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INTERPRETATION OF THE WESTERN LAKE SUPERIOR GRAVITY LOW

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INTRODUCTION

The Midcontinent Gravity High is closely associated with gravity minima along its entire extent from Kansas northeastward into the Lake Superior region. No gravity minima along this trend have attracted as much attention or analysis as have the Bayfield (gravity) low and the Chefswet (gravity) low, herein combined as the Western Lake Superior Gravity Low. The significance of the geologic interpretation of the Western Lake Superior Gravity Low is related to its geophysical magnitude, its proximity to Keweenawan outcrop, and its on-trend association with the central gravity maxima axis of the Midcontinent Gravity High.

Interpretation over the past three decades has concentrated on causitive geology within Upper Keweenawan sedimentary rocks, Middle Keweenawan volcanic rock, and deeper crustal or mantle associations.

The discovery, geographic delineation, and geologic interpretation of the Midcontinent Rift System has been greatly aided through the collection and analysis of gravity data. Woollard (1943) first reported "a very strong (gravity) high" centered on station 378 near Clay Center, Kansas, situated along a transcontinental survey he supervised between New Jersey and California. He suggested that this anomalous gravity reading, the highest recorded between Pennsylvania and Nevada, was caused by a subsurface gabbroic mass approximately 20 km in width. On the basis of a series of gravity traverses conducted in the midwestern United States, Woollard (1951) again reported that the Kansas anomaly extended north and northeast into the Lake Superior district, a distance of 1,300 km. Thiel (1956) named this gravity feature the "midcontinent gravity high" and proclaimed it "one of the most prominent gravitational features in the United States," and Lyons (1959) proclaimed it to be "the most significant gravity maxima anomaly on the North American continent ...."

The term "midcontinent gravity high" might be considered a misnomer because along a majority of its length, this feature is flanked by gravity lows. These minima are equally distributed on both sides of the gravity maxima axis, and they display negative magnitudes of comparable value to the centrally located positive magnitudes. The local gravity relief between these magnitudes ranges from 125 mgal in southwest Iowa, to 170 mgal in northeastern Iowa, and to 130 mgal in west-central Wisconsin. At these same sites the width of the Midcontinent Gravity High, as measured from gravity minimum flank axis to adjacent gravity minimum flank axis is, respectively, 105 km, 80 km, and 97 km.

Except for the Lake Superior region, the geologic structure causing the Midcontinent Gravity High is buried beneath Phanerozoic strata. In northwest Wisconsin, particularly Douglas, Bayfield, Ashland, and Iron Counties, exposures of Precambrian sedimentary and igneous rock are randomly distributed. These rocks belong to the Middle and Upper Keweenawan of the Middle Proterozoic. The rock associated with the Midcontinent Gravity High in Wisconsin is classified into three series: a dense and thick series of gabbro and basalt, the latter with thin layers of inter-flow sedimentary rock; an overlying series of conformable clastic rock termed the Oronto Group; and a second unit of clastic rock unconformably overlying the Oronto Group, the Bayfield Group. Both the Oronto and Bayfield Groups are composed of three formations. From oldest to youngest the Oronto Group is composed of the Copper Harbor Conglomerate, the

Nonesuch Formation, and the Freda Formation. The Bayfield Group is made up of, in the same order of age, the Orienta Sandstone, Devils Island Sandstone, and the Chequamegon Sandstone. The Oronto and Bayfield Groups have been combined in recent years by the U.S. and Ontario Geological Surveys into the Keweenawan Supergroup (Morey and Green, 1982).

Thiel (1956) demonstrated that the Midcontinent Gravity High inclusive of the associated flank gravity lows was the geophysical expression of Keweenawan geology in northwestern Wisconsin and adjacent parts of the Upper Peninsula of Michigan. Thiel (1956) stated that "the positive anomalies correlate with Keweenawan lava and gabbro," whereas the flanking minima were correlated to wedge-shaped basins filled with sedimentary rock that thinned away from the central structural high. This central high, later named the St. Croix Horst by Craddock and others (1963), is bounded by high angle reverse faults. The north and northwest flank of the St. Croix Horst is marked by the Douglas-Isle Royale Fault System (fig. 1). The Thiel model was subsequently extended southwestward along the Midcontinent Gravity High trend into Minnesota (Mooney and others, 1970; Morey, 1974), Iowa (Anderson and Black, 1982), and Nebraska (Lidiak, 1972). In Kansas recent studies indicate the Thiel model is being discarded in favor of an asymmetric basin model associated with granitic or interbedded basaltic and clastic units (Yarger, 1983; Somanas, 1984; Serpa and others, 1984).

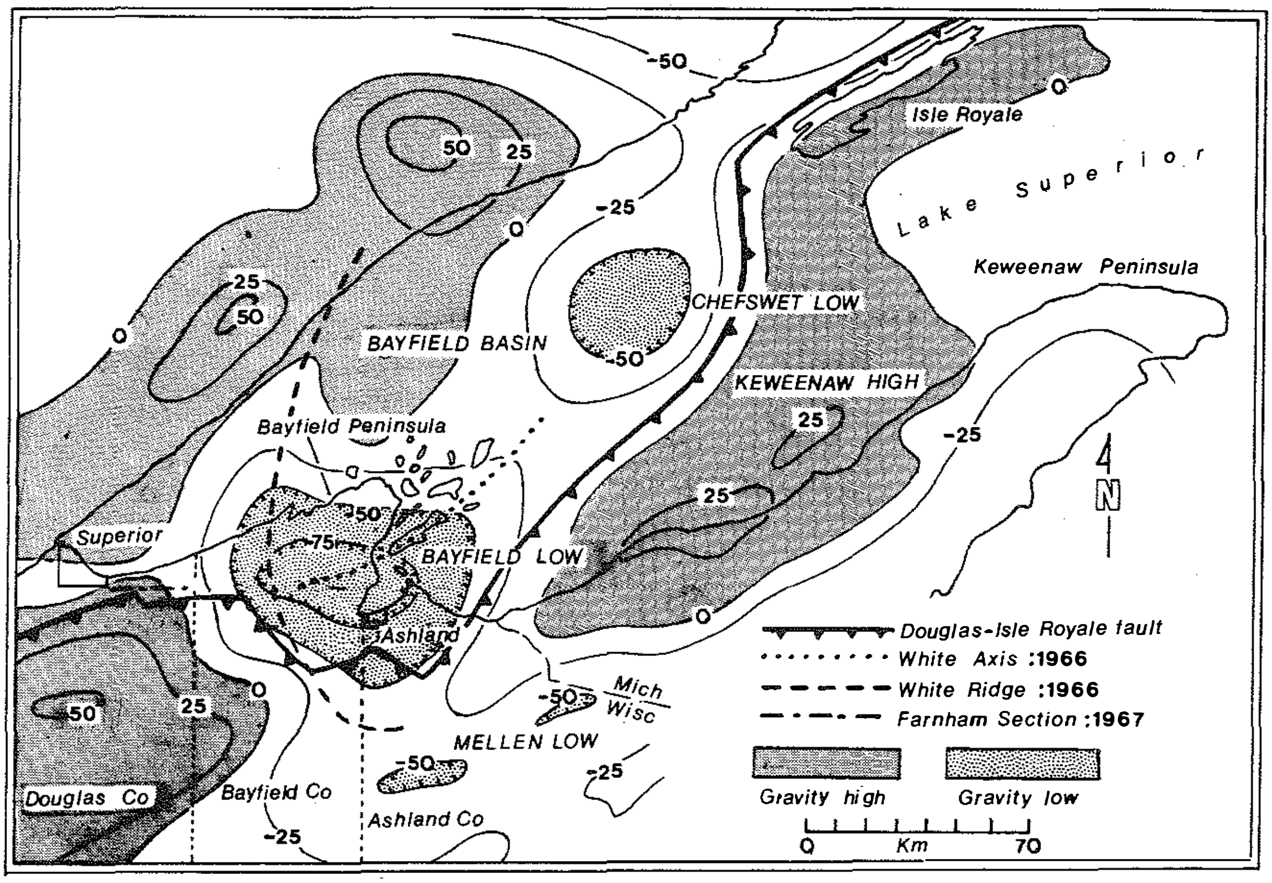

Figure 1. Simplified Bouguer Gravity Anomaly map of the western Lake Superior area. Contour interval 25 mgal.

After general acceptance of the uniqueness and geographic extent of the Midcontinent Gravity High, the tectonic feature was formally named the "central North American rift system" by Ocola and Meyer (1973). In 1982 Wold and Hinze simplified this nomenclature to the "Midcontinent Rift System." This rift system, strictly defined to extend from northeastern Kansas north and northeastward through Nebraska, Iowa, Minnesota, Wisconsin and into the Upper Peninsula of Michigan, is exemplified by its simplicity of gravity expression. The Midcontinent Gravity High maintains its average width of 95 km and is interrupted only twice between Kansas and Wisconsin: at the Kansas-Nebraska border and immediately south of the Minneapolis-St. Paul, Minnesota. Both of these interruptions are along displacements of apparent left-lateral movement. The Kansas-Nebraska border displacement can be seen on aeromagnetic data (King and Zietz, 1971) and is suggested to be a major transcurrent or wrench-fault system (Arvidson and others, 1982). The offset in Minnesota is better documented and attributed to strike-slip movement of approximately 160 km along the Belle Plaine Fault (Sloan and Danes, 1962).

GRAVITY LOW INTERRUPTIONS

In Bayfield County, Wisconsin, the basic continuity of the axis of the Midcontinent Gravity High is abruptly terminated and replaced by a gravity minima of more than 90 mgal. This low, herein termed the Bayfield low, is situated over the Bayfield Peninsula and is centered 18 km northwest of Ashland, Wisconsin. Further to the northeast a second low of 65 mgal, herein named the Chefswet low after the modern Lake Superior topographic basin of that name (Kemp and others, 1978), is located at midpoint between the Bayfield Peninsula and Isle Royale (fig. 1). Discussion in this paper combines the Bayfield low and the Chefswet low as the Western Lake Superior Gravity Low. This regional low is parallel to and lies immediately northwest of the Douglas-Isle Royale Fault and the Keweenaw (gravity) high as mapped by Weber and Goodacre (1966). They considered the Keweenaw Gravity High to "be on offset of the Midcontinent Gravity High." Since discovery of the Western Lake Superior Gravity Low, the geologic cause or causes of either one or both of its components has been discussed by Wold and Ostenso (1966), Coons (1966), White (1966a), Mooney and others (1970), King and Zietz (1971), Wold and others (1982), Hinze and others (1982), Luetgert and Meyer (1982), and Van Schmus and Hinze (1985).

A review of this literature indicates the cause of the Western Lake Superior Gravity Low can be related to one, or some combination of, three contrasting geologic associations: an abnormally thick column of relatively low density, Upper Keweenawan sedimentary rock; change in either thickness or density of the Middle Keweenawan volcanic rock; or pre-Keweenawan deep crustal or upper mantle effects.

UPPER KEWEENAWAN SEDIMENTARY ROCK MODEL

Prior to the mapping of the Chefswet low by Weber and Goodacre (1966), the Bayfield low was described by Thiel (1956) as being associated with a maximum accumulation of "low-density sandstones and shales of the Upper Keweenawan." Thiel (1956), after conducting several shallow refraction seismic shots along a northsouth traverse through the center of the Bayfield gravity low, ruled out attributing any part of the Bayfield low to a thick accumulation of Pleistocene glacial sediments. The results, however, show till thicknesses ranging from 100 m to 175 m, higher than normal for northwestern Wisconsin. Coons (1966) reported thicknesses of 2,450 m to 3,000 m for the sedimentary rock underlying the Bayfield Peninsula. Farnham (1967) combined a series of refraction lines into a 90 km long east-west seismic section situated along the axis of the Bayfield Basin (fig. 1). Although he was unable to designate depth to the Middle Keweenawan basalts, Farnham seismically analyzed sedimentary units down to the Copper Harbor Conglomerate and determined this part of the Keweenawan section to increase from a minimum of 1,850 m near Superior, Wisconsin, to more than 3,050 m over the center of the Bayfield low.

In an attempt to determine depth to basalt basement over the Bayfield low, Mooney and others (1970) suggested that the Middle Keweenawan basalt basement could not occur at depths of "less than 4 km" anywhere in northern Bayfield County. The low gradient of aeromagnetic data as mapped by Wold and Ostenso (1966) supports this seismic interpretation. If correct, the stratigraphic thickness differential reported between the studies of Farnham (1967) and Mooney and others (1970) suggests that the Copper Harbor Conglomerate is at least 1,000 m thick in the vicinity of the Bayfield low, as compared to the 120 m to 250 m exposed in outcrop section approximately 50 km to the southeast of the Bayfield low in Ashland County. Mooney and others (1970) concluded by stating that the thickening of the Keweenawan Supergroup into the Bayfield low area is due entirely to thickening within the Oronto Group, whereas the Bayfield Group, which unconformably overlies the Oronto Group, thins in the direction of Oronto thickening. The unconformable relationship between these groups would explain the lack of conformity of surface strike and dip patterns to the expected morphology of this postulated sedimentary basin.

White (1966a) concluded his tectonic review of the Lake Superior Basin by recognizing an "axis of a sedimentary trough of late Keweenawan time ... along which the section of Upper Keweenawan sedimentary rocks, both Bayfield and Oronto Groups, is assumed to be thickest." The majority of this axis of sedimentation spatially coincides with the Bayfield gravity low (fig. 1). Wold and others (1982) verified this sedimentation trough by seismic-reflection profiling and identified it as a "southwestward-plunging syncline trending under the Bayfield Peninsula."

If the Bayfield low is the geophysical result of an abnormally thick sequence of Upper Keweenawan sedimentary rock, it would appear logical to assume the same cause for the Chefswet low. In this volume, in "Nature of the northern boundary of the St. Croix Horst," I suggest that high gravity gradients on the southeast flank of the Western Lake Superior Gravity Low are evidence for the extension of the Douglas Fault trace into Lake Superior and connecting with the Isle Royale Fault. Thus, both the Bayfield and the Chefswet lows should be considered sites of local deepening within the Bayfield Basin because this basin is positioned immediately to the northwest of the Douglas-Isle Royale Fault System.

MIDDLE KEWEENAWAN VOLCANIC MODEL

The residual gravity field of the Lake Superior area shows a 70 mgal low over the Bayfield Peninsula and an approximate 30 milligal low located over the Chefswet low (Hinze and others, 1982). Hinze and others (1982) suggested that such remaining lows meant that the mafic volcanic rock is "absent or thin" in the area. In an earlier study King and Zietz (1971) had a similiar concept in mind when they stated "if the volcanic rocks are present under the Bayfield gravity low, they must be thin and very deeply buried."

White (1966a) has probably considered the cause of the Bayfield low more than any other researcher. Although he did not possess data pertinent to the Chefswet low at the time of his report, he promoted a dual, rather than a single, cause for the Bayfield low by stating that "the anomaly marks the high-angle intersection of the axis of a thick prism of Upper Keweenawan sedimentary rock with a ridge of pre-Keweenawan rock -- an area in which the middle Keweenawan lavas are thin or absent." The pre-Keweenawan ridge was identified after White (1966a) mapped a thin trend line of Middle Keweenawan basalt running from south of Ashland, Wisconsin, north and northeast through the Bayfield Peninsula and onto the north shore of Lake Superior (fig. 1). White also suggested that where present, Middle Keweenawan lava might contain a higher than normal percentage of lower density rhyolite as compared to higher density basalt, thus further contributing to the gravity minima.

PRE-KEWEENAWAN MODEL

Specifics of deeper structures in the Lake Superior Basin are not well known and involve fundamental questions relating to the extent of crustal separation across the Midcontinent Rift System, the degree to which this rift was initiated as a triple (rrr) junction and increased crustal thicknesses into the Lake Superior Basin. White (1966a) attempted to explain the Bayfield low as partially resulting from density distribution within the pre-Keweenawan rock, especially as these may relate to the northeast trending gravity low found south of Mellen, Wisconsin (fig. 1), but admitted such analysis must remain in the "realm of speculation." Hinze and others (1982), however, further encouraged this idea by pointing out that lows such as the Bayfield low "are of the same order of magnitude as (those) north of the lake (Superior) where pre-Keweenawan crystalline rocks crop out," and therefore consideration must be given to "the possible presence of anomalies arising from pre-Keweenawan rocks underlying the (Lake Superior) basin."

In developing his rift tectonic model Thiel (1956) adjusted the regional Bouguer gravity field of northwestern Wisconsin by eliminating the effect associated with Middle Keweenawan basalt. He found that this exercise still resulted in a negative gravity field over the Bayfield Peninsula and suggested one explanation might "be a contribution from depths deeper than here considered." This concept of crustal deepening, or warping, down to the Moho appears to have been initially applied to the general area of the Midcontinent Gravity High by Lyons (1959) and Farnham (1967), who considered the structure to be a tectogene, a "downwarp or trough" caused by the crust being forced downward by "convection currents in the mantle." This compressional concept was subsequently altered to one of initial extensional movements followed by compressional forces, as the processes of rifting became better understood. Significant to the newer interpretation was the Lake Superior (seismic) Experiment, conducted in 1963 and 1964 (Steinhart and Smith, 1966). In summarizing these studies, Halls (1982) presented a crustal thickness map showing "a region of anomalously thick crust centered on eastern and central Lake Superior, on the axis of the Midcontinent Rift System ... that connects with similarily thick crust ... reported further west along the rift in Wisconsin." The actual increase shown within the Lake Superior basin by Halls (1982) is on the order of 35 percent, with a maximum thickness of approximately 54 km reported for the area off the Keweenaw Peninsula (fig. 1), as compared to a regional thickness of 40 km. Such crustal thickness, also reported by Luetgert and Meyer (1982), would have the effect of producing broad, regional gravity minima that, in turn, would contribute to the intensity of localized negative anomalies such as the Western Lake Superior Gravity Low.

In their review of refraction seismic surveying in Lake Superior, Halls and West (1971) discussed the geologic sources of the 85 mgal low that occupies the area of Keweenaw Bay, southeast of the Western Lake Superior Gravity Low. They suggest that approximately 28 percent of this gravity anomaly results from Upper Keweenawan sedimentary rock with the remainder attributed to Middle and pre-Keweenawan effects with "primary" emphasis on pre-Keweenawan "deep crustal effects." The applications of these percentages and their associated geologic conditions to the underlying causes of the Bayfield and Chefswet lows should result in a Bouguer gravity distribution similiar to that mapped in the subject area of this paper.

CONCLUSIONS

Of the numerous gravity lows associated with the Midcontinent Gravity High, none have attracted as much attention or analysis as has the Western Lake Superior Gravity Low located in northwestern Wisconsin and adjacent offshore waters of Michigan. Interest in the Western Lake Superior Gravity Low has been sustained by its unique spatial association with outcrop of Middle and Upper Keweenawan rocks, generally accepted as the principal cause of the Midcontinent Gravity High, and by its geographic location, whereas other Midcontinent Gravity High minima of residual magnitude in excess of 50 milligals occupy flank positions, the Western Lake Superior Gravity Low lies on trend with the central gravity maxima of the Midcontinent Gravity High.

In spite of numerous geological and geophysical studies within the Lake Superior Basin area over the past three decades, the cause of the Western Lake Superior Gravity Low is still being debated. Enough information has been gathered, however, to suggest the ultimate answer will be associated with some combination of the following causes: (1) an abnormally thick column of relatively low density, Upper Keweenawan sedimentary rocks, (2) alteration in either the thickness or density of Middle Keweenawan volcanic rock, and (3) pre-Keweenawan deep crustal or upper mantle effects.

Until further investigations are conducted, the most significant of which would be the on-land drilling of a deep (4,000 m to 6,000 m) stratigraphic bore-hole within the geographic confines of the Bayfield low, the prioritization of this list of geologic causes must remain speculative.

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