of burial of the anomaly source, and the type of cover overlying the anomaly source. According to Jahren (1963), the amplitude of a magnetic anomaly is also determined by the size and shape of the rock mass and the volume % of magnetite present within the rock. Ostenso (1965) suggests that in the Lake Superior region a change in bedrock elevation beneath a constant flight elevation can only account for an amplitude attenuation of perhaps 20%. The lack of exact depth control, variability of polarization, and horizontal and vertical variations of k and Q make the quantitative interpretation of magnetic data difficult.

Magnetic Anomaly Analysis

The magnetic data of Balsley and others (1962; 1963 a-k) were compared to the geologic maps compiled by Cornwall (1954a-c; 1955), Cornwall & Wright (1954; 1956a; 1956b), Davidson and others (1955), White and others (1953), and White and Wright (1956). The following magnetic anomaly patterns were observed (Plate V, Fig. 3).

Table 2.

Summary of magnetic properties of rocks found in the Lake Superior region from Hinze and others (1966, p. 102).

Rock Types	Susceptibility $k \times 10^{-6}$ cgs	Königsberger Ratio $Q = I_r/kH$ $H = 0.6$ oersted
Paleozoic sediments	Negligible	Negligible
Keweenawan rocks		
Sediments	Negligible	Negligible
Basic flows	10,000-1,000	3.0-1.0
Basic intrusions	9,000-2,000	2.0-1.0
Acid intrusions and flows	3,000- 100	-------
Pre-Keweenawan rocks		
Acid intrusions and gneisses	3,000- 100	Generally low
Metabasic intrusions and flows	4,000- 200	2.0-0.5
Iron formations	900,000- 500	10.0-0.0
Metasediments	200- 0	Negligible
Undifferentiated Precambrian	Variable	Variable

South of the Keweenaw fault, within the Jacobsville sandstone, the magnetic anomaly patterns have a very flat gradient and exhibit lows relative to the Portage Lake lava series. This type of pattern is observed because of the homogeneity and negligible k and Q values characteristic of this sediment (Table 2).

The magnetic anomaly pattern that correlates with the Portage Lake lavas is characterized by steep gradients and closures, which do not always parallel the strike of the strata. The steepest gradients observed correlate with the Scales Creek flow. This type of pattern is observed to correlate with the Portage Lake Lavas because the contrasting lithologies present within this unit have a wide range of k values. A large k contrast may account for the changes in amplitude observed. The presence and orientation of the previously mentioned closures may be explained by the presence of numerous faults that cut obliquely across the strike of the strata.

Within the lower portion of the Copper Harbor conglomerate, termed the Great conglomerate (Irving, 18-3), the magnetic anomaly pattern parallels the strike of the strata and has a flatter gradient than that of the underlying Portage Lake lavas. The anomaly pattern of the Great conglomerate is undulatory east of longitude 88°10'W and has a flat gradient. To the southwest of longitude 88°10'W, the anomaly pattern becomes less undulatory and has a flatter gradient. This pattern is observed because the Great conglomerate is homogeneous and composed of sediments which have negligible k and Q values (Table 2). The underlying Portage Lake Lavas and the overlying Lake Shore Trap member (Irving, 1883) of the Copper Harbor conglomerate also have an effect on the anomaly pattern of the Great conglomerate. The anomaly pattern characteristic of the Lake Shore Trap parallels the strike of this unit and has a steep gradient and closures. The appearance of this anomaly pattern can be explained by the basic composition and correspondingly high k values (Table 2) of this unit. These high k values are in contrast with the k values of the underlying Great conglomerate and overlying Outer conglomerate (Irving, 1883) of the Copper Harbor conglomerate. The magnetic anomaly pattern that correlates with the Outer conglomerate has a flatter gradient and fewer closures than the magnetic pattern of the Lake Shore Trap. The upper mafic member of the Copper Harbor conglomerate has a magnetic anomaly pattern similar in appearance and origin to that of the Lake Shore Trap and extends into Lake Superior near point a. (Fig. 3). The magnetic anomaly pattern that correlates with the Nonesuch shale and the Freda sandstone is similar in appearance and origin to the magnetic pattern of the Outer conglomerate.

The magnetic anomaly pattern observed on the Keweenaw Peninsula continues eastward to Manitou Island, bends southeasterly, and decreases in amplitude (Plate V). This broad, symmetrical anomaly extends to the area near point a. (Plate V), where it merges with a northwesterly trending anomaly to form a saddle-shaped anomaly.

The source of the southeasterly trending anomaly is, according to Hinze and others,(1966, p. 106), a continuation of middle Keweenawan lavas from the Keweenaw Peninsula. According to White (1966, p. 10), the U-shaped nature of this anomaly suggests folding.

The northwesterly trending anomaly observed in the Stannard Rock area is the northwest portion of an anomaly described by Hinze and others (1966, p. 106) as a continuation of the previously discussed southeasterly trending anomaly. Hinze and others (1966, p. 106) suggest that the northwesterly trending anomaly "indicates that the volcanics dip toward the east and are generally more deeply buried southeastward along strike."

A possible explanation for the saddle-shaped anomaly near point a. (Plate V) is the existence of the east-west trending fault (Hinze and others, 1966, p. 105), which is located to the south of Caribou Island (Fig. 2). The existence of this fault may explain the closure observed on the ends of the previously discussed southeast and northwest trending anomalies. If the source of these anomalies is the same geologic body, a disruption such as faulting may explain the break in anomaly pattern observed at point a. (Plate V). If these anomalies do not originate from within the same geologic body, this saddle-shaped anomaly may represent the contact of two different rock masses. The magnetic data provide no evidence to substantiate the existence of the north-south fault (Hinze and others, 1966, p. 105) that extends from Ashburton Bay to Big Bay (Fig. 1).

Analysis of Seismic and Magnetic Profiles

The Peter's Slope Method, discussed in detail by Peters (1949), was used to estimate the depth to the top of anomaly sources. The results of these calculations are on file in the Department of Geological Sciences at the University of Wisconsin-Milwaukee. The Peter's Slope Method is based on the following assumptions: 1.) that the anomalous mass has the shape of a vertically-sided slab of a constant thickness and that this mass extends to an infinite depth and has a horizontal top; 2.) that the mass is uniformly magnetized in the vertical direction and has a magnetization different from surrounding materials; and 3.) that the magnetization is induced and not remnant.

When selecting an anomaly for analysis, care must be taken to select an anomaly that has least interference from adjacent anomalies. If the sides of the anomaly source are sloping more than 10°, the Peter's Slope Method yields extraneous results. If the sides of the rock mass are sloping outward, the depth estimate is too great. If the sides of the rock mass are inward-sloping, the depth obtained is too shallow. A too shallow depth estimate is also obtained if the top of the anomaly source extends into non-magnetic sediments (Wold, 1972, personal communication).

Profile A-A'

Profile A-A' (Fig. 8) is a portion of traverse that is located southwest of Eagle Harbor (Plate I). This profile was selected for study to determine the relationship of the fault observed on the seismic profile to the magnetic anomaly on the profile. The sediment cover overlying bedrock, as observed on the seismic profile, ranges in thickness from about 30 to 160 ms. (Table 1). Near the 2000 time mark, a trough-like feature approximately 160 ms. thick is observed. The magnetic profile, from the 2000 to approximately the 2048 time mark, remains nearly constant at about 60,100 gammas. Near the 2048 time mark, a magnetic anomaly is detected, and the total magnetic intensity increases to 61,100 gammas. This magnetic anomaly coincides with the normal fault observed on the seismic profile near the 2048 time mark. This fault strikes approximately north-south, and its downthrown block is to the west (Plates II & III).

On the Keweenaw Peninsula, in the Ahmeek quadrangle mapped by White and others (1953), northwest-southeast faulting is observed (Fig. 3). One of these onshore faults cuts through the upper portion of the Portage Lake Lava series, the Copper Harbor conglomerate, and into the base of the Nonesuch shale; the other extends from the middle of the Copper Harbor conglomerate into the base of the Nonesuch shale. Offsets due to these faults are especially observed in the upper mafic member of the Copper Harbor conglomerate. Offshore, a similar offset is observed in the bedrock topography near the normal fault (Plate III).

A depth estimate to the anomaly source was completed using the Peter's Slope Method. A depth of 550 feet to the top of the anomaly source was computed. Near the 2048 time mark, the water is 100 to 150 feet deep and approximately 100 to 150 feet of unconsolidated sediment overlie bedrock. If the depth obtained is correct, an additional 200 to 350 feet of cover overlies the anomaly source. This 200 to 350 foot discrepancy is explained by the fact that the strata have a dip to the north in this area. This dip provides an outward-sloping side for the anomaly source. As previously mentioned, an outward-sloping side of the anomaly source causes depth estimates obtained by the Peter's Slope Method to be too great. The analysis of profile A-A' shows the normal fault to coincide with the magnetic anomaly observed near the 2048 time mark on the profile. The lakeward projection along strike of the upper mafic member of the Copper Harbor conglomerate intersects profile A-A' near the 2048 time mark (point a. of Fig. 3). Offsets due to onshore faults are observed in this mafic member; similar offsets are observed in the area of the normal fault (Plates II & III). If the offshore fault occurred at the same time as the onshore faults, an age for the offshore fault is lower Nonesuch shale time.

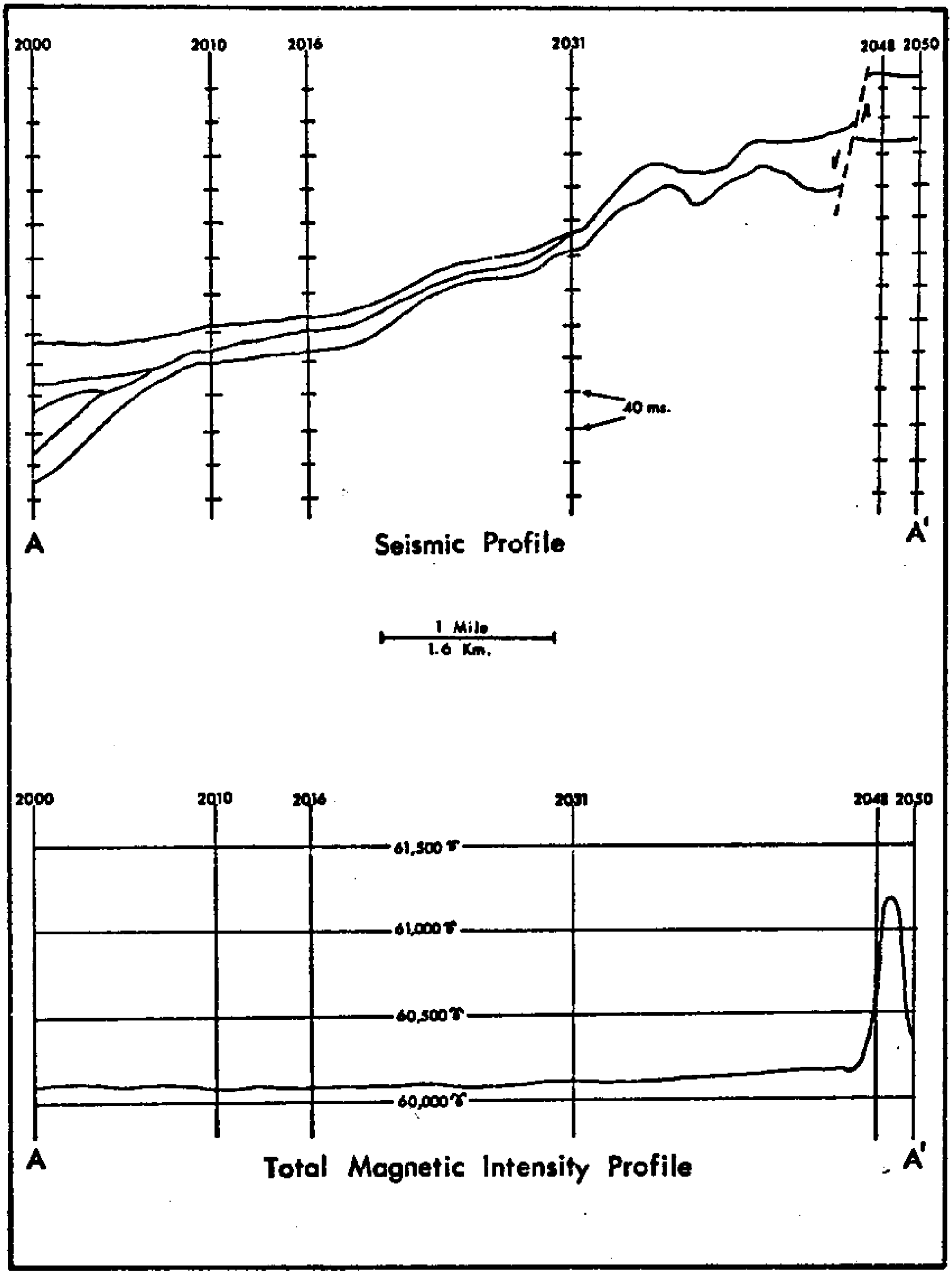

Figure 8. Profile A-A'. Seismic and magnetic profiles located southwest of Eagle Harbor, Michigan. Frequency range of seismic profile is 80 to 525 Hz.

Profile B-B'

Profile B-B' (Fig. 9) is a north-south trending section of traverse located between Manitou Island and Keweenaw Point (Plate I). This profile was selected for analysis in order to find the offshore location of the Keweenaw fault. The high resolution and refraction profiles of Moore and others (1972, Fig. 6) were compared to the magnetic profiles.

On the high resolution profile, at approximately the 0909 time mark, a steeply-sided topographic feature is observed. The downthrown side of this feature is to the south as is the downthrown block of the Keweenaw fault. The magnetic profile in the vicinity of the 0909 time mark resembles the total magnetic field across the Keweenaw fault observed by Bacon (1966, p. 46) remarkably well with respect to shape and amplitude. An offset of the 4.7 km/sec layer on the refraction profile is observed at approximately the 0909 time mark. This offset as well as the features previously noted on the high resolution and magnetic profiles indicate that the offshore location of the Keweenaw fault is at point b. (Fig.3).

The lakeward projection along strike of the rock units on the eastern end of the Keweenaw Peninsula (Cornwall, 1955) correlate with relative magnetic maxima and minima (Fig. 3) that are observed on the magnetic profile (Fig. 8). At approximately the 0928 time mark, a magnetic low, which reaches a minimum of 59,221 gammas is observed. This low, which is located at point d. (Fig. 3), correlates with the Great conglomerate of the Copper Harbor conglomerate. From the 0928 to 0932 time marks, a relative magnetic high, which reaches a maximum of 61,806 gammas, correlates with the Lake Shore Trap of the Copper Harbor conglomerate at point e. (Fig. 3). From the 0932 to 0945 time marks, a relative magnetic low is observed near point f. (Fig. 3). This low correlates with the Outer conglomerate of the Copper Harbor conglomerate (Fig. 3).

Using the Peter's Slope Method, a depth estimate to the top of the anomaly source was calculated at approximately the 0927 time mark; a depth of about 215 feet was obtained. This depth agrees with other depth data at this location. The water depth is 100 feet and 100 to 150 feet of unconsolidated sediments overlie bedrock at the 0927 time mark. The 0927 time mark is at point f. (Fig. 3) and correlates with the Portage Lake Lava series. Although the depth estimate obtained agrees with other depth data, it is possible that, because the rocks at this location have a dip to the north, the depth estimate could be in error. This northerly dip provides an outward-sloping side for the anomaly source resulting in too large of a depth estimate. If the anomaly source has a non-horizontal top (topography developed on it), a shallow estimate would result. It is possible that these two effects have

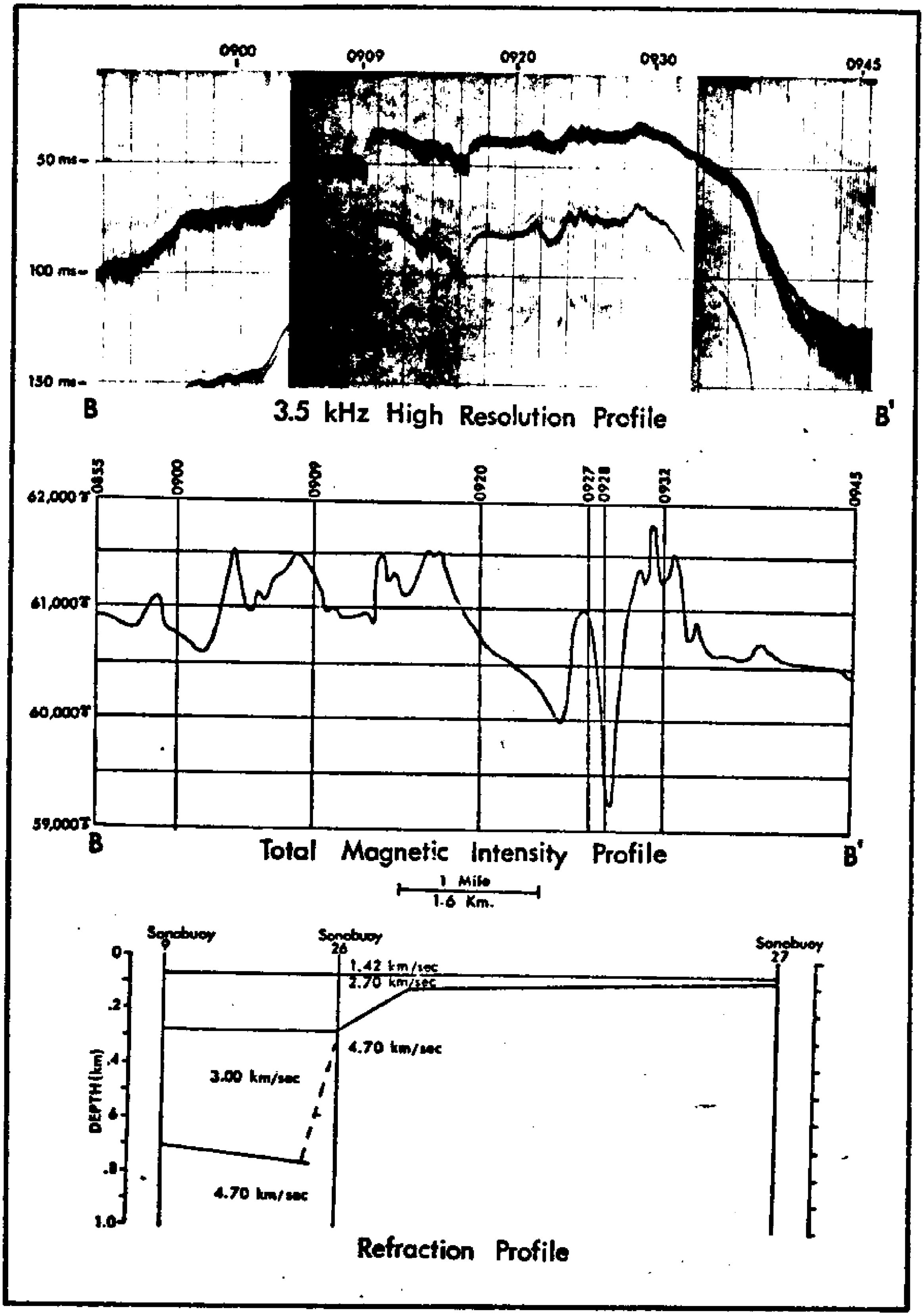

Figure 9. Profile B-B'. High resolution, refraction, and magnetic profiles located between Keweenaw Point and Manitou Island, Michigan. High resolution and refraction profiles from Moore and others (1972, Fig. 6).

compensated for one another, thereby, resulting in a reasonable depth estimate to the top of the anomaly source.

The analysis of profile B-B' shows that the Keweenaw fault extends into Lake Superior to point b. (Fig. 3). Correlation of magnetic maxima and minima with known geology is observed at points c, d, e, and f (Fig. 3).

Profile C-C'

Profile C-C' (Fig. 10) is a northeast-southwest trending section of traverse that is located northwest of Stannard Rock (Plate I). This profile was analyzed to find evidence for or against the existence of the Keweenaw fault in eastern Lake Superior. Two possible paths for the Keweenaw fault in eastern Lake Superior have been suggested by Hinze and others (1966, p. 105). One path extends from the Keweenaw Peninsula, curves to the southeast near Manitou Island, and passes to the southwest of Stannard Rock. The other path extends from the Keweenaw Peninsula and joins the east-west trending fault that is located to the south of Caribou Island (Fig. 2).

Unconsolidated sediments along the seismic profile range from 100 to 180 ms. in thickness. Deep accumulations of unconsolidated sediments are found near the 0715 and 0815 time marks. The magnetic profile is broad and reaches a maximum value of 60,550 gammas near the 0815 time mark and reaches a minimum value of 59,750 gammas near the 0715 time mark. These maximum and minimum values both occur over the areas of thickest unconsolidated sediment accumulation.

Depth to the anomaly source was determined between the 0815 and 0830 time marks using the Peter's Slope Method; the depth obtained was 4,600 feet. The water is 500 to 600 feet deep and 300 to 400 feet of unconsolidated sediments overlie bedrock between the 0815 and 0830 time marks. A 3,400 to 3,600 foot discrepancy exists in the depth control.

Hinze and others (1966, p. 106) state that the "volcanics dip toward the east" in this area. An outward sloping side of the anomaly source causes the depth estimate to be too great. The shape of the magnetic anomaly near the 1230 time mark is not of the 'pure' elliptical shape required for an accurate depth estimate with the Peter's Slope Method. This method works best when an anomaly is elliptically shaped and its major axis is three to four times greater than its minor axis. Profile C-C' is part of a previously discussed magnetic anomaly thought by Hinze and others (1966, p. 106) to originate within the Portage Lake lava series. If the depth to the anomaly source is correct, the additional 3,400 to 3,600 feet of cover would explain the broadening and decrease in amplitude observed in the magnetic anomaly pattern southeast of Manitou Island. The magnetic profile does not attain highs where the

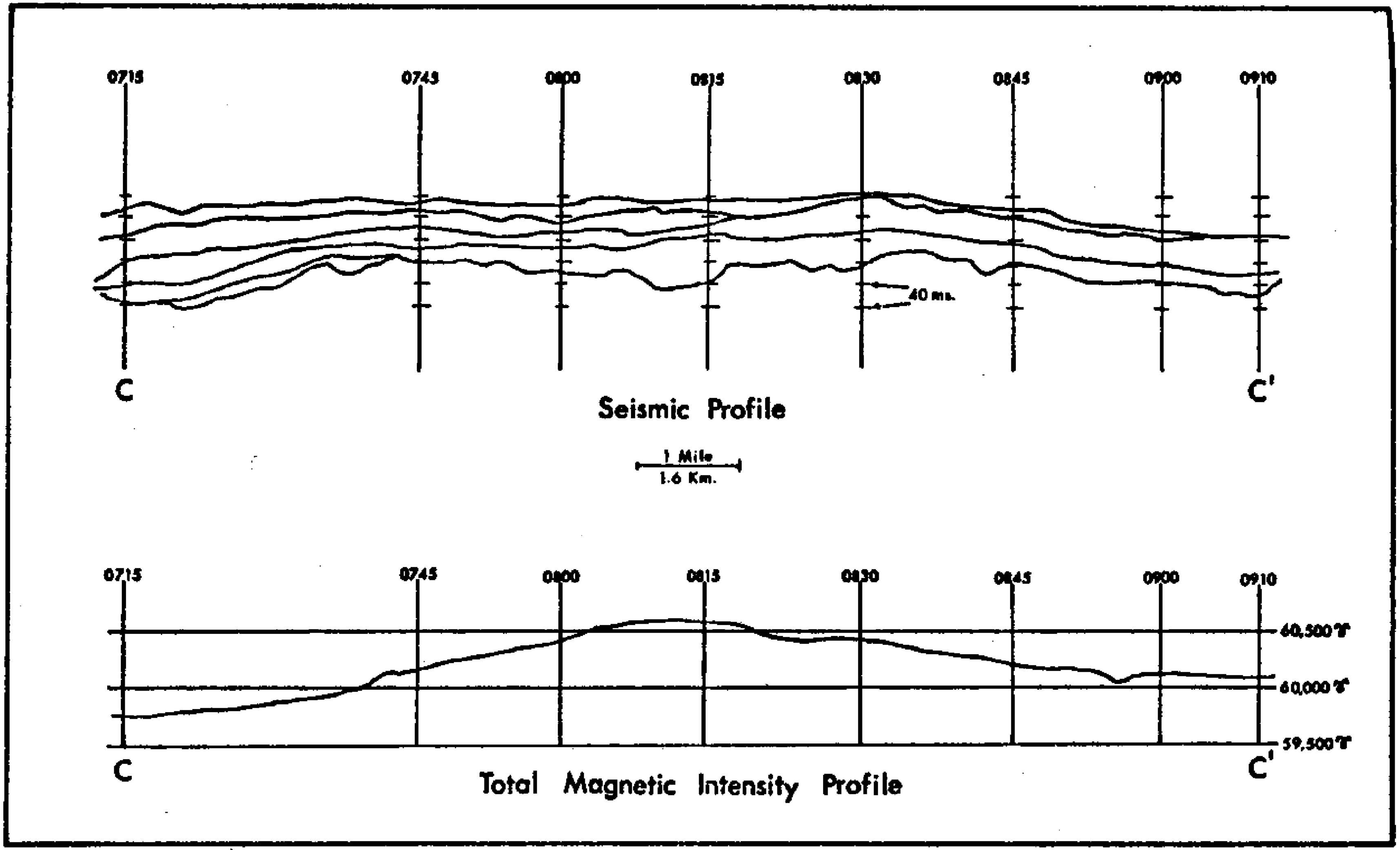

Figure 10. Profile C-C'. Seismic and magnetic profiles located northwest of Stannard Rock, Michigan. Frequency range of seismic data is 105 to 650 Hz.

bedrock surface is near the lake bottom. This observation can be explained by assuming that the deepest reflector observed on the seismic profile is not the top of the Portage Lake lava series, but the top of a thick layer of late Keweenawan or Paleozoic sediments that overlie the Portage Lake Lava series. These seismic and magnetic profiles provide no evidence for faulting.

Profile D-D'

Profile D-D' (Fig. 11) is a section of traverse located east and southwest of Stannard Rock (Plate I). This profile was selected for analysis to determine a possible location of the Keweenaw fault near Stannard Rock and to investigate the cause of the magnetic anomaly observed near the 1230 time mark.

Unconsolidated sediments on the seismic profile range from 20 to 80 ms. in thickness (Table 1). The thickest accumulation of these sediments is found near the 1115 mark. The total magnetic intensity profile ranges in value from a minimum of about 59,800 gammas near the 1243 time mark to a maximum of about 61,300 gammas near the 1230 time mark. The magnetic profile attains relative highs between the 1003 and 1045 time marks and near the 1230 time mark. At these locations, the magnetic highs are accompanied by bedrock elevations that are near the lake bottom.

Near the 1230 time mark, depth to the anomaly source was determined as approximately 625 feet using the Peter's Slope Method. The water is 350 to 400 feet deep and approximately 50 feet of unconsolidated sediments overlie bedrock near the 1230 time mark. A 175 to 225 foot discrepancy exists in the depth data. This discrepancy could be due to error in the Peter's Slope Method caused by an outward-sloping side of the anomaly source. This would make the depth estimate obtained by the Peter's Slope Method too large.

The magnetic anomaly near the 1230 time mark may be due to faulting: however, no evidence of faulting is observed on the seismic profile. Faulting at depth may occur but was not observed because of poor penetration. Detailed magnetic and seismic coverage to the north and south of Stannard Rock may provide evidence for faulting.

CONCLUSIONS

More detailed coverage consisting of seismic refraction, magnetic, and deeper seismic reflection data is needed in the southeastern portion of the lake to resolve the structure and geology of eastern Lake Superior.

A seismic reflection system utilizing multiple 300 cubic inch air guns fitted with bubble suppressors might achieve deeper penetration. The bedrock surface is an excellent reflector and, as a result, most of the seismic energy arriving at the bedrock surface is reflected away from rather than into the bedrock.

The major conclusions of the study are:

1.) The patterns of unconsolidated sediments (Plate II) and bedrock topography (Plate III) resemble features described by Parker (1964) that result from glacial erosion and deposition.

2.) The normal fault and magnetic anomaly located southwest of Eagle Harbor occur near the 2048 time mark of Profile A-A'. The lakeward projection along strike of the upper mafic member of the Copper Harbor conglomerate intersects profile A-A' near the 2048 time mark. Offsets due to onshore faults are observed in this mafic member; similar offsets are observed in the area of the normal fault (Plates II & III). The onshore faults cut into the base of the Nonesuch shale. If the offshore fault occurred at the same time as the onshore faults, an age for the offshore fault is lower Nonesuch shale time.

3.) According to Hinze and others (1966), the middle Keweenawan volcanics, which comprise part of the south limb of the Lake Superior syncline, curve to the southeast near Manitou Island and extend to the Stannard Rock area. The broadening and decrease in amplitude of the magnetic anomaly pattern southeast of Manitou Island may be due to burial of the Keweenawan volcanics by late Keweenawan or Paleozoic sediments.

4.) The saddle-shaped magnetic anomaly pattern located near point a. (Plate V) may be due to the existence of the east-west trending fault (Hinze and others, 1966) that is located to the south of Caribou Island (Fig. 2).

5.) The Keweenaw fault extends into Lake Superior to point b. (Fig. 3). After extending to point b., the Keweenaw fault may curve to the southeast, follow the strike of the middle Keweenawan volcanics, and pass to the southwest of Stannard Rock (Hinze and others, 1966). Instead of following the above course, the Keweenaw fault may extend to the east of point b. and join the east-west trending fault (Fig. 2) that is located to the south of Caribou Island (Hinze and others, 1966).

6.) These magnetic and seismic data can neither prove nor disprove the existence of the north-south trending fault suggested by Hinze and others (1966), which extends from Ashburton Bay to Big Bay (Fig. 1).

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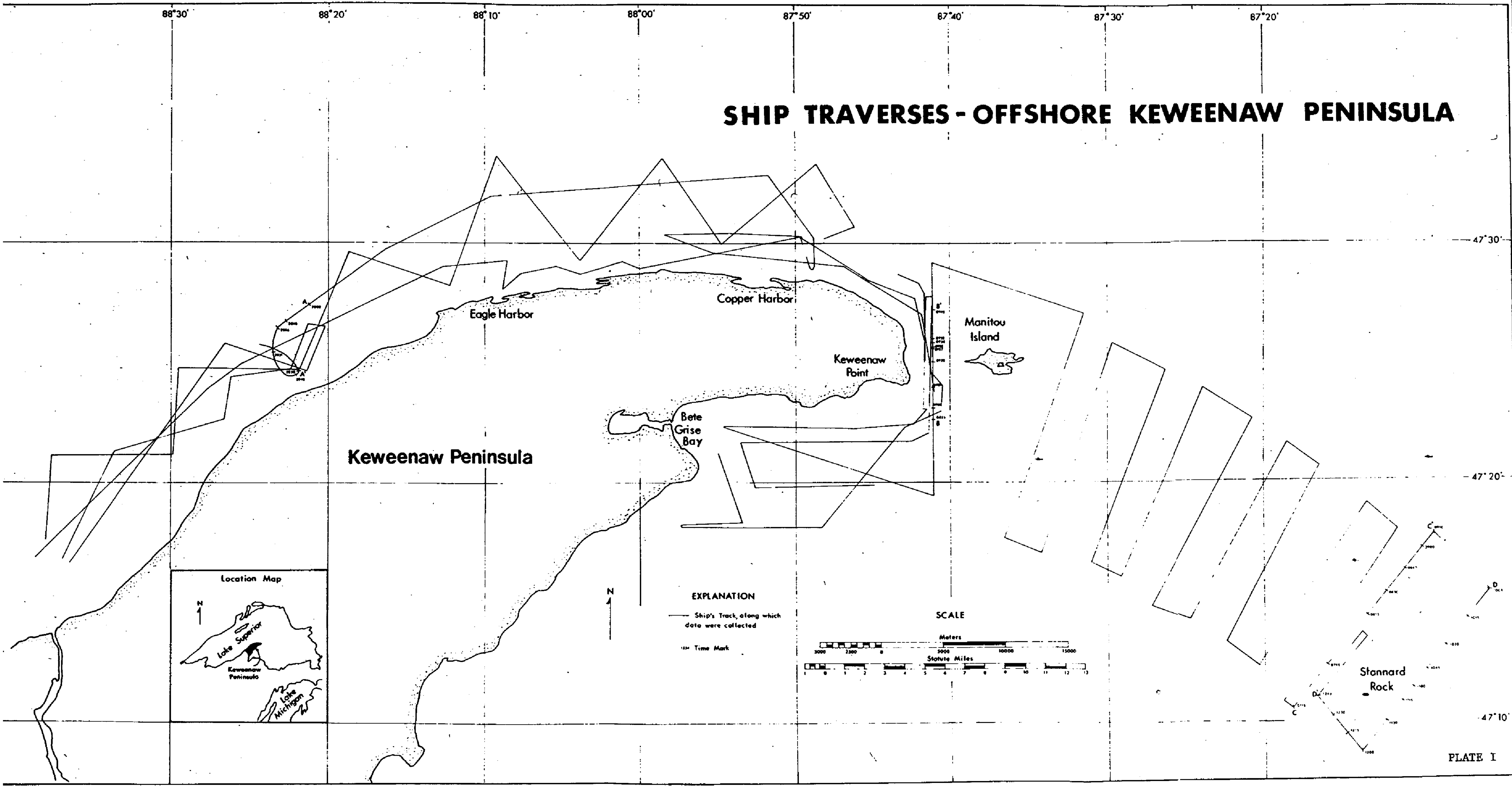

SHIP TRAVERSES - OFFSHORE KEWEENAW PENINSULA
88°30'
88°20'
88°10'
88°00'
87°50'
87°40'
87°30'
87°20'
47°30'
47°20'
47°10'
Eagle Harbor
Copper Harbor
Manitou Island
Keweenaw Point
Bete Grise Bay
Keweenaw Peninsula
Stannard Rock
Location Map
Lake Superior
Keweenaw Peninsula
Lake Michigan
N
EXPLANATION
Ship's Track, along which data were collected
Time Mark
SCALE
Meters
Statute Miles
PLATE I

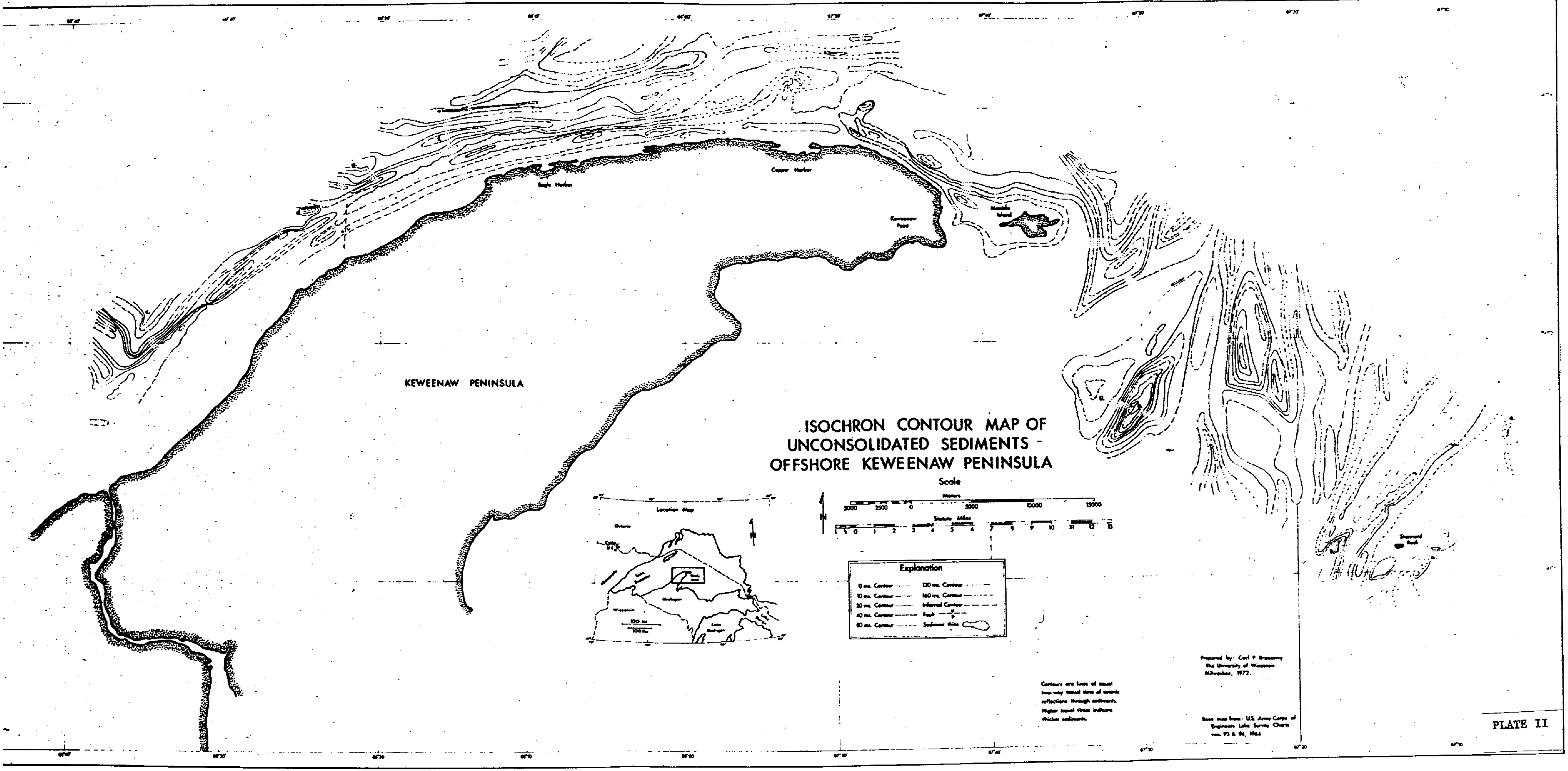
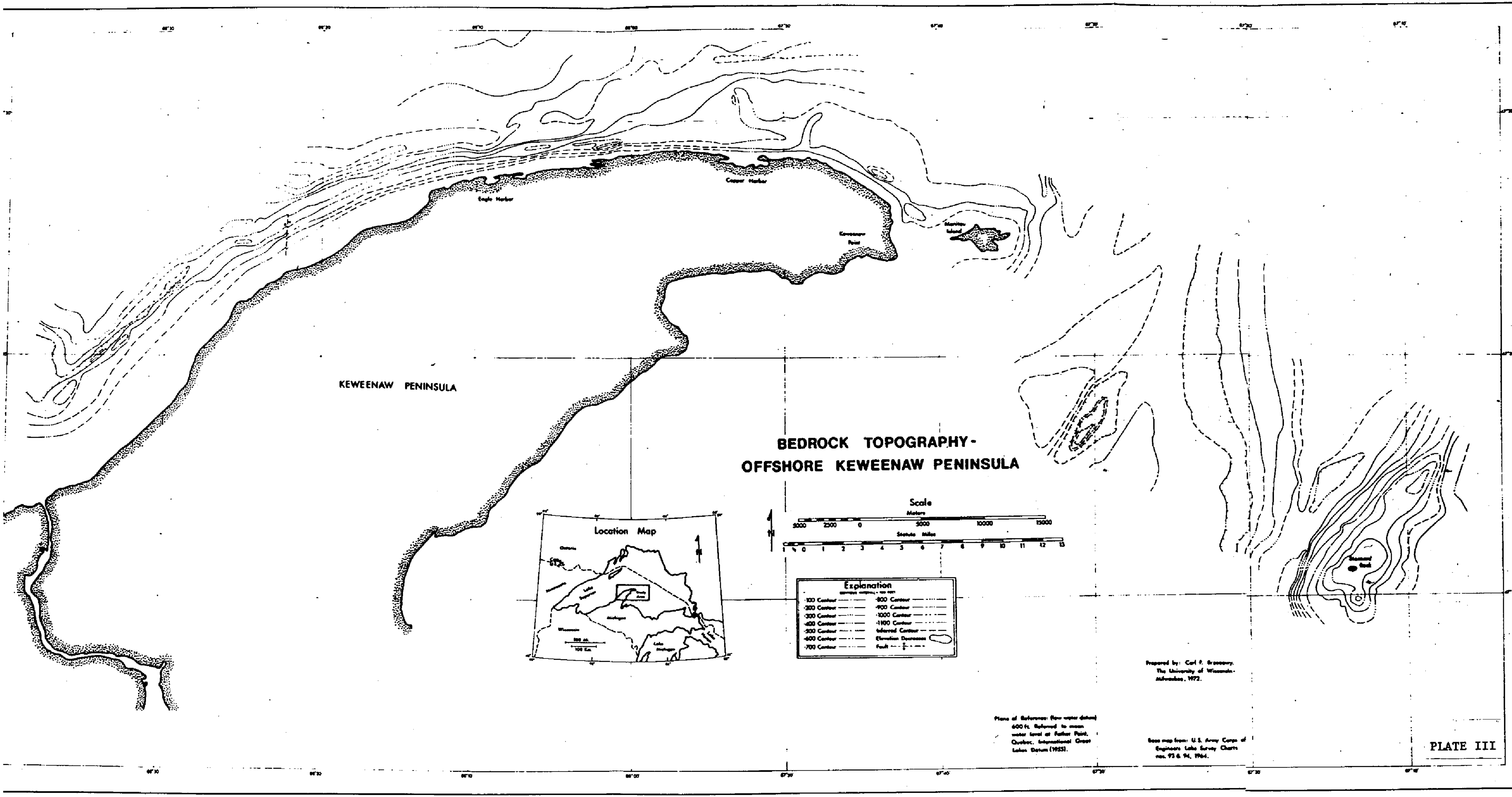
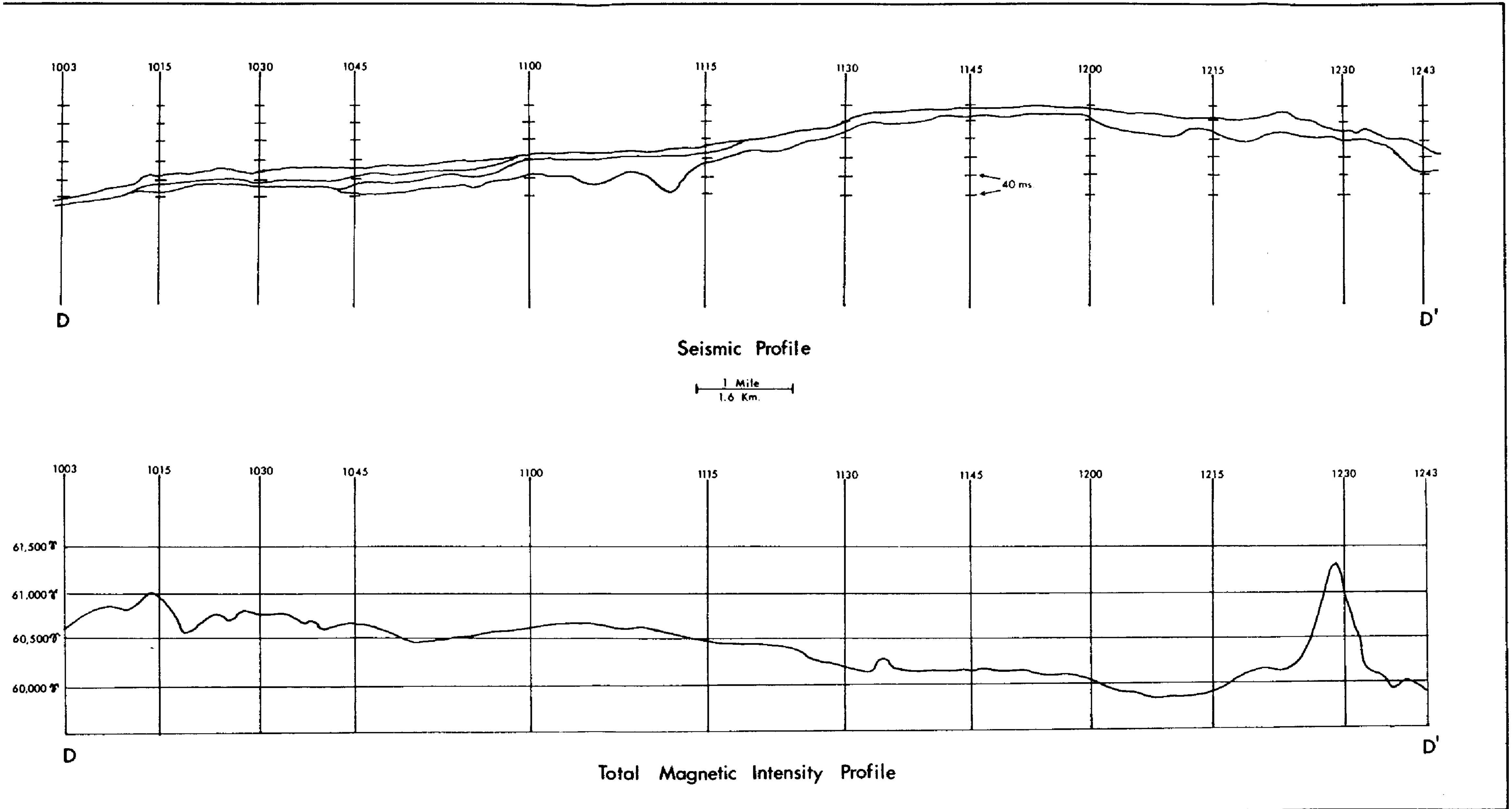

KEWEENAW PENINSULA
Eagle Harbor
Copper Harbor
Keweenaw Point
Manitou Island
ISOCHRON CONTOUR MAP OF
UNCONSOLIDATED SEDIMENTS -
OFFSHORE KEWEENAW PENINSULA
Scale
Meters
5000 2500 0 5000 10000 15000
Statute Miles
1 0 1 2 3 4 5 6 7 8 9 10 11 12 13
Location Map
Explanation
0 ms. Contour
10 ms. Contour
20 ms. Contour
40 ms. Contour
80 ms. Contour
120 ms. Contour
160 ms. Contour
Inferred Contour
Fault
Sediment thins
Contours are lines of equal two-way travel time of seismic reflections through sediments. Higher travel times indicate thicker sediments.
Prepared by: Carl P. Brzezowy
The University of Wisconsin - Milwaukee, 1972.
Base map from: U.S. Army Corps of Engineers Lake Survey Charts nos. 93 & 94, 1964

PLATE II

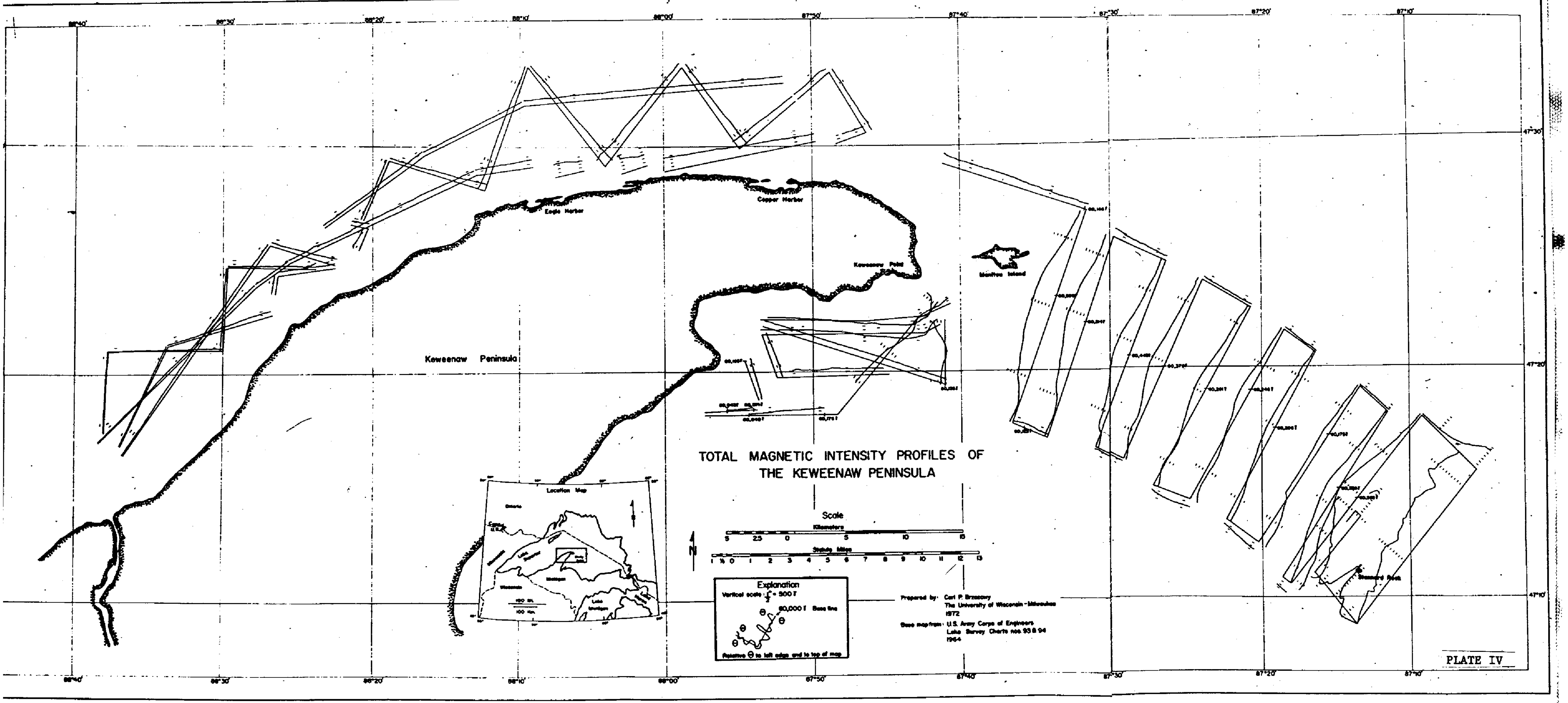


BEDROCK TOPOGRAPHY-
OFFSHORE KEWEENAW PENINSULA
KEWEENAW PENINSULA
Eagle Harbor
Copper Harbor
Location Map
Scale
Meters
5000 2500 0 5000 10000 15000
Statute Miles
1 ½ 0 1 2 3 4 5 6 7 8 9 10 11 12 13
Explanation
-100 Contour
-200 Contour
-300 Contour
-400 Contour
-500 Contour
-600 Contour
-700 Contour
-800 Contour
-900 Contour
-1000 Contour
-1100 Contour
Inferred Contour
Elevation Depression
Fault

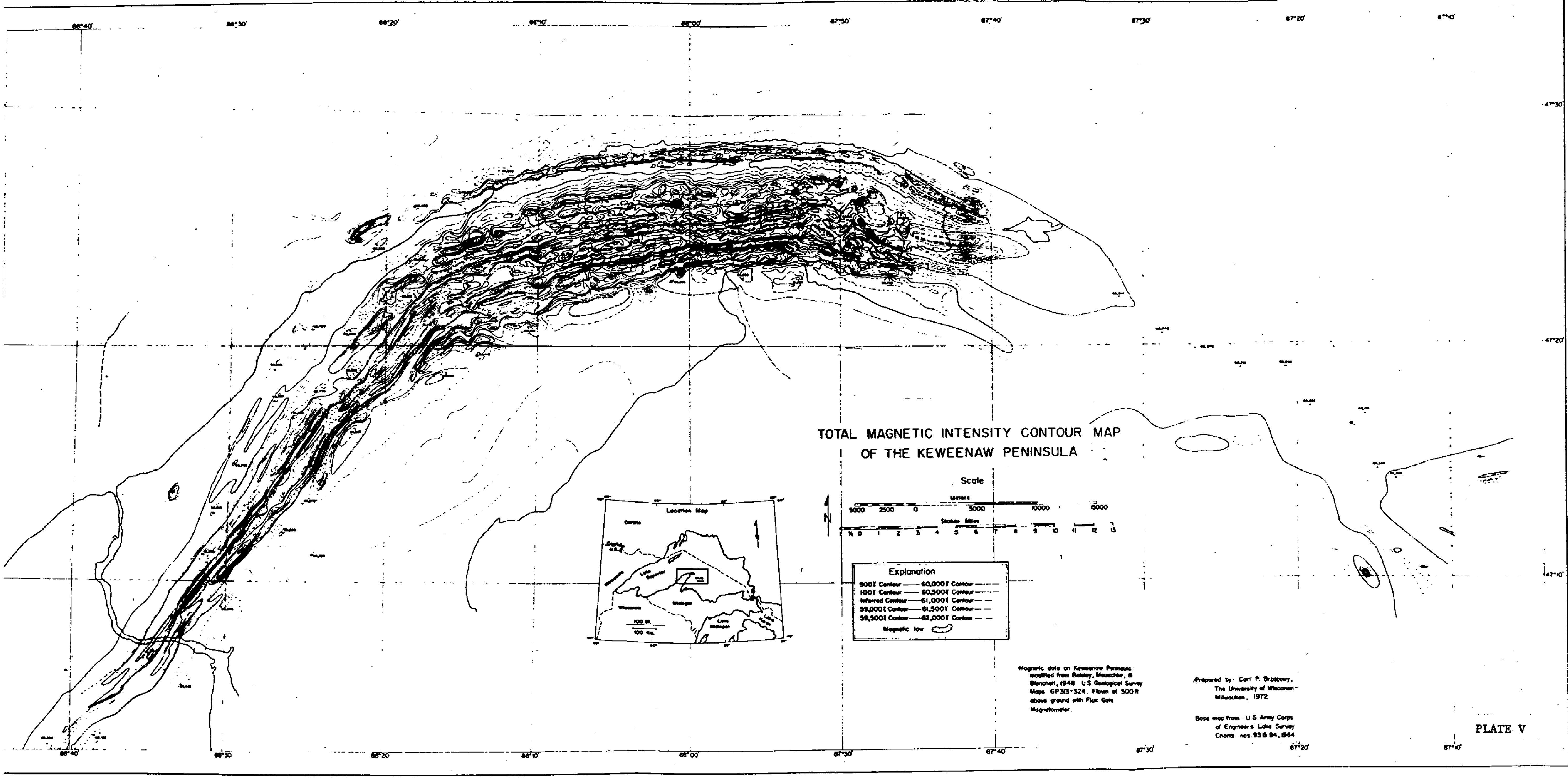
PLATE III



gure 11. Profile D-D'. Seismic and magnetic profiles located east and southwest of Stannard Rock, Michigan. Frequency range of seismic data is 40–150 Hz.



TOTAL MAGNETIC INTENSITY PROFILES OF THE KEWEENAW PENINSULA
Keweenaw Peninsula
Eagle Harbor
Copper Harbor
Keweenaw Point
Manitou Island
Location Map
Scale
Kilometers
Statute Miles
Explanation
Vertical scale = 500 γ
60,000 γ Base line
Relative Θ to left edge and to top of map
Prepared by: Carl P. Brzozowy
The University of Wisconsin - Milwaukee
1972
Base map from: U.S. Army Corps of Engineers
Lake Survey Charts nos. 93 & 94
1964
PLATE IV



TOTAL MAGNETIC INTENSITY CONTOUR MAP
OF THE KEWEENAW PENINSULA
Scale
Meters
5000 2500 0 5000 10000 15000
Statute Miles
½ 0 1 2 3 4 5 6 7 8 9 10 11 12 13
Location Map
Explanation
500γ Contour — 60,000γ Contour
100γ Contour — 60,500γ Contour
Inferred Contour — 61,000γ Contour
59,000γ Contour — 61,500γ Contour
59,500γ Contour — 62,000γ Contour
Magnetic low
Magnetic data on Keweenaw Peninsula: modified from Balsley, Meuschke, & Blanchett, 1948. U.S. Geological Survey Maps GP313-324. Flown at 500 ft. above ground with Flux Gate Magnetometer.
Prepared by: Carl P. Brzozowy, The University of Wisconsin-Milwaukee, 1972
Base map from: U.S. Army Corps of Engineers Lake Survey Charts nos. 93 & 94, 1964
88°40' 88°30' 88°20' 88°10' 88°00' 87°50' 87°40' 87°30' 87°20' 87°10'
47°30' 47°20' 47°10'

PLATE V