LINEAMENTS AND FAULTS OF WISCONSIN, MINNESOTA AND THE WESTERN PART OF THE NORTHERN PENINSULA OF MICHIGAN

by

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Plates

INTRODUCTION

The lineament and fault map of Wisconsin, Minnesota and the western part of the northern peninsula of Michigan was produced under U.S. Geological Survey contract 14-08-0001-18290, Cenozoic Neotectonics of the U.S. Portion of the Canadian Shield. The objectives of the contract were first, to investigate regional crustal warping since the Cretaceous in the Great Lakes region and second, to examine known or suspected faults and lineaments on satellite imagery for evidence of post-Pleistocene offset. The results of the first objective are described in Dutch (1981a) and Dutch (1981b), and the results of the second objective described here.

The fault and lineament map consists of four sheets. Sheet 1 is a compilation of all published faults in the study area, together with major geophysical lineaments and surface lineaments which appear on LANDSAT false-color imagery. Sheet 2 portrays the bedrock geology of the study area. Sheet 3 illustrates relationships between LANDSAT lineaments and Precambrian basement structure. Sheet 4 is a general index map to tectonic and geographic features mentioned in this report. Numbered features in this report refer to index numbers on sheet 4.

LIMITATIONS OF THIS STUDY

Neotectonic study of the mapped region is greatly hampered by the scanty depositional record since the Devonian. Jurassic rocks occur in northwestern Minnesota (Sims, 1970) and Cretaceous marine rocks over a wide area of Minnesota (Sloan, 1964). The Windrow Formation, a probable continental equivalent of the Cretaceous marine rocks, occurs as scattered remnants in eastern Minnesota and western Wisconsin (Andrews, 1958). These Cretaceous deposits, coupled with estimates of Cretaceous sea level (Vail and others, 1977; Hays and Pitman, 1973) allow post-Cretaceous regional uplift and subsidence in the Great Lakes region to be estimated (Dutch, 1981a). There is no presently known further depositional record in the mapped area until the Pleistocene, and little is known of Pleistocene history before the retreat of the Wisconsinian ice sheet across the mapped region about 18,000-10,000 years ago.

The conclusions of this report are subject to several limitations.

(1) The record of recent surface movements extends back only to the latest Wisconsinian. Fault ruptures of the surface older than 10,000-18,000 years would have been buried or planed off by later glacial advances and would be impossible to detect solely from surface data. Offsets within bedrock that do not affect Pleistocene deposits can only be said to be younger than the bedrock.

(2) Local bedrock dips up to 3^{o} are common in the mapped region and are due either to Paleozoic bottom topography or post-depositional epeirogenic warping of the crust. Post-Pleistocene tectonic tilting of a few degrees or less would not be distinguishable from older bedrock tilting or original dip. Locally steep dips can also result from collapse of caverns in the Paleozoic carbonate units or from slump, but such non-tectonic tilting can usually be readily identified.

(3) Glacio-isostatic tilting of late Pleistocene beaches and terraces in the Great Lakes is one of the clearest indicators of post-Pleistocene neotectonism in the mapped region (Goldthwait, 1907, 1908; Farrand, 1962). Goldthwait noted that elevation errors of five or ten feet (1.5 to 3m) were possible for some lake-level indicators, and his

reconstruction of the warped Glacial Lake Algonquin and Glacial Lake Nipissing lake levels shows a scatter of about 5 feet (1.5m) or more about each best-fit elevation curve. The warped beaches of the Pleistocene Great Lakes rise smoothly in elevation northward and appear to rule out any large offsets by faulting, but fault offsets or surface warping of 5 to 10 feet (1-5-3 m) could not be ruled out from beach elevation data alone. Some estimates of current uplift in this region are derived from tide-gage data (Walcott, 1972). Unless faulting or strong near-surface warping occurred between two closely-spaced stations, tide-gage data would not distinguish clearly between glacio-isostatic uplift and crustal movements of other sorts.

(4) Offsets within areas of thick Pleistocene deposits would be difficult to identify unambiguously unless they were very recent, very large (vertical offset of several meters), visible because of effects on ground water flow and vegetation, or exposed by excavation. Transcurrent fault offsets are unlikely to be large enough to produce readily discernible offset and are most likely to be manifested by effects on ground water movement and vegetation patterns. Because of the generally moist climate of the mapped area, abundant vegetation including large forested areas, and such factors as soil creep, it is believed that Holocene surface offsets of Pleistocene deposits would most likely be expressed on satellite imagery by changes in vegetation type or color, or soil color. Pronounced topographic lineaments are most likely pre-Pleistocene bedrock fractures in areas of thin Pleistocene cover. Mapping of these lineaments is pertinent to this report because the lineaments may have been active during the Holocene or may be zones of future faulting.

METHOD OF COMPILATION

The map shows major faults and lineaments in the study region. Mapped faults were taken from Sims (1972) and Morey (1976) for Minnesota, Dutton and Bradley (1970), LaBerge (1976), and Sims and others (1978) for Wisconsin, and King and Beikman (1974) for Michigan. Where maps of the same area differed the most recent interpretation was depicted. Klasner and others (1979) was the primary source for faults beneath in Lake Superior.

Geophysical lineaments were taken from the magnetic maps of Minnesota (Zeitz and Kirby, 1970), northern Wisconsin (Zeitz and others, 1979) and Michigan (Zeitz and others, 1974) and from the gravity map of Wisconsin (Ervin and Hammer, 1974). A conservative approach was used in proposing geophysical lineaments. That is, geophysical lineaments were not proposed unless they were clearly expressed and appeared to cut across the regional structural grain or unless there was geological evidence to suggest that they might represent faults. For example, some E-W striking linear magnetic anomalies in northern Michigan are omitted because they are caused by sedimentary iron-formations.

LANDSAT lineaments were derived from EROS standard false-color images projected to match the base map scale. Linear features were positioned on the base map with reference to nearby landmarks, but some positional errors are likely due to plotting errors and ambiguity in defining the precise location of the lineament. Such errors should be less than 2 Km (3 mi.) in most cases. The error estimate is based on observed position errors in plotting lineaments that coincide with geographic features on the base map.

Many cultural features are easily seen on the LANDSAT imagery. Land-survey grid patterns are conspicuous and individual highways and railroads are commonly visible. Many linear features were determined to be cultural by comparison with the base map and were therefore eliminated. However, cultural features often have an underlying geological explanation. For example, the strongest expression of a linear feature may be a road, but the road may be linear because it follows a linear, structurally controlled valley. Over most of the central U.S., the prevalent pattern on imagery is the north-south and east-west grid of roads and section boundaries. Oblique features are easy to spot on this background, but true north-south or east-west lineaments may be difficult to detect and verify unless there is independent geological evidence for their existence. The general procedure used in compiling the lineament map was to exclude features suspected of being purely cultural in origin unless there was evidence for a geologic origin for the feature, such as control by a topographic lineament or the presence of nearby lineaments of similar orientation. Nevertheless, it is likely that a few true lineaments were excluded and some spurious features included.

LANDSAT images are consistently illuminated from the southeast, and spurious NW-SE or NE-SW trends sometimes appear, due simply to lighting effects. There is abundant independent geological evidence in the mapped area for NW-SE and NE-SW lineaments and the lineaments noted on the map are considered to be real features rather than artifacts of lighting.

TECTONIC HISTORY OF THE STUDY AREA

The study area had a complex early and middle Precambrian history of orogeny and intrusion, followed by a much quieter late-Precambrian and Phanerozoic history of cratonic warping and minor tectonism. The major Precambrian events are summarized in Table I and are discussed here in detail only to the extent that they influence Phanerozoic structures.

Sims and others (1980) proposed that a major Precambrian crustal suture, the Great Lakes Tectonic Zone (Sheets 1-4) extends across the mapped area. This suture separates a Precambrian W granite-greenstone belt basement province on the north from an older gneiss terrain on the south, and also marks the dividing line between thin Precambrian X supracrustal rocks on the north and thick rocks of the same age, including abundant volcanic rocks, on the south.

Tectonic activity in the mapped area culminated about 1900-1850 m.y. ago in the Penokean orogeny. There followed an erosional interval during which thick orthoquartzites accumulated, and an episode of anorogenic intrusion about 1500 m.y. ago, when extensive granitic intrusions were emplaced in eastern Wisconsin.

About 1100 m.y. ago a major episode of rifting and basaltic volcanism resulted in the formation of the Keeweenawan Complex. The Keeweenawan Complex is arcuate in form and can be traced by geophysical means from Kansas to Lake Superior, thence southeast beneath Michigan (King and Zeitz, 1971). The only surface exposures of Keeweenawan rocks are around western Lake Superior, where basaltic volcanic rocks are exposed on the Keeweenaw Peninsula of Michigan and the north shore of Lake Superior in Minnesota. A related intrusive

There is evidence for Silurian uplift in Minnesota; Silurian rocks are absent in Minnesota but average 600 feet thick in Wisconsin. Devonian marine rocks occur both in Minnesota and Wisconsin.

After the Silurian, possibly during the late Paleozoic (Heyl and others, 1970), copper-lead-zinc mineralization and minor folding and faulting occurred in southwestern Wisconsin, northeastern Iowa and northwestern Illinois (Sheet 2). Apart from the mineralization, no Phanerozoic intrusive activity was known anywhere in the mapped region until a small kimberlite pipe was discovered in northern Michigan in 1979 (Cannon and Mudrey, 1980). An additional example of a possible intrusive or explosion structure is the Glovers Bluff Structure (Ekern and Thwaites, 1930; Koenen, 1956), a small area of brecciated lower Ordovician dolomite. It is also possible that the Glovers Bluff disturbance is due to cavern collapse. In general the study area is remarkable for its lack of recent igneous activity. No Phanerozoic dikes or sills have been documented anywhere in the region.

There is no sedimentary record in the study area from the Devonian to the Jurassic. Jurassic continental sediments occur in northwestern Minnesota (Sims and Morey, 1972) and Cretaceous marine rocks are widespread in Minnesota (Sloan, 1964). The Cretaceous transgression was probably due to a global rise in sea level of about 350 m or 1150 feet (Hays and Pitman, 1973; Vail and others, 1977) relative to present North American sea level. The elevation of the top of the Cretaceous rocks and preserved late Cretaceous shorelines in Minnesota are generally at about 1000-1200 feet. Therefore little net vertical movement has occurred over most of Minnesota since the latest Cretaceous. The major exception is northeastern Minnesota, where Cretaceous marine rocks occur in the Mesabi Range at over 1500 feet. The evidence for post-Cretaceous vertical motion in the Great Lakes region is described in detail in Dutch (1981a).

complex, the Duluth Gabbro, occupies much of northeastern Minnesota. Clastic sedimentary rocks which also form part of the Keeweenawan Complex are exposed in northwestern Wisconsin (Craddock, 1972).

The geology of the Keeweenawan Complex beneath Lake Superior and southern Michigan is complex and incompletely understood. From Lake Superior to Kansas, the Keeweenawan Complex appears to have a simpler structure. The major geophysical expression of the Keeweenawan Complex is a strong gravity high, the Midcontinent Gravity High (King and Zeitz, 1971), which is generally flanked by gravity lows. Maxima of about +60 m gal, and minima of about -100 m gal occur along the Midcontinent Gravity High and its flanking lows. The structure of the Midcontinent Gravity High is interpreted from geophysical data and well samples to consist of a central horst of mafic volcanic rocks flanked by deep sedimentary basins. The causes of the uplift of the horst are unknown. It is also not clear whether the Midcontinent Gravity High is in isostatic equilibrium, and if it is not, how the crust can support what appears to be an enormous load.

Precambrian Z or early Cambrian clastic sedimentary rocks were deposited in the Lake Superior region. Marine sedimentation occurred throughout the mapped area during the early Paleozoic. Subsidence occurred east of the study area, in the Michigan Basin, and also in western Wisconsin and southeastern Minnesota in the Hollandale Embayment (Sims and Morey, 1972). Subsidence also occurred in western Minnesota during the Ordovician. Most of Minnesota was dominated by the NNE-SSW trending Transcontinental Arch during the early Paleozoic.

Several hiatuses occur in the Cambrian and Ordovician sections (Austin, 1972; Ostrom, 1967) due either to local uplift or to global sea level fall.

Sims and others (1980) described several lines of evidence for Cretaceous to Holocene vertical offset along the Great Lakes Tectonic Zone. The most persuasive of their arguments are tilted Cretaceous rocks dipping up to 27° along the Minnesota-South Dakota border (Schurr, 1979) and the occurrence of several earthquakes along the Great Lakes Tectonic Zone (Mooney, 1979; Herrmann, 1979).

There is no further evidence relating to tectonism in the mapped region until the end of the Pleistocene. Shorelines of glacial lakes ancestral to the present Great Lakes were tilted by isostatic uplift following the retreat of the Wisconsinian ice sheet. This recent uplift is the subject of an extensive literature (Goldthwait, 1907, 1908; Farrand, 1962; Hough, 1963; Walcott, 1972) and will not be covered in detail in this report.

A puzzling physiographic feature of this region is the presence of a highland rim adjacent to Lake Superior and with summit elevations about 100 m above the surrounding region. This rim may have resulted from isostatic uplift following excavation of the Lake Superior basin by late Tertiary fluvial erosion and Pleistocene glacial scour. This hypothesis is discussed in detail in Dutch (1981b).

MAPPED FAULTS

Mapped faults in the study area are those faults which have been described in the geological literature. They are indicated by solid lines ornamented with circular dots. Faults which offset only rocks of Precambrian age are marked with dots spaced about one inch (2.54 cm) apart; faults which offset Paleozoic rocks are marked with dots spaced about 0.5 inch (1.25 cm) apart.

On the basis of a review of well data and the history of past geological interpretations, Kuntz and Perry (1976) raised doubts about the existence of several faults in northeastern Wisconsin. Additional review of well data in this area was carried out by the author. The faults are generally based on offsets of stratigraphic horizons observed in closely-spaced wells or quarries, but there are few localities where faults can be precisely located and no direct evidence for the trace of the fault between control points. In some cases sharp offsets in stratigraphic contacts may be related to reef structures rather than to faults. Additional evidence for faults is provided by closely-spaced wells or outcrops which indicate greatly different elevations of the Precambrian surface; however, the Precambrian surface is an erosional unconformity of considerable relief and caution must be exercised in using the Precambrian surface to delineate faults. There are virtually no LANDSAT lineaments in northeastern Wisconsin that coincide with the location or orientations of mapped faults, except for a portion of one fault in Waupaca County which is paralleled by a nearby lineament (1). The author concludes that the available evidence suggests offset of Paleozoic rocks at several localities in northeastern Wisconsin, but the control data are not sufficient to locate the traces of the faults with confidence. The faults in question are therefore indicated as "doubtful" on the map.

Actual exposures of faults are rare in the study area. The principal areas where faults have been located by bedrock mapping are the northern peninsula of Michigan and the immediately adjoining parts of northeasternmost Wisconsin, and northeastern Minnesota. In both of these areas the faults are not known to cut any rocks younger than the Precambrian. Some faults in Paleozoic rocks are known from bedrock mapping, and some in wothwestern Wisconsin are known from surface mapping or subsurface geology in the lead-zinc mining district (Sheet 2), but most are known primarily from well data, and control of the faults ranges from good to questionable, as in the case of the doubtful faults above. Faults which offset Paleozoic rocks rarely show any surface expression.

Most of the faults in Precambrian rocks have been inferred from geophysical data. These faults include the faults of northwestern Minnesota (Sims, 1970), most of the faults of north-central Wisconsin (Sims and others, 1978), and all underwater faults in Lake Superior (Klasner and others, 1979). Locations of many of the inferred faults are approximate. For example, faults in northern Minnesota (Koochiching County) differ in location by up to 10 km (6 mi.) on the maps of Morey (1972) and Morey (1976).

The faults shown by Klasner and others (1979) are defined by steep gravity graidents and offsets of major gravity anomalies, but the interpreted locations of the faults could easily be in error by 5 to 10 km (3 to 6 mi.). Other interpretations of the geophysical data are possible as well.

Cataclastic zones, which are represented by wavy lines on the map, have been mapped in Marathon County, Wisconsin (LaBerge, 1976) and isolated examples of cataclastic rocks have been found elsewhere (Myers, 1974, 1977, 1978a-c; LaBerge, 1978; Dutch, 1979). There is good reason to expect that there are many undiscovered or concealed cataclastic zones in the study area. All known examples are in Precambrian rocks. Few cataclastic zones are associated with lineaments. The most conspicuous case is the Eau Claire Dells Mylonite Zone (2), in eastern Marathon County, which marks the course of the Eau Claire River. Field examination of this area by the author has disclosed no evidence for post-Precambrian activity along this zone. Exposure is nearly continuous across the

the strike of this zone and no indication of any secondary ductile or brittle deformation of the cataclastic rocks, apart from jointing, was observed. Many of the cataclastic zones of Marathon County have been intruded by later Precambrian igneous rocks and show no evidence of post-intrusion reactivation.

GEOPHYSICAL LINEAMENTS

Both gravity and magnetic lineaments are evident in the study area. Magnetic lineaments are predominently indicated by truncations of magnetic trends, whereas gravity gradients are marked mostly by steep, linear gravity gradients. Geophysical lineaments are denoted on the compilation by solid lines ornamented with squares. Gravity and magnetic trends are indicated by G or M, respectively.

The most conspicuous geophysical features in this region are the boundaries of the Midcontinent Gravity High, which are inferred to be fault boundaries. Where the fault is exposed, such as the Keeweenaw Fault (2), in northern Michigan, or a fault has been postulated in a publication on geophysical grounds, the conventional faults symbol is used instead. A few other magnetic lineaments have been noted in Minnesota and northern Michigan on the basis of the magnetic maps of Zeitz and Kirby (1970) and Zeitz and others (1974). Most well-documented magnetic lineaments in Wisconsin are in north-central Wisconsin, in the area covered by the detailed magnetic map of Zeitz and others (1978). These lineaments have mostly been interpreted as faults by Sims and others (1978). Magnetic coverage for the remainder of Wisconsin is coarse and not suitable for accurate delineation of lineaments.

Several gravity lineaments are shown in Wisconsin. These are evident on the Bouguer gravity map of Wisconsin (Ervin and Hammer, 1974), and on computer-enhanced maps made by the author (Dutch, 1978). No lineaments of this sort were indicated unless they were evident on the original gravity map; thus not all the possible linear features on the computer-generated maps are shown.

LINEAMENTS AND LINEAR STRUCTURES ON SATELLITE IMAGERY

Linear features on high-altitude or satellite images may have many possible tectonic or non-tectonic origins. Tectonic linear structures include faults, dikes, joints, fold limbs, foliation, and outcrop bands of dipping strata. Non-tectonic linear structures include drainages established on smooth, uniform slopes or along the margins of glacial lobes, ice-streamlined features, such as drumlins or striated terrain, wave-smoothed coastlines, longitudinal dunes, and cultural features. A major problem in using high-altitude imagery to interpret the neotectonics of the study region is to separate the tectonic from the non-tectonic features, and then to determine which of the tectonic features represent neotectonic activity.

The complex glacial history of the Midwest complicates the task of detecting and interpreting lineaments. There are many linear features of glacial origin in this region. For example, large outwash aprons at the margins of the ice sheets often show linear downslope drainages due simple to the uniform slope. Some linear streams in central Wisconsin are developed on outwash aprons (Hadley and Pelham, 1976). Parts of Wisconsin and Minnesota have well-developed drumlin fields which effectively mask underlying structures. For example, a large drumlin field northeast of Madison, Wisconsin imparts a pronounced northeasterly grain to the topography and renders any bedrock lineaments of similar trend unrecognizable. Former ice-marginal drainages are the dominant features of the landscape in southwestern Minnesota (Matsch, 1972) where most major streams trend southeast. Large-scale mosaics of satellite imagery show a clear pattern to major drainages in this region, and indicate that the drainage pattern probably was established along the margins of the retreating Des Moines glacial lobe. The complex relationships between lineaments, surficial features, and structure are illustrated well in this region. The Des Moines lobe advanced along the Minnesota River Valley (3; Matsch, 1972; Wright, 1972), which is cut into Precambrian bedrock and which is quite linear. If the linearity of the Minnesota River is partly due to erosion along a structural lineament, then many other southeasterly drainages in this region mimic that structural trend because of its influence on ice movement. Some linear drainages and topographic features in central Wisconsin are also ice-margin features. Features of probable glacial origin, as determined from the references cited above, were excluded from the lineament map.

One test for Holocene neotectonism would be to examine regions of thick Pleistocene deposits for lineaments. However, the presence of lineaments in areas which are buried by glacial deposits does not invariably signify post-Pleistocene tectonic activity. Lineaments may be preserved in glaciated areas by filling structurally-controlled valleys or banking escarpments with ice. After the retreat of the ice sheet, the lineament may be marked by a chain of kettle ponds. This mechanism has been shown to preserve traces of preglacial valleys in southern Michigan through several glacial advances (Rieck and Winters, 1979).

It is instructive to consider the relations between bedrock and glacial geology and the expressions of lineaments in several areas. An illustration of the complex relationships between structure, glacial geology and cultural features is found in northern Wisconsin. The most conspicuous LANDSAT lineaments in Wisconsin (4) trend southeast from near the northwestern corner of Wisconsin for a distance of about 150 miles. For a large part of that distance, the lineament is paralleled by highways, which are conspicuous on the LANDSAT images, but the lineament is also topographic in nature and consists of a shallow valley between belts of hillier terrain. This region is generally covered by glacial deposits 50-100 feet thick and bedrock exposures are rare. The linearity of this feature and its parallelism with other known lineaments and mapped faults suggests that it is a true bedrock lineament which is topographically expressed in the overlying glacial deposits.

Several other SE-trending lineaments (5,6) occur in east-central Wisconsin. Although this region is part of a wide belt of recessional moraines, there are several exposures of Precambrian granitic rocks in the vicinity of the lineaments. There are many elliptical hills in this area which are oriented roughly parallel to the lineaments. The hills have been considered drumlins (Thwaites, 1943) but field reconnaissance by the author strongly suggests that the hills are actually bedrock mantled with drift and that the orientation of the hills reflects joint systems in the Precambrian rocks. The strongest lineaments are made up of stream courses, elongated bogs and ponds and low topographic scarps, and are probably especially-pronounced eroded joints that are visible through a locally thin drift cover.

An interesting example of lineaments that change their node of expression depending on their depth of burial occurs in Ontario just north of the

Minnesota border (7,8,9). A large flat area east of Lake of the Woods is probably mantled by glacial lake sediments (Goeben and Walton, 1979). North of this area, lineaments are prominently expressed in the exposed bedrock as shallow valleys, stream courses and linear lakes. Within the lake plain, several of the lineaments are visible as spots and streaks of lighter or darker vegetation color than their surroundings. In general lineaments in areas of thick glacial lake deposits, outwash, or Cretaceous rocks tend to be expressed as subtle color or albedo features rather than topographically.

A number of criteria must be employed in deciding whether a lineament indicates post-Pleistocene tectonism. Lineaments which are marked by glacial features such as kettle ponds are preglacial in origin, because the kettle ponds formed when stagnant ice was trapped along the lineament. Differential erosion on a large scale is unlikely to be significant in recent, unconsolidated deposits, therefore major linear drainage channels are likely to be inherited from the preglacial landscape rather than produced by post-glacial erosion along a zone of disturbance in surficial deposits. Minor linear drainage features, however, might signify post-glacial disturbance, especially where they align to form a long composite lineament. The most likely indicators of small post-Pleistocene surface faulting would be lineaments which reveal disruption of ground water flow, such as conspicuous changes in vegetation type or color. Such lineaments might result from non-tectonic causes as well, such as sharp soil boundaries. In some cases, the underlying cause of the soil boundary may be an old, inactive tectonic feature. For example, a bedrock lineament may have stopped or diverted ice flow and caused a linear boundary between two different types of till.

Most of the observed lineaments can be related to structures in the Precambrian basement and can be inferred from the criteria described above to be pre-Pleistocene. The relative rarity of lineaments in area of thick Paleozoic, Cretaceous, or Pleistocene cover suggests as well that most of the lineaments in areas of exposed Precambrian rocks are due to pre-Pleistocene (and likely Precambrian) differential erosion along Precambrian faults and joint systems. There appears to be no clear evidence that any of the observed lineaments have been affected by Holocene ground movements.

JOINTS

Six joint rose diagrams have been included on the compilation map. Diagrams A and B are taken from Sims (1972) and Morey (1972), respectively. Diagram C is recalculated from a contoured stereoplot in Dalziel and Dott (1970) and is somewhat approximate, although the accuracy of the rose diagram is believed to be good. Diagram D is taken from Dutch (1980), E from Agnew (1963) and F from Taylor (1964).

There is a general tendency for joints to be similar in attitude to nearby structural trends. Unfortunately, half of the available joint plots are in Precambrian rocks. More joint data for Paleozoic rocks would be valuable for determining the extent to which Precambrian structural trends have been reactivated.

In addition to joint formation by reactivation of Precambrian fracture patterns, existing weakly-developed joints in Paleozoic rocks might be enhanced by differential loading during Pleistocene ice advances or retreats. The stratigraphic sequence in eastern Wisconsin consists of competent dolomite units 100-300 feet thick interbedded with less competent shale and sandstone units. A thick (up to 1000 feet) succession of friable Cambrian sandstones lies between the Precambrian basement and the base of the lowest carbonate unit, the Prairie du Chien Group (Ostrom, 1967). Glacial loading of competent rocks which overlie less competent rocks might enhance pre-existing weakly-developed joints which had previously been formed by re-activation of Precambrian basement fractures. Thus, glacial loading could create the impression that reactivation of Precambrian basement fractures had been stronger than was actually the case.

TOPOGRAPHIC LINEAMENTS

Topographic lineaments are indicated on the compilation as heavy solid lines, ornamented with the appropriate symbol where they coincide with mapped faults or preglacial valleys. Topographic lineaments include linear or curvilinear portions of major drainage systems, linear Paleozoic bedrock escarpments, and underwater linear features on the bathymetric chart of Lake Superior (Farrand and Zumberge, 1966). Topographic lineaments which are solely of surficial origin, such as recessional moraines or ice-marginal drainages, are excluded.

In some areas, LANDSAT imagery shows a pronounced fine-scale grain which usually reflects bedding or foliation. In such areas, individual lineaments are not portrayed unless they are of unusual length or unless they cut across the topographic grain. The strike of the topographic grain is indicated by a two-headed arrow. Areas which have a pronounced topographic grain of probable galcial origin are also indicated as an aid to evaluation of lineaments. In such cases the arrow is barbed only on one side.

For several topographic lineaments, the evidence for structural control is speculative. For example, the Fox River (10) and the Silurian escarpment

(11) of northeastern Wisconsin are indicated as topographic lineaments. The Fox River is probably controlled in part by the strike of Paleozoic rocks. The evidence for structural control of the Silurian escarpment is equivocal (Dutch, 1980). A few joints occur parallel to the trend of the escarpment, but they are by no means dominant in the regional joint pattern (see joint rose diagram D).

The most speculative topographic lineaments shown are the straight SE-trending stretches of the Minnesota and Mississippi Rivers (3 and 12, respectively). The straightness of both features and their parallelism with other structural trends suggests structural control. The straight reach of the Mississippi River nearly aligns with the strike of the Sandwich Fault in Illinois (McGinnis and others, 1976). It is also interesting to note that the linear trend of the Mississippi River is interrupted where it crosses the Keeweenawan Complex.

A large circular feature in western Wisconsin (13) is a prominent and puzzling feature on LANDSAT imagery. It is bounded on the southwest by the Mississippi River, on the north by the Chippewa River, and on the south by the Black River. The northeast quadrant is the most poorly defined portion, but even there it is clearly outlined by minor drainages and by a pronounced change in topography: the NE quadrant coincides with the boundary between the Central Plain and Western Uplands physiographic provinces (Paull and Paull, 1977). This feature attracted some notoriety when the Milwaukee Sentinel (November 10, 1977) published a report of a hypothesis that it might be a meteor impact crater. The report cited a University of Wisconsin graduate student, Donna Stetz, as the originator of this hypothesis. The report was based on a brief reference in her thesis (Stetz, 1978). Structural evidence for either a Paleozoic or Precambrian impact origin is absent. Nevertheless, it is unlikely that the ring is only a fortuitous arrangement of drainage and topographic features. The remarkable regularity of this feature is difficult to ascribe to completely random erosional features, as is the fact that the La Crosse River (14), south of the ring, displays the same curvature as the southern portion of the ring. On the other hand, apart from the major drainage features already described, there are almost no physiographic features concentric with the ring, and no major gravity or magnetic anomalies clearly related to it.

Linear features beneath Lake Superior are difficult to interpret. At least some are deeply-scoured glacial valleys, others appear to be submerged bedrock escarpments. Many are probably due to lithologic control of glacial erosion and may reflect joint patterns or attitudes of layered rocks. The orientation of the linear features in Lake Superior is quite different from the lineament pattern on land and may reflect the structure of the Keeweenawan Complex beneath eastern Lake Superior.

FILLED PREGLACIAL VALLEYS

The filled preglacial valleys, shown as solid lines with crosshatching, are taken primarily from Trotta and Crotter (1973). In some cases, where the valley follows a major present drainage, the heavy line symbol for major topographic lineaments is used with crosshatching added. In east-central Wisconsin, these valleys form a gridlike pattern of NE and NW-trending linear valleys. This orientation is believed to represent joint control of preglacial drainage systems. The valley floors do not slope uniformly. Instead, there are closed depressions up to 600 feet (180 m) deep and about

10 miles (16 Km) long (Thwaites, 1943; Thwaites and Bertrand, 1957) which have been interpreted in several ways. The most obvious explanation for such depressions is simply glacial scour. Some local depressions adjacent to Paleozoic bedrock escarpments may be plunge pools or the result of locally vigorous water erosion during the retreat of the ice sheets. Other depressions may be due to erosion of glacial forebulges though the lengths of the major depressions seem to be too small to be explained this way, because forebulges should be on the order of 100 miles (160 Km) wide (McGinnis, 1968). Apart from deep closed depressions, the floors of preglacial valleys in the study region are typically buried beneath 100 to 300 feet of outwash. Valley floors in Wisconsin generally are at altitudes of 400 to 550 feet above present sea level. To the south, in Illinois, the range is from 400 feet in the north to 250 feet in the south (Horberg, 1950). These elevations are reasonable for river valleys, especially when viewed in light of low Pleistocene sea levels and correspondingly lower base levels. Thus there is evidence for structural control of preglacial valleys, probably by joints, but no evidence for major changes in elevation since the valleys were cut, other than glacio-isostatic effects.

DISCUSSION

There are a number of patterns evident on the map. The most obvious is a general SW-NE and NW-SE orientation to all types of linear trends, with subordinate sets of E-W features in some areas. Most areas show a strong parallelism of all types of lineaments, but when viewed in detail, there are slight divergences between lineaments of various types. For example, the mapped faults of north central Wisconsin, which are primarily inferred from geophysical data, appear to be fairly consistently oblique to LANDSAT lineaments. The mapped faults appear to form a conjugate pattern, as do the LANDSAT lineaments, but the inferred faults appear to trend more easterly than the corresponding family of lineaments. The reason for this divergence is not clear. Observed lineaments do not always coincide closely with faults which have been inferred from geophysical data, and it may be that the lineaments and the inferred faults are different expressions of the same stress regime. For example, the lineaments might be relatively minor, brittle-deformation phenomena, whereas the major displacements occurred along the faults in a more ductile manner. Some long faults may have been inferred from geophysical data by linking short en echelon features. In such a case, the lineaments may provide a means of refining the locations of some faults.

There are few faults in the region which displace Paleozoic rocks, and apart from the Great Lakes Tectonic Zone, there appears to be no clear evidence either for displacement of the Cretaceous rocks of Minnesota or displacement of Pleistocene deposits. Lineaments are most numerous and most strongly expressed in areas where Precambrian rocks are at or near the surface. Lineaments are less common or more weakly-developed in western and central Minnesota, where Cretaceous rocks or thick Pleistocene deposits occur, and also in southeastern Minnesota and southwestern Wisconsin, where the Paleozoic section is thickest. It is significant that very few faults have been mapped in the deeply-dissected area along the Mississippi River, despite the good exposure and stratigraphic control in that area. Most of the faults which have been mapped in that area are associated with the lead-zinc mining district.

Considering how profound the rifting was which occurred in the Midcontinent 1100 m.y. ago, Phanerozoic expression of the Keeweenawan Complex is conspicuous by its absence. Where the Precambrian rocks are exposed, Keeweenawan faults and lineaments are evident on LANDSAT imagery and from surface mapping. Where the complex is covered by Paleozoic rocks, however, hardly any expression of Keeweenawan structure is visible at the surface. The only major exception is the Belle Plaine Fault in central Minnesota (Cary and Sibley Counties) which coincides with a SE-trending transform-like lineament in the Keeweenawan Complex (Chase and Gilmer, 1972, 1973). Possible transforms are also expressed as lineaments in northwestern Wisconsin and eastern Minnesota (15). These lineaments trend ESE.

Another feature of the Keeweenawan Complex is that the SE and SW lineament pattern so evident elsewhere on the map is largely absent within the Keeweenawan Complex or the rocks which overlie it. There appears to have been little propagation of the SE and SW lineaments into the Keeweenawan Complex and little reactivation of Keeweenawan fractures. Further south, however, the late Paleozoic Nemaha Uplift of Kansas may represent reactivation of one of the Keeweenawan Complex boundary faults.

Epeirogenic warping during the Paleozoic may have been controlled by the Keeweenawan Complex. The Michigan Basin, Hollandale Embayment and Forest City Basin coincide with portions of the complex. There is also paleogeographic evidence that the Lake Superior area was a basin from the late Precambrian to the mid-Cambrian (Hamblin, 1961).

The Great Lakes Tectonic Zone is generally not marked by lineaments, either in Minnesota or in northern Michigan.

TABLE I MAJOR PRECAMBRIAN EVENTS IN THE WESTERN GREAT LAKES REGION

	570 m.y.	
PRECAMBRIAN Z		Clastic sedimentation in Lake Superior Basin
		Grenville Orogeny (900-1100 m.y.)
	1000 m.y.	
	1100 m.y.	Rifting and basaltic volcanism and associated clastic sedimentation. Formation of the Keeweenawan Complex or Midcontinent Gravity High
PRECAMBRIAN Y	1500 m.y.	Anorogenic granitic plutonism. Intrusion of the Wolf River Batholith.
		Mild deformation and metamorphism. Folding of the Baraboo Syncline. Metamorphism of quartzites.
		Widespread orthoquartzite deposition. Baraboo, Rib Mountain, McCaslin, Sioux and related quartzites
	1650 m.y.	Block-faulting, cataclasis, rhyolitic volcanism
		Granitic intrusions, Medium to high-grade metamorphism related to the Penokean Orogeny (1700-1900 m.y.)
PRECAMBRIAN X		Volcanism. Vertical movement along Great Lakes Tectonic Zone
	2000 m.y.	Sedimentation
	2500 m.y.	Formation of Great Lakes Tectonic Zone ?
PRECAMBRIAN W		Formation of granite-greenstone belt terrane of Superior Province
	3000 m.y.	Formation of southern Minnesota-central Wisconsin migmatite-gneiss complex

Major sources: Van Schmus, 1976 and Sims and others, 1980.

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