

Rift structure beneath the Michigan Basin from COCORP profiling

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ABSTRACT

COCORP (Consortium for Continental Reflection Profiling) surveys across the mid-Michigan gravity anomaly, near the McClure-Sparks No. 1 deep well, delineate a thick layered sequence of relatively strong reflectors that define a structural trough within the Precambrian beneath the Michigan Basin. These deep reflections, which correlate spatially with the mid-Michigan gravity and magnetic high, are interpreted to be a pile of basaltic extrusive rocks intercalated with clastic rocks and correlative with Keweenaw volcanics exposed in the Lake Superior region to the northwest. A reflection-poor zone between the base of the Paleozoic, as found in the deep well, and the top of the deep layered sequence probably corresponds to the upper Keweenaw clastic assemblage. Direct evidence of faulting within the inferred volcanic sequence is lacking, although sharp flexures, structural benches, and dips of as much as 10° suggest subsidence controlled by fault-block motions. Reflections from beneath the inferred volcanic pile are rare, the deepest clear event being at about 18 km. There is no unequivocal evidence on these sections to indicate whether Precambrian structures were reactivated to affect the overlying Paleozoic strata of the Michigan Basin proper, although data quality may be insufficient to detect such effects.

INTRODUCTION

The Michigan Basin is the classic intracratonic basin. It began to take on its present form as a remarkably circular structural depression (Fig. 1A) in Middle to Late Ordovician time, although an embryonic basin was present as early as Late Cambrian (Catacosinos, 1973). As it has been an area of active oil and gas exploration and production (see, for example, Landes, 1970), its geologic history is well documented. However, the

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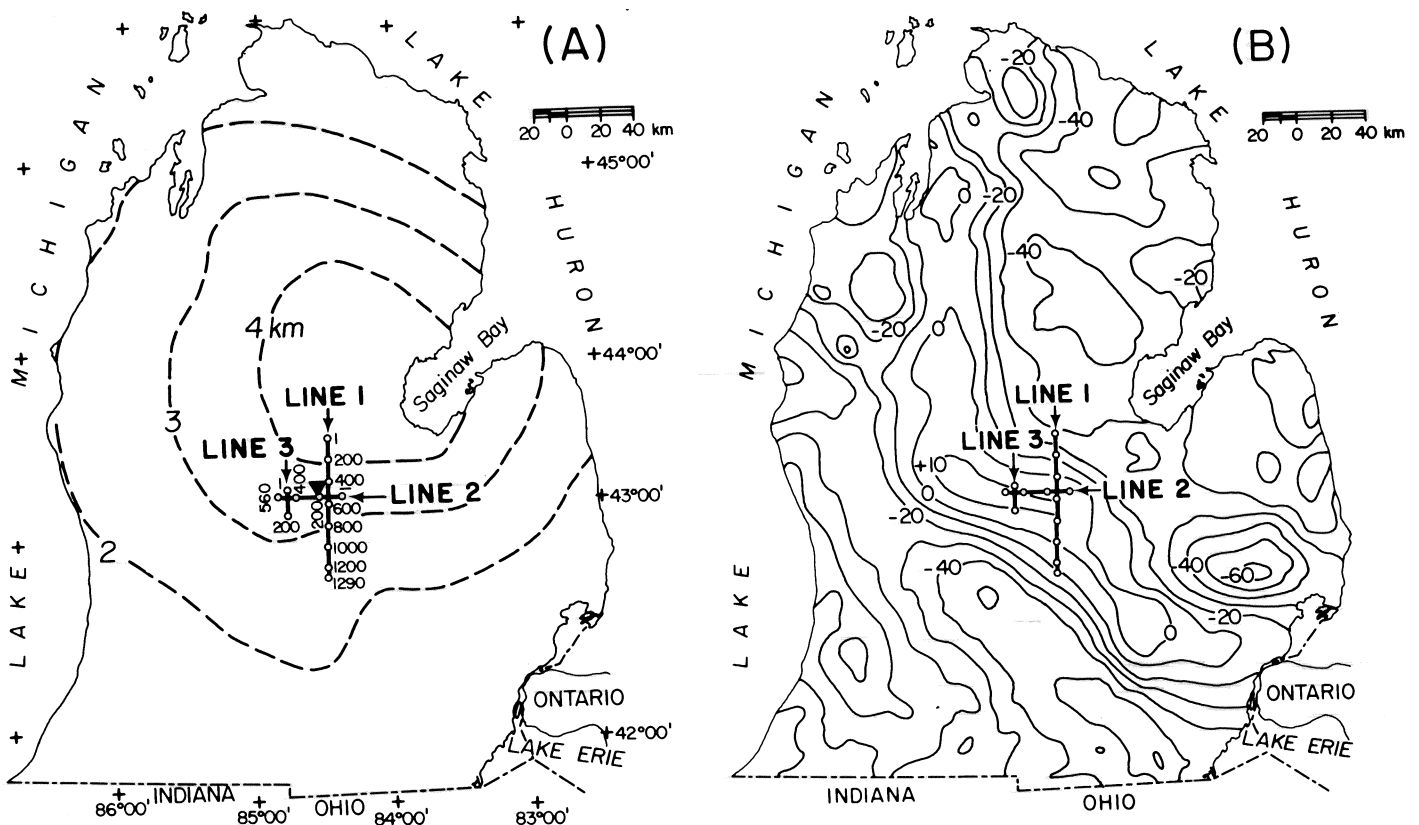


Figure 1. (A) Depth to basement, in kilometres (after Sleep and Sloss, 1978) within Michigan Basin, with location of COCORP seismic lines 1, 2, and 3. Numbers refer to vibration points (VPs). Inverted triangle indicates location of McClure-Sparks deep well. (B) Location of COCORP lines relative to mid-Michigan gravity anomaly. Bouguer gravity anomaly contours in milligals from Hinze and others (1971).

underlying cause of subsidence is still a matter of considerable speculation. Various models have been proposed, including such processes as lithospheric heating and subsequent cooling, lower crustal phase changes, and diapiric injections into the lithosphere (Sleep and Snell, 1976; Haxby and others, 1976; Falvey, 1974), but geologic and geophysical evidence fail to discriminate the dominant mechanisms.

Cutting across the Michigan Basin from northwest to southeast is a major gravity anomaly with central highs of more than 10 mgal and flanking lows of as much as -60 mgal (Hinze and others, 1975; Fig. 1B). This linear belt, with an associated, albeit less well-defined magnetic high, has been interpreted as representing a buried rift, correlative with the Midcontinent Geophysical Anomaly (also referred to as the Midcontinent Gravity High) which extends from Lake Superior to Kansas (Chase and

Gilmer, 1973). Rocks associated with the Midcontinent Geophysical Anomaly are exposed in the Lake Superior region as the Keweenaw volcanic assemblage (Halls, 1966). A deep well—McClure Oil Company's Sparks, Eckelberger, and Whightsil No. 1-8 in the central part of the Michigan Basin (Fig. 1A)—encountered Precambrian redbeds and basic igneous rocks that are interpreted to correlate with the Keweenaw sequence (Sleep and Sloss, 1978).

In the fall of 1978, COCORP ran three deep Vibroseis (trademark of Continental Oil Company) surveys in the central part of the Michigan Basin near the McClure-Sparks well (Fig. 1A). Acquisition and processing, carried out by Petty-Ray Geophysical, was similar to that described by Schilt and others (1979).

Although the quality of the seismic data in the Michigan Basin is poorer than that obtained by COCORP in other areas, the

surveys clearly delineate a remarkable sequence of sub-basin reflections. In the discussion here these reflections are correlated with and interpreted in terms of the Keweenaw rift sequence—a massive pile of volcanic and clastic sedimentary rocks marking an aborted breakup of the central North American craton in the late Precambrian.

RESULTS

Interpretative line drawings of the original unmigrated seismic sections from lines 1, 2, and 3 are shown in Figure 2. Part of the seismic section for line 2 is shown in Figure 3. Reflection dips are sufficiently gentle that migration is not critical to the following interpretations. The vertical and horizontal scales were chosen to minimize exaggeration in the deeper parts of the seismic section—that is, at times greater than about 2 s, corresponding to average velocities of about 6 km/s (Fig. 4). Note that interval velocities calculated from Figure 4 are too poorly constrained to allow meaningful comparison with the measurements of Wang and Simmons (1978) on gabbroic samples recovered from the deep well.

Although numerous reflections can be identified in the upper 5 s on these lines, they are generally weak (Fig. 3). Even the shallow, flat sedimentary reflectors of the Paleozoic sequence are not particularly strong. Oil-exploration experience suggests that many parts of the Michigan Basin are "poor" data areas, due in large part to static problems related to glacial till (see, for example, Caughlin and others, 1976). Although reflection strength is poor, continuity is generally sufficient to identify principal structures and sequences. Efforts to further enhance these data with specialized processing have been made by several groups, including commercial exploration firms; however, they are unlikely to change the major aspects of the preliminary interpretation presented here.

The upper 1.5 s on all three lines is dominated by a flat-lying sequence of reflections showing little or no structural disruption (Fig. 2). Velocity estimates (Fig. 4) suggest that this sequence is 3.8 km thick. These reflections dip slightly (less than 2°) northward toward the center of the basin. Below 1.5 s and above 3 s, reflec-

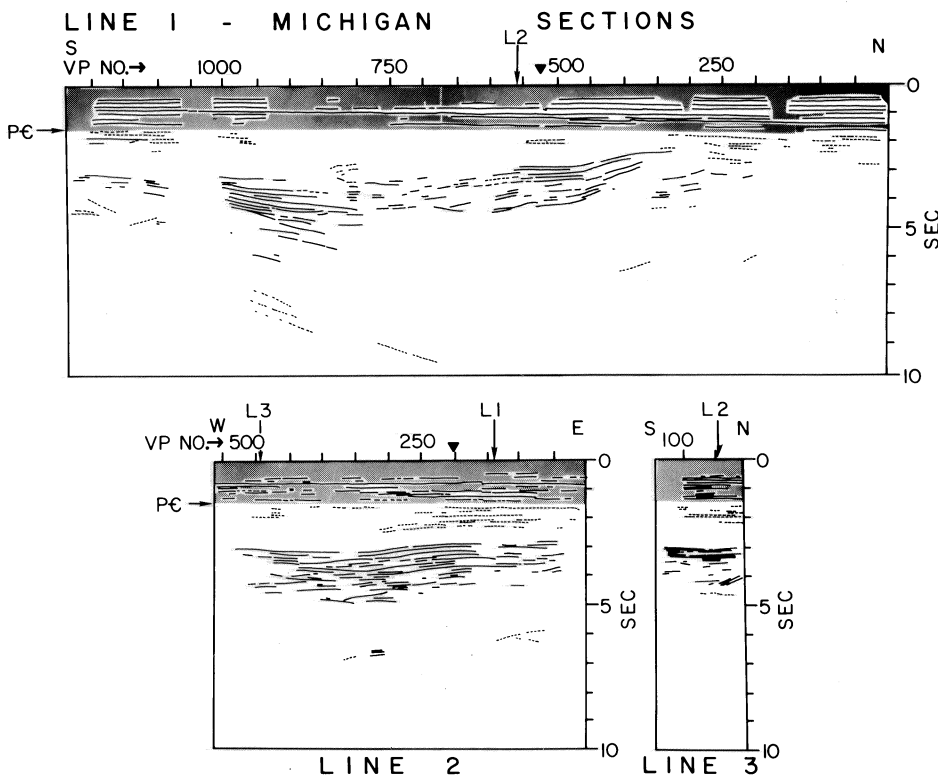
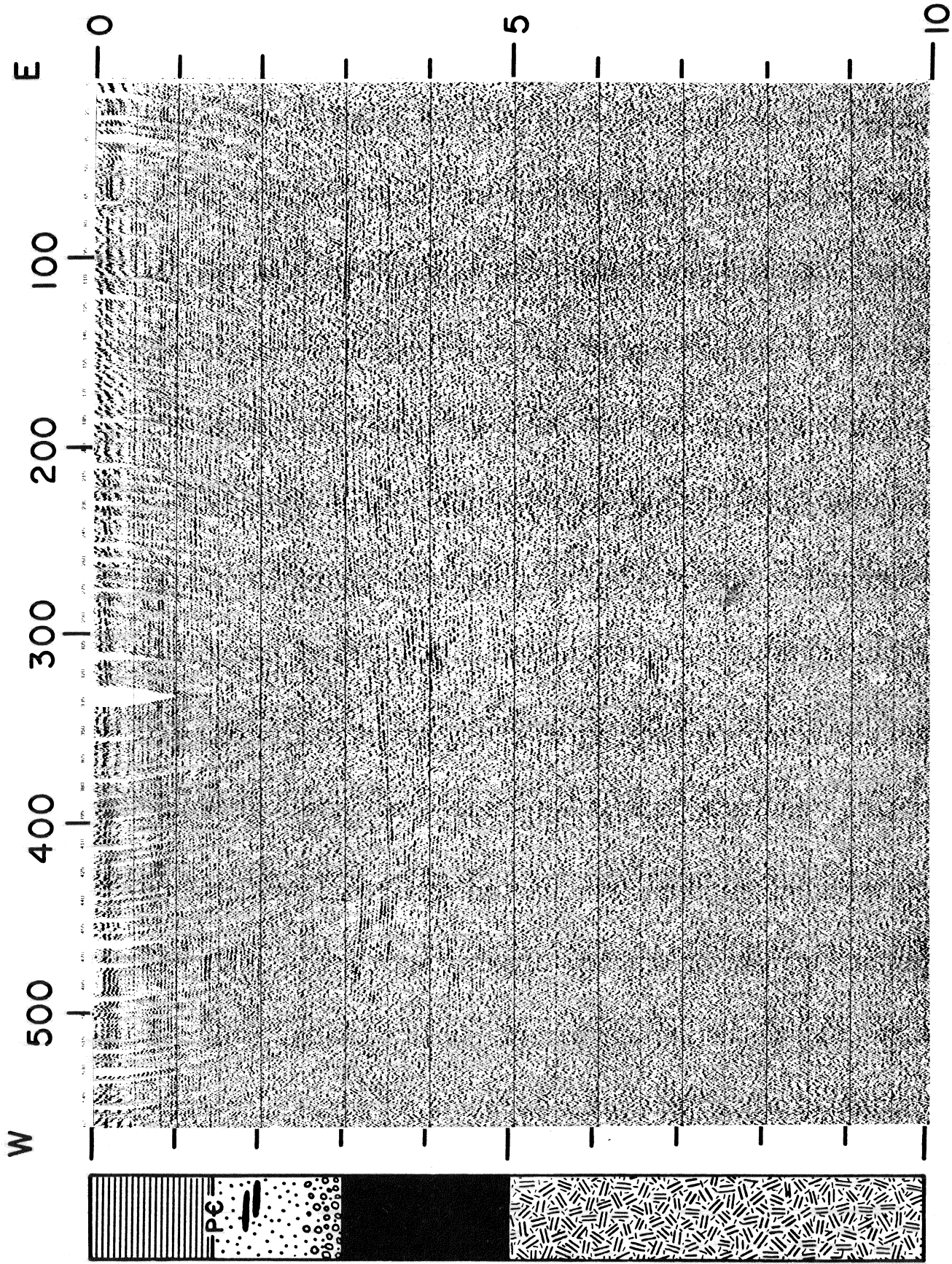


Figure 2. Line drawings of COCORP Michigan lines 1, 2, and 3. Vertical scale is two-way travel time. Horizontal scale corresponds to distance along profile; numbers refer to VPs spaced 64 m apart. Inverted triangle marks location of McClure-Sparks deep borehole. Shaded area represents Paleozoic sedimentary section of Michigan Basin.

Figure 3. Part of Michigan seismic line 2. Correlative stratigraphic section, as interpreted in this paper, is shown on left. Ruled pattern = Phanerozoic section; stipple = upper Keweenaw sandstone; irregular circles = upper Keweenaw sandstone, shale, and conglomerate; black = middle Keweenaw volcanic and clastic rocks. Identity of lowermost unit is debatable; it could be pre-Keweenaw basement (about 1.6 b.y. old) or mafic (oceanic or transitional?) crust emplaced by rifting.

MICHIGAN LINE 2



SECS

E

5

10

100

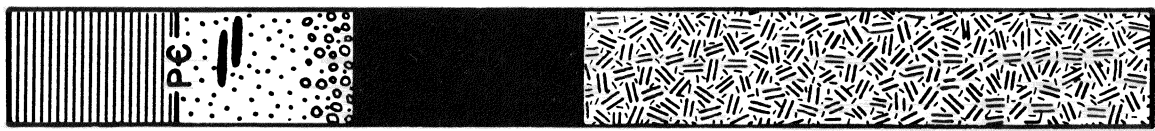
200

300

400

500

W



tions are still relatively flat but become fewer and less continuous with depth. Since most of the reflections in this band conform to the overlying strata, some may be seismic multiples generated by shallower reflectors.

Beginning at about 3 s (8.3 km) is a series of relatively pronounced reflections extending to times of 5 s (13.8 km) or more. Although flat-lying in places, these events are generally discordant with the overlying section and thus cannot be multiples generated within it. As can be seen from line 1 (Fig. 2), these events appear to define a basinlike structure with well-defined flanks. Its northern flank is delineated by south-dipping reflections that appear to begin at about VP (vibration point) 260. Whether the deeper events between 3 and 4 s beneath VPs 250 to 270 also belong to the same sequence is not clear. The south flank of this basin is represented by the north-dipping events between VPs 800 and 1000. Farther south this sequence becomes more difficult to trace, but the reflection at 3 s at the south end of line 1 suggests that it extends at least that far. As represented on the seismic section, the basin is asymmetric—deeper to the south—with the entire sequence suggesting a southward-tilted crustal block. Reflections from the central part of the basin (VPs 600 to 800) are weaker and less continuous than those on the flanks. Line

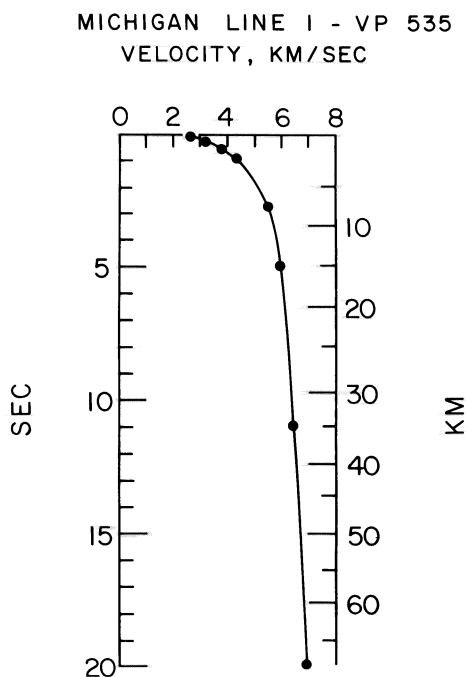


Figure 4. Stacking velocity–depth function determined for central part of line 1, used to convert travel time to approximate depth. Lateral variations from this function were minor. This velocity estimate is poorly constrained below about 4 s.

2, perpendicular to line 1, traces the same reflections westward, apparently along strike (Fig. 3). Although the deep layered sequence is also evident on line 3, this line is too short to further constrain its overall shape.

The monoclinical flexure in the deep reflector sequence beneath VP 450 on line 1 suggests that subsidence was controlled at least in part by fault-block motions. Reflections in the sequence between VPs 450 and 550 seem to delineate a structural bench with flat reflectors perched at shallower depths than presumably correlative reflectors on the southern flank. Specific correlation of the northern and southern flank reflectors is virtually impossible because of lack of continuity in the intervening basin.

Reflections at times greater than about 5 s are very few, and those that do exist are weak. Furthermore, many of these tenuous deep events may be multiples generated in either the upper or lower layered sequences. The most substantial of the deeper reflections occurs at 6.5 s beneath VP 320 on line 2 (Figs. 2, 3). It is a short layered segment that seems to have no unequivocal counterpart on lines 1 or 3. Although 20 s of data were recorded, deeper events—for example, from Moho depths—are absent on the seismic sections. This absence of very deep reflections may be due to a corresponding lack of appropriate deep reflecting interfaces or, more likely, insufficient coherent energy penetration through the overlying crust.

INTERPRETATION

Interpretation of these seismic lines centers upon proper identification of the three main “stratigraphic” sequences defined by the reflection patterns: the upper (less than 1.5 s) layered unit, the middle (1.5–3.0 s) reflection-poor zone, and the lower (3.0–5.0 s) layered unit. An important guide to this identification is provided by the nearby deep well (McClure-Sparks No. 1) that penetrated 3.8 km of Paleozoic section and 1.4 km of underlying Precambrian rocks (Sleep and Sloss, 1978).

Although the stratigraphy of the Paleozoic rocks in the Michigan Basin attracts most of the economic interest, scientific attention has also focused on the nature of the rocks that underlie the Phanerozoic section. The upper layered sequence on the COCORP seismic sections (shaded in Fig. 2) clearly corresponds to the Paleozoic strata of the Michigan Basin proper and its underlying Cambrian-Ordovician sequence. According to the velocities shown in Figure 4 and the corresponding stratigraphy encountered in the McClure-Sparks well,

the base of the Cambrian Mt. Simon Sandstone corresponds to a time of about 1.5 s. This time also matches the transition from the upper, layered seismic sequence and the underlying reflection-poor zone.

Below the Cambrian the drill encountered recurring beds of sandstone grading upward into mudstone, similar to the red beds that were encountered by drilling on Beaver Island, 260 km to the north along the mid-Michigan gravity high (Fowler and Kuenzi, 1978). Within the red-bed sequence two mafic sills (either metabasalt or metagabbro) were intersected, one at 4.8 km and the other at 5.3 km where the hole bottomed (McCallister and others, 1978). These pre-Mt. Simon sedimentary rocks were interpreted by Fowler and Kuenzi (1978) as turbidites overlying the Jacobsville Formation, the latter being part of the upper Keweenawan clastic sequence. However, Catacosinos (1981) interpreted these same samples as time equivalents of the Freda Sandstone that underlies the Jacobsville Formation. The thickness of upper Keweenawan clastic rock has been estimated to be as much as 9 km (or 3 s; Halls, 1966), more than enough to account for the 1-s-thick middle sequence on the seismic section for this area. Reflections within this intermediate zone become fewer as one goes deeper. This seismic character change, if not an artifact of decreasing multiple strength or processing, may correspond to the transition from well-layered upper clastic units—whether the turbidites of Fowler and Kuenzi, the quartzose sandstones of the Jacobsville Formation, or the arkosic Freda Sandstone—to the interbedded arkoses, conglomerates, and subordinate volcanics and shales of the underlying Copper Harbor and Nonesuch Formations (Fowler and Kuenzi, 1978). On the basis of bedding regularity, the upper sandstones might be expected to form more effective reflectors than the conglomerates.

The middle Keweenawan rocks of the Lake Superior region consist of a thick (6–9 km) sequence of deformed volcanics and subordinate interstratified conglomerates and arkosic sandstones (Halls, 1966). The layered sequence filling the deep trough on the COCORP sections is most easily interpreted as an equivalent volcanic pile. Its thickness (2 s or 6 km between VPs 400 and 1000) is comparable to the exposed sections to the north. The deep basin as delimited on line 1 correlates remarkably well with the central part of the mid-Michigan gravity anomaly (Figs. 1B and 2), just as the Keweenawan volcanics lie along the Midcontinent Geophysical Anomaly. Furthermore, the gravity high

itself is consistent with a structural trough of the dimensions suggested by the seismic data, the volcanics serving as a density excess (Hinze and others, 1975). Contacts between the volcanic rocks and the inter-fingered clastic rocks should provide excellent acoustic contrasts for generating the relatively strong reflections evident on the seismic sections. Furthermore, extensive volcanic flows may be expected to exhibit the relatively good continuity seen on the flanks of the trough, assuming minimal post-eruptive faulting. Fowler and Kuenzi (1978) postulated that inter-fingered clastic and volcanic rocks would occur primarily on the flanks of the central rift structure, again consistent with the more pronounced reflections on the flanks. Lack of reflector continuity in the central part of the trough could be attributed to disruption by volcanic feeders penetrating upward in the central graben, more intensive graben faulting, or more uniform lithology lacking the requisite acoustic contrasts. The flexure on the north flank and the associated structural bench suggest high-angle block faulting (for example, Brown and others, 1980), although unequivocal fault offsets in the layered sequence itself are difficult to identify. There is no clear correlation on the COCORP seismic sections between Keweenawan structures and features in the overlying Paleozoic strata; however, data quality is too poor to rule out the possibility that small offsets in the lower Paleozoic section may be related to offsets or down-warps in the underlying rift.

Very little can be said about the identity of the isolated event at 6.5 s (20 km) of line 2. It may or may not be related to the overlying rift-fill units, and it could be due to any of several geologic structures, such as a small mafic intrusion, a "tuned" layer segment, focused energy from a small fold, or even fortuitous imaging conditions. The nature of the crust beneath the layered basement reflections is also uncertain. It could be pre-Keweenawan continental basement or, if rifting had proceeded as far as envisioned by Fowler and Kuenzi (1978), mafic material representing transition to oceanic crust.

If the lithostratigraphic identifications outlined above and shown in Figure 3 are correct, the upper Keweenawan clastic sequences would appear to be substantially more extensive than the underlying middle Keweenawan volcanics. This relationship fits well with the evolutionary model proposed by Fowler and Kuenzi (1978) in which volcanics are deposited in an initially narrow rift valley and are later covered by more extensive fluvial and marine deposits when the incipient rift fails and founders.

SUMMARY AND CONCLUSIONS

Reflectors beneath the Paleozoic sedimentary rocks of the central Michigan Basin most likely correspond to Keweenawan clastic and volcanic rock deposited in and over a late Precambrian rift. The seismic section defines at least two distinct Precambrian units: an upper, more poorly layered, zone of considerable extent, probably consisting of upper Keweenawan clastics (red-bed sandstones grading down into conglomerates) and a lower sequence of strong, layered reflections most likely composed of lower Keweenawan volcanics interbedded with clastics. This lower volcanic sequence appears to fill and define a narrow (60 km) trough that correlates spatially with the mid-Michigan gravity high. The gravity high is consistent with dense mafic rocks filling the trough defined by the seismic section. Sharp flexures, structural benches, and relatively steep dips in the volcanic layering suggest that subsidence was controlled by fault-block motions consistent with horst and graben tectonics.

There is no unequivocal evidence on these sections that Precambrian structure was reactivated to deform the overlying Paleozoic strata, but poor data quality may be obscuring such relationships. Lower crustal and Moho reflections were not observed. In spite of these new details of Precambrian structure, the fundamental problem of the Michigan Basin itself—what caused it to subside more than 600 m.y. after activity in the underlying rift presumably ceased—remains unresolved. However, these initial surveys are relatively short compared with the dimensions of the basin; it may be that even longer deep seismic traverses must be completed before the appropriate structures come into focus.

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