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ONTONAGON AND GOGEBIC COUNTIES, MICHIGAN

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ABSTRACT

A GRAVITY INVESTIGATION OF THE PORCUPINE MOUNTAINS AND ADJACENT AREA, ONTONAGON AND GOGEBIC COUNTIES, MICHIGAN

By William Roger Miller

A gravity study consisting of 294 observation points was made of the Porcupine Mountains and neighboring area in the Northern Peninsula of Michigan. A Bouguer gravity anomaly map, superimposed on a geologic map by White, 1962, is presented.

The Keweenaw fault, as defined by closely spaced, parallel gravity contours, extends completely across the study area. Gravity lows can be correlated with the Presque Isle and Iron River synclines. A linear gravity high north of the Keweenaw fault delineates the high-density, Portage Lake lava series. Two parallel series of closely spaced gravity contours correlate with the White Pine fault and suggest another fault northeast of and parallel to the White Pine fault.

The "cross-profile" method was attempted to separate the residual from the regional gravity anomaly, but was found to be unsatisfactory. The "smooth-contour" method was attempted and was found to be satisfactory.

The Talwani two-dimensional method was used to compute anomalies from bodies of assumed geometric configurations and density contrasts to fit the residual anomalies.

Variation in the regional gravity is attributed to thickening of the lavas down-dip.

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By
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INTRODUCTION

Nature and Scope

The Porcupine Mountains are an arcuate spur of the Keweenaw Trap Range in the northwest corner of Ontonagon County, in the Northern Peninsula of Michigan (Figures 1 and 2). They are the result of an anomalous geological structure in the Keweenaw rocks on the south shore of the Lake Superior Basin. This structure is an arcuate dome, parallel to Lake Superior. It interrupts the normal succession and dip of the rocks.

Although the regional geologic picture is known, limited outcrops and accessibility and lack of exploration drilling have hindered detailed geological mapping and geophysical investigations. To contribute to our geologic knowledge of the area, 294 gravity stations were established in the Porcupine Mountains and adjacent area. The known geology was correlated with the Bouguer gravity anomaly map. Limited quantitative calculations were performed on the resulting anomalies to better define the geology.

Previous Work

The geology of the Lake Superior Region has been studied for over a century. Logan (1863) was the first

to recognize the succession of rocks commonly accepted today. The historical development of Lake Superior geology is well summarized by Irving (1883) and by Van Hise and others (1911).

The first comprehensive study of the rocks of Keweenaw age on the south shore of Lake Superior was carried out by Lane (1911). He described the stratigraphy in detail and tabulated rock densities. Later Butler and Burbank (1929) made contributions concerning the petrology and ore deposits of rocks of the Keweenaw Peninsula. More recently, Leith (1935) and Broderick and others (1946) summarized work done since 1900 in this important copper producing area. Unfortunately, most of these workers were primarily concerned with the native copper district to the northeast, and gave little attention to the Porcupine Mountain area, the area covered by this study.

Thaden (1950) summarized the work done in the vicinity of the Porcupine Mountains and described the rhyolite exposed in the area. White (1954) described the geology of the White Pine copper deposits. Later, 1957, he described the regional tectonic setting of the Michigan copper district and in 1962 mapped the Nonesuch shale from Black River, on the Michigan-Wisconsin border, to Calumet, Michigan. Hamlin (1961) studied the paleogeography of the sedimentary rocks of Upper Keweenaw and Cambrian ages.

Aldrich (1923) applied geophysical methods to the study of the Keweenaw rocks of northern Wisconsin. Broderick (1928) found electrical and magnetic methods applicable to mapping faults and lava flows in rocks of Keweenaw age in Michigan. Theil (1956) and Bacon (1957) illustrated the relationship of Bouguer gravity anomalies to geology of the south shore of Lake Superior. Theil correlated the "midcontinent gravity high" with the gravity anomalies over the Keweenaw of Wisconsin. The regional gravity study by Bacon showed a similar high in the Northern Peninsula of Michigan. Recently the U. S. Geological Survey (1964) has released an aeromagnetic map of part of the study area.

GEOGRAPHY

Location

The study area is shown in Figures 1 and 2. It consists of the western two-thirds of Ontonagon County and the adjoining area of Gogebic County in the Northern Peninsula of Michigan. It includes approximately 900 square miles between parallels $46^{\circ} 30'$ and $46^{\circ} 55'$ north and meridians $89^{\circ} 15'$ and $90^{\circ} 00'$ west (Figure 2). Michigan State highways M-23 and M-64 and United States highway US-45 make the edges of the area accessible. The City of Ontonagon lies in the northeast corner of the area.

Climate

The climate of the area is tempered by its proximity to Lake Superior. Autumn and Spring are later than in other areas at the same latitude. The mean annual temperature is near 40° F. The winter average is near 23° and the summer average is near 56° F. Highs of 100° F and lows of -30° F have been recorded. Variations in the daily temperature of $40-50^{\circ}$ F are not uncommon. The average annual precipitation is near 30 inches, with snowfall in excess of 100 inches per year.

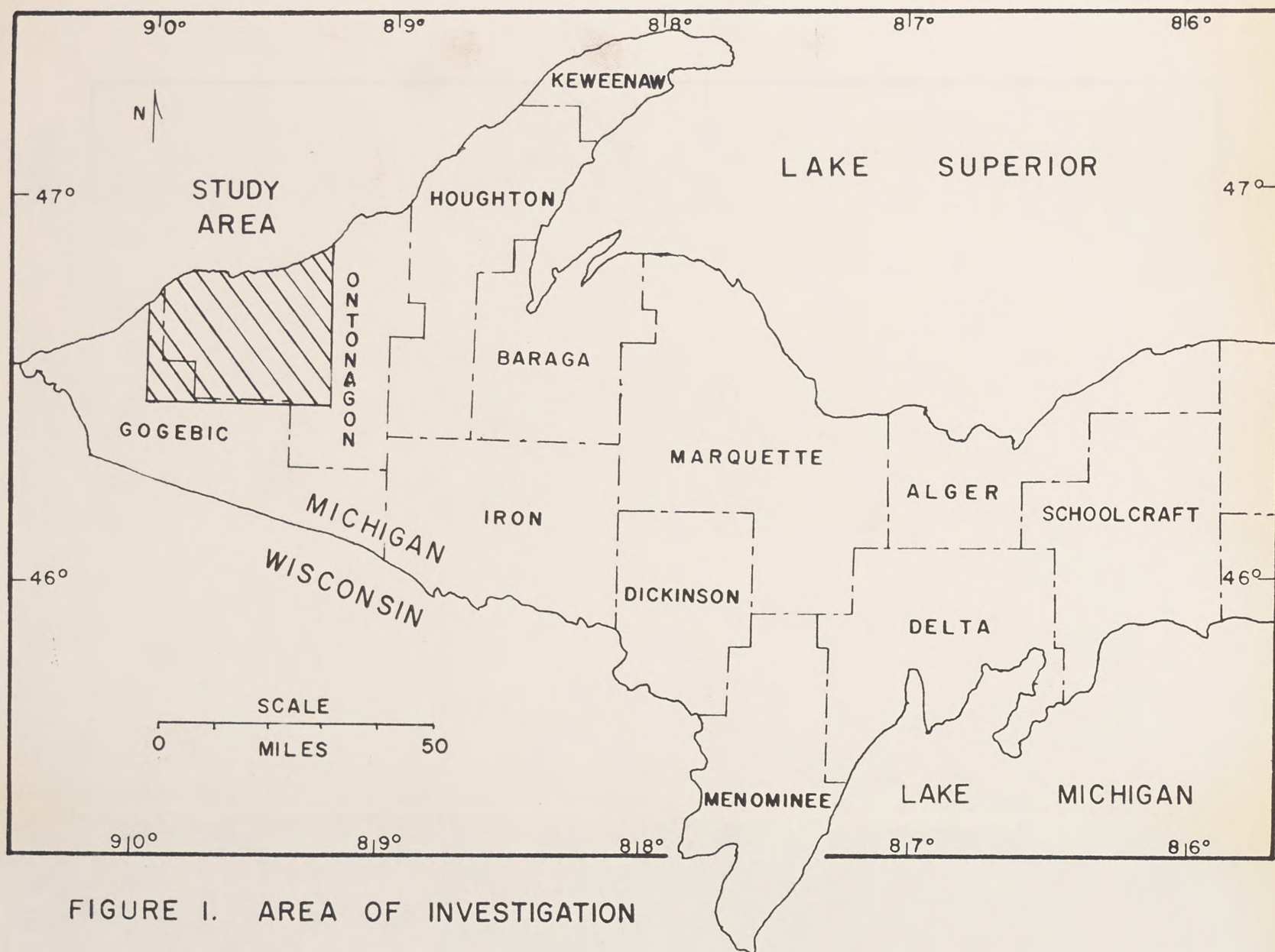


FIGURE 1. AREA OF INVESTIGATION

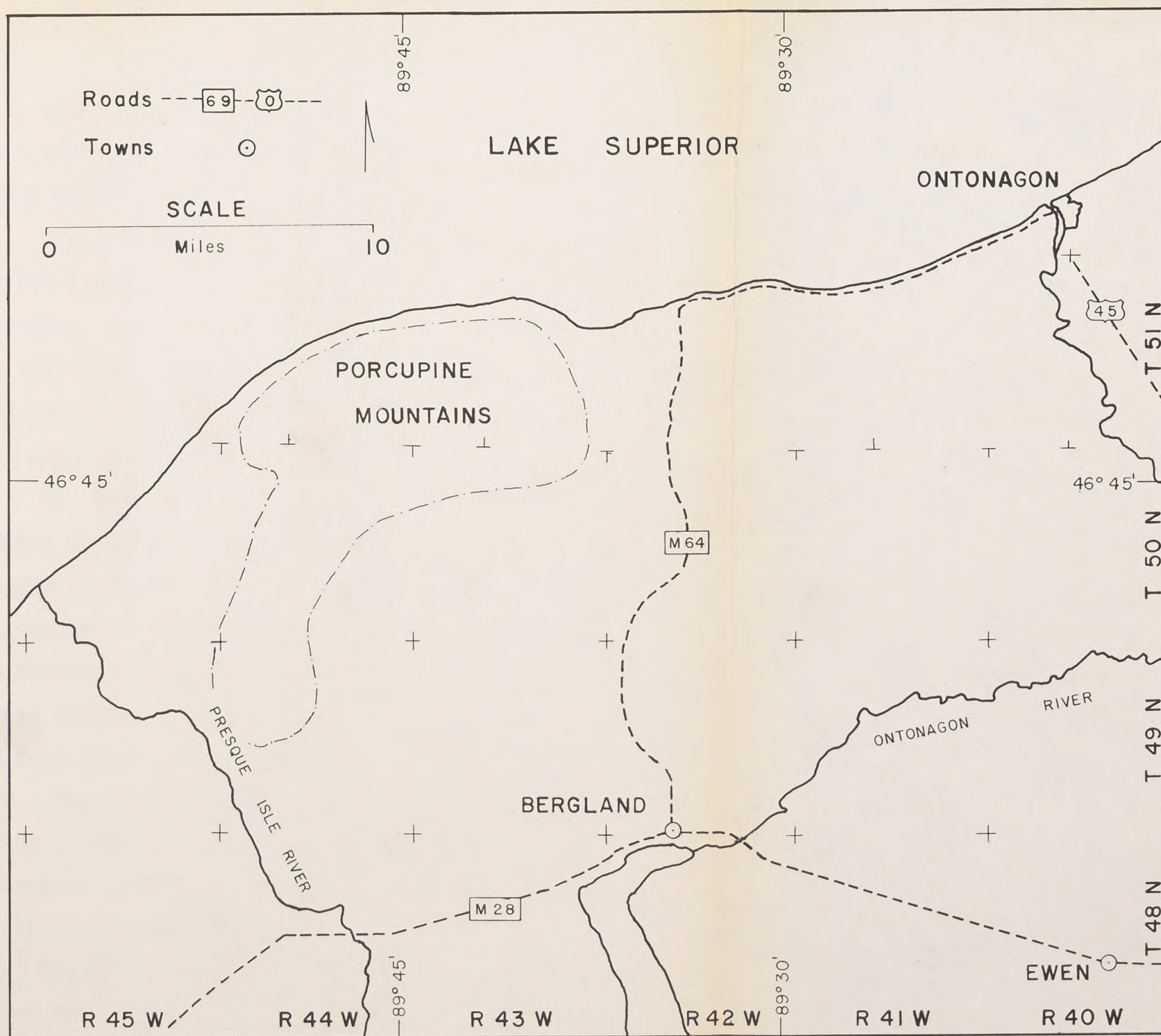


FIGURE 2. DETAIL MAP OF AREA OF INVESTIGATION

Physical Geography

An extensive description of the physical geography of the area is given by Martin (Van Hise, 1911). Only a brief resume will be attempted here.

The most prominent topographic features in the area are the Keweenaw Trap Range and the Porcupine Mountains. The overall relief in the area is greater than 1300 feet, varying from 602 feet above mean sea level (the mean elevation of Lake Superior) to 1953 feet above mean sea level in the Porcupine Mountains.

The Keweenaw Trap Range is a northeastward trending homoclinal ridge, sloping northwest. It extends from the northern edge of T. 49 N., R. 40 W. to the southwest corner of the study area. The mean elevation of this feature is near 1500 feet above sea level. The overall relief is near 500 feet. The highest point is 1775 feet above mean sea level at the Bergland fire tower. The topography, the result of differential erosion of the more resistant lavas and the less resistant sedimentary rocks, is rugged. Transverse water gaps cut the ridges in many places.

The Porcupine Mountains are in the northwestern part of the area of investigation. They are an arcuate, convex northward spur of the Keweenaw Trap Range and

are parallel to Lake Superior. The north slope is relatively steep, and increases some 800 feet above lake level less than two miles inland. The mean elevation of the Porcupine Mountains is about 1500 feet above mean sea level. The average local relief is near 300 feet. The highest point in the Porcupine Mountains is an unnamed peak, 1958 feet above mean sea level.

South of the Keweenaw Trap Range is a broad, relatively flat plain. It has an average elevation of 1300 feet above mean sea level. The local relief is 100 feet. North of the Keweenaw Trap Range a flat plain gently slopes toward Lake Superior.

The southern portion of the area is drained by the Ontonagon and Presque Isle Rivers. They flow northward through gaps in the Trap Range at either end of the study area. Streams on the northern slopes of the Trap Range generally flow northward toward Lake Superior. They are perpendicular to the strike of the ridges and have relatively small drainage basins. The largest of these streams, the Iron River, drains an oblate shaped basin between the Porcupine Mountains and the Trap Range. The Carp and Little Carp Rivers drain the main part of the Porcupine Mountains. They follow subsequent valleys until they cut the ridges in the southern part of the Porcupine Mountains. Several of the streams show evidence of stream piracy, indicating fluctuations in the drainage of the area.

During Pleistocene time, the area was covered by the Chippewa and Keweenaw lobes of the Wisconsin ice sheet (Leverett, 1929). Except for several of the valleys which have been deepened and widened, the topography is believed to be much the same now as it was before glaciation. Drift in the Trap Range is thin where present. Most of the lower elevations are covered by relatively thin drift or glaciolacustrine deposits.

Industry

The major industry in the areas is mining, with lesser importance given to agriculture, lumbering and tourism. The native copper deposits in the area were first exploited by prehistoric Indians (Drier, 1961). Mining by the "white man" did not begin until about 1840, (Butler and Burbank, 1929). Since that time mining activity has fluctuated considerably. The White Pine copper mine is the only deposit presently being exploited.

Agriculture is limited to dairy farming and root and hardy orchard crops. The lumbering is primarily of pulpwood and minor hardwood. Tourism is rapidly becoming an important industry.

GEOLOGY

General

The Precambrian rocks of the Lake Superior region can be subdivided into three distinct groups or systems, separated at most places by major unconformities. They are overlain in places by Paleozoic rocks and generally are concealed by glacial debris of Pleistocene age.

The Upper Precambrian is the predominate age of rocks in the study area. It is a thick sequence of relatively unmetamorphosed, interbedded lava flows and sedimentary rocks. These rocks are called the Keweenaw series. They are conformable with rock units of earlier and later age.

The Lake Superior structural basin and the Keweenaw fault are two major structural features which control the structures in the study area.

Stratigraphy

The formations in the study area are: the Portage Lake lava series of Middle Keweenaw age; the Copper Harbor conglomerate, the Nonesuch shale and Freda sandstone, the lower units of the old Oronto group (Thwaites, 1912), of Late Keweenaw age. The youngest unit in the area is the Jacobsville sandstone which is late Keweenaw

1

or Cambrian in age and has been correlated with the Bayfield group of Wisconsin. A generalized geologic column is given in Table 1.

The Portage Lake lava series (White, 1953) is a thick sequence of basalt and andesite flows, with a few interbedded rhyolitic conglomerates and, locally, rhyolites. It comprises the four groups of Irving (1883); the Bohemian Range group, the Central Mine group, the Ashbed group, and the Eagle River group.

The Bohemian Range group is a sequence of amygdaloidal basalt flows. It contains subordinate conglomeratic beds and rhyolites. It attains a thickness of 10,000 feet. A basal conglomerate rests unconformably on the Animikie or Middle Precambrian rocks (Allen, 1915).

The Central Mine group is a similar sequence characterized by thick lava flows. Associated with these flows are minor interbedded rhyolitic conglomerates and thin ash beds.

The Ashbed group is described as a series of interbedded lava flows and subordinate coarse, sedimentary rocks. In the Porcupine Mountains the lower part is a thick sequence of rhyolite (Thaden, 1950).

The Eagle River group, a 2000 foot sequence of basic lava flows, is interbedded with minor amounts of rhyolitic conglomerates.

The total thickness of the Portage Lake lava series

TABLE 1.. GENERALIZED GEOLOGIC COLUMN

CENOZOIC

Quaternary

glacio-fluvatile deposits

----- unconformity -----

PALEOZOIC (?)

Cambrian

Jacobsville sandstone

-----?-----?-----?- unconformity -?-----?-----?-----?--

PRECAMBRIAN

Keweenawan

Upper

Oronto group

Freda sandstone

Nonesuch shale

Copper Harbor group

Outer conglomerate

Lake Shore trap

Great conglomerate

Lower

Portage Lake lava series

Eagle River group

Ashbed group

Central Mine group

Bohemian Range group

----- unconformity -----

Huronian

is 25,000 feet at Houghton, Michigan but it thins westward. It is probably no more than 5000 feet thick in Wisconsin.

The Copper Harbor conglomerate is the thickest and most persistent conglomerate of the Keweenaw sequence. It can be traced from Keweenaw Point to Black River on the Michigan-Wisconsin border and further west. In the Porcupine Mountains it is 5000 feet thick and comprises three distinct units, known in the older literature as; the Great and Outer conglomerates which are separated by the Lake Shore Traps. Lithologically the sedimentary units are poorly stratified conglomerates, containing minor interbedded, medium to coarse grained, arkosic sandstones. These units interfinger and pinch out in relatively short distances. The ratio of sandstone to conglomerate is unknown due to absence of continuous exposures. El-Kjalidi (1950) found a predominance of sandstone in measured sections on the north flank of the Porcupine Mountains. The Lake Shore traps are a 300-400 foot series of basic lava flows. They form the escarpment overlooking Lake of the Clouds in the Porcupine Mountains.

A sharp lithologic break separates the Copper Harbor conglomerate from the overlying Nonesuch shale and Freda sandstone. These units are a series of silty shales, siltstones and sandstones, several thousands of feet thick.

The Nonesuch shale is predominately a flaggy, grey

to reddish-gray siltstone, 800 feet thick, with interbedded gray to greenish-gray, silty shales. The presence of ripple marks and mudcracks indicate a shallow marine or continental environment, possibly deltaic. Nonresistant heavy mineral suites and angular detritus suggest deposition near to the source.

The contact between the Nonesuch shale and the Freda sandstone is gradational. The Freda is a well sorted, fine to medium grained, red to greenish-gray arkose. It contains minor amounts of red to green, micaceous shales and siltstones. The Freda is generally considered to be the youngest formation of the Keweenaw sequence. Accurate measurements of the thickness of the Freda are not available, however, data from scattered exposures near the Porcupine Mountains indicate a thickness of 14,000 feet (Hamblin, 1958).

The Jacobsville sandstone comprises the rock unit southeast of the Keweenaw fault. It is a medium to fine grained, red to white, quartzose sandstone. It is 4000 feet thick (Hamblin, 1961). It has been correlated with the Bayfield group in Wisconsin and is believed to lie between rocks of Keweenaw and Croixian ages. Because no contacts have been found, its relationship with the underlying Freda sandstone is still conjectural.

The rhyolites and other acidic rocks on the Keweenaw Peninsula occur in all definitely Keweenaw lithological

units (Reed, 1964). The exact relation of these bodies to the sedimentary rocks is not fully known. However, they could be sources for some of the rhyolitic conglomerates of the Keweenaw series.

Structure

Regional Lake Superior occupies a great synclinal structure, the Lake Superior Basin, in the southern Canadian Shield. The periphery of the western half of the basin is composed of rocks of Keweenaw age. Except for a subordinate fold in the Porcupine Mountains, the beds dip toward the center of the basin. They are steeper on the south than on the north limb. A general flattening of dip occurs from the base to the top of the Keweenaw section, with thickening of the units down-dip. These factors indicate a depositional basin. Furthermore, bent pipe amygdules (Butler and Burbank, 1929) indicate that the lava flowed from the center toward the margin of the basin. However, foreset bedding and pebble imbrication in the Upper Keweenaw (Hamblin, 1958 and 1961) indicate stream flow from the margin to the center of the basin.

White (1957) explains this apparent paradox by a relatively flat basin floor and generally continuous downwarping. When lava accumulation keeps pace with subsidence, the floor remains flat and the lava spreads

1

outward. This causes the streams to flow parallel to the basin and to pond at the margins. When extrusion is interrupted, continued subsidence of the basin will cause the streams to flow toward the center of the basin. Later eruptions will flow from their source to the lowest point in the basin and from there outward.

Folds The south limb of the Lake Superior Basin is quite irregular; broad, transverse anticlines and synclines plunge down-dip toward the center of the basin. Many minor fluctuations occur on these major flexures.

The Porcupine Mountains are an arcuate dome, parallel to Lake Superior. They are connected to the Keweenaw Trap Range by a saddle. Thaden (1950) confirmed the presence of rhyolite in the center of the Porcupine Mountains as previously mentioned by Butler and Burbank (1929).

The Iron River syncline lies between the Porcupine Mountains and the Keweenaw Trap Range. It is assymetric and strikes northeast. It is truncated on the northeast by the White Pine fault. The beds on the north limb are near vertical and locally overturned.

The Presque Isle syncline is on the west flank of the Porcupine Mountains. It plunges northwest.

Several other folds exist. Many are the result of drag along faults. They vary in size from a few feet, to several miles in magnitude.

Faults The Keweenaw fault is a high angle reverse fault. It strikes northeast and dips northwest. It has been mapped along the southern edge of the Keweenaw Trap Range from the end of the Keweenaw Peninsula to the northern edge of Lake Gogebic. A broad trough-like area exists between the Keweenaw fault on the north and the South Trap Range and Precambrian highlands to the southeast. This trough is generally thought to contain a wedge of Jacobsville sandstone deposited prior to deformation. Figure 3 is the postulated configuration of the fault and associated sedimentary wedge.

The rocks are offset in many places by other faults. The majority of these are transverse faults associated with post-depositional deformation. Lane (1911) notes the occurrence of longitudinal strike and dip faults.

The White Pine fault, a major transverse fault, strikes northwest and dips steeply northeast. It is a right-handed tear fault. Lateral displacement is only about one mile and vertical displacement is only a few hundreds of feet (White, 1954). Other faults in the area are minor. Figure 4 is a generalized structure map of the area and shows only the major structural features.

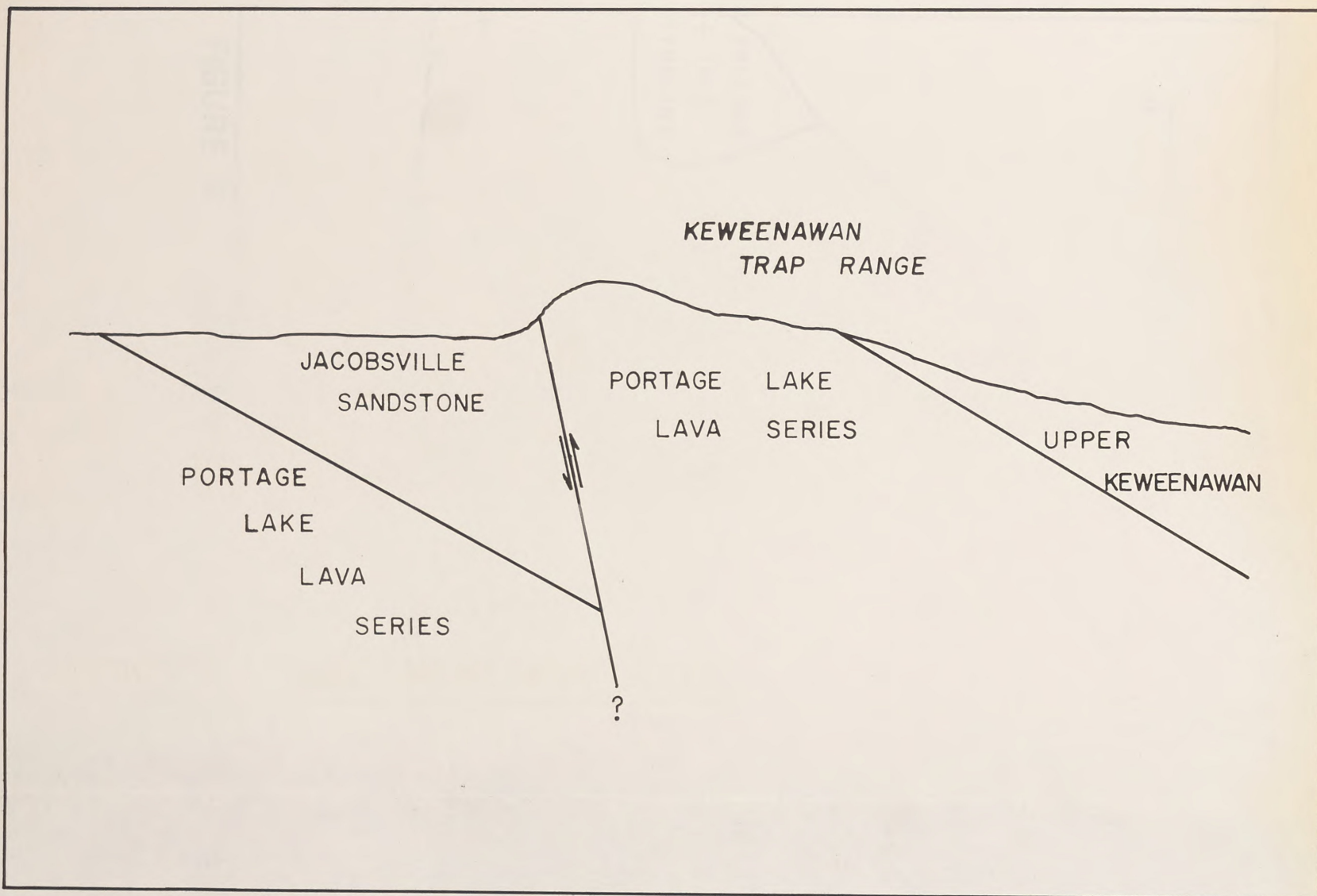


FIGURE 3. THE KEWEENAW FAULT

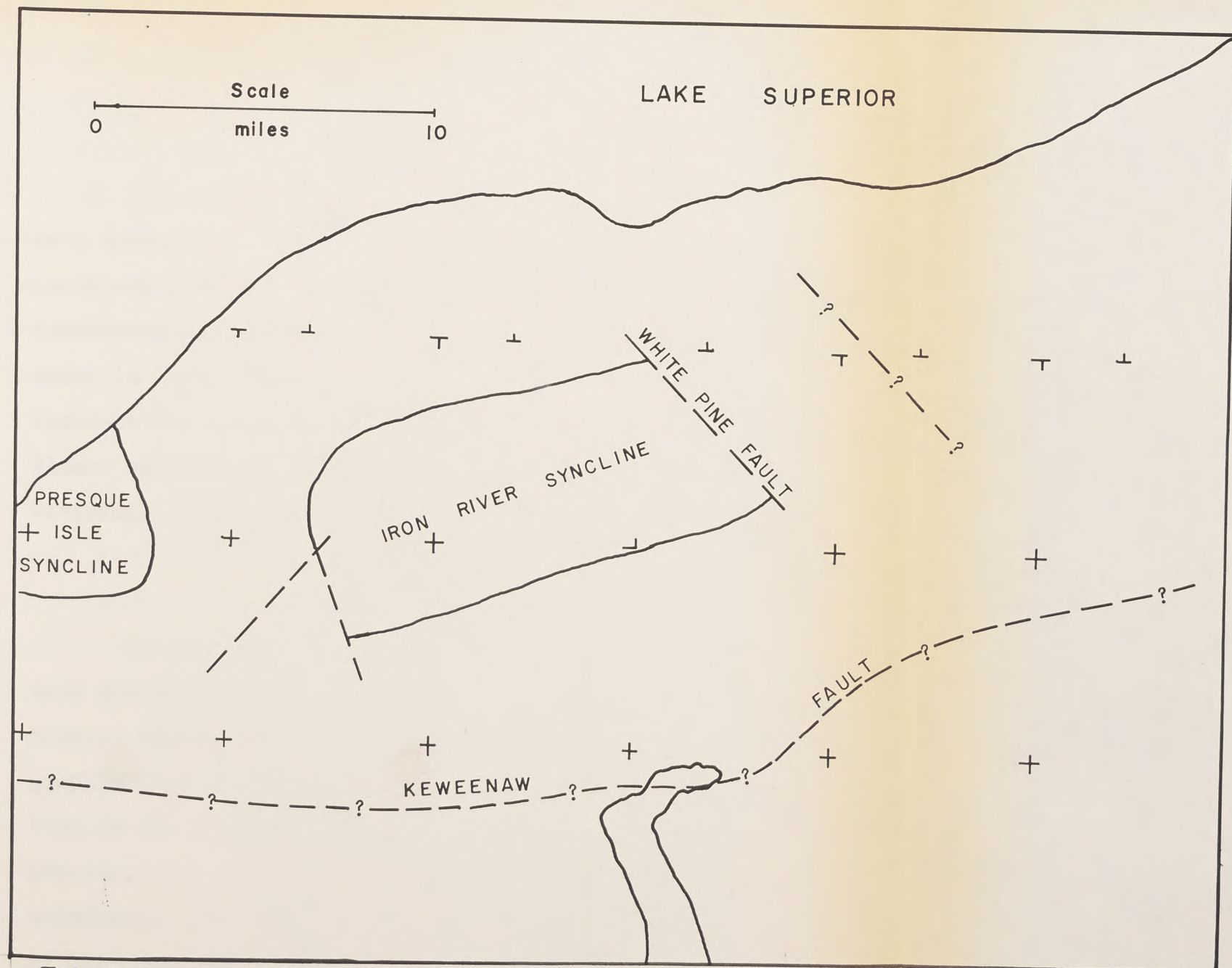


FIGURE 4. SIMPLIFIED STRUCTURE MAP OF STUDY AREA

FIELD PROCEDURE

Instrument

The gravity observations were taken in the study area during July and August, 1963, employing Worden gravimeter no. 99. The gravimeter measures the relative acceleration of gravity with a sensitivity of 0.01 mgals, which is about one part in 100 million of the earth's acceleration of gravity (980 gals). The meter has a linear calibration constant of 0.994(5) mgals per scale division and a range of about 80 mgals without resetting.

Stations

Gravity stations (Plate 1), were placed at one-two mile intervals along the existing road system. They were plotted from U. S. Geological Survey, 15 minute, topographic maps with an accuracy of 0.1 miles. Transportation to the majority of the stations was by automobile. However, foot traverses were made to remote areas where necessary. One foot traverse was made along the shore of Lake Superior on the Lake Superior Trail from the east end of Porcupine Mountain State Park to the mouth of the Presque Isle River, a distance of 15 miles. Elevations were ascertained for this traverse with a hand level using Lake Superior as a reference datum.

Gravity base stations (Figure 5), located on or near easily accessible roads, were chosen to minimize travel time and the number of times the gravimeter needed to be reset. They were tied to each other by the method of looping (Figure 5). Station "A" was chosen as the primary base and the others as secondary bases. The study was adjusted to the "international gravity datum" through the Bergland and Wakefield gravity bases of Professor Lloyd Facon (Hinze, 1964).

Elevations

The majority of the gravity stations were placed within 50 feet of U.S. Geological Survey or U.S. Coast and Geodetic Survey "bench marks" or at road intersections with known elevations. Elevations for these stations were determined with a hand level and have an accuracy of $\pm$ 2 feet. Elevations at road intersections given on U.S. Geological Survey topographic maps, with a 20 foot contour interval have an accuracy of $\pm$ 2 feet (Meyer, 1963). The remainder of the stations were established at road or trail intersections and the elevations interpolated from the 20 foot contour interval. It is the author's opinion that these elevations have an accuracy of at least $\pm$ 20 feet and might approach $\pm$ 10 feet.

Drift

The elastic properties of the working parts of the

The number of lines
between stations indicates the
number of direct gravity ties

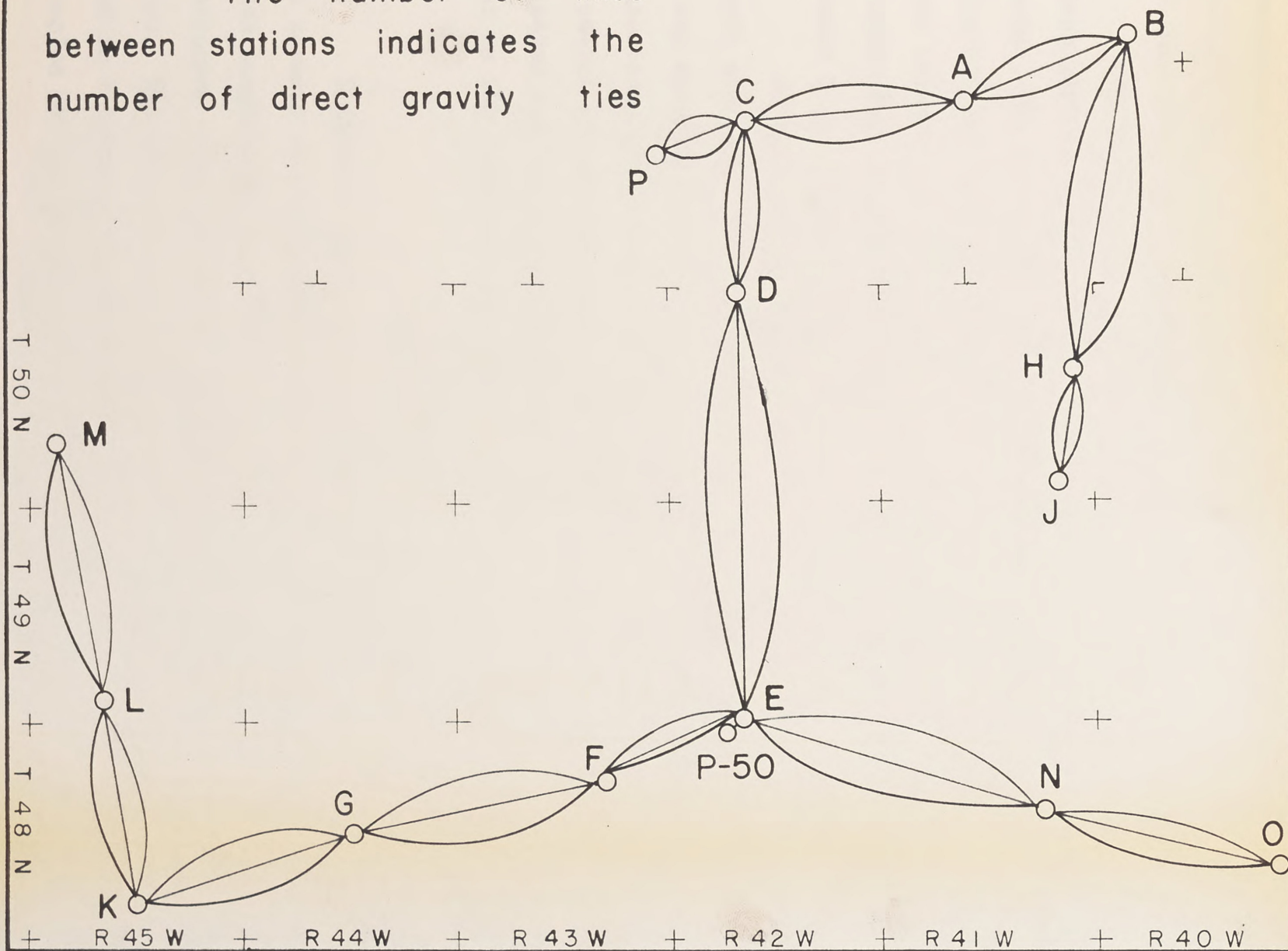


FIGURE 5. GRAVITY BASE LOOPING

gravimeter and temperature variations cause changes of readings with time. This change is called drift. Control of this drift was accomplished by one of two methods.

For automobile traverses, stations of known gravity (base stations) were occupied at least once every two hours. The gravimeter readings were then plotted versus time and the indicated drift removed from the stations read between the base stations. This method assumes linear drift and is called the "base-check" method. Figure 6 is a typical daily drift curve.

On foot traverses, the "rate" method (Woollard, 1958) was used. This is accomplished by occupying any given station at least twice during each traverse. In this case, each station was read at least twice during a period of one-half hour. The rates of drift are then plotted and the indicated drift removed in a manner similar to the "base-check" method.

Rock Sampling

Samples of various lithological units were collected at several sites throughout the area. Limited outcrops made sampling of all units difficult. Only the more resistant units (those that were well exposed) were sampled. The Nonesuch shale was sampled at the Nonesuch mine and in the White Pine mine. The conglomerates were sampled at various exposures along the shore of Lake

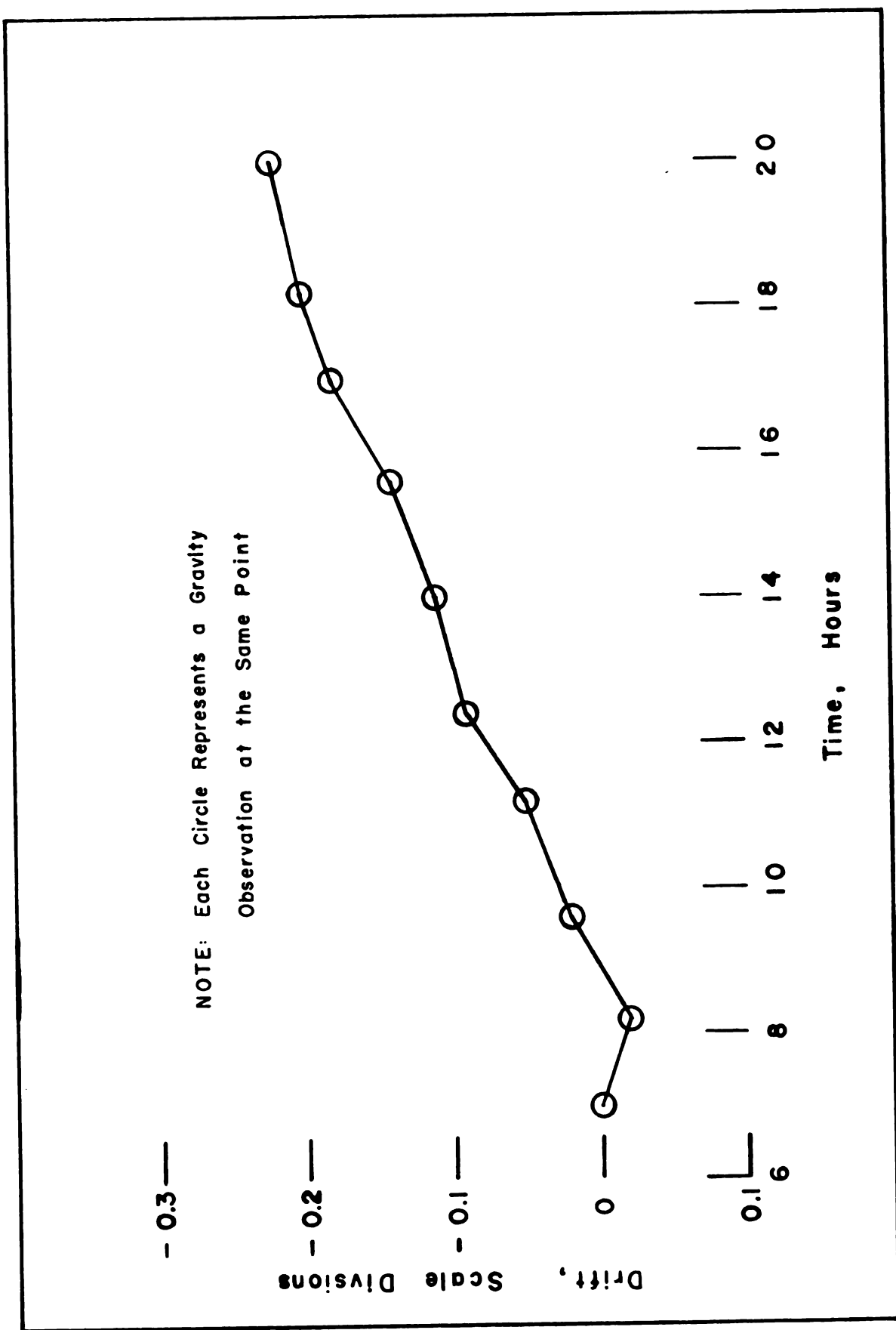


Figure 6. Typical Daily Drift Curve

Superior as well as on the south flank of the Porcupine Mountains. Basic rocks were collected from the escarpment overlooking Lake of the Clouds and from scattered exposures in the Keweenaw Trap Range. Fresh, unweathered samples are necessary for reliable density measurements. However, fresh samples were not always obtainable. Therefore, a certain amount of error has been introduced.

LABORATORY PROCEDURE

Rock Densities

Lane (1911) compiled a list of densities for Keweenawan rocks of Michigan. He used values previously determined by MacFarlane (1886), Marvin (1873) and others.

Recently Theil (1956) discussed the density relationships of gravity anomalies with Keweenawan rocks in northern Wisconsin. Mack (1957) also studied densities of Wisconsin rocks. Density values presently accepted by Professor Lloyd Bacon (Hinze, 1964) are incorporated into this study. Densities were measured of rock specimens collected by Thaden (1950) and by the author.

The densities were determined by the normal method of loss of weight in water. More than one determination was made for each specimen. The first measurements were of initially dry samples, the second after soaking for a period of one week, and the third after soaking for a period of one month. Some of the samples disaggregated with soaking. Gradual increase in densities was observed with soaking, especially the more porous units. This increase may be explained by saturation of the more permeable rocks. The densities determined by the author are given in Table 2.

The densities determined by the writer are

Table 2...Densities Determined in This Study

Rock Type and Locality	pop.	1st deter (1)		2nd deter (2)		3rd deter (3)	
		Mean	Range	Mean	Range	Mean	Range
Rhyolite: Porcupine Mountains (Thaden, 1950)	16	2.53	2.32-2.76	2.56	2.42-2.73	2.56	2.38-2.70
Miscellaneous	6	2.56	2.40-2.68				
Basic Rocks: Porcupine Mountains and Trap Range	11	2.99	2.95-3.02	3.00	2.97-3.03		
Shale: Nonesuch shale from White Pine Mine	2	2.65	2.64-2.66	2.72	2.67-2.78	2.74	2.73-2.74
Nonesuch shale from Nonesuch Mine	4	2.86	2.75-2.91	2.87	2.84-2.89	2.93	2.89-2.95
Miscellaneous	6	2.79	2.65-2.83				
Conglomerates: Lake of the Clouds	4	2.59	2.58-2.60 2.58-2.60	2.65	2.61-2.71		
Nonesuch Mine	4	2.58	2.49-2.66	2.65	2.57-2.79		
Lake Superior shore	4	2.64	2.60-2.66				
M-107	5	2.55	2.51-2.66	2.70	2.65-2.76		

Table 2...Densities determined in this study (cont'd.)

Rock Type and Locality	pop.	1st deter (1)		2nd deter (2)		3rd deter (3)	
		Mean	Range	Mean	Range	Mean	Range
Sandstones: South of Porcupine Mountains (highly ferruginous)	4	2.77	2.63-2.81	2.81	2.67-2.87	2.84	2.68-2.94

1.) Samples initially dry.

2.) Samples soaked for 1 week.

3.) Samples soaked for 1 month.

4.) The population is the number of samples measured; the mean is the arithmetic mean; and the range is the lowest measured value through the highest measured value.

appreciably different from those determined by others who have studied the rocks of Keweenawan age (Table 3).

Table 3. Densities as determined by other workers and by the author.

	Lane	Theil	Bacon	Miller
Sandstones and Shales	----	2.30-2.35	2.25	2.35
Conglomerates	2.74	-----	----	2.65
Rhyolite	2.60	-----	2.67	2.55
Basic rocks	2.87	2.91	2.90	3.00

Table 4. Densities used in Reduction

Lithology	{ Dens } { g/cc }
Sandstones and Shales	2.40
Conglomerates	2.60
Rhyolite	2.55
Basic Rocks	2.90

Because only a limited number of exposures were sampled and those that were sampled are the more resistant units, they are not representative of the total section. Therefore, the densities measured are probably not entirely valid. To be consistent with other gravity studies of Keweenawian rocks, the densities used in this study are those used by Professor Lloyd Bacon (Table 4). Exceptions are the densities of the rhyolite and the conglomerates.

Reduction of Data

Observed gravity data must be reduced to remove the effects of latitude, elevation, and mass distribution. The reduction is according to the equation:

$$g_B = g_0 - g_{\theta} / g_F = g_M / g_T$$

where g_B = Bouguer gravity anomaly; g_0 = observed gravity; g_{θ} = theoretical sea level gravity; g_F = free air correction; g_M = Bouguer or mass correction; and g_T = terrain correction.

The Bouguer gravity anomaly is the gravity value that exists after the Bouguer correction has been applied to a level datum (AGI Glossary, 1960). It is the difference between the calculated theoretical and the observed gravity at the station site.

Observed gravity is the measured acceleration of gravity at any point. It is computed by multiplying the meter readings, corrected for drift and adjusted to the primary base of this study, by the meter calibration constant.

The theoretical sea level gravity or latitude correction removes the effect of the decrease in the acceleration of gravity from the equator to the poles. It is expressed by the "1930 international gravity formula":

$$g_{\theta} = 978.049(1 + 0.0052884\sin^2\theta - 0.0000059\sin^2 2\theta)$$

where 978.049 is the mean sea level gravity at the equator and g_{θ} is the gravity at latitude θ .

Nettleton (1940) has shown that differences in latitude corrections are negligible for small latitude changes. The correction factor used in this study is the average of the corrections for the least and the greatest latitudes of the study area. The latitude correction is added to the observed gravity if the station is south of the primary base latitude and subtracted if it is north.

Table 5. Latitude Corrections

	Latitude	Correction (mg/ml)	Factor (mg/ft)
Least latitude	46° 30'	1.3052	0.0002471
Greatest latitude	46° 55'	1.3041	0.0002469
Mean		1.30465	0.000247

The free air correction compensates for the elevation of the gravity station above a common level datum. It is found by multiplying the elevation of the station above the datum by the vertical gradient of gravity, 0.00405 mgals per foot.

The Bouguer or mass correction compensates for the mass distribution between the station and datum. It is found by multiplying the elevation of the station above datum by 0.01276 mgals per foot, where ρ is the density of the mass between the station and datum.

Different densities for the Bouguer reduction were assigned to the gravity stations according to the geology as mapped by White (Plate 1). The data was reduced to a datum of 600 feet above mean sea level, the approximate level of Lake Superior. As stated by Vajk (1956):

- "1. If the density of the surface rocks varies, the effect of the topography cannot be eliminated from the gravity data by computing the Bouguer correction with a constant density.
2. Bouguer corrections with varying density must be used only to the datum surface of the topography..." (the lowest elevation in the study).

Terrain corrections account for the variations in the Bouguer assumptions (Nettleton, 1940). They were determined according to the method outlined by Hammer (1939). Only zones E-K inclusive were found to be applicable to the study area. These zones include the area between circles with radii of 553 feet to 32,490 feet

away from each station. Because of their proximity to major topographic features, 25 per cent of the gravity stations were selected for terrain corrections. The corrections were applied only where they exceeded 0.1 mgal.

All calculations in the reduction and interpretation of the data were performed by the CDC 3600 digital computer. Exceptions were the drift and terrain corrections. The original data and the computer programs are on file at the Department of Geology, Michigan State University.

The principal facts for the gravity bases are given in Table 6.

Sources of Error

U. S. Geological Survey, 15 minute topographic maps at a scale of 1/62500 were used to locate stations for latitude corrections. The location accuracy is ± 0.1 miles, which creates a gravity effect of about ± 0.13 mgals. Elevation errors vary from ± 2 to ± 20 feet and introduces a maximum error of ± 0.13 to ± 1.26 mgals in the reduction of the data. The combined errors resulting from observation and removal of drift are estimated to be no greater than ± 0.1 mgals. Terrain results in a maximum error of 0.1 mgals.

An accuracy of ± 0.50 mgals was sought in this survey and undoubtedly has been achieved for the majority of

Table 6...Principal Facts

Sta- tion	Latitude Deg Min	Longitude Deg Min	Elev. (ft)	Observed Gravity (1)	Bouguer Gravity Anomaly		
					(Mgals) (2)	This Study (Dens)	Density of 2.67 (3)
A	45 50.3	89 26.2	612	785.50	- 8.68	2.40	27.01
B	46 51.8	89 20.6	621	784.45	-12.52	2.40	23.17
C	46 49.8	89 33.9	(4) 615	790.30	- 4.03	2.40	31.66
D	46 46.0	89 34.3	858	758.66	-15.11	2.60	20.24
E	46 35.5	89 34.3	1330	690.63	-38.79	2.90	- 4.09
F	46 36.2	89 38.9	1310	685.10	-46.54	2.40	-11.80
G	46 34.9	89 47.9	1335	674.04	-54.16	2.40	-19.46
H	46 44.2	89 22.4	944	739.14	-26.84	2.40	8.39
J	46 41.1	89 23.0	1105	718.79	-32.77	2.90	2.24
K	46 31.1	89 55.6	1349	673.98	-47.61	2.90	-13.25
L	46 39.6	89 57.0	1226	726.38	-12.85	2.90	21.99
M	46 42.3	89 58.3	717	755.56	-11.37	2.40	24.17
N	46 33.3	89 23.5	1245	657.89	-73.43	2.40	-38.61
O	46 32.1	89 15.4	1215	654.55	-76.70	2.40	-41.84
P	46 49.1	89 37.1	615	790.15	- 3.07	2.60	32.62
(5)							
P-50	46 35.5	89 85.5	1209	602.53	*****	****	- 3.35
A-140	46 28.5	89 56.4	1525	674.64	*****	****	-25.28

1.) 9.8×10^5 mgals plus value in observed gravity column.

2.) Bouguer gravity, this study; datum 600 feet above MSL; density, as shown in density column.

3.) Bouguer gravity: datum MSL; density, 2.67 g/cc.

4.) Elevation interpolated from contours.

5.) Base stations of L. O. Bacon, 1960.

the stations. However, individual stations may be in error by ± 1.6 mgals.

INTERPRETATION

General

Bouguer gravity maps reflect variations in the Bouguer gravity anomaly resulting from horizontal changes in density. These changes are caused by surface and subsurface geology, deep-seated structures, and regional as well as local changes in lithology. The variations in the Bouguer gravity anomaly can be areally large with gentle gradients or can be local with abrupt changes and are the combined effect of shallow and deep-seated sources. Deep-seated, as well as shallow, widespread sources (widespread with respect to the size of the area of investigation) produce broad, areally large anomalies with generally gentle gradients. These broad anomalies are called the regional gravity anomalies. Local anomalies with abrupt changes in gradient are called residual gravity anomalies.

Gravity Map

Plate 1 is the Bouguer gravity anomaly map drawn at a two mgal contour interval and superimposed on the geologic map as adapted from White (1962). The median gravity anomaly value is - 33 mgals. This value is appreciably lower than the average of zero mgals observed

from a regional gravity study of the same area by Bacon (1957). This difference is explained by the use of a reduction datum of 600 feet above sea level instead of the sea level datum that was used by Bacon.

The total variation in gravity is 75 mgals. The gravity values increase from south to north. They vary from - 78 mgals in the southeastern part of the study area to a maximum of - 2 mgals on the north side of the Porcupine Mountains.

The correlation of the observed gravity anomalies with the geology of the area is excellent. However, inadequate station density in some remote areas limits the complete reliability of the correlation.

A linear gravity high occurs over the high density basic flows of the Keweenaw Trap Range. A well defined gravity low exists over the Iron River syncline. An ill-defined low of lesser magnitude occurs over the Presque Isle syncline and extends to the northwest out of the study area. A broad gravity low defines the trough south of the Keweenaw fault.

A series of closely spaced contours parallel the Keweenaw fault. They indicate that the fault extends completely across the study area. Parallel to the White Pine fault are a series of closely spaced contours. A similar anomaly exists six miles northeast of the White Pine fault. These two anomalies delineate an elongate

positive gravity feature, several miles long, which strikes northwest. It may represent a horst-like structure.

An east-west trending gravity high occurs south of Ewen in the vicinity of sections 26-29, T. 48 N., R. 40 W. It could originate from an elongate intrusive into the sedimentary rocks, or it may represent an old ridge of Keweenaw lavas buried beneath the Jacobsville sandstone and glacial debris.

A series of tightly grouped contours extends southwest across sections 4, 8 and 18, T. 49 N., R. 44 W. It correlates with a fault previously mapped by White. A fault mapped as extending across sections 4, 10 and 15, T. 49 N., R. 44 W. is not defined by the Bouguer gravity anomaly map, probably because of inadequate station coverage.

A flexure in the Bouguer gravity contours in sections 9-11 and 14-16, T. 49 N., R. 42 W. represents a gravity minimum that correlates with a body of rhyolite mapped by Wright (1909). It has a magnitude of about five mgals.

Several other variations exist in the Bouguer gravity anomaly map. However, more detailed station coverage is necessary for further interpretation of these anomalies.

Isolation of Anomalies

There are many methods of isolating the residual gravity anomalies from the regional gravity picture. Only the graphical methods were considered in this study, because of inadequate station coverage and inconsistent station spacing.

Several sets of cross-profiles were drawn from the Bouguer gravity anomaly map to isolate the residual anomalies, but, this method was not utilized in the final analysis because a great many interpretations were found to be plausible and it was impossible to determine which interpretation was most correct. In view of the uniform gravity gradient that exists in the area of investigation, the method of "smooth-contouring" was used to isolate the residual gravity anomalies from the regional picture. This method involves drawing smooth contours over the anomalies connecting the regular spaced contours on the margins of the study area.

Plate 2 is the map of the regional gradient of the Bouguer gravity. It shows that the gradient increases at a rate of 2 mgals per mile northward. This increase can be attributed to the thickening of the lava flows down-dip. In general, the contours roughly parallel the strike of the Keweenaw rocks.

Interpretation of Profiles

Seven profiles (Plate 2) were drawn normal to the strike of the regional gravity and the anomalies to be studied. The Talwani two-dimensional method (1959) was used to compute anomalies from bodies of assumed geometric configuration and density contrasts to fit the residual anomalies. Several assumptions were made in fitting the computed anomalies to the observed residual gravity anomalies. They are:

1. The residual gravity anomalies obtained from the "smooth-contouring" method are the true residual gravity anomalies.
2. The densities used in the reduction of the gravity data are valid.
3. The density contrasts between the inferred bodies and the host are correct.
4. The bodies that produce the gravity anomalies which satisfy the observed residual gravity anomalies are geologically reasonable.

Profiles A-A' to F-F' inclusive were drawn to study the depth extent and the geometric configuration of the Keweenaw fault and the adjacent trough to the south containing the Jacobsville sandstone. There are several factors which influence the position and shape of the gravitational field over a fault. Among these are; the magnitude and depth of the density contrast that exists between the upthrown and downthrown sides

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of the fault, the dip of the fault, and the throw of the fault.

The Keweenaw fault may produce two possible sources of density contrasts. Near the surface, there exists juxtaposition of the low density Jacobsville sandstone to the south ($\rho = 2.4$ g/cc) with the high density lava flows to the north ($\rho = 2.9$ g/cc). This gives a density contrast of 0.5 g/cc which should result in a gravity low south of the fault. In addition, a density contrast may occur at depth between the lava flows and the underlying basement rocks. If this deep-seated density contrast exists, it should be reflected in the Bouguer gravity anomaly, either as a negative anomaly on the north side of the fault or by a plateau in the gravity gradient. This, however, is not evident on the Bouguer gravity map.

Several explanations may be offered for the apparent lack of anomaly due to a deep-seated density contrast. The juxtaposition of the lava flows with the basement rocks may be at such great depths, that the gravity effect is too widespread to be identified in the Bouguer gravity anomaly. In addition, the density contrast may be too small to have any detectable effect on the Bouguer gravity. Also, the dip of the fault may change with depth resulting in an anomaly whose effect

is not evident near the surface trace of the fault.

Because there is no reflection of a deep-seated density contrast evident on the Bouguer gravity anomaly map, it is assumed that variations on the Bouguer gravity map are caused by near surface structures.

Profile A-A' (Figure 7) originates in section 34, T. 48 N., R. 45 W. and extends north-northwest to section 28, T. 49 N., R. 45 W. The anomaly has a minimum value of - 17 mgals. A 3100 foot wedge of sediments could cause a gravity anomaly that would fit the residual anomaly.

Profile B-B' (Figure 8) extends from section 33, T. 48 N., R. 44 W. to section 29, T. 49 N., R. 44 W. A simple wedge of sedimentary rocks 2300 feet thick would account for the 20 mgal anomaly which is shown.

Profile C-C' (Figure 9) begins in section 34, T. 48 N., R. 43 W. and extends to section 30, T. 49 N., R. 43 W. This 20 mgal anomaly is an unusual one to fit. All geologically reasonable geometric configurations failed to account for a large deficiency of gravity over the northern portion of the profile. Study of topographic maps and aerial photographs reveals a circular shaped hill which shows marked topographic similarities to exposures of rhyolite further east. It is concluded that a rhyolite body with a density of 2.55 g/cc occurs in

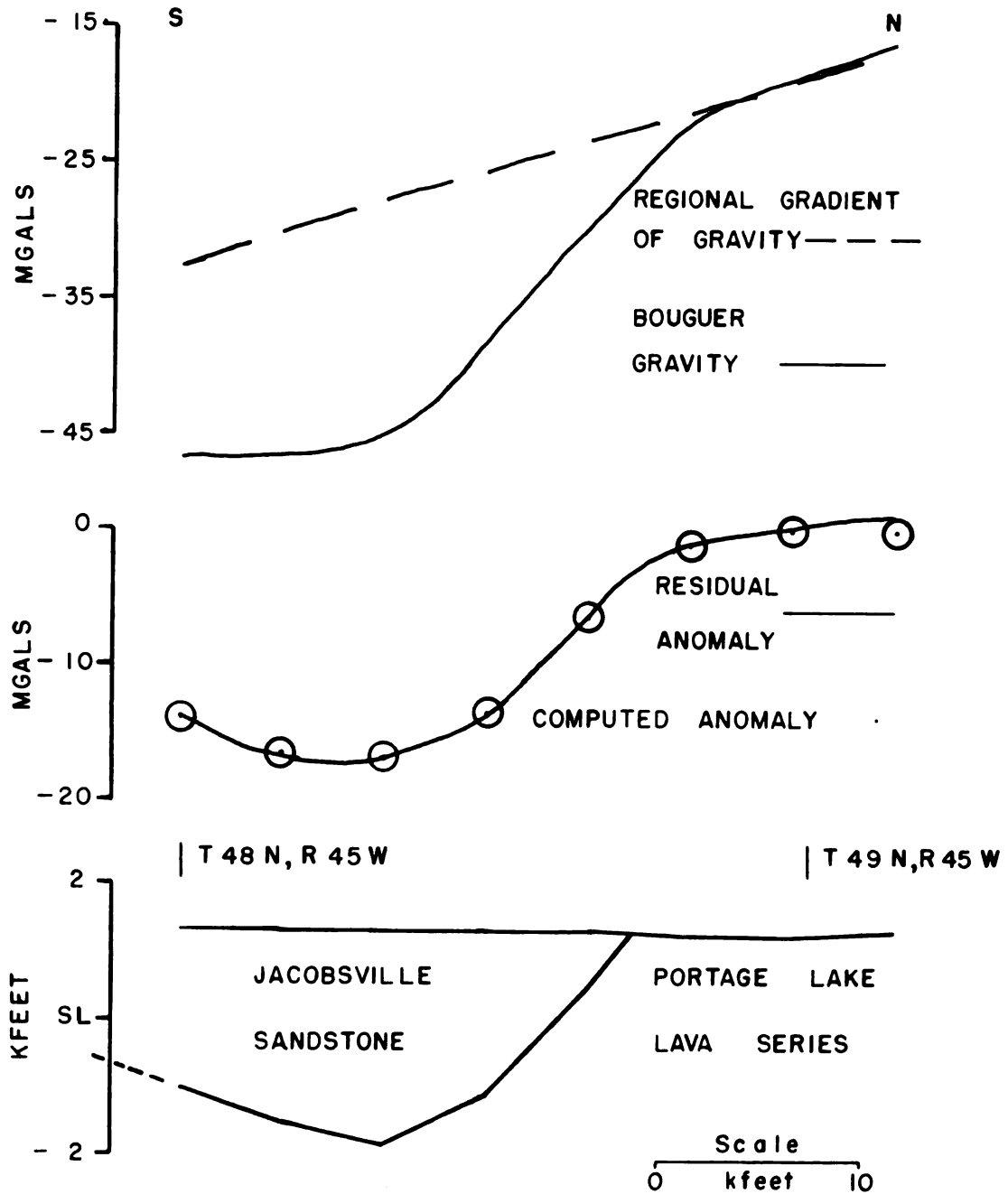
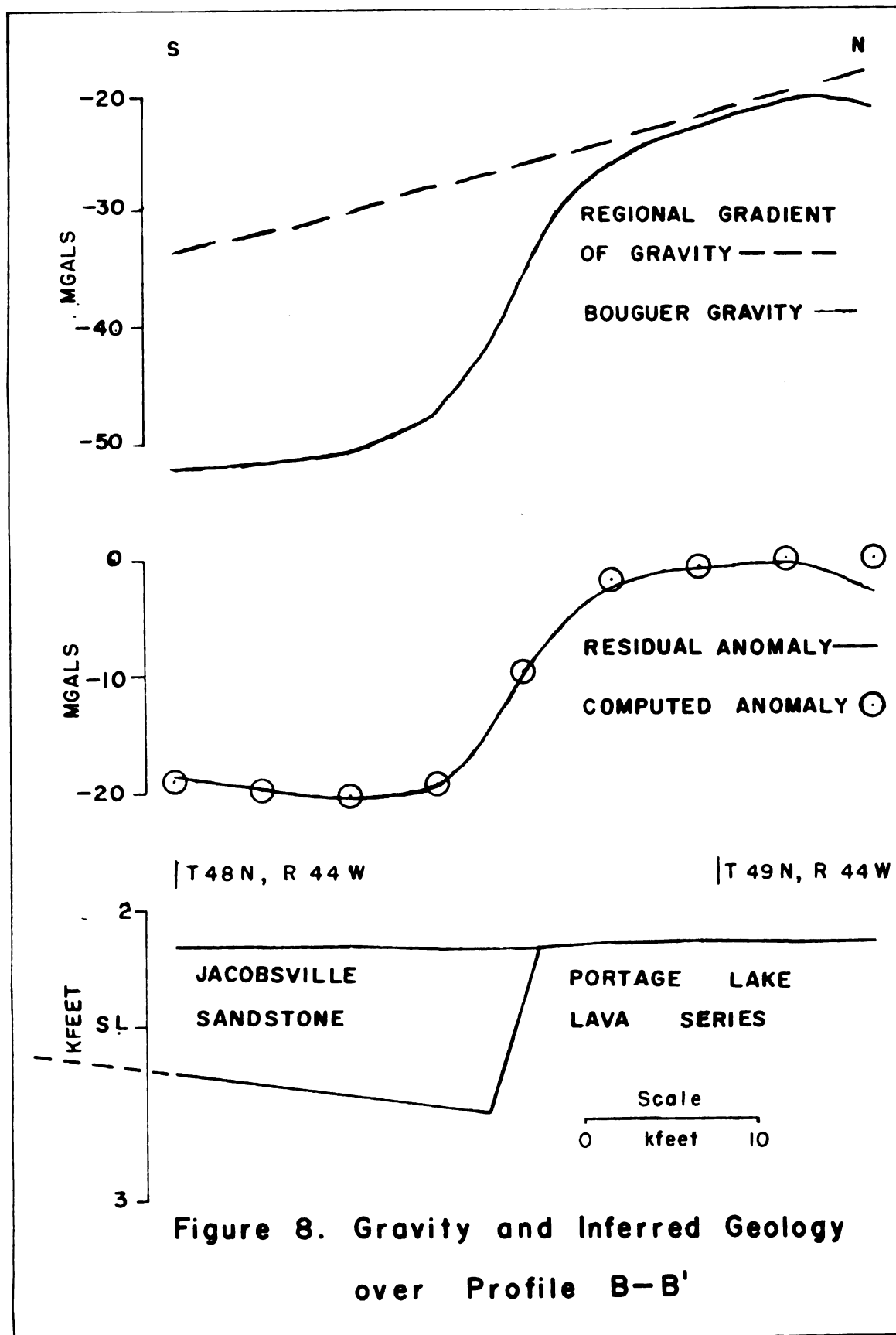
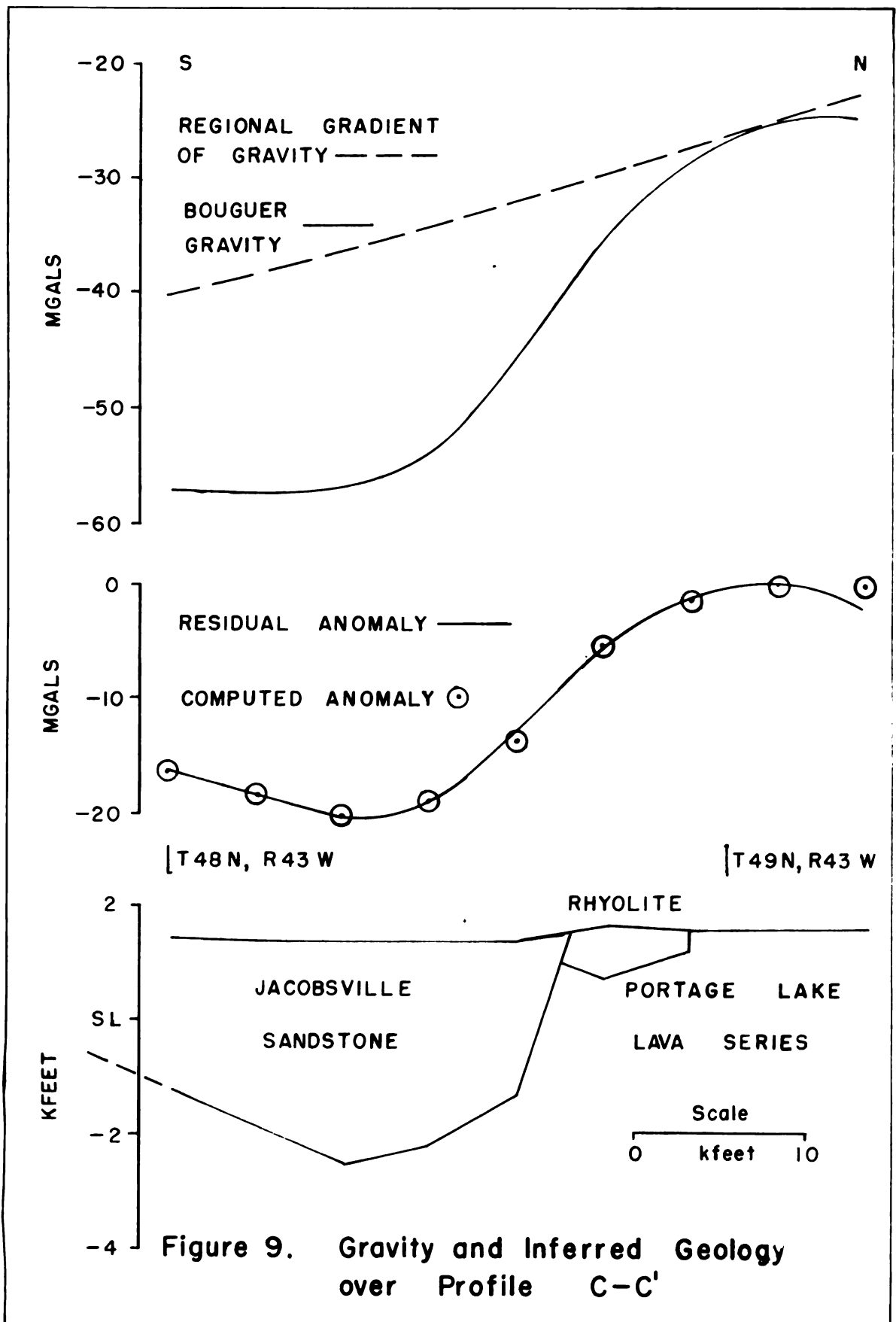


Figure 7. Gravity and Inferred Geology Over Profile A-A'





this part of the area. The residual anomaly is satisfied by a wedge of sedimentary rocks 3800 feet thick plus a body of rhyolite 1000 feet thick. The geometric configuration of the rhyolite used to fit the anomaly suggests a possible intrusive body.

Profile D-D' (Figure 10) extends from section 35, T. 43 N., R. 42 W. to section 29, T. 49 N., R. 42 W. A 3300 foot wedge of sediments is believed to cause this 17 mgal anomaly. The north side of this wedge, the Keweenaw fault, appears to be vertical.

Profile E-E' (Figure 11) has a total anomaly of 21 mgals. It begins in section 9, T. 43 N., R. 41 W., and extends northwest to section 14, T. 49 N., R. 42 W. A wedge of sediments 4700 feet thick fits the anomaly very well.

The largest of these anomalies, 33 mgals, occurs over profile F-F' (Figure 12). This profile extends from section 30, T. 49 N., R. 40 W., to section 21, T. 50 N., R. 41 W. A 6100 foot wedge of sediments would account for this anomaly.

The geometric configuration of the trough of Jacobsville sandstone as determined from the interpretation of the gravity profiles is different from that normally postulated and as illustrated in Figure 3. The north side of the trough, which is the Keweenaw

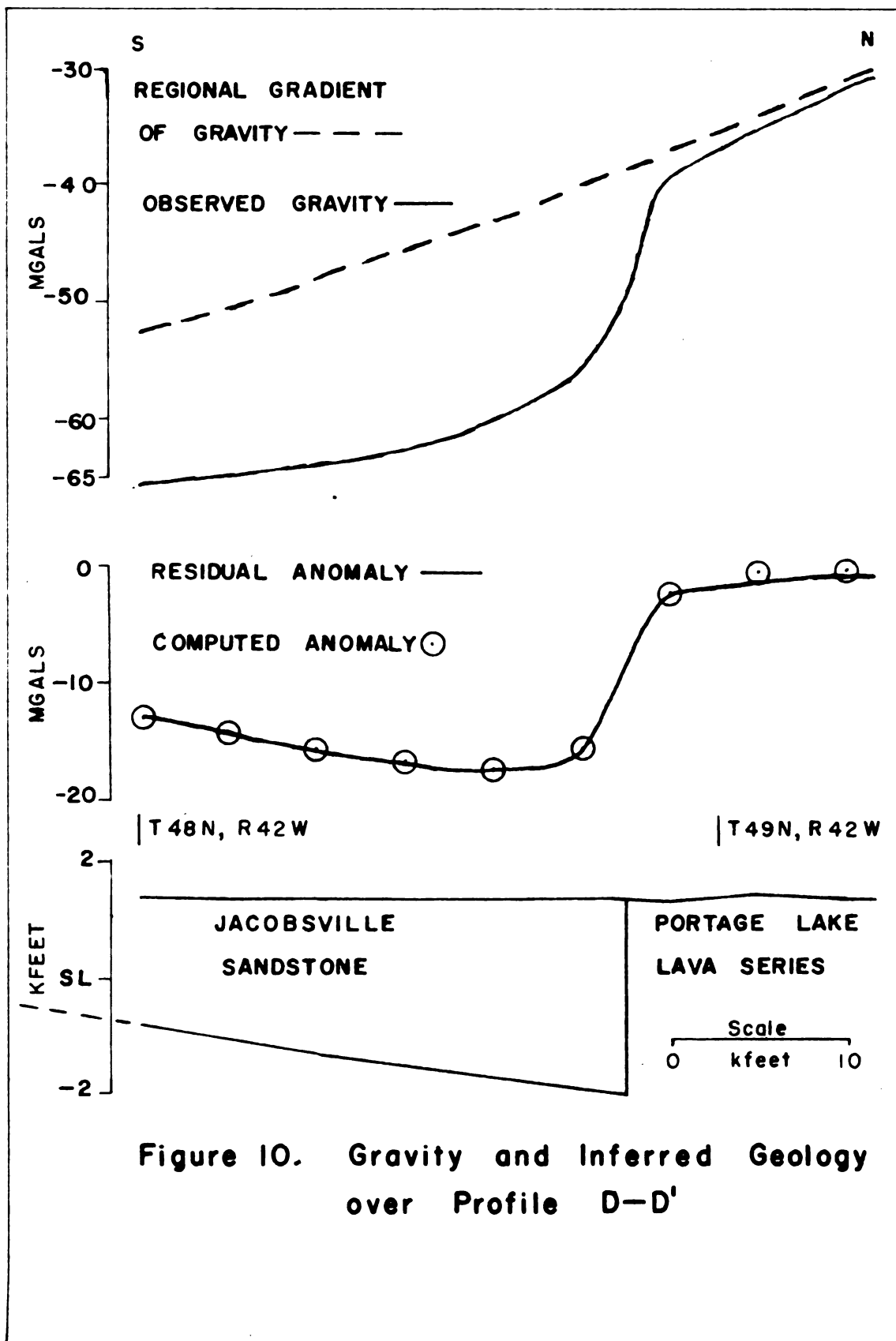
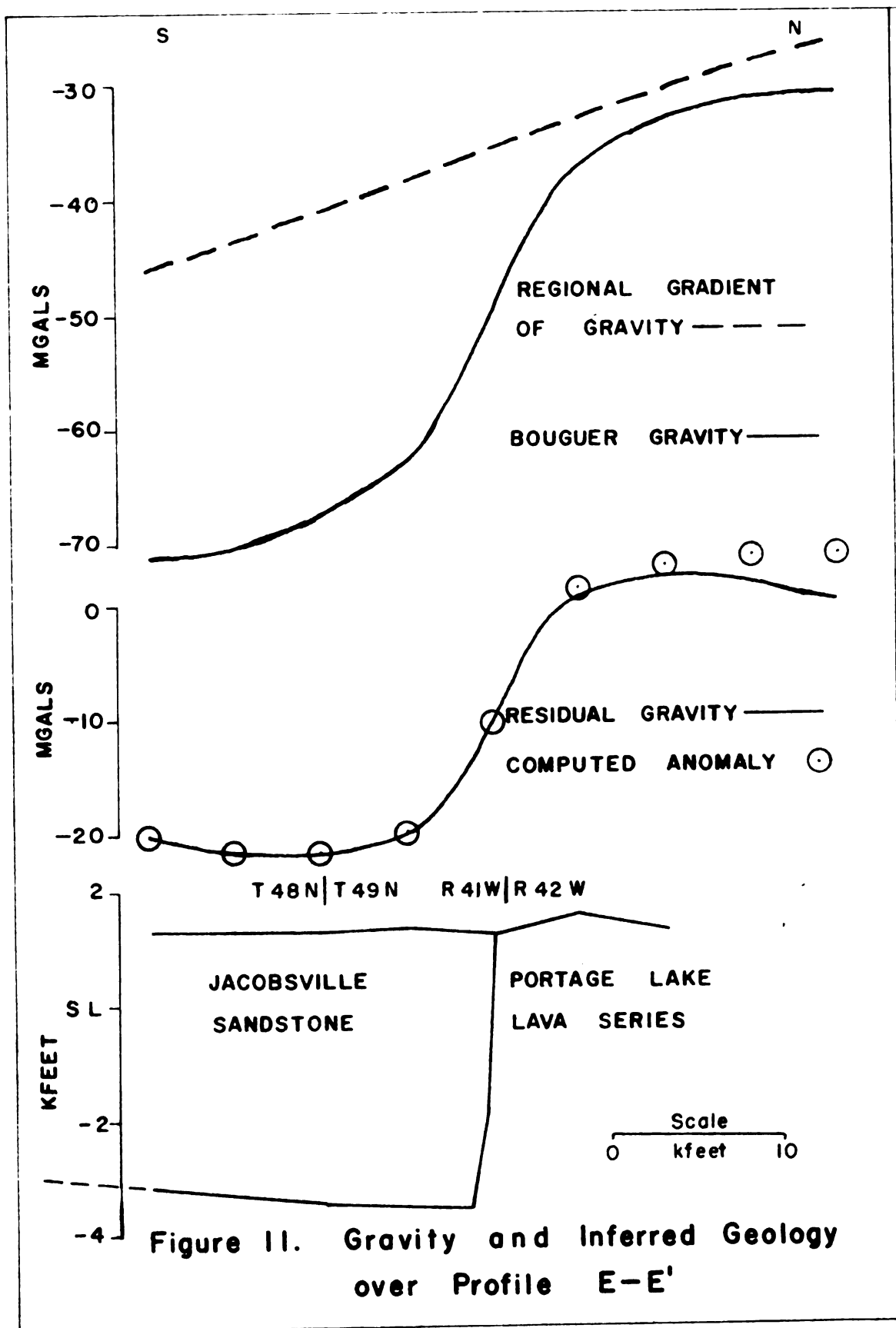


Figure 10. Gravity and Inferred Geology over Profile D-D'



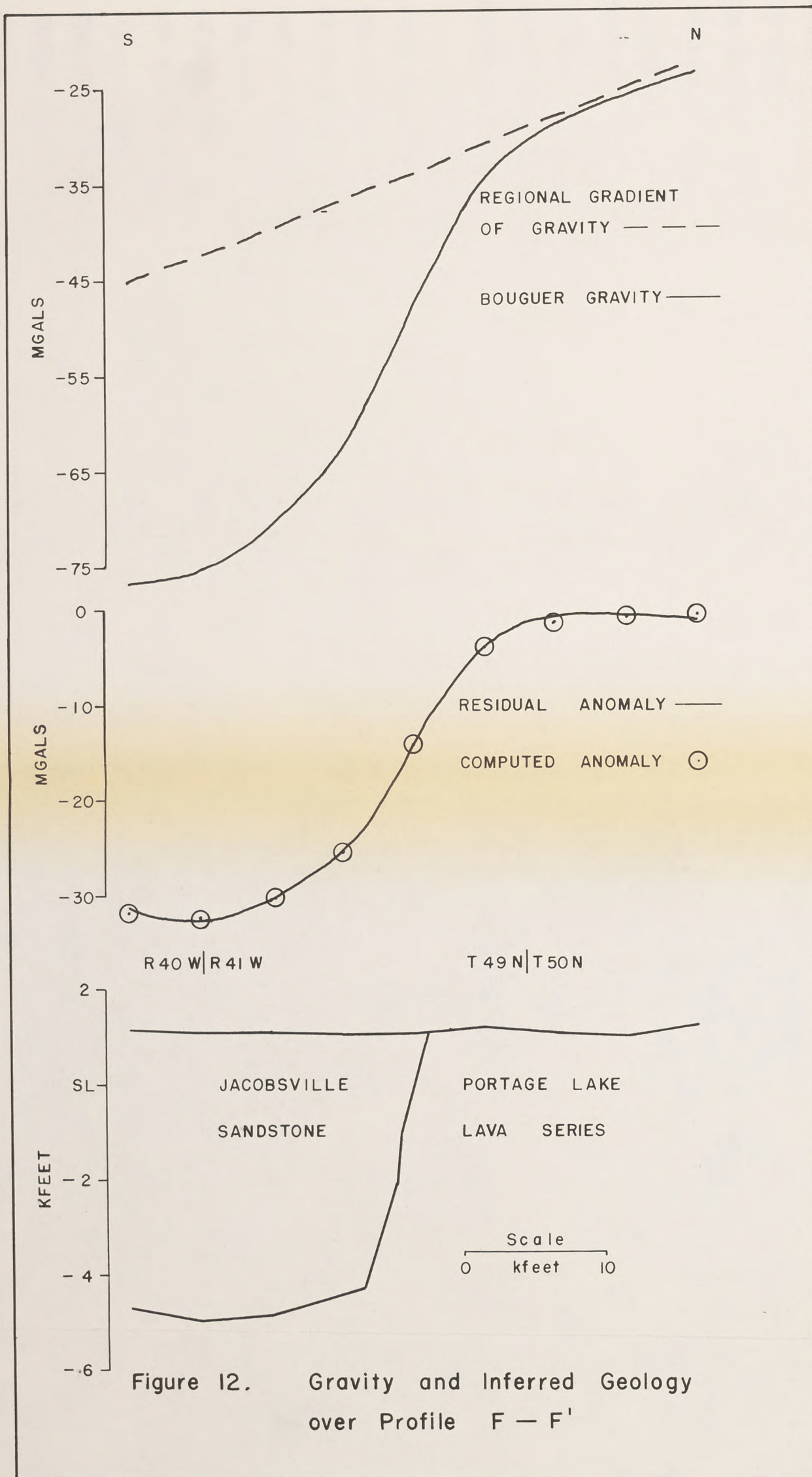


Figure 12. Gravity and Inferred Geology over Profile F — F'

fault, is found to dip south, possibly at a high angle, rather than north. There are several possible explanations for this interpretation. It is generally believed that the Keweenaw faulting occurred in post-Jacobsville time (Hamblin, 1958). If the faulting occurred as a series of parallel faults instead of one major fault, the resulting anomaly could be misinterpreted as due to a vertical or south dipping fault. More detailed gravity investigations over the Keweenaw fault may reflect the presence of parallel faults in the Bouguer gravity anomaly.

As is readily evident from the gravity profiles, there is an apparent change in dip of the fault from the west to the east end of the study area. The dip of the fault apparently changes from near vertical, east of Lake Gogebic, to south on the western side of the lake. This may be the result of change in the dip of the fault or it may be evidence of the fault dying out and changing to a monoclinial ridge.

An alternative interpretation that may explain the configuration of the trough south of the Keweenaw fault, suggests that deformation is concurrent with deposition. If this is the case, each vertical movement of the fault will result in deposition of clastic material to the south from the upthrown side of the fault. This will result in a wedge of sediments similar to a bajada.

The density of this wedge will decrease away from the source as a function of sorting (Kane, 1961). This change in density may result in a Bouguer gravity that may be interpreted as a fault with a south dip.

The above interpretations are only tentative because of the difficulty in defining the regional gradient of gravity. Several attempts were made to decrease the apparent regional gradient of gravity. This would steepen the residual gravity profiles and result in a gravity interpretation nearer to that of Figure 3. However, such attempts resulted in regional gradients that did not fit the observed gradient of the Bouguer gravity. The regional gradient of gravity used in this interpretation is assumed to be valid. However, extension of the survey to the west and south may result in better resolution of the regional gradient of gravity and better definition of the residual anomalies.

Profile G-G' (Figure 13) begins in section 32, T. 43 N., R. 42 W. and extends north-northwest across the Iron River syncline to the north slope of the Porcupine Mountains in section 17, T. 51 N., R. 44 W. A residual low of 13 mgals exists over the trough south of the Keweenaw fault. A low of 25 mgals exists over the Iron River syncline.

A 3000 foot wedge of sedimentary rocks fits the

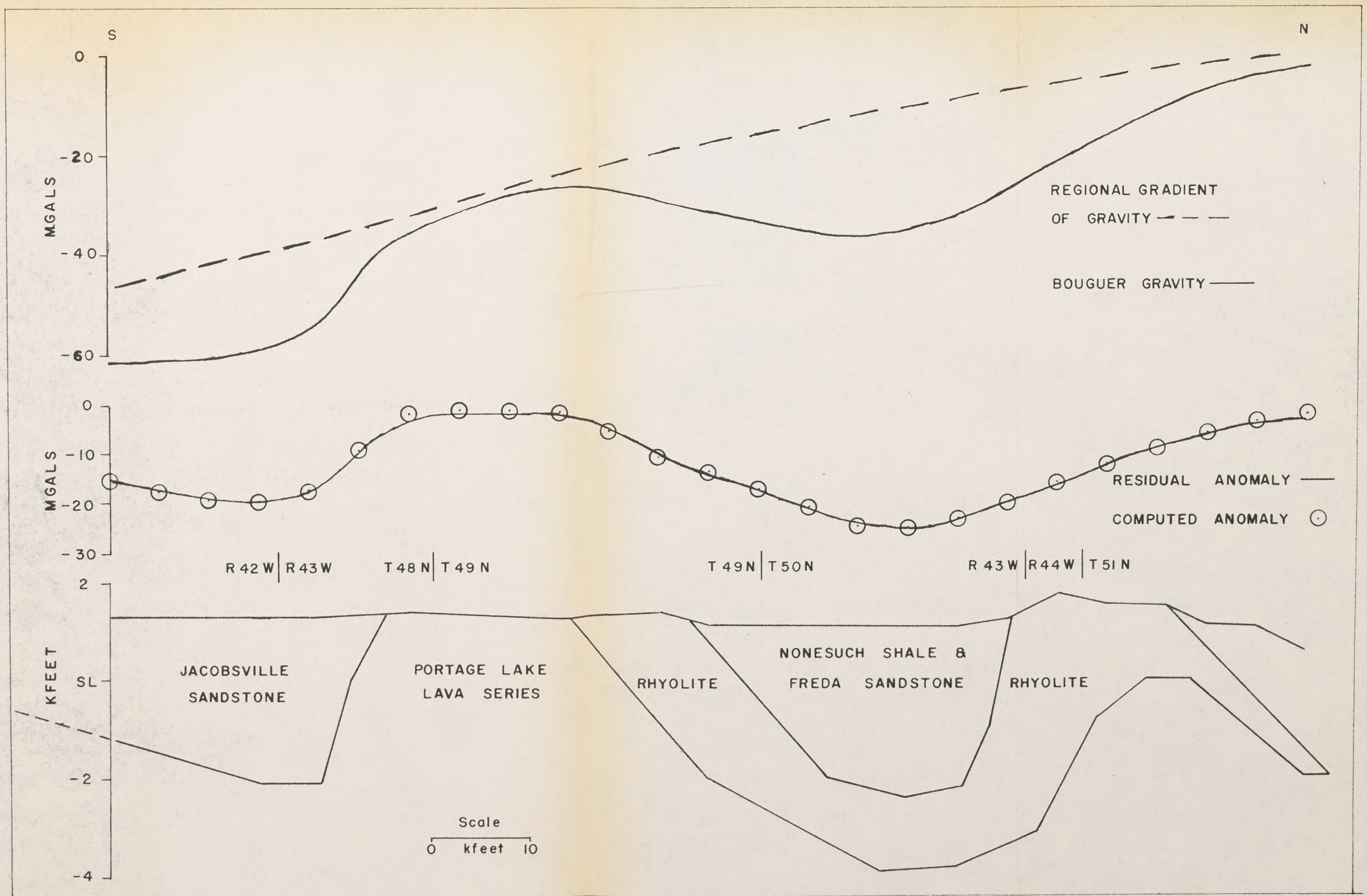


Figure 13. Gravity and Inferred Geology over Profile G-G'

residual anomaly south of the Keweenaw fault. The configuration of the Iron River syncline is relatively well known to the base of the Nonesuch shale. The geometric configuration used for the Iron River syncline is a triangular shaped body 3500 feet deep and six miles wide, as determined from a structure-contour map by Hardenberg (1964). A density of 2.4 g/cc was used for the Nonesuch shale and the overlying Freda sandstone. However, the anomaly computed to the base of the Nonesuch shale resulted in a gravity deficiency when compared with the residual gravity anomaly. An additional anomalous source must be used to fit the observed anomaly. Rhyolite is found in drill holes south and within the Iron River syncline and in the Porcupine Mountains. Consequently, a body of rhyolite is proposed to help account for the anomaly. The density of the rhyolite was assumed to be 2.55 g/cc.

The body of rhyolite roughly parallels the base of the Nonesuch shale. To the south of the syncline the rhyolite is two miles across strike and appears to thin to no more than 2500 feet thick under the syncline. It extends to the Porcupine Mountains where it attains a thickness of 1500 to 2000 feet. Because of limited station coverage, the configuration of the rhyolite in the Porcupine Mountains proper must be considered as tentative.

CONCLUSIONS

1. A Bouguer gravity anomaly map has been prepared for the study area which shows some of the most interesting gravity anomalies that occur in rocks of Keweenaw age.

2. In general, the gravity map correlates very well with the geology as mapped by White (1962).

3. The positive anomalies correlate with the lava flows of Keweenaw age.

4. The major gravity lows between the Porcupine Mountains and the Keweenaw Trap Range and south of the Keweenaw fault correlate with the Iron River syncline and the trough of Jacobsville sandstone, respectively.

5. Gravity profiles drawn over the Keweenaw fault indicate a decrease in throw from northeast to southwest varying from 6000 feet north of Ewen to 3000 feet west of Lake Gogebic. The dip of the fault appears to be south instead of north as previously postulated.

6. The Bouguer gravity anomaly map indicates the Keweenaw fault extends completely across the study area.

7. There is no apparent effect of a deep-seated density contrast that might occur with the Keweenaw fault on the Bouguer gravity map.

8. A gravity anomaly exists that correlates with the White Pine fault. A similar anomaly occurs six miles

northeast of the White Pine fault.

9. A gravity anomaly exists that correlates with an unnamed fault which extends southwest through sections 4, 8 and 13 in T. 49 N., R. 44 W.

10. The Iron River syncline may be underlain by a thick rhyolite body that extends into the Porcupine Mountains. It is 2000-3000 feet thick under the syncline, 1500 feet thick in the Porcupine Mountains and extends for some distance to the south of the syncline.

11. The method of cross-profiling does not appear to be applicable to the study area. However, smooth-contouring proved adequate.

12. The regional gradient of gravity, which increases northward, can be attributed to thickening of the lavas down-dip.

13. The application of gravity methods to the investigations of Precambrian Terranes is a useful tool for geological exploration.

SUGGESTIONS FOR FUTURE WORK

1. A detailed sampling of the various lithologic units should be attempted, using both available well cores and outcrops. The subsequent densities obtained should be applied to the original data collected by the author if significantly different from the values used in this study.

2. Several detailed profiles are necessary to study the Keweenaw fault for possible solutions of the apparent southerly dip of the fault.

3. Among the many causes of variation in the Bouguer gravity anomaly map which warrants further investigation are the White Pine fault and associated anomaly to the northeast, and the faulting which occurs in the southwest part of the study area.

4. A detailed field mapping and petrological study of the rhyolite which crops out south of the Iron River syncline is in order.

5. Several gravity stations should be placed in critical points of the survey area to increase the validity of this study.

6. The survey area should be extended to the east and west for better resolution of the regional gradient of the Bouguer gravity.

7. The area should be extended to the south to include the South Trap Range to study the thickness of the Jacobsville sandstone and its relationship to the lava flows.

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• 1. The first step in the process of creating a new product is to identify a market need. This involves conducting market research to determine what consumers want and what problems they are trying to solve. Once a need is identified, the next step is to develop a concept for a product that addresses that need.

• 2. The second step is to create a prototype of the product. This involves designing and building a small-scale version of the product that can be used to test the concept and gather feedback from potential customers. The prototype should be functional and resemble the final product as closely as possible.

• 3. The third step is to conduct a feasibility study. This involves evaluating the technical, financial, and market viability of the product. The study should consider factors such as the cost of production, the potential for sales, and the competitive landscape. If the study shows that the product is viable, the next step is to develop a business plan.

• 4. The fourth step is to develop a business plan. This involves creating a detailed document that outlines the business model, marketing strategy, financial projections, and other key aspects of the business. The business plan is used to attract investors and secure financing for the product development process.

• 5. The fifth step is to secure financing. This involves raising the capital needed to develop and launch the product. This can be done through a variety of methods, including crowdfunding, venture capital, and bank loans. Once financing is secured, the next step is to begin production.

• 6. The sixth step is to begin production. This involves manufacturing the product at a scale that allows it to be sold to the market. This step requires a significant investment in time and resources, but it is essential for the product to reach consumers.

• 7. The seventh step is to launch the product. This involves marketing and distributing the product to the target market. This step requires a strong marketing strategy and a distribution network that can get the product into the hands of consumers.

• 8. The eighth step is to monitor the product's performance. This involves tracking sales, customer feedback, and other key metrics to determine how well the product is performing in the market. This information is used to make adjustments to the product and the marketing strategy as needed.

• 9. The ninth step is to iterate and improve the product. This involves using the feedback from customers and the data from the market to make improvements to the product. This step is an ongoing process that continues throughout the product's life cycle.

• 10. The tenth step is to exit the market. This involves deciding when to stop selling the product and what to do with the remaining inventory. This step is typically the last step in the product development process, but it is important to have a plan in place for what happens after the product is no longer sold.

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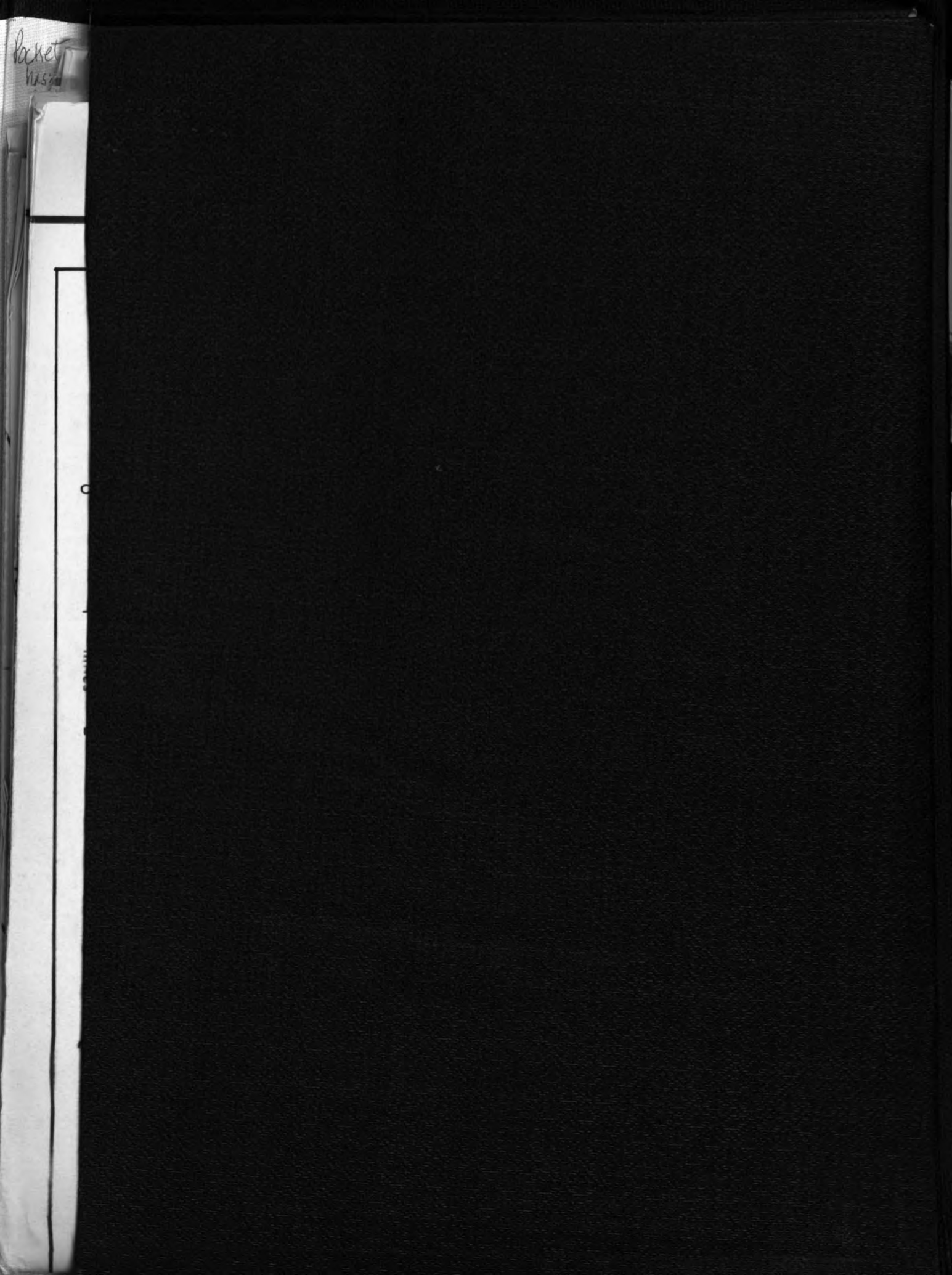


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