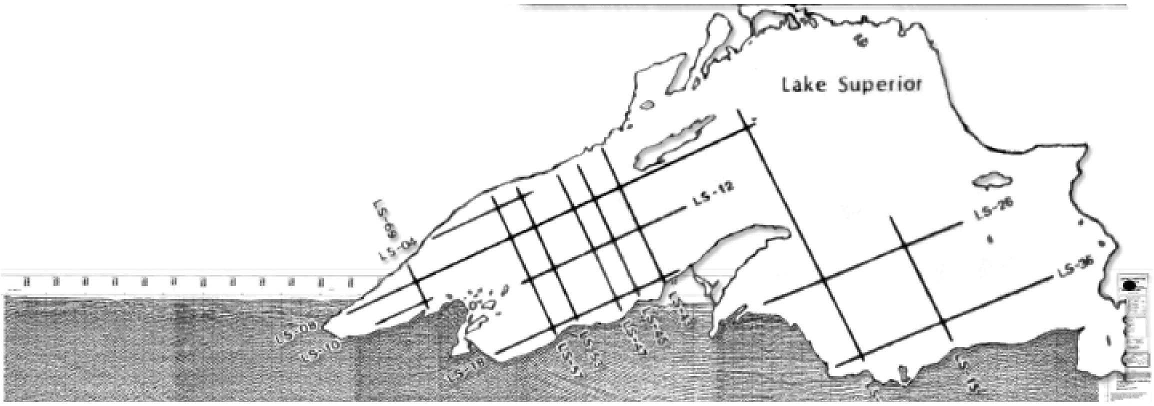
Seismic Reflection Profiling and Tectonic Evolution of the Midcontinent Rift in Lake Superior

L.D. McGinnis and M.G. Mudrey, Jr.



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ABSTRACT

An orthogonal grid of 1837.784 line km of seismic reflection profiles in Lake Superior, which covers approximately 20 percent of the length of the Midcontinent Rift, provided a comprehensive data set that assisted structural and stratigraphic analysis of the rift beneath the lake. The data allowed us to identify several distinct basins and interconnecting troughs, a large anticlinal structure, and major boundary faults and folds. In addition, we were also able to revise locations and characteristics of previously known boundary faults and their relationship to rifted blocks.

Integration of information obtained from outcrops with data reported here indicated that the rift is associated with as many as four major strike faults, including the Douglas Fault, the Keweenaw Fault, the Isle Royale Fault, and a fault along a hinge line on the north flank of the basin south of the Isle Royale Fault. The Douglas and Keweenaw Faults are subparallel strike faults bounding the rift and sag basins on the south flank of the rift graben. Strike faults and hinge lines form the rift graben boundaries.

INTRODUCTION

In this report we present deep reflection seismic profiles in Lake Superior, shot by Grant Norpac, Inc., and leased by Argonne National Laboratory to be made available to the geological research community. The locations of all deep seismic profiles shot in Lake Superior, including Great Lakes International Multidisciplinary Program for Crustal Evolution (GLIMPCE) data (see Behrendt and others, 1988) and some profiles shot, but not leased, are shown in figure 1.

The initial interest in this proprietary seismic data stemmed from the recognition that late Precambrian rock may contain recoverable petroleum (Dickas, 1986) and that basins of rift origin are noted worldwide for their hydrocarbon productivity. Following their discovery and exploitation on other continents, rift basins of Precambrian age have only recently been recognized as potential sources of hydrocarbons in North America. Although petroleum reserves have not been identified along the Middle Proterozoic Midcontinent Rift System, oil seeps emanate from the Nonesuch Formation in the White Pine mine on the Keweenaw Peninsula (Dickas, 1986). More recent interest in the seismic data has focused on the evolution of large-scale continental rift basins. Proprietary seismic data suggested that major revisions to the geometry of the Midcontinent Rift were necessary; as a result, Cannon and others (1989) supplemented that proprietary data with publicly acquired seismic data.

Since the acquisition of these data, several deep petroleum tests have been made that help in the understanding of the stratigraphy and tectonic set-

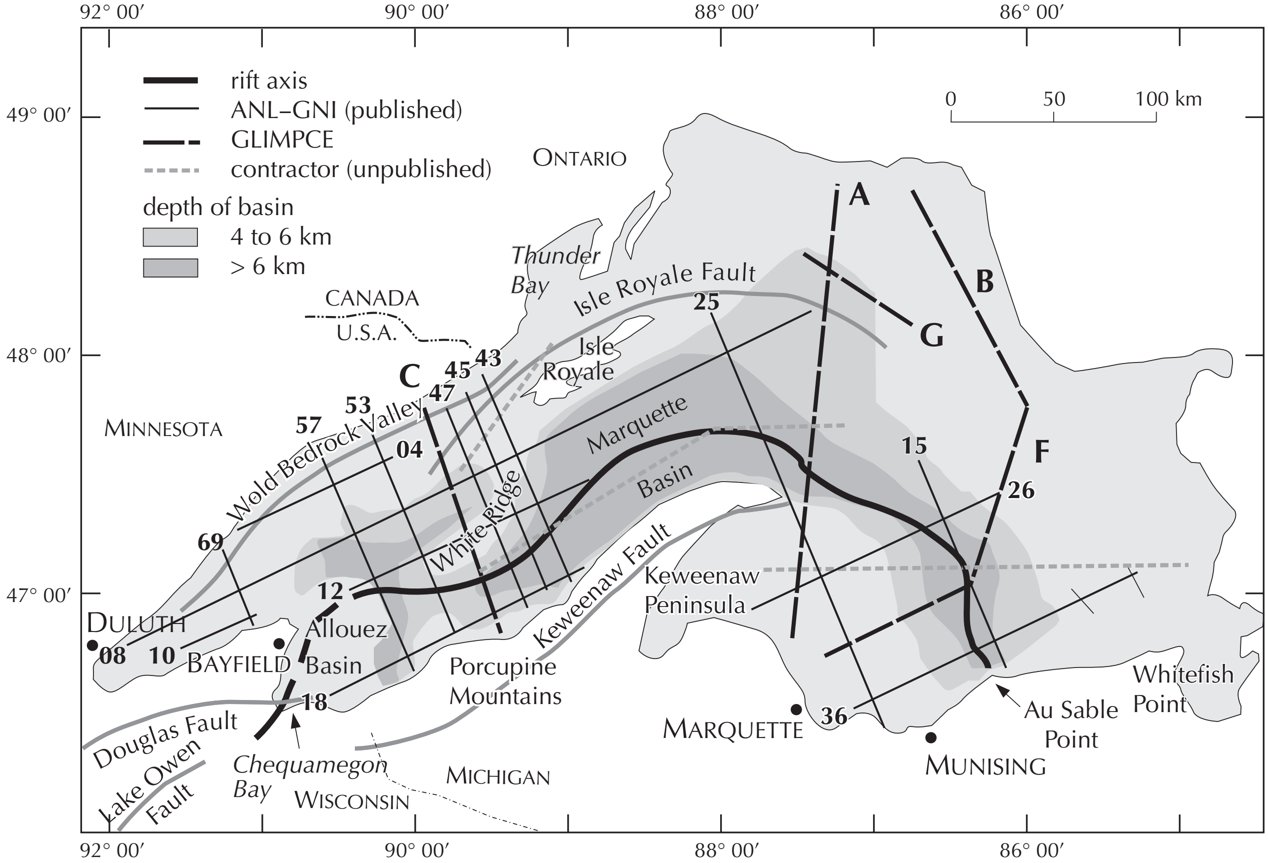

Figure 1. *Outline map of Lake Superior showing location of Argonne–Grant Norpac (ANL–GNI) reflection seismic lines (numbered) and GLIMPCE reflection seismic lines (alphabetic). Shaded areas show depth to base of Keweenawan sedimentary rock section. For conversion from travel time to depth, an average sedimentary rock velocity of 4.5 km/s was assumed. Sedimentary rock section incorporates the composite facies (mixed sedimentary rock and volcanic rock unit).*

ting of the various subbasins within the Midcontinent Rift (Kansas: Kansas Geological Survey and Texaco USA, 1988; Iowa: Anderson and others, 1990; Wisconsin: Dickas and Mudrey, 1999; Midcontinent tectonics: Ojakangas and others, 1997).

The Lake Superior section of the rift composes only about 20 percent of the entire Midcontinent Rift System; however, on the basis of the number of literature citations, it has been the subject of a large share of geological and geophysical research. The more intensive studies of this part of the rift resulted from the abundant exposures of rift-related rock along the shoreline and the ease of access for a variety of geophysical experiments that the lake provides. The remaining sections of the rift, although of equal importance to an understanding of Precambrian tectonism, lack equivalent study because hundreds (and in some cases thousands) of meters of overlying sedimentary rock prohibit conventional geological study, and deep drilling and acquisition of seismic information are costly.

The Midcontinent Rift is an example of a structurally intact continental rift that nearly formed an oceanic basin. Intense data gathering over the past 20 years about all aspects of the rift, including timing, petrology and magma evolution, structural elements, and subsequent evolution, has led to an improved understanding of this structure. It stretches 2,000 km from the Grenville Front through the Lake Superior region to Kansas and contains at least 2 x 10^6 km^3 of volcanic rock that was emplaced within about 22 My at 1.1 Ga (Bornhorst, 1997).

Subsequent to the formation of the rift, geologic events include continued rifting and subsequent plate convergence near a Precambrian plate margin, late Precambrian (Middle to Late Proterozoic) and Early Paleozoic crustal subsidence, Mesozoic reorientation and migration of the North American plate from an equatorial to a polar position, and Cenozoic continental glaciation and deep scouring during the Pleistocene.

As a consequence of these events, one of Earth's largest lakes is now superposed over the axis of one of Earth's largest intracontinental rifts. Lake Superior has been a topographically low area for millions of years (Hamblin, 1965), and the most recent geologic events served only to modify and deepen the basin. The superposition of a lake over a continental rift permits deep seismic reflection sounding data to be acquired in a marine mode, using air guns and hydrophone streamers, resulting in high-quality data. In addition, the ability to traverse a rift segment along any azimuth, with total disregard to the usual constraints of access, permits a high level of confidence in the construction of geological models from geophysical observations.

The data quality and the location of the ends of many lines near outcrops on shore permitted correlation between reflectors and a detailed reconstruction of rift evolution, crustal subsidence, and post-subsidence faulting and compressional deformation. Such detail aids in a better understanding of not only Precambrian rift processes in the vicinity of Lake Superior, but of the interaction of the rift with the contemporaneous Grenville orogeny to the east and to Precambrian processes in other parts of the world.

We interpreted faults to be in areas where the continuity of reflectors is lost or offset, where the gradient of dip is altered noticeably, and where features such as bow ties and concentrated diffraction patterns indicated point sources or edges of discontinuities or terminations. Of course, all these features do not always indicate faulting, but where many of them are spatially concentrated, and when they are compared with nearby data or with lines in similar structural settings, faults seem a reasonable interpretation.

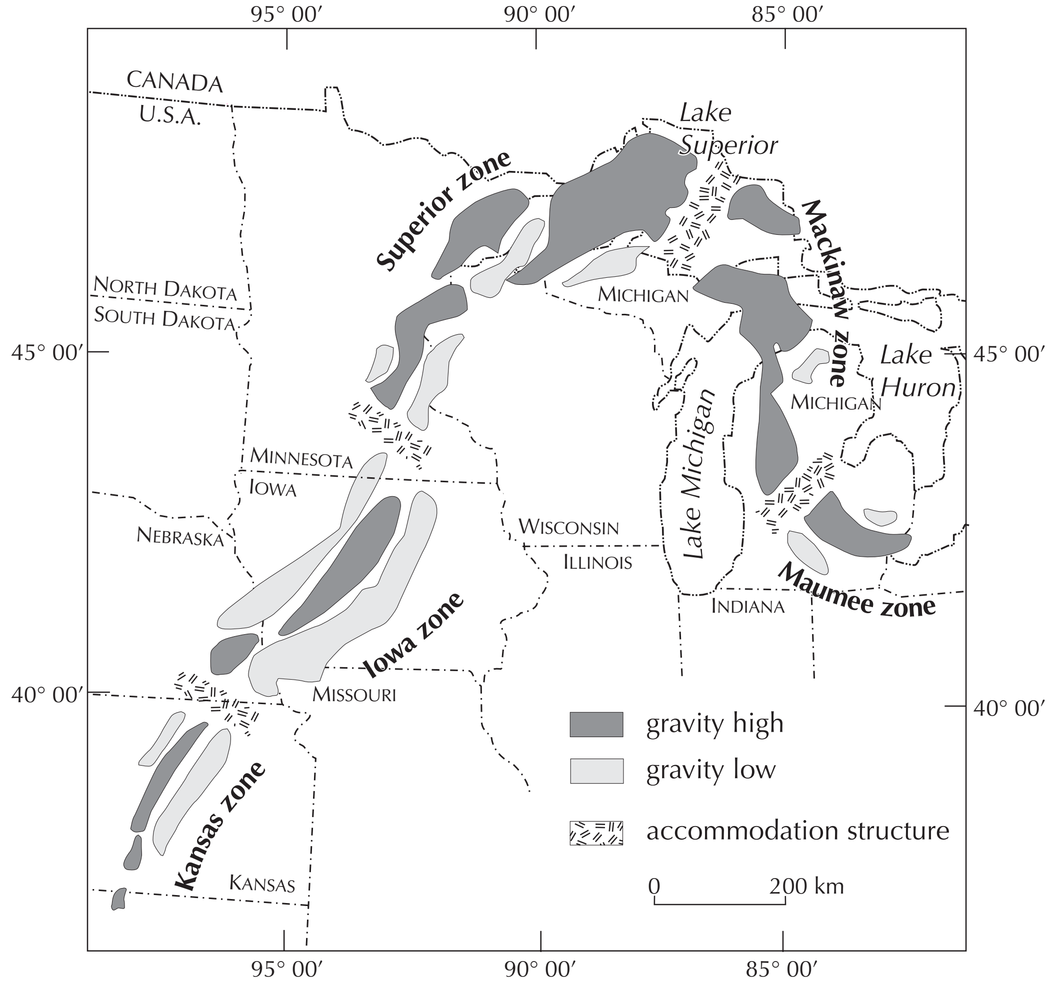

Figure 2. *Simplified map of the Midcontinent Rift defined from gravity surveys (from Dickas and Mudrey, 1997). The Midcontinent Gravity High extends from Kansas northeast to the central section of the Lake Superior Basin. The Mid-Michigan Gravity High extends from the eastern section of Lake Superior Basin southeast to the Michigan–Ohio border. The rock sequences causing these geophysical trends constitute the Midcontinent Rift System. The areas of positive gravity anomaly are underlain by mafic volcanic and intrusive rock; the areas of negative gravity anomaly are underlain by thick sequences of sedimentary rock or domal uplifts of Archean granite. Also shown, as hachured bars cutting across the axis of the Rift System, are the locations of four accommodation features of first-order structural significance (Dickas and Mudrey, 1997). These accommodation features subdivide the Rift into five zones, named from principal geographic* features.

REGIONAL GEOLOGIC SETTING

Lake Superior is underlain by part of a continuous and sinuous rift basin of Middle Proterozoic age. Because much of the rock in the basin is volcanic or gabbroic, the extent of the rift basin is clearly defined by a strong gravity anomaly (Hinze and Wold, 1982). The signature consists of a central positive gravity anomaly over the horsted parts of the rift, flanked by negative gravity anomalies over the sedimentary rock-filled grabens (fig. 2). The axis of the rift extends from Kansas in the south, widening in the Allouez and Marquette Basins in western and central Lake Superior, respectively, narrowing north of the Porcupine Mountains and south of White Ridge, and narrowing again east of the Keweenaw Peninsula. The rift trend has been broken into a series of apparently structurally related segments and subsegments (Mudrey and Dickas, 1988; Dickas and Mudrey, 1997). In the Superior Zone, the large segment from central Minnesota north of the Belle Plaine structural boundary north to Lake Superior has been divided into four rift units (fig. 3, the Chisago, Brule, Ontonago, and Manitou Units). Each of the units evolved somewhat independently within a larger tectonic setting (the Superior Zone). The seismic lines discussed below were acquired in the Ontonagon and Manitou Units and in the Mackinaw Zone (figs. 2 and 3).

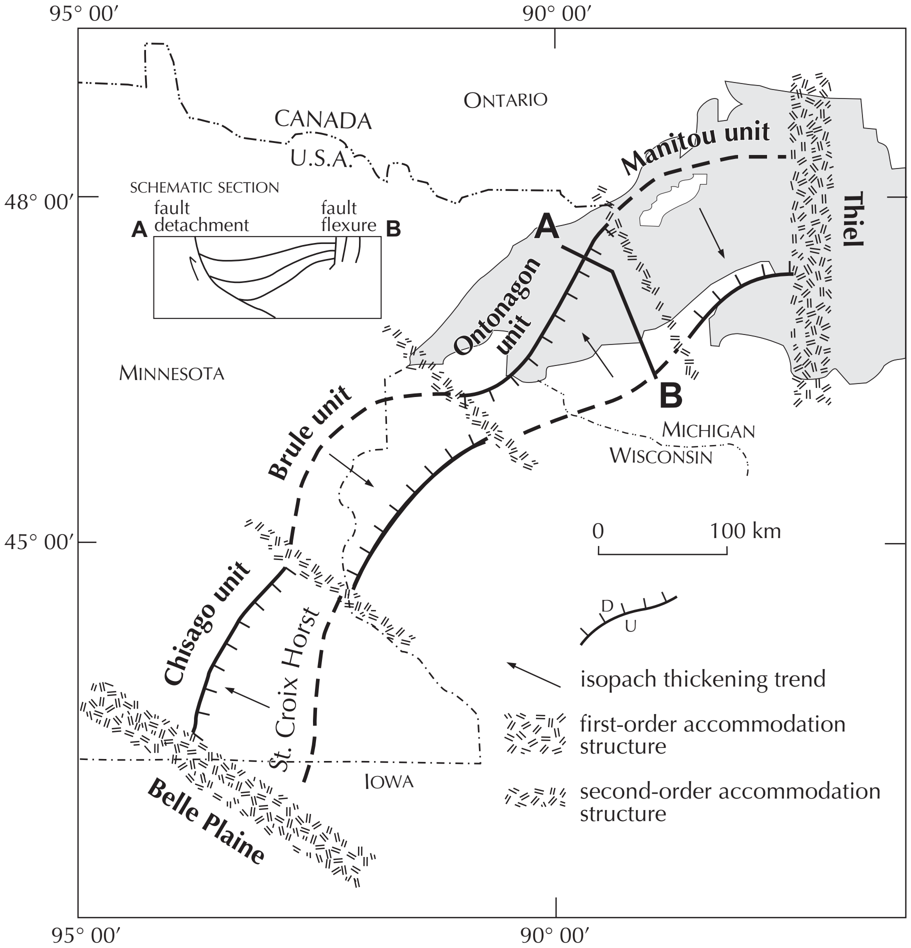

Figure 3. *Detailed structural interpretation of the Superior Zone of the Midcontinent Rift System (from Dickas and Mudrey, 1997). The Superior Zone (see fig. 2) is bounded by the Belle Plaine structure in central Minnesota and the Thiel Fault in eastern Lake Superior. This zone is divided into four fundamental rift units by three accommodation structures of second-order tectonic significance. Note that each of the identified rift units possesses a sedimentary rock thickening direction opposite to that of an adjacent rift unit. The barbed border of each rift unit represents the location of Keweenawan faults bounding the thick wedges of volcanic and associated sedimentary rock. The dashed line identifies the position of a hinge line that became active during the later contractional phase of the rift system, creating the present-day horst and graben structure.*

A broad, shallow basin bends southeast around the Keweenaw Peninsula in the eastern half of the lake, continuing southeast to where it exits the lake with its axis in the vicinity of Au Sable Point. An unnamed basin, east of the primary axial trend, is separated from the continuous series of basins by a narrow arch at the far eastern end of the lake. The basin is variable in

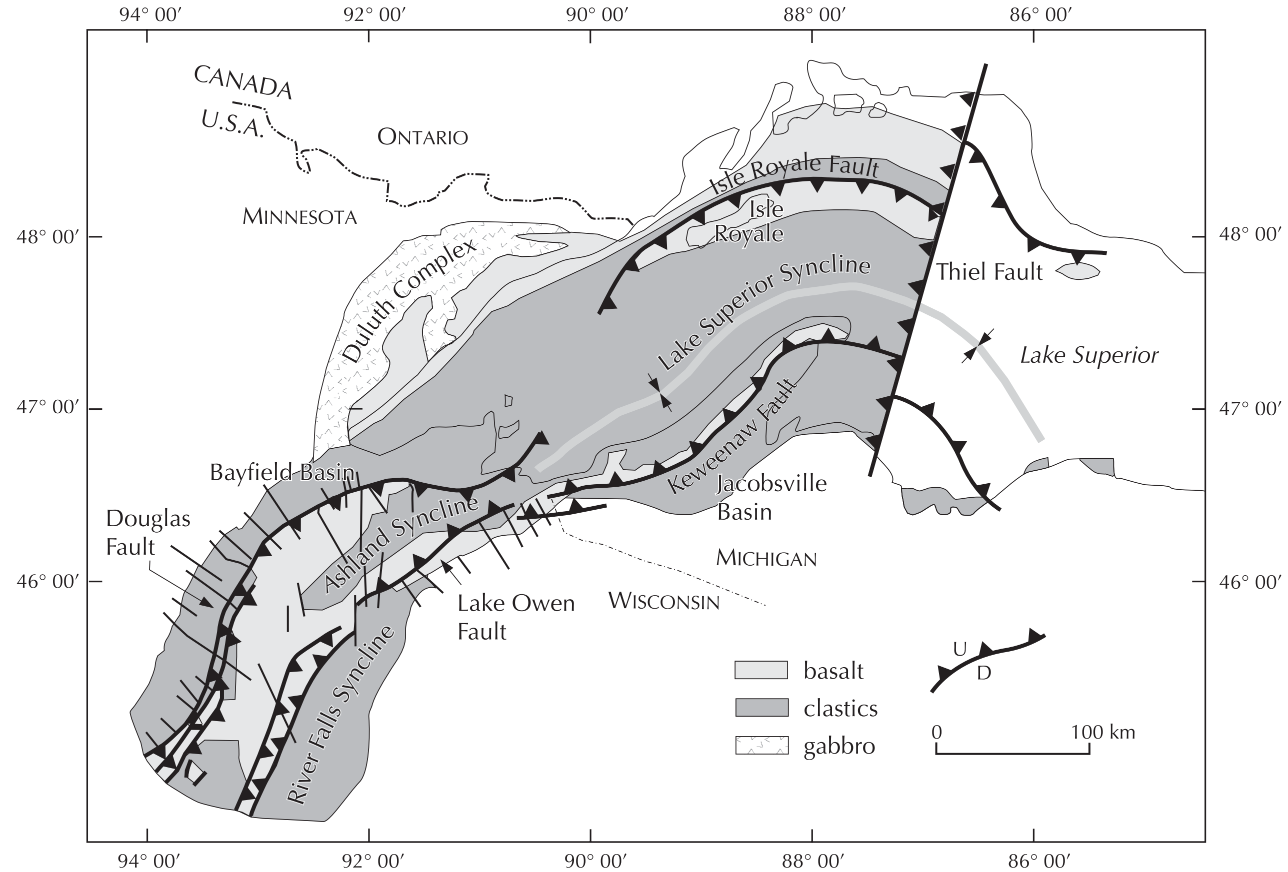

Figure 4. *General geology of the western Lake Superior Basin part of the Midcontinent Rift System (from Dickas and Mudrey, 1997). The central horst, originally a graben, is flanked by half-graben basins and bordered by regional fault systems. The strikes of these faults parallel the rift axis, but fault dip directions are inward toward the rift axis.*

depth, but descends beyond the point of detection (24 km) of this study and is partially filled with Keweenawan-age volcanic flows resting on Animikean- or Archean-age crystalline basement. The flows are, in turn, covered with late Keweenawan sedimentary rock reaching thicknesses of 8 or more kilometers.

The geology of surface exposures in the Lake Superior area has been well studied since 1844 (fig. 4; Wold and Hinze, 1982). The rock sequence in the Midcontinent Rift (fig. 5) consists of thick successions of mafic volcanic rock, including the Portage Lake Volcanic Group, exposed on the south shore of Lake Superior, and the North Shore Volcanic Group, exposed on the Minnesota shore of Lake Superior. The Portage Lake Volcanic Group rests unconformably on the North Shore Volcanic Group, as seen in line LS-57 (plate 14). Up to 10 km of volcanic rock is known from outcrops (Green, 1982); however, seismic reflection and refraction studies as part of the GLIMPCE program (GLIMPCE Seismic Refraction Working Group, 1990) documented a 36 km thickness of volcanic and sedimentary rock. A maturing-upward sedimentary sequence occupies the central graben of the Midcontinent Rift, the Ashland–Lake Superior Syncline (Mudrey and Brown, 1988), and was developed on the volcanic rock. Its basal unit consists of conglomerate and interbedded shale (the Copper Harbor Conglomerate of Wisconsin and Michigan and the Solor Church Formation of Minnesota). The feldspathic Bayfield Group lies with presumed angular unconformity on the Oronto Group (the Freda and Orienta Formations). A quartzose sandstone (Devils Island Formation of Wisconsin and Hinckley Sandstone of Minnesota [Morey and Ojakangas, 1982]) is at the top of the sequence.

Daniels (1982) described the uncommonly thick (>12,000) Freda Formation section along the Montreal River between Wisconsin and Michigan. Mudrey and Brown (1992) suggested that down-to-basin movement along fracture cleavage resulted in the apparent thickness due to the section being repeated. In places, such as on the Bayfield Peninsula, the maturing trend may be reversed and additional feldspathic sandstone deposited (the Chequamegon Formation of Wisconsin and the Jacobsville Sandstone of Michigan).

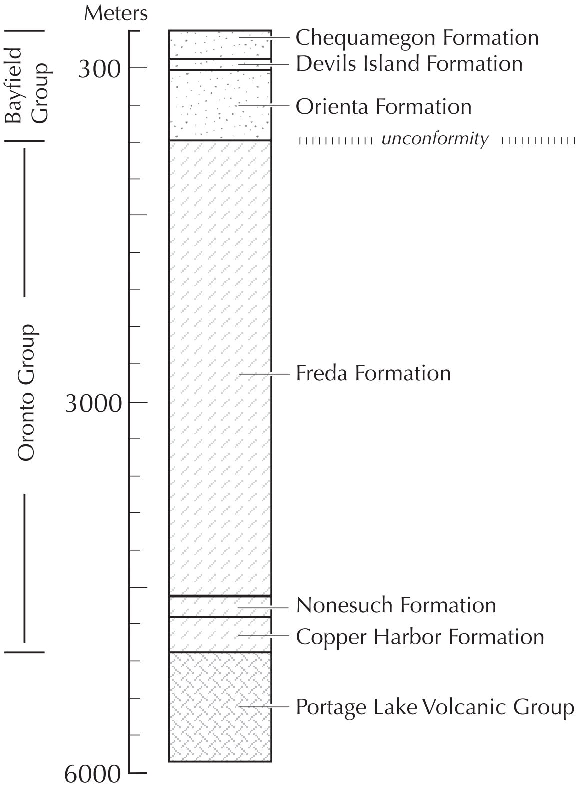

Figure 5. *General stratigraphic section in the western part of the Lake Superior Basin showing Middle Proterozoic volcanic and intrusive rock overlain by a sedimentary rock sequence (modified from Dickas and Mudrey, 1999; see Daniels, 1982, for details).*

The essential basin-forming process for the deposition of the volcanics and sediments was the crustal extension of approximately 50 km (Chase and Gilmer, 1973), which was followed by plate convergence and crustal shortening of approximately 30 km; the major component of thrusting was from the southeast. Most evidence for thrusting is found in the western half of the lake. Shortening occurred after development of rift grabens and their filling with lava flows, but before deposition of the final sag basin sedimentary rock. White Ridge, a prominent positive relief feature separating the Marquette and Allouez Basins and joining Isle Royale and the Porcupine Mountains (fig. 1), is a product of thrust faulting and crustal shortening.

Earlier work that helped to define the limits of the Midcontinent Rift included reflection seismic data acquisition and analysis and velocity determination and structure (Anzoleaga, 1971; Berry and West, 1966; Cohen and Meyer, 1966; Halls, 1969; Halls and West, 1971; Luetgert and Meyer, 1982; Mooney and others, 1970; Ocola and Meyer, 1973; Steinhart and Smith, 1966), and these studies have assisted us in interpretation of the reflection seismic data presented here.

OVERVIEW OF SEISMIC REFLECTION DATA

We have displayed the data on 15 plates and interpreted and evaluated the significance of features observed on the plates. A detailed description of rift stratigraphy is not offered here, but can be found in Dickas and Mudrey (1999). Profiles reported here provide a comprehensive reflection seismic data set that permits correlation of structure and stratigraphy of the rift beneath Lake Superior. The names of major structures used in western Lake Superior are from Mudrey and others (1990); those in the eastern half of the lake are from Cannon and others (1989).

These seismic reflection data integrate structural details throughout the Lake Superior province. Integration of information obtained on land with data reported here indicated that the rift in western Lake Superior is associated with as many as four major strike faults, including the Isle Royale Fault, an unnamed fault along a hinge line on the north flank of the basin, and two subparallel faults on the south flank of the basin referred to in the literature as the Douglas and the Keweenaw Faults (see Cannon and others, 1989). These strike faults do not cross the basin, but remain subparallel to the basin axis.

Faults were previously recognized in the Lake Superior Basin; however, White (1966) noted that the major faults cannot be interpreted as marginal normal faults as would be anticipated from a classic rifting event (also noted by Hinze and Wold, 1982). It has been shown by Mudrey and Dickas (1988), Cannon and others (1989), and Dickas and Mudrey (1997) that the Keweenaw–Lake Owen Fault and the Douglas Fault were marginal normal faults, and during a later epoch, they were reactivated to become the high-angle thrust faults now observed on land. This helps to explain the structural observations seen in the seismic data and emphasizes the complex, segmented nature of the rift as a whole (Dickas and Mudrey, 1997).

Profiles oriented along strike, such as lines LS-08 (plate 2), LS-12 (plate 4), and LS-18 (plate 6), do not display normal faulting, but do display thrust faults tangential to the basement surface. Thrust faulting is confined to a relatively short period of deformation following infilling by volcanic flows, but terminating prior to being inundated with thick blankets of sedimentary rock (Davis and Paces, 1990).

The essential difference between our interpretations and those of White (1966) is the timing of the arch or White Ridge. According to White, the feature was principally developed prior to or early in the history of midcontinental rifting; in our interpretation, the timing of such features was during the main phase of tectonism and directly related to the evolution of the region.

The rift is decidedly asymmetric west of Isle Royale. Lines LS-43 (plate 10), LS-45 (plate 11), LS-47 (plate 12), GLIMPCE line C, LS-53 (plate 13), and LS-57 (plate 14) (see fig. 1 for locations) cross the rift west of Isle Royale and collectively display a deformational history that is diagnostic of stress direction, stress change through time, and lithologic competence. From east to west, beginning with line LS-43 (plate 10), a relatively gentle sag basin is apparent; the only discernible faulting is where the line crosses the western extension of the Isle Royale Fault. A distinct change in gradient on the north flank of the basin, referred to here as the "hinge line," suggests that the line crosses the deeper rift basin at this point. Deep faulting may be present below the hinge line, but it is not seen on this section. An unusual "diapiric" structure seen also on LS-25 (plate 7) is observed just south of the basin center. This feature does not appear to be caused by bottom topography. Line LS-45 (plate 11), only 10 km west, shows the same Isle Royale Fault extension and a much more prominent hinge line near the center of the profile where the basin converts from sag to rift. Each of these two lines shows only a moderate rise to the south shore, although the flexure at the south margin of the basin is sharp.

The hinge line on the north flank of line LS-47 (plate 12), 10 km west of line LS-45 (plate 11), is well marked and is associated with a prominent series of folds and a major thrust fault, suggesting compression from the south. GLIMPCE line C lies subparallel to the rest the lines and about 5 to 10 km west of LS-47 (plate 12). The hinge line on C is also associated with thrust faulting, which Cannon and others (1989) have called an extension of the Douglas Fault. This cannot be the Douglas Fault because of the lack of evidence for it on lines LS-08 (plate 2), LS-43 (plate 10), and LS-45 (plate 11). Line C shows a deep and more narrowly confined central basin. On the south flank, the line crosses a hinge line near the shoreline and connects with data on shore. We suspect that the Douglas Fault lies beneath or shoreward of the hinge line or terminates to the east.

Line LS-53 (plate 13) crosses a very narrow valley. The broad platform on the north is adjacent to the uplift referred to by Mudrey and others (1990) as White Ridge. The northern hinge line here is well marked, and it is associated with prominent thrust faulting. The south flank is faulted as well. This profile provides the best example of an inverted basin. Line LS-57 (plate 14) is west of the western flank of White Ridge and does not show White Ridge to the east.

Strata on structural platforms on the northwest flank of the basin in the western lake, lines LS-47 (plate 12) and LS-53 (plate 13), are generally undeformed and dip gently south into a deep trough. The platform is separated from the axial basins or trough by a thrust-faulted hinge line, south of which gradients steepen to a maximum of 45°. The hinge line south of Isle Royale (LS-47, plate 12) is faulted where it separates White Ridge from a connecting trough to the south, grades to folds in the south center of the ridge, and becomes simply a gradient change to the east. The hinge line decouples White Ridge from the narrow rift basin that connects Allouez and Marquette Basins (LS-18, plate 6, and LS-25, plate 7).

On the south flank of the basin, abutting the Porcupine Mountains and east around the Keweenaw Peninsula (LS-25, plate 7), a major boundary fault and hinge line separate the deep basin on the south from steep, south-dipping reflectors. This feature may be an offshore continuation of the Douglas Fault. The feature is observed as it bends around the Keweenaw Peninsula on the profiles reported here and on the GLIMPCE lines. Cannon and others (1989) identified it on GLIMPCE line A as the Manitou Structural Zone, north of the Keweenaw Fault. It is probable that boundary faults originally developed as normal graben structures and later served to accommodate major compression. The Keweenaw and Lake Owen Faults accommodated thrusting along the decoupling zone between the sag basin platform and the less deformed lithosphere to the south; the Douglas Fault is also continuous along the rift and is subparallel to the Keweenaw Fault, decoupling the deep rift basin from the platform.

In summary, the integration of information obtained from outcrops with data reported here indicates that the rift is associated with as many as four major strike faults, including the Douglas Fault, the Keweenaw Fault, the Isle Royale Fault, and a fault along a hinge line on the north flank of the basin south of the Isle Royale Fault. The Douglas and Keweenaw Faults are subparallel strike faults bounding the rift and sag basins on the south flank of the rift graben. Strike faults and hinge lines form the rift graben boundaries.

DATA ACQUISITION AND PROCESSING

The total profile length in Lake Superior is 1,837.784 line km. Data were collected to 8 seconds, two-way travel time (TWT), which is equivalent to exploration depths of approximately 24 km, assuming mean velocity to an 8-second reflector is 6 km per second. The profiles provide comprehensive coverage of the lake in United States water. Lines are oriented along strike and across rift structure, providing the detail required for stratigraphic and structural interpretations. Data were recorded by Grant Norpac, Inc., field party 507 in June 1985.

- Recording parameters: Texas Instruments DFS V, field format SEG-B, sample interval 2 ms, record length 8 sec, navigation system LORAN C SATELLITE, field filter 8-125 HZ.
- Source parameters: 20-gun tuned air gun array, 2,968 cu in. array depth 8 m, gun pressure 2,000 PSI.
- Receiver parameters: cable SEC Century, cable length 2,975 m, cable depth 10 m.
- Geometry: shot interval 25 m, group interval 25 m, channels/record 120, near trace 200 m, far trace 3,175 m, fold 60.

- Processing sequence: demultiplex to 32 bit floating point, 4 ms sample rate, trace edit, common depth point gather 60 fold 25 m CDP, interval, spiking deconvolution 424 ms, operator length 1 percent prewhitening, velocity analysis every 128 cdp, normal moveout correction, trace mute, common depth point stack, deconvolution 144 ms, operator length 24 ms lag, filter 8-40 HZ F/K filter, trace balance, migration (finite difference).

Line numbers, total number of shot points, and length of lines are listed in table 1. Reference numbers appear along the top of each section, and generally represent kilometers. Specific shot point and location information is not reproduced with this report.

Table 1. Summary of length of seismic lines.

Line	Total number of shot points	Miles	Kilometers
LS-04	2,491	38.696	62.275
LS-08	13,713	213.023	342.829
LS-10	1,441	22.385	36.025
LS-12	5,016	77.920	125.401
LS-15	3,851	59.822	96.275
LS-18	5,391	83.745	134.775
LS-25	7,906	122.814	197.651
LS-26	5,521	85.765	138.026
LS-36	6,086	94.542	152.151
LS-43	4,201	65.260	105.026
LS-45	3,780	58.720	94.501
LS-47	4,365	67.807	109.125
LS-53	4,184	64.995	104.600
LS-57	4,396	68.289	109.901
LS-69	1,169	18.159	29.224

Description, interpretation, and discussion of individual seismic profiles

The following paragraphs describe the seismic sections shown in plates 1 to 15. Unless noted otherwise in the text, the statements listed below always refer to the migrated sections shown in the plates. Where estimates of depth are made, velocities were obtained from papers by Cannon and others (1989), Jefferson and others (1989), and Shay and Trehu (1989).

Although deeper seismic reflectors show little distortion and are clearly seen in the entire study, some difficulties in seismic interpretation persist with lake-bottom multiples and uneven bottom topography, which cause a lack of continuity of reflectors beneath these areas. These problems were also noted in the GLIMPCE study (Samson and West, 1989). Caution must be observed, therefore, when interpreting data in the upper 2 seconds. Where the bottom contains thick, soft sedimentary rock, the problem with multiples is not severe; however, most of the profiles suffer from this problem.

Line LS-04

Line LS-04 (plate 1) was shot along a northeast heading in western Lake Superior (fig. 1), crossing line LS-57 (plate 14) and terminating northeast near the terminus of line LS-53 (plate 13). The profile crosses the northern flank of the Allouez Basin where the TWT to the base of the sedimentary rock sequence reaches a maximum of 1.6 seconds. A large bedrock valley, first recognized by Wold and others (1982) and referred to here as the Wold Bedrock Valley, is evident on the western end of the profile where TWT to the contact with the base of the glacial fill reaches 1 second. The Wold Bedrock Valley can be seen at the west end of line LS-04 (plate 1) and on the north ends of lines LS-57 (plate 14), LS-53 (plate 13), GLIMPCE line C, LS-47 (plate 12), and LS-43 (plate 10). It is not evident on line LS-45 (plate 11). The trend of the bedrock valleys recognized by Wold and others (1982) is controlled by the orientation of the rift axis and depositional and structural trends in the western lake bathymetry. These trends are northeast–southwest; in the eastern lake, where the rift curves around the Keweenaw Peninsula, the trends are north–south. Glacial flow directions were controlled by Keweenawan structures; bedrock topography evolved as a consequence of lithology, structure, and ice flow.

Line LS-08

Line LS-08 (plate 2) was shot along ship heading 248°, is the longest line in the lake, and is orthogonal to and crosses seven northwest–southeast lines. Because of its nearly 343 km length and its axial orientation along the rift, and because it completely traverses three structural terranes, partially crosses two others, and links seven cross lines, line LS-08 (plate 2) is critical to the interpretation of all the Lake Superior reflection profiles. The profile is dominated by a central ridge that is flanked by two basins, features identified by Mudrey and others (1990) as the Allouez Basin on the west, the centrally located White Ridge, and the Marquette Basin on the east.

The eastern end of the profile shows prominent, subhorizontal multiples in the upper 2 seconds above west-dipping reflectors that have characteristics similar to the layered volcanic rock reported by Cannon and others (1989). The sedimentary rock section, with some volcanic flow units in its deeper part, extends to just more than 4 seconds on the western side of the Marquette Basin. The base of this unit is about 8 km deep. The volcanic section is deeper than the detection limit (greater than 24 km). The succession of lake-bottom multiples nearly obscures gentle, westward-dipping strata fanning out from a buried platform on the east into the basin. No faulting or folding is evident from the eastern end of the line to the basin center.

Reflectors representing the volcanic and sedimentary rock sections rise out of the basin to the west where they abut White Ridge. The deepest layer of flows undergoes massive thickening from the east flank of White Ridge to the east; the upper flow unit is subject to only modest thickening. The flows and deeper sedimentary rock units are abruptly truncated by a prominent erosional surface capping White Ridge and the eastern flank of the ridge. The erosional surface varies in depth across the ridge, ranging from about 2.2 seconds directly over the ridge to approximately 1 second over the east flank of the ridge where the surface has bowed upward. Several planar, en echelon, east-dipping, low-angle reflectors near the base of the deepest flow unit and tangential to its contact with basement are suggestive of fault planes, of which the western termini lie directly below the erosional unconformity at the ridge center. These apparent thrust faults do not extend into the overlying sedimentary rock units, but do underlie the upward bulge on the erosional surface mentioned earlier. Where the ridge is buried more deeply, as along line LS-12 (plate 4), 25 km to the south, faulted and folded volcanic units overlie the ridge.

Undeformed sedimentary rock strata continue uninterrupted across the ridge along line LS-08 (plate 2) and to the west without dips, folds, or faults. We believe that a long wavelength undulation in the upper second over the west flank of the Allouez Basin between locations 65 and 75 was caused by multiples produced by an uneven bedrock surface. The zone of uneven bedrock topography also coincides with the edge of a submerged basement platform, from which the deep volcanic basin plunges abruptly to the east. Minor thickening is noticeable in the deepest part of the Allouez Basin, an almost perfectly symmetrical sag. The Allouez Basin, including sedimentation and volcanic flows, is shallower than in the Marquette Basin to the east. The Allouez Basin displays far fewer prominent reflectors in either its sedimentary rock or its volcanic sections, suggesting more uniform, passive subsidence and deposition than in the Marquette Basin. The volcanic fill in the Allouez Basin extends to depths of approximately 21 km.

A cover of sedimentary rock thins to a feather edge toward the lakeshore near Duluth, coinciding with line LS-08 (plate 2) and crossing line LS-69 (plate 15). There are no reflectors that can be identified below the basement surface on the western platform. An easterly dipping reflector, beginning between 3 and 4 seconds near the shore, is not associated with any known geologic feature on shore.

From the seismic profiles orthogonal to line LS-08 (plate 2), it appears that the two basins are connected by a trough bending around the southern nose of White Ridge, north of the Porcupine Mountains. White Ridge is a broad arcuate volcanic nose, curving between the two basins southwestward from Isle Royale.

Line LS-10

Line LS-10 (plate 3) was shot along a northeast line parallel to lines LS-04 (plate 1) and LS-08 (plate 2) in the western end of the lake, parallel to the Bayfield Peninsula shore. Line LS-10 crosses the eastern end of line LS-69 (plate 15). Sedimentary rock extends to TWT of 1.6 seconds along the profile. Basement is flat and no structural features are evident in the sedimentary rock, which is probably representative of the Bayfield Group found onshore to the south. The sedimentary rock section is directly underlain by a chaotic pattern of reflectors that resemble more the Archean than layered Keweenawan volcanic rock.

LINE LS-12

Line LS-12 (plate 4), shot along ship heading 65°, essentially parallels line LS-08 (plate 2) and traverses deeper parts of the Allouez and Marquette Basins and White Ridge. A marked monoclinal fold or thrust fault having displacement of nearly 0.5 seconds is present on the crest of White Ridge. The fold is near where line LS-12 (plate 4) crosses line C of the GLIMPCE study (Cannon and others, 1989). Converted to depth, vertical displacement on the monocline is approximately 1 km. Deformed features are below about 2 seconds; the flat-lying sedimentary rock of the Bayfield and Oronto Groups is above. This feature was not observed on line LS-08 (plate 2). Lake-bottom multiples distort the stratification detail down to about 2 seconds over the disturbed zone; however, it is possible to "see through" the multiples to the true, lower amplitude reflectors in the background. A prominent bedrock valley 10 km east of the monocline–thrust fault may represent a near-surface zone of weakness due to deep-seated thrust faulting.

LINE LS-15

Line LS-15 (plate 5), eastern Lake Superior, was shot along azimuth 336°. The line, which crosses line F of the GLIMPCE study (Cannon and others, 1989), is entirely contained in an intrabasin terrane. The sedimentary rock section extends to about 3 seconds. Areas of steeply dipping strata and at least four major faults displace the upper sedimentary rock section above 3 seconds and the deeper volcanic units. The major displacement along the profile is associated with south-dipping reflectors and bow-tie diffraction patterns in the central part of the section. Faulting may extend from the lake bottom and increase in amplitude of displacement to the deepest observed reflectors, suggesting diminishing, but persistent deformation over a long time period.

LINE LS-18

Line LS-18 (plate 6), along the southwestern lakeshore along the Keweenaw Peninsula, was shot along azimuth 65°. The line roughly parallels the shore from near Ashland, Wisconsin, to Houghton, Michigan. Three structural elements are evident: an eastern basin with sedimentary rock extending to about 3 seconds, a ridge just west of center with a west-facing fault or displacement scarp with volcanic flows having more than 2 seconds displacement dropping to the west, and a western basin extending to just more than 3 seconds. The scarp between the western basin and ridge is a major, high-angle fault that originated as a normal, extensional feature, but in its later stages was converted into a thrust fault.

The thickening of strata from east to west, in the sedimentary rock section and in the volcanic basin, suggests that the two basins were at one time joined and that the thrust fault occurred near the end of volcanism and after much of the period of sedimentation near the former center of the basin, culminating in an inverted basin. The scarp is immediately east of the intersection of lines LS-18 (plate 6) and LS-57 (plate 14). The eastern margin of the ridge is near the intersection of line LS-18 (plate 6) with line LS-53 (plate 13). The ridge is not continuous with White Ridge, across the rift graben to the north; however, the juxtaposition of the Porcupine Mountains and White Ridge on opposite sides of the rift basin suggests a possible relationship. The narrowing of the rift basin, the uplift of the Porcupine Mountains, repetitive folds seen on several lines crossing the ridge, and the apparent fault-block uplift of White Ridge may reflect late stage convergence following the main rifting event.

The deepest strata of the eastern basin, including volcanic and overlying sedimentary rock, rise up to the ridge; upper units terminate along a horizontal unconformity, where they are overlain by flat-lying sedimentary rock on the east flank of the ridge. Strata beneath the crest of the ridge are folded and deformed below the unconformity; above the unconformity, the sedimentary rock appears to be flat lying and relatively undisturbed, although minor displacement of sub-lake bottom sedimentary rock suggests that faulting continued until late in the history of the development of the structure. The line does not extend far enough west to cross the northward extension of the Douglas Fault as proposed by Cannon and others (1989).

LINE LS-25

Line LS-25 (plate 7), shot along azimuth 156°, ties seismic lines in the eastern half of Lake Superior with those in the west. The line crosses lines LS-08 (plate 2), LS-26 (plate 8), LS-36 (plate 9), and GLIMPCE line A (Cannon and others, 1989). Line LS-25 traverses two major structures, a broad basin and the approach to its north flank in the center and north of the line, and a broad platform on the south. These features are abruptly truncated near the Keweenaw Peninsula by a steeply dipping zone approximately 25 km wide bounded by two faults, one on the basin side and one on the platform side. The fault on the platform side is the extension of the Keweenaw Fault as plotted by Cannon and others (1989).

Dips south of the basin fault are reversed from those in the broad basin, rising to the south and then flattening south of the Keweenaw Fault onto a platform where the line terminates between Marquette and Munising, Michigan. The quality of the shallow reflectors in the southern third of the profile, from the southern basin platform margin to the southern limits of the line, is diminished by large amplitude lake-bottom multiples. In addition, this line is the lake bottom, which is rough and tends to obliterate or at least diminish reflection quality in the upper part of the section.

A diapiric-appearing feature located near reference number 90, which is similar to that observed on line LS-43 (plate 10), at the south basin margin near the basin fault, may be an artifact caused by uneven bottom topography. A similar diapiric structure on GLIMPCE line A was noted by Cannon and others (1989), who interpreted it as the Manitou Structural Zone. We suggest that the Manitou Structural Zone is an eastward continuation of the Douglas Fault from Bayfield Peninsula and trends along the shoreline. The Douglas Fault, therefore, does not cross the lake as a continuation of the Isle Royale Fault, but is a south shore feature.

LINE LS-26

Line LS-26 (plate 8), in the eastern part of the lake and shot along azimuth 246°, extends from the southern platform at the southern end of line LS-25 (plate 7) to the northeast. Line LS-26 crosses lines LS-25 (plate 7) and LS-15 (plate 5) of this study and GLIMPCE lines A and F (Cannon and others, 1989). A basin fault and a shelf fault are again evident; however, the basin fault is not as well pronounced as it is in the profiles to the west and is marked more by an abrupt change in gradient from the basin to the basin flank. A bedrock valley is again evident over the basin fault, suggesting that deformation continued until late stages of basin formation. This fault probably developed in response to a later period of deformation associated with thrusting and convergence rather than rifting and basin growth. Strata between the two faults drop abruptly from the platform to a deep basin. A continuous reflector can be followed from the platform to the basin with the an increase in depth of nearly 4 seconds TWT, roughly equivalent to a deepening of 8 km over a distance of approximately 30 km.

LINE LS-36

Line LS-36 (plate 9), which was shot in the eastern lake along azimuth 66°, begins near Marquette and terminates at the point farthest east of all the Lake Superior profiles, northwest of Whitefish Point, Michigan. Very rough lake-bottom topography on the western half of the profile diminishes the quality of near-surface reflectors. The line begins on a structural platform on the southwest. Strata descend steeply into a basin after crossing two boundary faults, rise gently to the east where the line crosses a broad anticline, and then descend again into an unnamed basin. Major faulting decoupled the unnamed basin from the central anticline. The faults on the west from the basin are thought to be the southeast extensions of the Keweenaw Fault and Manitou Structural Zone.

Line LS-43

Line LS-43 (plate 10) was shot along azimuth 156°; it was the first of five lines crossing the axis of the rift west of Isle Royale. These lines are subparallel to GLIMPCE line C and display grossly similar (but subtly different) structural characteristics because of their traversing of White Ridge along different sections of its protrusion into the Allouez and Marquette Basins and the trough joining the basins. The line begins on the north, near the Minnesota–Ontario boundary, where reflectors are dipping from the lake bottom into the subsurface offshore. A near-shore bedrock valley is 0.3 seconds below lake bottom. The lake bottom rises from the north shore to a ridge that we interpret to be a westward extension of the Isle Royale Fault. Deeper reflectors dip offshore; they show a marked change in gradient and increase in southerly dip south of the Isle Royale Fault. Strata descend steeply into the Marquette Basin, crossing a hinge line and further steepening in dip until the bottom of the sedimentary basin flattens out south of the lines crossing line LS-12 (plate 4). The deepest part of the sedimentary basin reaches about 3.5 seconds, where it then rises gently to the south before crossing line LS-18 (plate 6). The sedimentary basin floor begins to rise more steeply about 8 km from the south end of the line. Strong bottom multiples that obscure much of the shallow section are present across the entire profile.

Below the sedimentary rock section, volcanic flow units thicken into a fan shape from the north and south flanks of the basin. The volcanic center of the basin is approximately 5 km south of the sedimentary basin center. An argument cannot be made for major thrust faulting anywhere along the profile, except beneath the lake-bottom feature, which may be a westward extension of the Isle Royale Fault.

Line LS-45

Line LS-45 (plate 11) was shot along azimuth 335°, 10 km west of line LS-43 (plate 10). The section is similar to line LS-43 (plate 10), with a faulted, lake-bottom structure in line with a projected Isle Royale Fault, a hinge line (from which flows can be inferred dipping into a deep basin where line LS-45 [plate 11] crosses line LS-12 [plate 4]), and a gentle rise on the far south end of the line. South of the Isle Royale Fault, flat-lying strata overlie a marked angular unconformity, below which layers associated with strong reflectors dip uniformly to the south. Large-scale faulting cannot be identified beneath the hinge line. A possible diapiric structure is near the south end of the line. Much of the overlying sedimentary rock section south of the hinge line is obscured by large amplitude multiples down to about 2 seconds. The floor of the sedimentary basin is observed at about 3.4 seconds.

LINE LS-47

Line LS-47 (plate 12), shot along azimuth 156°, displays at the north end of the line southward-dipping reflectors that are probably caused by volcanic flows. The flows subcrop on the north, near a lake-bottom discontinuity that may be the western extension of the Isle Royale Fault. The flows dip uniformly south to a hinge line at the crossing of line LS-12 (plate 4). A prominent series of folds and a thrust fault above the hinge line suggest deformation in the sedimentary rock section resulting from thrusting from the south. Folding can be observed between lines LS-12 (plate 4) and LS-08 (plate 2), the amplitude of the folds diminishing northward. Only the deeper, older units of the sedimentary rock section are involved in the folding, although faulting may extend upward to the lake bottom. The basin above the present keel south of the hinge line contains sedimentary rock units down to about 3.5 seconds. The sedimentary rock section south of the hinge line dips gently and uniformly southward, although high amplitude multiples generated at the lake bottom tend to obscure the subsurface section. Flows beneath the basin are recognizable down to about 7 seconds and are perhaps 10 km thick at their deepest point in the basin. The overlying sedimentary rock section is 6 to 7 km thick.

LINE LS-53

Line LS-53 (plate 13) was shot along azimuth 155°. In relation to its parallel counterparts to the east and west, it has a broad platform on the north and a narrow, confined volcanic rock-filled basin to the south. Reflection quality on the northern shelf is poor, but volcanic reflectors can be seen dipping uniformly to the south from a shallow subcrop and possible near-shore faulting beneath the lake. Dipping strata on the north are presumably the North Shore Volcanic Group, which underlie more gently dipping units of relatively high reflectivity. A major unconformity is seen between the steeply dipping North Shore Volcanic Group and the overlying, more gently dipping reflectors that fail to reach the north shore.

The profile crosses a marked hinge line and major fault near the crossing with line LS-12 (plate 4), where gradients steepen markedly. A broad swale or synclinal fold in the sedimentary rock lies immediately north of the fault. The basin rises steeply to the south shore, where it abuts the northeast end of the Porcupine Mountains.

High-angle thrust faulting is evident in the section about 5 km north of the crossing with line LS-12 (plate 4). Flows are thrust northward, approximately 7 km over younger sedimentary rock. Some disturbance is also evident in the upper part of the section on the south end of the line in the deepest part of the basin. However, these are primarily diffractions due to bedrock roughness or irregularities because gently dipping strata can be seen continuing through, but reversing dip beneath the disturbance.

This line is perhaps the best example of basin inversion, involving a narrow, normal fault-bounded, asymmetric graben followed by major thrusting on its north flank. The basin on this line is part of a narrow connection, only 35 km wide, between the Allouez Basin on the west and the Marquette Basin on the east.

LINE LS-57

Line LS-57 (plate 14), shot along azimuth 156° 25 km southwest of line LS-53 (plate 13), contains structures different from those shown in line LS-53 (plate 13). A bedrock valley, 3 km from the north end of the line, overlies what may be a minor thrust fault. Reflectors dip gradually into a deep basin, with the sedimentary rock section extending to about 2.3 seconds and the volcanic flows to about 7 seconds. The basin along line LS-57 (plate 14) is much broader and more flat bottomed than it is along the lines to the east, and reflectors dip from the north more gently into the basin with no apparent hinge line. The keel of the basin is near the crossings of lines LS-57 (plate 14) and LS-12 (plate 4). The floor of the basin, near its southern flank, rises in three great steps to the southern shore near the southern Porcupine Mountains. The first riser emerges from the keel of the basin to a short, dipping step to a second riser and broad, flat-bottomed step. The second step ends abruptly at a major boundary fault approximately 10 km offshore, with volcanic units downdropped to the north about 6 km. Reflectors continue to rise at the south end of the line, which is approximately 2 km off shore. The differences between this line and those to the east suggest that line LS-57 (plate 14) is in a new structural domain.

LINE LS-69

Line LS-69 (plate 15) was shot along azimuth 335° at the western end of the lake. The most prominent feature on this short line is a near-surface (sub-lake bottom), filled valley that probably corresponds with the bedrock valley described by Wold and others (1982). The southern end of the line displays evidence of strata dipping into the west end of the Allouez Basin.

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