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THE MIDCONTINENT RIFT SYSTEM

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1. INTRODUCTION

One of the most prominent features on gravity and aeromagnetic maps of the United States is a series of major, generally linear anomalies that extend from central Kansas to Lake Superior and then turn southward into central Michigan (Figures 1, 2). This system of anomalies clearly reflects major geological features, and as such it must represent a very significant episode in the history of the North American continental lithosphere. The geologic features associated with these anomalies, particularly axial basins filled with basalt and immature clastic rocks along with evidence of crustal extension, indicate that the episode was probably one of incipient rifting.

Terminology

The features discussed in this review have been referred to by a variety of names, both descriptive and genetic. The major feature, which extends from central Kansas to Lake Superior (Figure 1), was originally recognized about 40 years ago as a major positive gravity anomaly and has been referred to as the "midcontinent gravity high" or the "midcontinent gravity anomaly." Subsequent aeromagnetic studies have shown that the designation "midcontinent geophysical anomaly" (or MGA) is more appropriate, and we follow this usage here, with the restriction that it only applies to the segment from Kansas to Lake Superior. Other segments or proposed extensions are referred to individually (e.g. Lake Superior basin,

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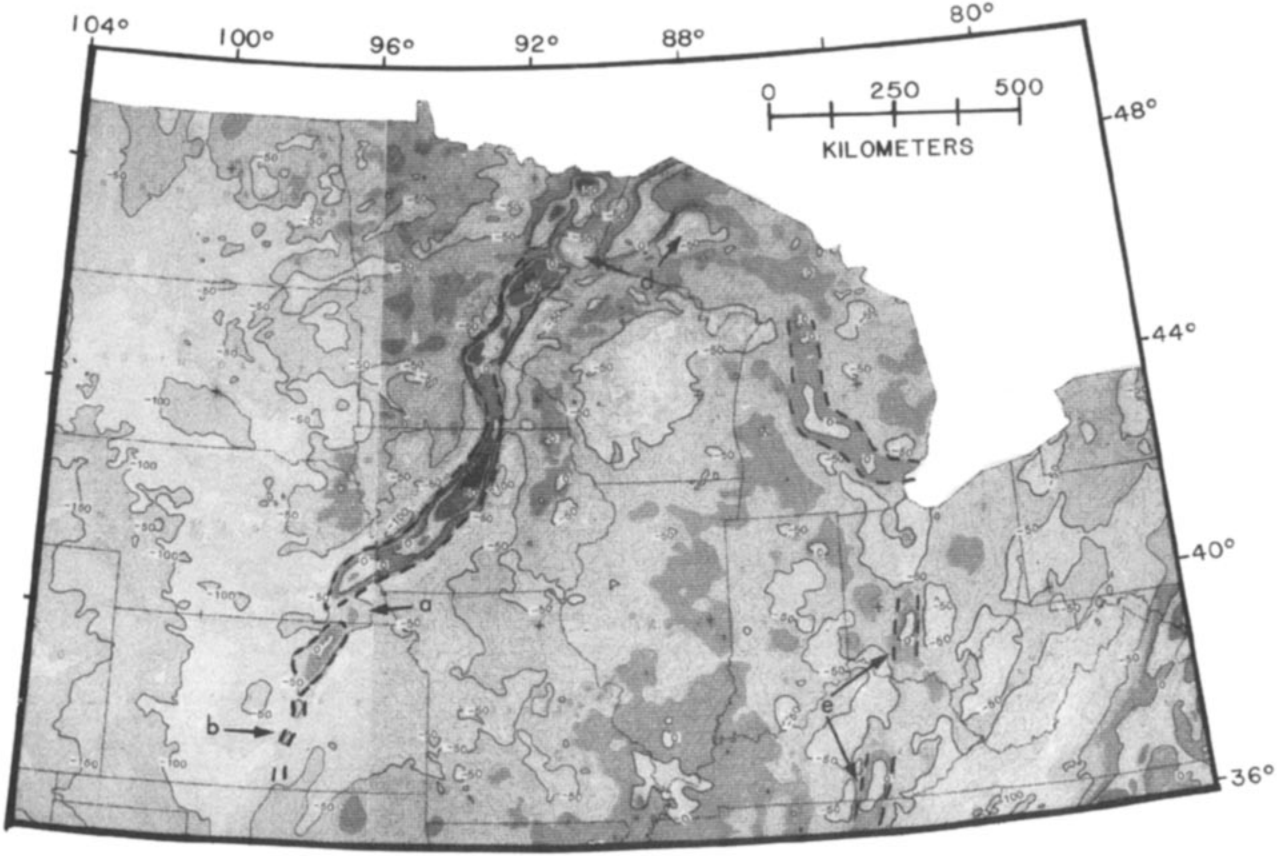

Figure 1 Bouguer gravity map of the *north-central portion* of the United States, showing the *major* anomalies associated with the midcontinent rift system (*outlined* with dashed lines). Letters refer to specific features mentioned in the text. Modified from Society of Exploration Geophysicists (1982). Heavy contours at 50-mgal intervals.

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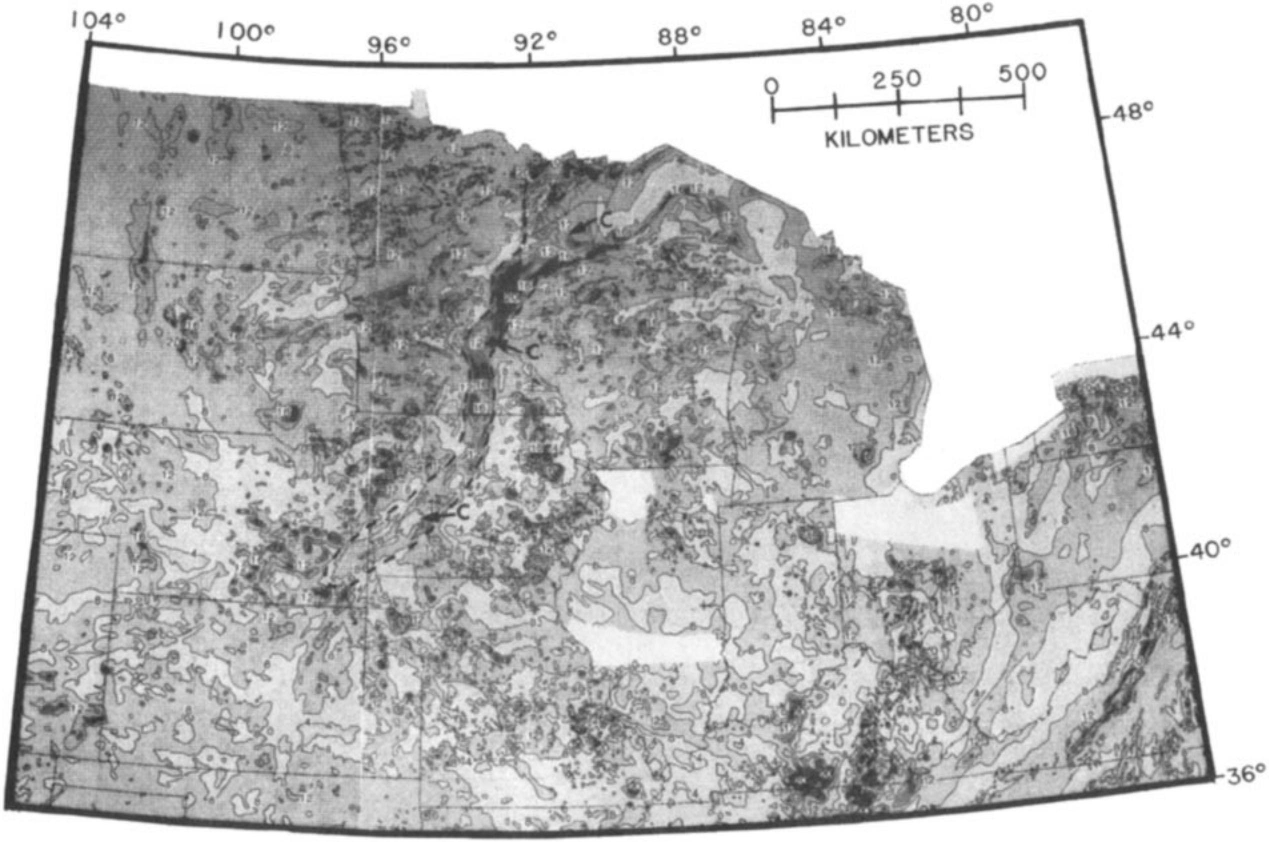

Figure 2 Aeromagnetic anomaly map of the north-central United States, showing the major anomaly pattern associated with the midcontinent geophysical anomaly (Figure 1; dashed lines). Modified after US Geological Survey (1982). Letters refer to features mentioned in the text. Heavy contours at 400-gamma intervals.

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mid-Michigan geophysical anomaly, east-continent geophysical anomalies, etc.).

Rocks associated with the MGA are exposed in the Lake Superior region and comprise the classical association of bimodal volcanic, plutonic, and clastic sedimentary units of the 1.0–1.2-Gyr-old "Keweenawan" suite (cf Morey & Green 1982). Genetic interpretation of the MGA and associated features as due to an incipient rift system goes back many years (e.g. Lyons 1959, King & Zietz 1971), and these features have been referred to as the "central North American rift system" (Ocola & Meyer 1973) or, more simply, the "midcontinent rift system" (Wold & Hinze 1982). In this review we follow the latter usage in genetic contexts.

Regional Geologic Setting

A major feature of the rift system is that it cuts across several Precambrian basement terranes of quite different age, structure, and composition in the craton that existed prior to 1.2 Gyr ago (Figure 3). The northern portion, including the Lake Superior basin, occurs in the Archean Superior Province of the Canadian Shield. In this region the Archean rocks are generally divided into a northern granite-greenstone terrane that has remained relatively stable since it formed 2.6–2.8 Gyr ago and a southern gneiss-migmatite terrane that formed 2.6–3.6 Gyr ago but was subjected to extensive deformation during Early Proterozoic orogenies (Morey & Sims 1976). The Lake Superior basin occurs within the granite-greenstone terrane, just to the north of the boundary (Great Lakes Tectonic Zone; Sims et al 1980) between the terranes. The rift system broadens within the Lake Superior basin, it becomes much wider, and the regional trend changes from NE-SW (MGA) to NW-SE (mid-Michigan segment). Klasner et al (1982) have suggested that this change in character and orientation may have been affected by differences between the two Archean terranes.

South of the Lake Superior basin, the southeastern and southwestern segments are narrower and occur for the most part in early Proterozoic crust, although the northern part of the MGA segment occurs in the Archean gneiss-migmatite terrane. Archean crust is not found south of central Wisconsin and southern Minnesota (Figure 3; Van Schmus & Bickford 1981, Nelson & DePaolo 1985). The Proterozoic crustal basement rocks in the midcontinent region formed 1300–1900 Myr ago and consist of 1600–1900-Myr-old new crust [which probably formed as orogenic continental margin assemblages (Van Schmus & Bickford 1981)] and 1300–1500-Myr-old anorogenic plutonic and volcanic rocks that formed by remelting of the older Proterozoic crust (Thomas et al 1984, Nelson & DePaolo 1985, Anderson 1983). According to Klasner et al (1982), the orientation of various segments of the rift system may be controlled by

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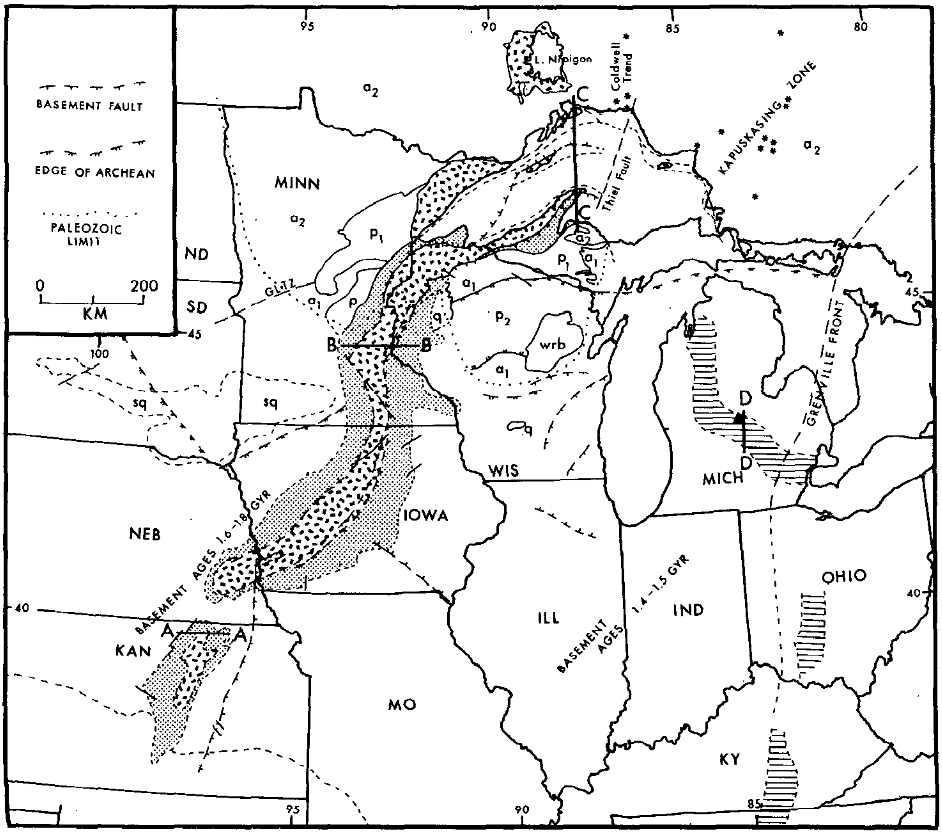

Figure 3 Generalized geologic map showing major features of the prerift Precambrian basement and principal geologic units associated with the midcontinent rift system. Random "=" represent central rift igneous rocks and associated sedimentary rocks, including Oronto Group; stippled pattern represents late Upper Keweenawan clastic rocks of the posttectonic phase (Bayfield Group, Jacobsville Sandstone, etc) in basins flanking the main rift sequence; horizontal-ruled pattern represents rift basin fill whose character is unknown in detail in the eastern region; asterisks north and northeast of Lake Superior represent alkaline complexes; dashed line labeled GLTZ is the Great Lakes Tectonic Zone. Abbreviations for older geologic units are as follows: a_1, older Archean gneiss-migmatite terrane; a_2, Archean granite-greenstone terrane; p_1, early Proterozoic cratonic cover; p_2, Early Proterozoic igneous complex; sq, Sioux Quartzite; q, other Early Proterozoic quartzites; wrb, 1500-Myr-old Wolf River Batholith. Compiled by the authors from various sources. Section lines AA, BB, CC, DD refer to Figure 7.

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structures within the Early Proterozoic basement. However, knowledge of structures in the basement is very limited, and other factors could be dominant.

Lithologic units associated with the midcontinent rift system are exposed only in the Lake Superior region and comprise the "Keweenawan" suite of rocks (Morey & Green 1982). They can be divided roughly into two groups: rift-basin igneous rocks (Duluth Gabbro, Keweenawan Volcanics) with associated red clastic rocks, and later crustal-depression-filling clastic rocks. These rocks are summarized in more detail below. Equivalent rocks are known from subsurface samples and indicate that there was extensive igneous activity and sedimentation along the midcontinent rift system at about 1100 Myr ago. This appears to be the youngest Precambrian igneous activity in the midcontinent region.

To the east of the midcontinent region is the Grenville Province, which represents a major crustal event. The Grenville Province is large and complex, but the combination of high-grade metamorphism, reworked continental crust, compressional structures, and abundant sialic crustal material strongly suggests that it represents a continental collision (e.g. Young 1980). Geochronologic studies of Grenville rocks show that much of the igneous and metamorphic activity of the Grenville event occurred 1150–900 Myr ago, with an earlier peak of activity 1100 ± 50 Myr ago and a second peak of activity 950 ± 50 Myr ago (e.g. Baer 1981). The proximity in time and space of the Grenville Province and the midcontinent rift system has led to suggestions that the two are genetically related, as is discussed below.

2. EXTENT AND GEOPHYSICAL EXPRESSION

Attention was first drawn to the MGA in Woollard's (1943) transcontinental gravity profile, which crossed the anomaly in eastern Kansas. As additional gravity data were observed and compiled (e.g. Lyons 1950, Black 1955, Thiel 1956, Coons et al 1967, Craddock et al 1969, Society of Exploration Geophysicists 1982), the gravity signature of the feature and its extent began to take shape. The anomaly, as first recognized, extends from Kansas to the western end of Lake Superior and is a major feature of the gravity anomaly field of the United States (Figure 1). A large amplitude range of up to 160 mgal over its central maximum and bordering minima, a cross-cutting relationship to the regional anomaly pattern, and a width of approximately 150 km combine to produce a characteristic and obvious anomaly. The MGA is also readily apparent in the magnetic anomaly field (Figure 2) as first recognized by King & Zietz (1971), although it is less prominent than in the gravity field.

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Since the delineation of the MGA, additional segments have been identified suggesting that the feature extends south into Oklahoma as well as in an arcuate pattern through Lake Superior and then southerly across Michigan and Ohio as far south as Tennessee. Additional minor components may extend northward from Lake Superior into Canada.

Midcontinent Geophysical Anomaly (MGA)

The MGA consists of several generally southwesterly trending coincident gravity and magnetic positive anomalies flanked by minima, and it extends from western Lake Superior in Minnesota and Wisconsin through central Iowa and southeastern Nebraska into Kansas. It strikes southwest from Lake Superior, makes a sharp turn in south-central Minnesota, and continues southeastward to the Iowa border, where it resumes its southwesterly course into southeastern Nebraska. At this point the anomaly shifts abruptly to the east by about 60 km, then continues south-southwesterly from the Kansas-Nebraska border into central Kansas. Data from subsurface samples in southeast Nebraska (Lidiak 1972, Treves & Low 1984) indicate that the anomaly marked "a" to the northeast of the Kansas segment in Figure 1 is not represented by Keweenawan units at the Precambrian surface and may not be part of the MGA. The gravity anomalies associated with the MGA north of central Kansas are measured in tens of milligals and thus are easily observed. The Minnesota and Iowa segments have the greatest amplitudes, with values ranging from greater than +70 mgal in Minnesota to less than −110 mgal in the flanking minimum in north-central Iowa.

In most discussions the MGA is terminated in central Kansas, but as pointed out by Lyons (1959), a subtle gravity anomaly component continues on strike with the major anomaly into Oklahoma ("b" in Figure 1) and perhaps as far south as southern Oklahoma. More recently, Yarger (1983) has shown that a system of linear magnetic anomalies that are particularly prominent in a second vertical derivative map extend south-southwesterly from the major magnetic anomaly in northern Kansas to at least the Oklahoma border. These lines of evidence strongly support continuation of the MGA to at least Oklahoma, but the anomalies, both gravity and magnetic, are greatly attenuated and indicate that the character of their source is different south of central Kansas, and the underlying disturbance of the crust is greatly reduced.

The gravity and magnetic anomalies of the MGA are correlative in a general sense—that is, major maxima and minima are spatially coincident (Figures 1, 2); however, in detail the anomalies are commonly not correlated. Gravity anomalies are smoothly varying over the central positive anomaly as well as the flanking minima. In contrast, the magnetic

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signature over the central gravity high consists of linear anomalies that parallel the strike of the feature and may range in length from a few kilometers to more than a hundred kilometers. In addition, prominent but featureless magnetic minima may occur within the confines of the central positive gravity anomalies (King & Zietz 1971). Broad, flanking magnetic "quiet" zones indicate increased depth to magnetic sources adjacent to the central anomaly. The differences in the gravity and magnetic anomalies are caused by the fundamental potential-field relationships associated with monopolar sources (gravity) versus dipolar sources (magnetics) and, more importantly, by geologic variations that differentially affect the controlling physical properties (density and magnetic polarization) of the sources.

Most of the MGA is overlain by Phanerozoic rocks that prevent direct study of the anomaly source. Drill holes to basement are limited in number and poorly distributed, so investigation of the source of the MGA has been largely by indirect geophysical methods. However, outcrops of the Precambrian basement at the western end of Lake Superior can be extrapolated into the subsurface by anomalous geophysical fields, principally gravity and magnetic anomalies. Thus, Thiel (1956) showed that the central positive gravity anomaly is associated with Keweenawan basalt deposited in an elongate depression, and that the flanking minima correlate with prisms of clastic rocks that thin away from the central gravity high. The central basin of basalt has been disrupted along high-angle reverse faults and brought into juxtaposition with younger sedimentary rocks. The latter were deposited in later, broader basins that originally completely covered the basalts, and the faults generally parallel the axis of the central, basalt-filled basin. This simple structural interpretation is the basis of current interpretations, although subsequent studies have shown that deeper crustal manifestations have a marked, and in some cases the predominant, effect upon geophysical anomalies.

As another example, King & Zietz (1971) have shown that mafic volcanic rocks are not only denser but also more magnetic than the surrounding basement country rocks, and that the relatively less-dense clastic rocks are essentially nonmagnetic. Furthermore, the mafic lavas retain a remanent magnetization acquired at the time of crystallization that may be three to five times as great as the magnetization induced by the Earth's present magnetic field and that differs radically in direction from the present field. This remanent magnetization complicates the magnetic anomaly pattern of the MGA, especially where lavas have been structurally deformed subsequent to their extrusion.

The situation is even more complicated, because the Earth's magnetic field reversed itself at least twice (N to R, R to N) during the period of development of the source of the MGA. As a result, reversely polarized

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lavas, dikes, sills, and plutons occur near the base of the igneous section (Green 1982), which result in strong negative (rather than positive) magnetic anomalies for some Keweenawan mafic units. King & Zietz (1971) have shown that the effect of remanent magnetization explains the relatively low magnetic values along the axis of the gravity anomaly, the persistent low along the western edge, and the marked positive along the eastern margin of the MGA. The long linear anomalies are probably related to upturned or faulted volcanic units that parallel the length of the anomaly. The broad, featureless magnetic minima along the axis of the gravity high, such as those observed in northwestern Wisconsin, over the Twin Cities basin at roughly 45°N, and along the length of the MGA in Iowa ("c" in Figure 2), are interpreted to be remnants of clastic basin fill that originally blanketed volcanic-filled troughs (King & Zietz 1971). The low-density clastic rocks of these basins contrast with the surrounding high-density lavas, producing subtle gravity minima in residual anomaly maps (Coons et al 1967, Hildenbrand et al 1982).

Lake Superior Basin

Both surface geologic data and geophysical anomalies establish the direct connection between the MGA and the Lake Superior basin. The evidence for this connection and the geology and geophysics of the Lake Superior region are summarized in a recent series of papers edited by Wold & Hinze (1982). The anomaly pattern of the MGA broadens and becomes much more complex as it passes into the basin near the western end of Lake Superior. Positive gravity and magnetic anomalies that occur over exposed and buried mafic volcanic rock delineate the limbs of an elongate basin, showing that the structural basin generally is outlined by the present shorelines of the lake (Hinze et al 1966, 1982). However, the anomaly pattern is considerably more complex than suggested by this simple interpretation. The gravity anomaly pattern is perturbed by relatively low-density clastic sedimentary rocks that overlie thick mafic volcanic rocks. Variations in thickness and density of the clastic rocks impose a variable negative effect upon positive anomalies associated with density contrasts of the mafic volcanic and intrusive rocks. Stripping off gravitational effects of the mass deficiency due to the low-density Upper Keweenawan clastic rocks shows that the entire lake is a positive gravity anomaly surrounded by negative anomalies. Particularly intense negative anomalies occur over the Bayfield Peninsula of Wisconsin and Keweenaw Bay of Michigan ("d" in Figure 1), which suggests that volcanic rocks of the basin are thin or absent in these areas (Hinze et al 1982). Magnetic anomalies of the Lake Superior basin are complicated by the strong remanent magnetization of the Keweenawan igneous rocks, which is aligned at a high angle to the

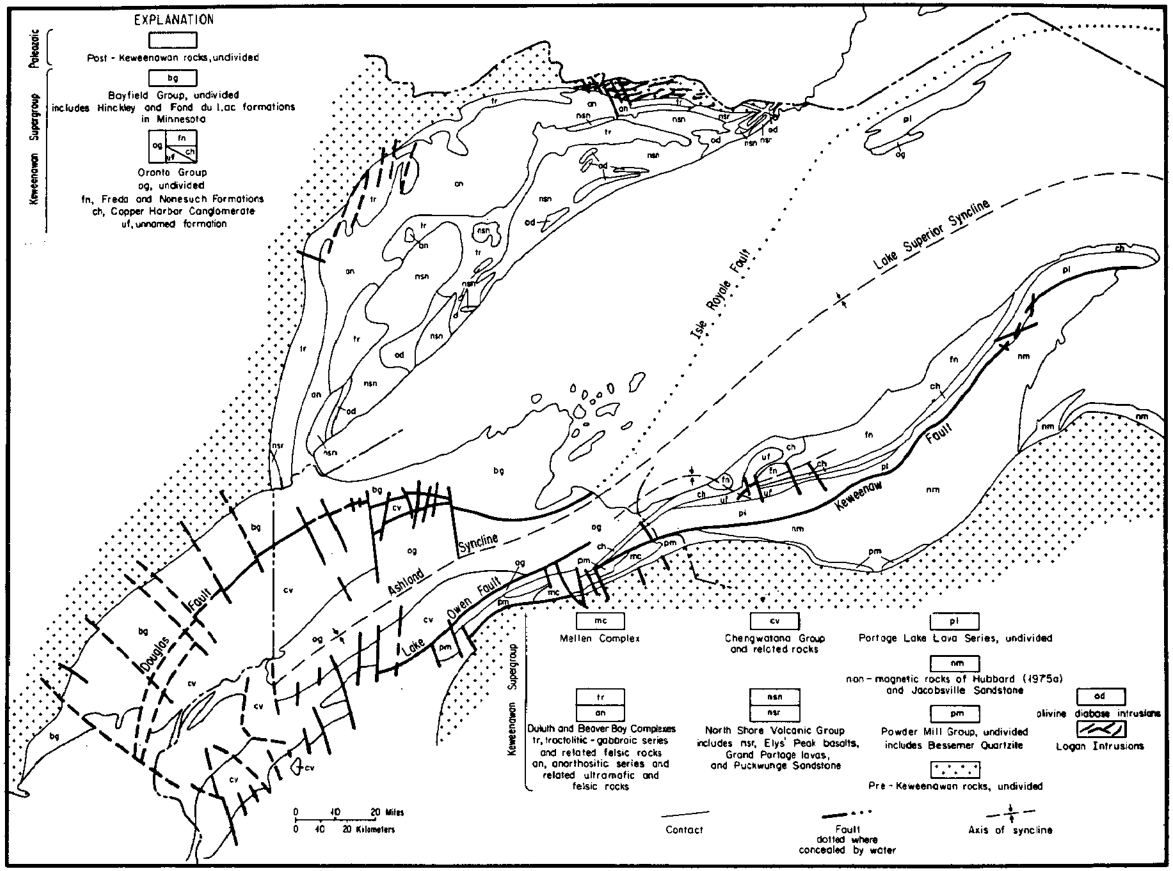

Figure 4 Generalized geologic map of the western Lake Superior region, showing the distribution and inferred stratigraphy of Keweenawan rocks (Morey & Green 1982). Stratigraphic units are not necessarily shown in sequence.

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present geomagnetic field. However, the axis of the structural basin is defined by a magnetic minimum (Figures 1, 4), and numerous faults paralleling and transecting the basin are indicated by discontinuities in the magnetic anomaly pattern (Hinze et al 1982).

Mid-Michigan Geophysical Anomaly

The mid-Michigan anomaly, which transects the Michigan basin from the northern margin to the southeast corner (Figure 1; Hinze 1963), is strikingly similar to the midcontinent geophysical anomaly (Hinze & Merritt 1969). Oray et al (1973) demonstrated the direct connection of this anomaly to the anomalies at the eastern end of the Lake Superior basin, and Hinze et al (1975) interpreted the anomaly as a rift feature that is a continuation of the structure associated with the MGA and Lake Superior basin. This interpretation was supported by results from a deep drill hole located in central Michigan on the maximum of the mid-Michigan geophysical anomaly (Figure 3; Sleep & Sloss 1978). At a depth of 3715 m the hole penetrated Keweenawan red clastic rocks (Catacosinos 1981), which underlie the basal Cambrian formations; it bottomed at a depth of 5324 m in metamorphosed mafic volcanic rocks, which were first encountered from 4970 to 4998 m and again from 5252 m to the bottom of the hole (McCallister et al 1978). Subsequently, deep seismic reflection profiling by the Consortium for Continental Reflection Profiling (COCORP) identified a structural trough containing layered formations beneath the Phanerozoic sedimentary rocks and coinciding with the mid-Michigan anomaly (see Section 4). The gravity anomaly of the mid-Michigan geophysical anomaly is continuous across the state of Michigan (Figure 1). However, the associated magnetic anomaly only occurs along segments of the feature (Figure 2), which suggests that volcanic rocks either are not present or are thin in portions of the rift, and that the positive gravity anomaly is related either to low-magnetization mafic intrusives at depth or to volcanic rocks that have been altered to a nonmagnetic form (Hinze et al 1982).

East-Continent Geophysical Anomalies

The southern limit of the eastern arm of the midcontinent rift system is generally placed in southeastern Michigan, either at the termination of the magnetic anomaly of the mid-Michigan feature or near the US-Canadian border slightly farther east, where the gravity anomaly terminates (Figure 1). However, more speculatively, a series of rectangular, N-S trending gravity maxima that extend southward across western Ohio into central Kentucky and Tennessee ("e" in Figure 1) have been interpreted as a southerly continuation of this arm of the rift (Lyons 1970, Halls 1978, Keller

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et al 1982). This interpretation is based on the form of the gravity anomalies and related positive magnetic anomalies, as well as on limited crustal seismic refraction and basement lithologic data. The lithologic data were all acquired from deep drill holes that penetrated through the Phanerozoic sedimentary rocks into the crystalline basement, and they are interpreted by Keller et al (1982) as indicating a strong correlation between the positive anomalies and bimodal igneous suites. These rocks are believed to have originated in the same rifting event that caused the MGA, but they were subsequently metamorphosed where they occur east of the Grenville Front (Lidiak et al 1984). Additional, but more speculative, rift blocks that may correlate with the MGA have been identified by Keller et al (1983) in the eastern midcontinent.

3. PETROLOGIC AND GEOCHEMICAL ASPECTS OF THE RIFT SYSTEM

Lithologic units associated with the midcontinent rift system can be divided into two major suites. The first includes units directly associated with the rifting: gabbro, bimodal volcanics, and clastic sedimentary rocks controlled by the rift structures and present as interflow sediments. The second suite consists of clastic sediments that formed after the main rifting phase and were deposited in large crustal depressions along the rift system. These units are related to each other and to older cratonic basement by a series of well-defined structures. Most data come from exposures in the Lake Superior region, complemented by fragmentary data from sparse subsurface samples, drill holes to basement, and regional geophysical interpretation. Figure 3 summarizes the geology of the midcontinent rift system, and various aspects are outlined below.

Lithologic Suites

As mentioned above, there are two major suites of rocks generally regarded as "Keweenawan": an igneous-sedimentary unit that occurs as primary rift-basin fill, and a later, entirely sedimentary one that occurs as late-stage fill of basins overlying the initial rock suite. In addition, a third, essentially pre-Keweenawan suite occurs locally and may have been deposited in structural depressions later occupied by the rift. The general stratigraphic relationships of Keweenawan and related units are complex and have recently been reviewed by Morey & Green (1982). Weiblen & Morey (1980), Green (1982), and Weiblen (1982) have reviewed the geology and geochemistry of the igneous units. A series of papers by Ojakangas & Morey (1982), Merk & Jirsa (1982), Daniels (1982), Morey & Ojakangas (1982), and Kalliokoski (1982), along with recent papers by Elmore (1984) and Cata-

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cosinos (1981), provide good summaries of the geology of the sedimentary units. Van Schmus et al (1982) have summarized the geochronology of Keweenawan rocks in the Lake Superior region, and Halls & Pesonen (1982) have reviewed the paleomagnetic aspects. Table 1 briefly outlines the key stratigraphic relationships in the Lake Superior region, and Figure 4 gives the geology as exposed in the western part of Lake Superior.

VOLCANIC UNITS Volcanic rocks constitute a major part of the units that fill the Lake Superior basin, with aggregate thicknesses up to 10 km in some localities (Green 1982). The volcanic units were extruded as fissure-fed continental flood basalts, and White (1972) and Green (1982) interpret the distribution of volcanic rocks as due to eruption from approximately eight major centers in the Lake Superior region (Table 2). Thus, individual flow units are not found everywhere but locally thicken and thin. This aspect of the volcanism complicates stratigraphic correlation, but the major reversals of the Earth's magnetic field that occurred during Keweenawan volcanism have been used extensively for regional correlation (Morey & Green 1982). Most of the volcanism occurred during an intermediate period of reversed field and after return to normal polarity; only limited volcanism occurred in the Lake Superior region during the "lower normal" polarity period of time.

The volcanic units were erupted into a broad, subsiding basin in the

Table 1 Stratigraphic summary for the Lake Superior region

Interval			Lithologic units	Approximate age (Myr)
			Post-Keweenawan, pre-Cambrian (poorly defined)	
Keweenawan Supergroup	Upper	Normal	Upper: mostly cratonic detritus (Bayfield Group and equivalent)	<1100
			Lower: mostly Keweenawan detritus (Oronto Group and equivalent)	<1100
	Middle		Interflow sediments	ca. 1100
			Later volcanic flows, sills, dikes; gabbro, anorthosite	
	Lower	Rev.	Early volcanic flows, sills, dikes	1100 to 1200
		Normal	Prevolcanic sediments	
			Pre-Keweenawan basinal clastic rocks (Sibley Gp.)	ca. 1340

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Lake Superior region, rather than into a narrow, fault-bounded rift valley. The axis of the basin at the top of the volcanic rocks generally follows the centerline of the lake, but it is shifted slightly to the south due to the asymmetric character of the basin (Figure 4). Geologic and geophysical evidence indicates that in general the dip of the volcanic rocks on the southern margin is steeper than for those on the northern side of the lake, with the dip of the southern margin rocks locally approaching vertical. Individual volcanic flow units probably do not universally thicken toward the center of the basin, although they probably thicken as a whole. Merk & Jirsa (1982) present evidence that volcanic units originally extended beyond the erosional limits of the present basin and were fed from fissures that we now observe as dike swarms in the adjacent older rocks (Green 1982). Gravity anomalies of the eastern half of Lake Superior are muted in comparison with those in the western half. This feature may in part be related to the depth of burial of the mafic rocks, but modeling by Hinze et al (1982) suggests the cause is a thinner volcanic layer in the east that has been much less drastically deformed than in the west.

As indicated above, detailed information about the distribution of volcanic rocks and their structure is much more limited for the buried southeastern and southwestern extensions of the rift system. However, the limited drill hole data that do exist (Craddock 1972, Lidiak 1972, Sleep & Sloss 1978, Yaghubpur 1979, Bickford et al 1979, Treves & Low 1984) indicate that volcanic units are present over most, if not all, of the length of the rift system (Figure 3). However, there is also evidence that the volcanic rocks are locally interbedded with or overlain by sedimentary units, much as in the Lake Superior region, and that the volcanic units are probably not continuous. The multiple extrusive center model proposed for the Lake Superior region probably is also reasonable for the rest of the rift system.

Table 2 Keweenawan volcanic centers (after Green 1982)

Volcanic plateaus	Polarity	Thickness (km)
Keweenaw Point–Isle Royale	N	2.5–5.2
Chengwatana	N	6
North Shore (normal)	N	3.7–7.1
Mamainse-Michipicoten	N	4.1–7.1
Mamainse (reversed)	R	2.5
Osler	R	2.8
Ironwood–Grand Portage–Nopeming	R	3.0–6.3
Siemens Creek	N	0.1

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Although basaltic compositions predominate, the volcanic rocks of the Lake Superior basin span the range from olivine tholeiite to rhyolite (Figure 5), and Green (1982) estimates that the population is bimodal, with the rhyolitic maximum significantly lower than the basaltic maximum. The basalts typically have high Al contents, and the transitional group has alkali contents that overlap the alkali-tholeiitic basalt fields. Green (1982) regards the Keweenawan volcanics as similar to other plateau basalts. However, attempts to model magma evolution have been only partly successful, and it is not yet clear how the various groups are related to one another or to Keweenawan plutonic units such as the Duluth Complex (see below). In any case, it appears from Sr, Pb, and Nd isotopic data (Leeman 1977, Dosso & Murthy 1982) that crustal contamination was significant in many areas for rhyolitic components, but that primitive mafic compositions have been derived directly from the mantle. One of the major questions is the degree to which the rhyolitic magmas were derived by fractional crystallization of basaltic magmas or by partial melting of older crustal rocks.

Basaltic rocks have also been encountered in the subsurface along the MGA and in a deep drill hole in central Michigan (McCallister et al 1982, Lidiak 1972). However, there are few chemical or isotopic data on these occurrences that can be used to define their origin.

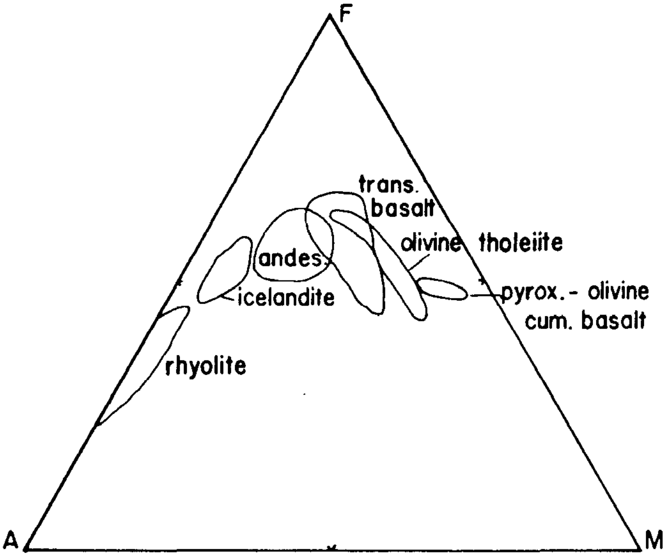

Figure 5 AFM diagram for Keweenawan lavas of the North Shore Volcanic Group, western shore of Lake Superior (Green 1982).

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PLUTONIC UNITS The geology, petrology, and geochemistry of plutonic units associated with the midcontinent rift system in the Lake Superior region have been reviewed recently by Weiblen (1982). The plutonic units can be divided into three principal suites: large gabbroic bodies, basaltic sills and dikes, and alkaline complexes. The first two are intimately associated with Keweenawan volcanic rocks, and their association with the rift system is obvious. The third group, a series of alkaline intrusions north and northeast of Lake Superior (Figure 3), is closely associated with the rift system in space and time, and many models of rift system development include the alkaline suite as an integral part of their history (Weiblen 1982).

Probably the best known of the large mafic intrusive units are the Duluth Complex sequence in Minnesota (Weiblen & Morey 1980), west of Lake Superior (Figure 4), and the Mellen Complex in northwestern Wisconsin. Both of these units have many features of typical layered gabbro sequences, although the stratigraphies and petrology are somewhat more complex than typical models. The various units are not related to one another by a simple model of cumulates or magmatic differentiation; instead, they indicate a complicated intrusive history that includes cross-cutting relationships and internal intrusive relationships. Early models of the Duluth Complex treated it as a lopolith (Grout 1918), but later workers have argued against this model because it does not fit the geophysical data, particularly the gravity data; for example, White (1966) argues that there is no evidence for the central feeder needed for the lopolith model. More recently, Weiblen & Morey (1980) have called on a "half-graben" model, in which the igneous units of the Duluth Complex were emplaced into space developed by subsiding crustal blocks during extensional phases of the rift system.

Although the general compositions of the igneous rocks in the mafic complexes are tholeiitic, they do not follow simple differentiation trends, and Weiblen & Morey (1980) present arguments for the existence of two main igenous sequences in the Duluth Complex. The earlier phase involved extensive and efficient melt and crystal segregation to produce rock types with very contrasting mineralogies, such as peridotite, anorthosite, and felsic differentiates. The later phase, referred to as the troctolitic phase, involved intrusion of magma more continuously, with less crystal segregation but with nonuniform fractionation trends. Weiblen & Morey (1980) have suggested that the magma responsible for the earlier phase can be related to that which provided the earlier, reversely polarized lavas of the North Shore Volcanic Group in Minnesota, and that the magma associated with the troctolitic phase can be related to the later, normally polarized lavas of these volcanics.

Mafic intrusive rocks are also extensively represented in smaller plutonic

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bodies, primarily as sills and dikes throughout the Lake Superior region, including Lake Nipigon, north of Lake Superior (Figure 3). These have also been recently reviewed by Weiblen (1982), who concludes that two distinct magma types can be recognized. The earlier dikes and sills tend to have quartz tholeiite compositions, whereas the later ones tend to have olivine tholeiite compositions. These compositional differences also correlate with the magnetic polarity of the dikes and sills; the earlier quartz tholeiite ones are generally reversely polarized, while the later ones are normally polarized. Weiblen & Morey (1980) and Weiblen (1982) have also concluded that it is reasonable to regard all the mafic igneous rocks of the Lake Superior basin as genetically related, with an overall subdivision into two compositional suites. The earlier suite includes the cumulate units of the Duluth Complex, quartz tholeiite sills and dikes, and Lower Keweenawan volcanic units, most of which are reversely polarized but appear to be related to one another in a rather complex way petrogenetically (Weiblen 1982). The second, later suite consists of the troctolite series of the Duluth Complex and equivalent units in other intrusions, olivine tholeiite sills and dikes, and the later, normally polarized volcanic units that may represent a simpler system of fractionating magma chambers, feeder dikes, and overlying volcanic flows (Weiblen & Morey 1980).

The other major plutonic suite of general Keweenawan age in the Lake Superior region is a series of alkaline complexes that occur to the north of Lake Superior as the Coldwell alkaline province and to the northeast of Lake Superior and as nepheline-carbonatite complexes in the Kapuskasing structural zone (Currie 1976, Weiblen 1982; Figure 3). The alkaline complexes are not tied to the Keweenawan igneous activity by any direct cross-cutting, intrusive, or depositional relationships, but they are approximately the same age (1000–1200 Myr; see below), and both reversed and normal magnetic polarities occur. Therefore, it is tempting to try to relate these units to an early stage in the tectonic evolution of the Lake Superior region (Burke & Dewey 1973, Weiblen 1982). However, although the alkaline and carbonatite complexes may be about the same age as the Keweenawan rifting and igneous activity, the Kapuskasing structural zone itself is a Late Archean to Early Proterozoic feature (Watson 1980, Percival & Card 1983).

At present there is very little direct evidence of plutonic units along the rest of the midcontinent rift system of the magnitude and variety found in the Lake Superior region. However, there are many gravity and magnetic anomalies along the system that could easily be related to such units, and some drill holes have penetrated mafic and alkaline bodies in the subsurface of Iowa and Nebraska near the MGA. These could be approximately the same age as the rift system (Yaghubpur 1979, Brookins et al 1975).

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Unfortunately, there have been no good age determinations on these units. Nonetheless, it is not unreasonable to expect that some features similar to those in the Lake Superior region occur along the rest of the midcontinent rift system; many of the anomalies in the immediate vicinity of the main anomaly system are potential targets of study in the search for such units.

SEDIMENTARY UNITS There are basically four sequences of sedimentary rocks associated with the rift system in the Lake Superior basin. In all cases the rocks are clastic units of varying grain size and texture, from conglomerates to shales. The older (pre-Keweenawan) suite is quite limited in occurrence and may not have a direct relationship to rift development. The three younger suites are directly associated with development of the rift system and can be divided according to whether they represent deposition during active rift volcanism (synvolcanic), whether they were deposited in a central trough that remained in the rift system after cessation of igneous activity (postvolcanic), or whether they were deposited in a broad sag basin that developed as a result of regional subsidence of the rift complex (sag basin).

Pre-Keweenawan sedimentary rocks The principal sedimentary unit that can be delegated to pre-Keweenawan status is the Sibley Group that occurs north of Lake Superior. It is about 1340 Myr old (see below) and underlies volcanic rocks of the Osler Group in the Thunder Bay–Nipigon region. Recent summaries of these rocks include those of Franklin et al (1980) and Ojakangas & Morey (1982). Franklin et al (1980) have suggested that the Sibley Group was deposited in a basin that formed as a third arm of the rift system, but these rocks are apparently considerably older than other early-stage Keweenawan rocks, and the location may either be fortuitous or represent a basin developed along structural weaknesses that later helped to control the rift system.

Synvolcanic sedimentary rocks Sedimentary units that are interbedded with volcanic rocks are somewhat limited in extent and have been reviewed recently by Merk & Jirsa (1982). They are typically coarse, immature, polymictic, red-bed clastic rocks that were deposited by streams flowing over the surfaces of Keweenawan volcanic flows. We have included in this category older units that occur as prevolcanic sedimentary rocks in the western Lake Superior region (Ojakangas & Morey 1982) but that are apparently close in age to the onset of Keweenawan igneous activity, since they appear to fit as part of the tectonic suite. The oldest Keweenawan lavas have normal polarity, and sedimentary units of this suite have both normal and reversed polarity, which indicates that some of them were deposited

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after the onset of volcanism. The beds of these formations are generally mature, quartz-rich sandstones that were deposited in shallow basins (Ojakangas & Morey 1982); these features suggest that rift development was not very advanced and, further, that volcanism began very early in the development of the rift.

Postvolcanic rift basin units The units included in this suite are postvolcanic rocks that show close association with the main rift tectonic activity and consist primarily of clastic debris derived from the volcanic rocks of the rift system. These units are generally included in the Oronto Group (Daniels 1982) and Solor Church Formation (Morey & Ojakangas 1982) and mark the beginning of Late Keweenawan time (Morey & Green 1982). The principal formations are the Copper Harbor Conglomerate (Elmore 1984), the Nonesuch Shale, and the Freda Sandstone. The Copper Harbor Conglomerate represents alluvial deposition contemporaneous with and following Late Keweenawan volcanism in depressions of the rift system. The Nonesuch Shale has been interpreted as representing anoxic lacustrine environments that flanked the rift system and were formed by the combined action of alluvial, volcanic, and tectonic processes (Daniels 1982). It is locally interbedded with units of the Copper Harbor Conglomerate. The Freda Sandstone overlies the other units and marks the transition upward into fluvial sedimentation more characteristic of a stable craton.

Younger sedimentary units Morey & Ojakangas (1982) have divided the postvolcanic sedimentary rocks of the Lake Superior region into those that consist of detritus derived primarily from the rift system itself (largely volcanic sources, discussed above) and those that consist of detritus derived primarily from the surrounding older Precambrian craton. The latter suite typically overlies the former suite and may be regarded as postdating active rifting. Instead, the depositional basins were formed largely by vertical processes, perhaps as crustal subsidence due to the increased mass of the crust along the rift system. The principal units that represent this phase of sedimentation include the Bayfield Group in Wisconsin, the Fond du Lac Formation and Hinckley Sandstone in Minnesota (Morey & Ojakangas 1982), and the Jacobsville Sandstone (Kalliokoski 1982) in the eastern Lake Superior region.

Formations with equivalent lithologic and structural relationships occur along almost the entire length of the midcontinent rift system and have been encountered in numerous drill holes to basement. Key examples are the Rice Formation in the subsurface of Kansas (Scott 1966), rocks similar to (and mapped as) the Bayfield Group in Iowa (Yaghubpur 1979), and red clastic rocks encountered in a deep drill hole in the Michigan basin, over the mid-Michigan anomaly (Catacosinos 1981, Fowler & Kuenzi 1978). These

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units have a much wider distribution than the rocks of the main rift system, and they approach thicknesses of 2–4 km.

Geochronology

Although there have been numerous geochronologic investigations of units of the Keweenawan suite, they have been of relatively little use in establishing the stratigraphic relationships among the Keweenawan units or between these units and others in the region of comparable age. There are two principal reasons for this. First, it appears that much of the development of the rift system took place over a relatively short period of time. In particular, Silver & Green (1972) have shown through U–Pb analyses of zircons that most of the igneous activity in the Lake Superior region took place over a very short period of time, about 1110 ± 10 Myr ago, so that resolution of relative ages during this event is probably only possible using the U–Pb method on zircons. Unfortunately, however, zircons are not common in most of the igneous units present in the Lake Superior region but are primarily restricted to felsic phases. Other common dating techniques that have been or could be applied to igneous rocks of the region either have poorer precision (and hence poorer resolution) or are more susceptible to later disturbances. As a result, there are many reported ages from 900 to 1200 Myr ago (Van Schmus et al 1982), but the range in ages is probably more apparent than real. Also, attempts to obtain meaningful ages on sedimentary units have been only partially successful, with many of the results uncertain because of later loss of radiogenic daughter product or because of incorporation of inherited daughter product in the detrital components.

One aspect of the history of the rocks that has helped establish relative as well as approximate absolute chronologies has been the paleomagnetic history. As mentioned above, there were at least two major reversals of the Earth's field during Keweenawan times (N to R, R to N) that can be used to help establish relative ages. Also, the paleopole position migrated rapidly during Keweenawan times, so that poles from units relatively close together in age are spatially resolved on the polar wander path for the interval involved (Figure 6; Van Schmus et al 1982, Halls & Pesonen 1982). The chronology that is summarized below is thus a result of both radiometric and paleomagnetic dating, along with traditional stratigraphic data.

Pre-Keweenawan sedimentary units, notably the Sibley Group, apparently formed about 1340 Myr ago (Franklin et al 1980) and probably predate the onset of Keweenawan structural and igneous development by at least 100 Myr. The earliest igneous event that might be related to the onset of rifting and igneous activity is the emplacement of basaltic dikes in the Sudbury, Ontario, region about 1225 Myr ago (Van Schmus 1975)

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during the early period of normal polarity. Although no genetic link has been demonstrated, structurally or petrochemically, these dikes may correspond in age to the volcanic units formed during the early normal polarity time. Age studies on the carbonatitic and alkaline complexes north and northeast of Lake Superior are not sufficiently precise or accurate to determine whether these bodies are older than, contemporaneous with, or younger than the main Keweenawan activity, but Weiblen (1982) has placed them in the older category.

The vast majority of igneous activity, in terms of both volume and stratigraphic units, apparently occurred over a very short time span about 1110 Myr ago (Silver & Green 1972). This includes much of the igneous activity during the reversed polarity interval as well as that occurring after the return to normal polarity. In fact, the dated units bracket the magnetic reversal from reverse to normal, thus dating it rather precisely at 1110 Myr. The only dates that are younger than 1100 Myr are either Rb–Sr whole-rock or K–Ar by various techniques. In both cases, there is considerable uncertainty because of possible loss of radiogenic daughter product, so that the existing data should be interpreted to indicate the possibility of younger units, but that there may in fact be very little igneous activity associated with the rift system after 1100 Myr. This is not unreasonable, since major igneous activity in more recent rift systems (e.g. Oslo graben, Rio Grande rift, Kenya rift) took place over intervals of only 20–30 Myr (Williams 1982). Rb–Sr ages from postvolcanic sedimentary units, particularly the None-

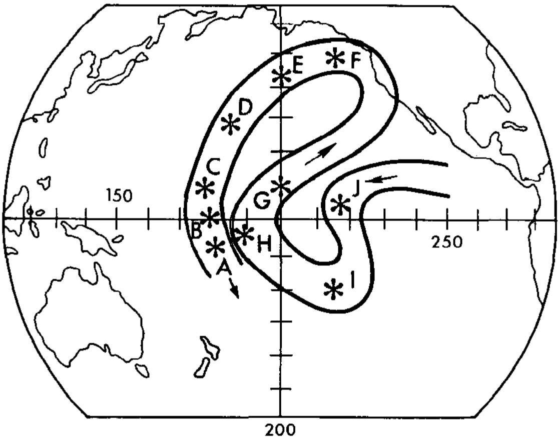

Figure 6 Sketch of apparent polar wander path for Lake Superior region units 1000–1500 Myr old (as listed in Table 3). After Van Schmus et al (1982) and Halls & Pesonen (1982).

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such Shale (1023±46 Myr; Chaudhuri & Faure 1967), yield ages close to 1100 Myr, which further indicates that volcanic activity could not have continued to much later than 1100 Myr ago.

The ages of the posttectonic sedimentary units are even more uncertain because they are not amenable to normal radiometric techniques. However, paleomagnetic data on younger units such as the Freda Sandstone and Jacobsville Sandstone show that the paleopole positions of these units are only slightly farther along the Keweenawan polar wander curve (Figure 6) than the Nonesuch Shale or the younger volcanic units (Halls & Pesonen 1982). If the rapid pole position movement that characterizes the earlier part of the curve continued through deposition of the Freda and Jacobsville sandstones, then they are probably not much younger than 1100–1000 Myr.

One of the more interesting aspects of the chronologic data is that the paleopole position changed very rapidly during the main period of igneous activity and, presumably, associated rifting (Table 3, Figure 6). This suggests that the craton was actively moving at the time and was also undergoing significant changes in direction that could have induced tensional forces (Halls & Pesonen 1982).

Initial isotopic data for radiometric systems in Keweenawan rocks are still somewhat limited. Van Schmus et al (1982) summarized Rb–Sr data that existed to that time and concluded that the mean initial Sr-87/Sr-86 ratio for Keweenawan igneous rocks was 0.7046±0.0005 on a regional basis, too close to the uncertainties in a mantle growth curve for significant interpretation. On a more detailed basis, Leeman (1977) reported a significant range for initial Sr and initial Pb composition from volcanic rocks in Minnesota, and Dosso & Murthy (1982) found significant

Table 3 Paleomagnetic poles for Lake Superior region[a] (Figure 6)

Unit	Age (Myr)	Polarity	Pole position (long)	(lat)
A. Jacobsville Sandstone	?	N	183	−9
B. Freda Sandstone	?	N	180	1
C. Nonesuch Shale	1023	N	177	10
D. Middle Keweenawan	1110	N	183	29
E. Middle Keweenawan	1110	R	203	42
F. Logan Sills	1150	R	220	49
G. Lower Keweenawan	?	N	200	10
H. Sudbury Dikes	1225	N	189	−3
I. Sibley Group	1340	N	214	−20
J. Croker Island Complex	1475	N	217	5

[a] After Van Schmus et al (1982) and Halls & Pesonen (1982).

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variations in initial Sr and Nd isotopic ratios. In general the isotopic data can be interpreted to indicate the involvement of older crustal rocks in the evolution of the felsic Keweenawan magmas. However, the basaltic magmas were apparently derived from enriched, heterogeneous mantle without significant crustal contamination.

Economic Deposits

Economic deposits commonly accompany rift systems, and the midcontinent rift system is no exception (Norman 1978, Weiblen 1982). There are at least four known or possible types of deposits associated with the rift system. The first of these is the classical native copper deposits of the Keweenaw Peninsula in Michigan (White 1968). These are basically stratabound deposits that formed as a result of hydrothermal solutions acting on copper-bearing lavas and volcaniclastic debris of the region (White 1971). Similar, but much smaller, examples occur in the Mamainse Point region along the east shore of Lake Superior. So far no occurrences of such deposits have been reported from the buried part of the rift system, but it is a distinct possibility that they exist. In fact, McCallister et al (1982) reported trace amounts of native copper from altered basaltic rocks encountered in the deep hole in the Michigan basin.

The second type of deposit is Cu–Ni sulfide mineralization associated with the lower phases of the Duluth Gabbro Complex in Minnesota (Weiblen 1982) as well as other plutons, sills, and dikes. Most of these are subeconomic, but the potential exists that igneous intrusions associated with the midcontinent rift system in places other than the Lake Superior region may have significant mineralization. Some mafic intrusions of possible Keweenawan age have been explored in Iowa, so far without success (Yaghubpur 1979).

The third type of occurrence is also primarily Cu mineralization, in this case associated with the 1100–1200-Myr-old alkaline and carbonatite complexes north and east of Lake Superior (Currie 1976, Norman 1978). As with the other types of mineralization, similar occurrences are not known from the buried portions of the rift system, but if the Lake Superior complexes are genetically related to the rifting, such features may occur elsewhere along the rift system. One possibility, in fact, is the Elk Creek carbonatite-bearing complex associated with the Elk Creek anomaly in southeast Nebraska (Irons 1979). It is reported to underlie basal Paleozoic sedimentary rocks (Brookins et al 1975), and a nearby gabbro plug in the subsurface yields an Ar–Ar age of about 1200 Myr (Treves 1981).

The existence of the fourth type of economic occurrence is still speculative. The Nonesuch Shale is locally organic rich, and Lee & Kerr (1984) and Dickas (1984) have recently summarized the hydrocarbon

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potential of similar types of units within the central sequence of the rift system along the MGA. Several test wells are currently underway or planned, and we shall have to await the outcome of this exploration. Even if the results from such drilling and related geophysical surveys are negative, they should eventually help in developing a better understanding of the stratigraphic sections and geological relationships within the buried rift basins.

Sawkins (1982) has summarized the metallogenesis associated with rift systems in general. The wide variety of mineral deposits, particularly strata-bound copper deposits, found associated with continental rift systems indicates that there may be significant economic potential, both metallic and nonmetallic, along the buried portions of the midcontinent rift system.

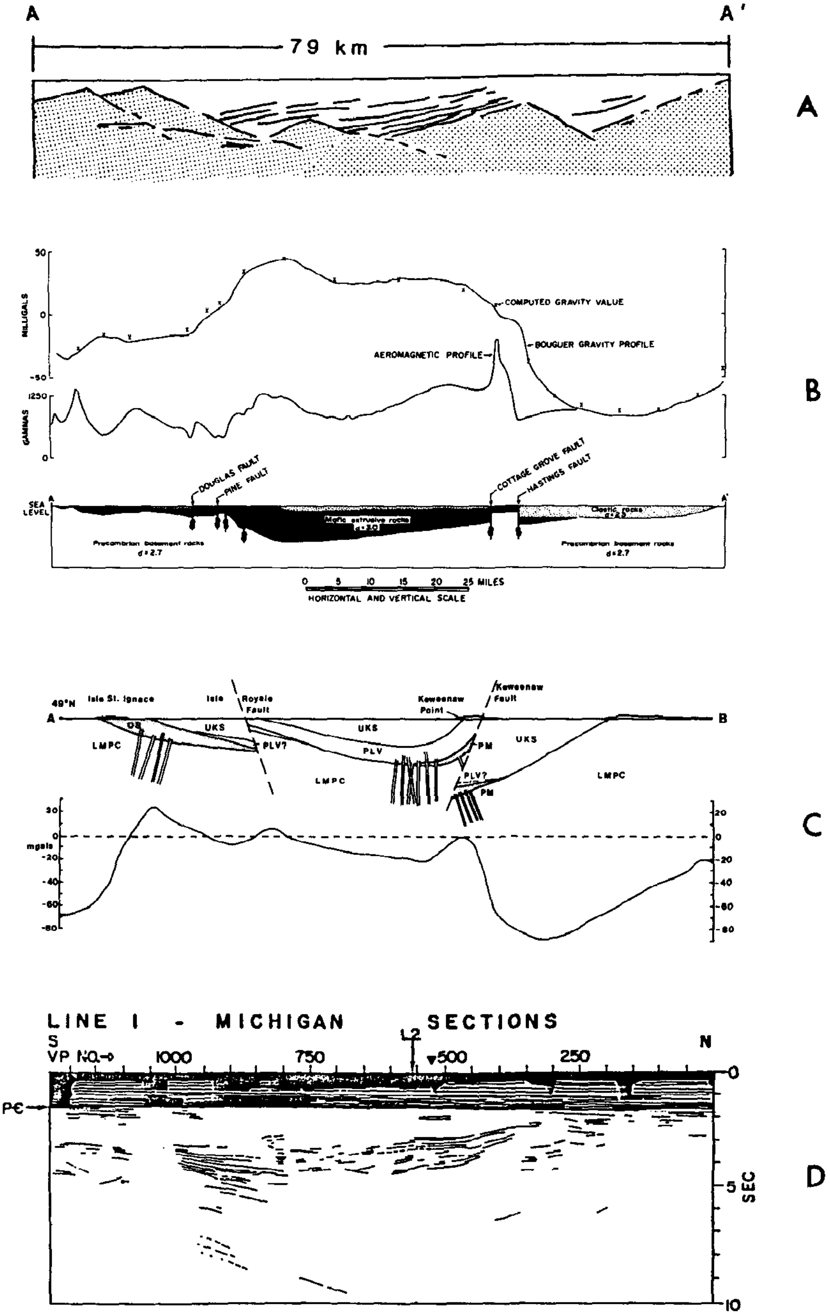
4. STRUCTURAL RELATIONSHIPS

Surface and Near-Surface Structure

The structure of the midcontinent rift system remains poorly known despite many years of investigation because outcrops are limited where the feature is at the surface in the Lake Superior region and because there is poor distribution of deep drill holes along the rest of its length. The lack of direct geologic information on the rift has focused attention on the interpretation of geophysical data, especially gravity and magnetic anomalies and seismic studies. However, gravity and magnetic studies have poor horizontal and vertical resolution, and seismic data have until recently been confined to regional crustal seismic measurements and shallow seismic investigations in Lake Superior. Two recent COCORP reflection profiles have helped in interpretation of the buried rift structure in Kansas (Serpa et al 1984) and central Michigan (Brown et al 1982), but in general structural detail is poorly constrained. Figure 7 summarizes interpretations of the rift structure at four places along the rift system.

→

Figure 7 Four interpretations of cross sections of the midcontinent rift system (Figure 3). (*a*) Based on COCORP data across the northern part of the Kansas segment (Serpa et al 1984), showing a basin formed by normal faults; stippled pattern = crystalline basement. (*b*) Based on interpretation of gravity, magnetic, and borehole data for the Twin Cities region of Minnesota (King & Zietz 1971), showing a central horst with flanking clastic basins. Note absence of deep root structure. (*c*) Based on surface geology in the Lake Superior region (Green 1982), showing inferred relationships of volcanic units (OS = Osler Series, PLV = Portage Lake volcanics, PM = Powder Mill Group) to Upper Keweenawan sedimentary rocks (UKS) and Lower to Middle Precambrian basement (LMPC). Note absence of deep root structure. (*d*) Based on COCORP survey across mid-Michigan anomaly (Brown et al 1982), showing major reflectors. Note absence of any significant vertical offsets in Precambrian units, suggesting a relatively smooth basin (Serpa et al 1984).


A
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AEROMAGNETIC PROFILE
DOUGLAS FAULT
PINE FAULT
COTTAGE GROVE FAULT
HASTINGS FAULT
SEA LEVEL
A
A'
Mafic extrusive rocks
d = 3.0
Clastic rocks
d = 2.5
Precambrian basement rocks
d = 2.7
Precambrian basement rocks
d = 2.7
0 5 10 15 20 25 MILES
HORIZONTAL AND VERTICAL SCALE
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49°N
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Isle Royale Fault
Keweenaw Point
Keweenaw Fault
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Geologic observations and geophysical interpretations show that faulting is characteristic of rift system units. The most striking faults observed in the midcontinent rift system are high-angle reverse faults, which formed along the margins of the central basins before deposition of Cambrian clastic sediments (Figure 7*b*). These faults cannot be interpreted as typical graben faults because, as White (1966) has pointed out, the patterns of sedimentation related to the faults and their attitudes prohibit such an interpretation. In fact, no major normal faults occur in the Lake Superior basin, and no evidence exists for an axial graben buried beneath the surficial rocks of the basin (Hinze et al 1982). The major marginal reverse faults of the basin (the Keweenaw, Douglas, and Isle Royale faults; see Figure 4) are particularly important structural features that have led to the development of prominent horsts. These horsts, which bring older volcanic rocks into juxtaposition with flanking clastic sedimentary rocks of a late-stage basin, are only observed in the western half of the lake and the extension to the south. This high-angle reverse-faulting event, which appears anomalous in an extensional (rift) domain, is a commonly observed phenomenon of continental rifts where subsequent compression has modified the structural regime (Milanovsky 1981). Therefore, if the faults bounding the central horst blocks are reverse faults, there must have been later compression.

The second major type of faulting in the Lake Superior basin and in areas of volcanic rock outcrop is represented by transverse faults that cut the older marginal thrust faults (Figure 4). Major strike-slip faults are not observed in the basin. Well-developed folds are commonly observed in the volcanic and overlying sedimentary rocks of the Lake Superior basin; they are believed to be pene- and postcontemporaneous with basin formation, while the faulting postdates folding (Davidson 1982).

A regional structural fabric that either predated or formed at the same time as the rifting is shown by the alignment of mafic dike swarms in the Lake Superior region (Figure 3). These dike swarms tend to parallel the northwest, northeast, and southern shores of Lake Superior and may indicate the orientation of extensional forces during volcanism.

The upper crustal manifestations of the rift system associated with the MGA have until recently been determined primarily by modeling of gravity and magnetic anomalies, utilizing geologic information extrapolated from outcrops in the Lake Superior region and drill hole data. Most models are similar to those proposed by Thiel (1956) on the basis of observed gravity anomalies. A typical example of a derived geologic model (King & Zietz 1971) is shown in Figure 7*b*. The detailed gravity anomaly profile modeled in this illustration was collected by Craddock et al (1963) across the Twin Cities basin in Minnesota and western Wisconsin. The gravity anomaly maximum is due to high-density mafic volcanic rocks that are preserved in

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an axial horst. The negative gravity anomaly on the eastern margin of the profile is caused by a wedge of low-density Upper Keweenawan clastic rocks. These rocks are younger than the volcanic rocks, so that the volcanic rocks have been relatively uplifted into juxtaposition with the clastic rocks.

A recent COCORP seismic reflection profile over the MGA in northern Kansas has provided new insight into the structure of the axial trough of the midcontinent rift (Serpa et al 1984). Their interpretation of the reflection data (Figures 7*a*, 8) shows an asymmetric basin consisting of two stratigraphic units. The lower unit, composed of high-amplitude reflections between 1 and 3 s, is interpreted as a 5-km-thick segment of interbedded basalts and clastic rocks. An overlying seismically transparent unit is interpreted to be made up of predominantly clastic rocks varying from 1 to 3 km in thickness. The nature of these rocks is supported by drill hole data (Bickford et al 1979). East-dipping reflectors (Figure 8) that truncate the inferred volcanic sequence across the entire width of the trough are interpreted as faults and cause the structural asymmetry. An earlier COCORP survey across the mid-Michigan anomaly in central Michigan (Figure 7*d*) indicated similar reflection sequences, and these are also interpreted as basal volcanic units with overlying clastic units (Brown et al 1982). A deep hole that had earlier been drilled near the site of the COCORP survey penetrated 1315 m of Precambrian red clastic rocks before bottoming in a metamorphosed mafic volcanic unit at a depth of 5324 m. Brown et al (1982) found only indirect evidence of faulting in the trough in the form of relatively steep dips, sharp flexures, and structural benches.

Interpretation of the seismic reflection profiles across the mid-Michigan and midcontinent geophysical anomalies suggests that the principal shallow manifestation of the midcontinent rift system is a trough that initially filled with interbedded volcanic and clastic rocks that were later covered by clastic sediments. Contrary to classical views of surface deformation associated with rifts, a central graben with marginal, steeply deepening normal faults has not been observed for the midcontinent rift system. Instead, faulting is limited to tilted fault blocks, with extension presumably taken up by rotation of fault blocks (Serpa et al 1984); Weiblen & Morey (1980) have called on similar processes for the extension that accompanied emplacement of the Duluth Complex. The interpretations from the COCORP surveys also indicate that later high-angle reverse faulting, with associated horsts, is not a universal feature of the midcontinent rift system and may be limited to the western Lake Superior region and the northern part of the MGA (Figures 7*b*,*c*).

The principal differences between the Lake Superior basin and the rest of the rift system are that it is broader and, apparently, deeper. Serpa et al

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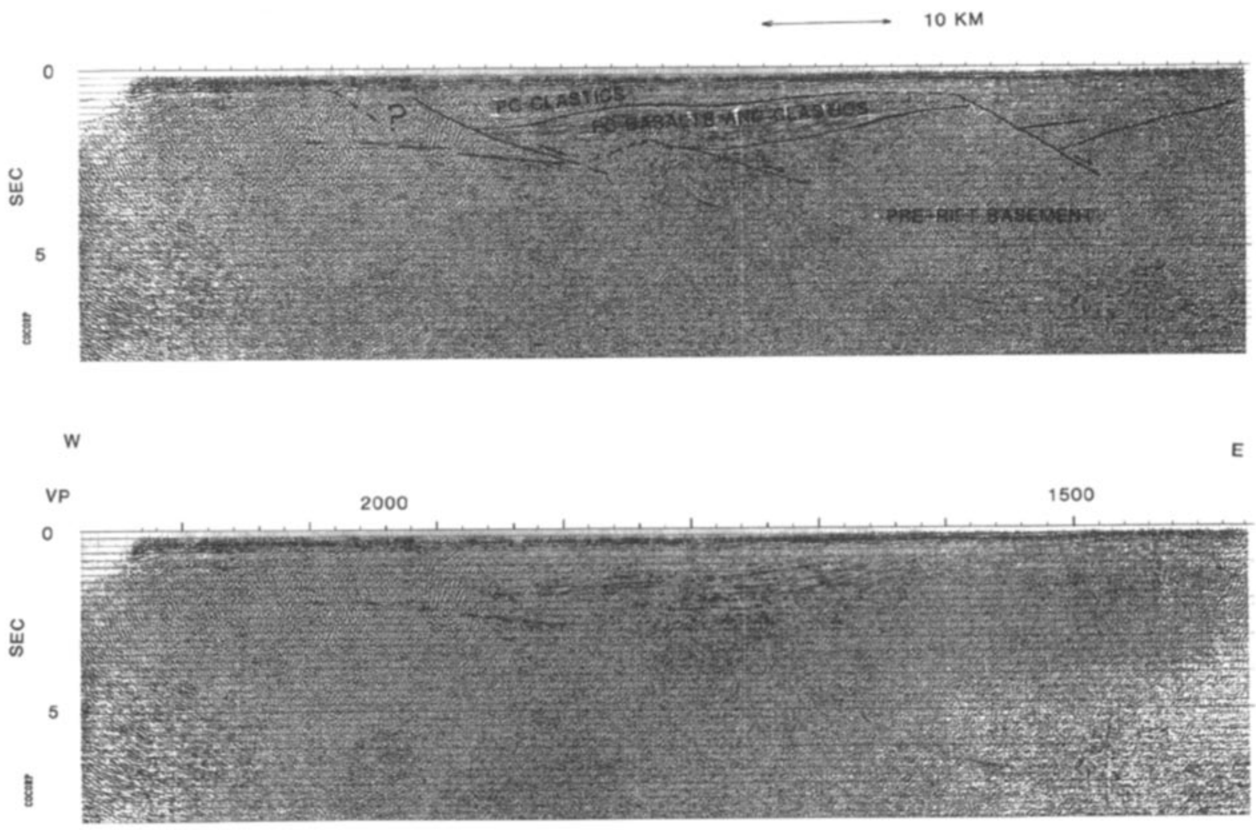

KANSAS LINE 1 (WESTERN HALF) MIGRATED

Figure 8 COCORP seismic reflection data for part of the survey across the MGA in northern Kansas (Serpa et al 1984), showing in more detail the rift basin model of Figure 7*a*.

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(1984) suggest a maximum depth of 8 km for the trough in northern Kansas, while geological data (Halls 1966), gravity data (Hinze et al 1982), and seismic refraction studies (Leutgert & Meyer 1982) indicate depths in excess of 10 km in the Lake Superior basin.

In addition to the vertical aspects of the structure of the rift system, several distinct lateral features can be noted. In particular, there are several places where the trend of the rift system is disrupted, as noted above. The largest offset occurs in southern Minnesota, where the MGA swings to the southeast and then back to the southwest. Some representations of this offset have shown it as a distinct break and have proposed a major transverse or transform fault (King & Zietz 1971, Craddock 1972, Chase & Gilmer 1973). However, the gravity map of the region clearly shows that the major gravity high is continuous, though narrower, throughout this segment. Thus, we consider it more probable that the rift system was deflected along preexisting structures, although the possibility of later faulting along the same structures cannot be discounted. The second major offset along the MGA occurs in southeastern Nebraska, at the Kansas border (Figures 1, 3). In this case there appears to be a definite discontinuity, and either the rift system was offset by later faulting or the rifting jumped along a preexisting structure. It is interesting to note that this offset coincides with extension of gravity and magnetic lineaments that trend SE-NW across Missouri and probably mark major structures in the older Proterozoic basement (Kisvarsanyi 1984, Arvidson et al 1984, Hildenbrand et al 1982). Interpretation of these structures has not progressed to the point where it can be stated whether they predate or postdate the midcontinent rift system. Other discontinuities occur at the southeast end of the mid-Michigan geophysical anomaly and between the east-continent anomalies. The significance of these are not known.

Deep Structure

Characteristically, the entire crust is disturbed in a rifting event, and expressions of this disturbance remain in paleorifts as a vestige of the thermal-tectonic processes (Ramberg & Morgan 1984). Seismic and gravity studies indicate that such is the case in the midcontinent rift system. Seismic refraction studies in the Lake Superior basin and along the MGA (e.g. Smith et al 1966, Cohen & Meyer 1966, Ocola & Meyer 1973, Leutgert & Meyer 1982) indicate higher crustal seismic velocities and a thicker crust. Halls (1982) has used crustal time terms derived from seismic experiments in the Lake Superior region to map crustal thickness. His results show a crust in central Lake Superior that reaches thicknesses in excess of 50 km, with arms of thickened crust extending southward from the ends of the lake along the MGA and mid-Michigan anomaly. COCORP seismic profiling

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in northern Kansas, across the MGA (Serpa et al 1984), indicates a disturbed crust. Serpa et al infer the presence of intrusions beneath the rift trough from seismic velocities, reflection character, and modeling of the gravity anomaly data. Similarly, Keller et al (1982) interpret the seismic results of Warren (1968) in the vicinity of the east-continent anomalies as evidence of disturbed crust.

Gravity modeling of the midcontinent rift system prior to the early 1970s was generally successful in explaining the entire anomaly (axial high with the marginal minima) with high-density volcanic material in an axial trough between adjacent clastic wedges of lower density rocks (Figures 7*b*,*c*). However, with the increasing availability of deep crustal seismic information and the realization that the entire crust remains disturbed as a result of the rifting event, it became apparent that a significant portion of the gravity high associated with the rift was due instead to increased density in the lower crust. Ocola & Meyer (1973), Hinze et al (1982), and Chandler et al (1982) ascribe the positive gravity anomalies in varying degrees to an increased crustal density, presumably caused by multiple mantle intrusions. These intrusions may have been initiated with the weakening of the crust under the extensional forces associated with the Keweenawan rifting event, and they probably served as feeders to the surface volcanic rocks. A typical example of gravity modeling that includes higher density lower crust is shown in Figure 9. The block of 3.0 g cm^{-3} density material shown is not intended to represent a homogenous unit of intruded material that is now anomalously denser and of higher velocity than the adjacent crust; instead, it should be taken to represent the average properties of a region of high-density intrusions. The shape of the high-density block is open to considerable modification because of ambiguities in modeling gravity data.

The gravity model across the western Lake Superior basin shown in Figure 9 incorporates the thickness of the crust beneath the rift zone that has been indicated by seismic studies. The thickened crust produces a regional gravity minimum that, when summed with the gravity high associated with the near-surface volcanic rocks filling the trough, results in negative anomalies bounding the central maximum. These marginal minima are represented in Figure 9 and are characteristically found along the linear gravity maximum of the midcontinent rift system. Commonly, these minima are related to the marginal clastic-rock-filled basins. However, White (1966) argues that in several areas of the Lake Superior basin and the MGA, the clastic rocks are inadequate to explain fully the observed minima. Thus, it follows that the minima at least partly reflect the broad gravity anomaly caused by an increased depth to Moho along the axis of the rift system.

Another aspect of the deep structure that has been discussed recently is

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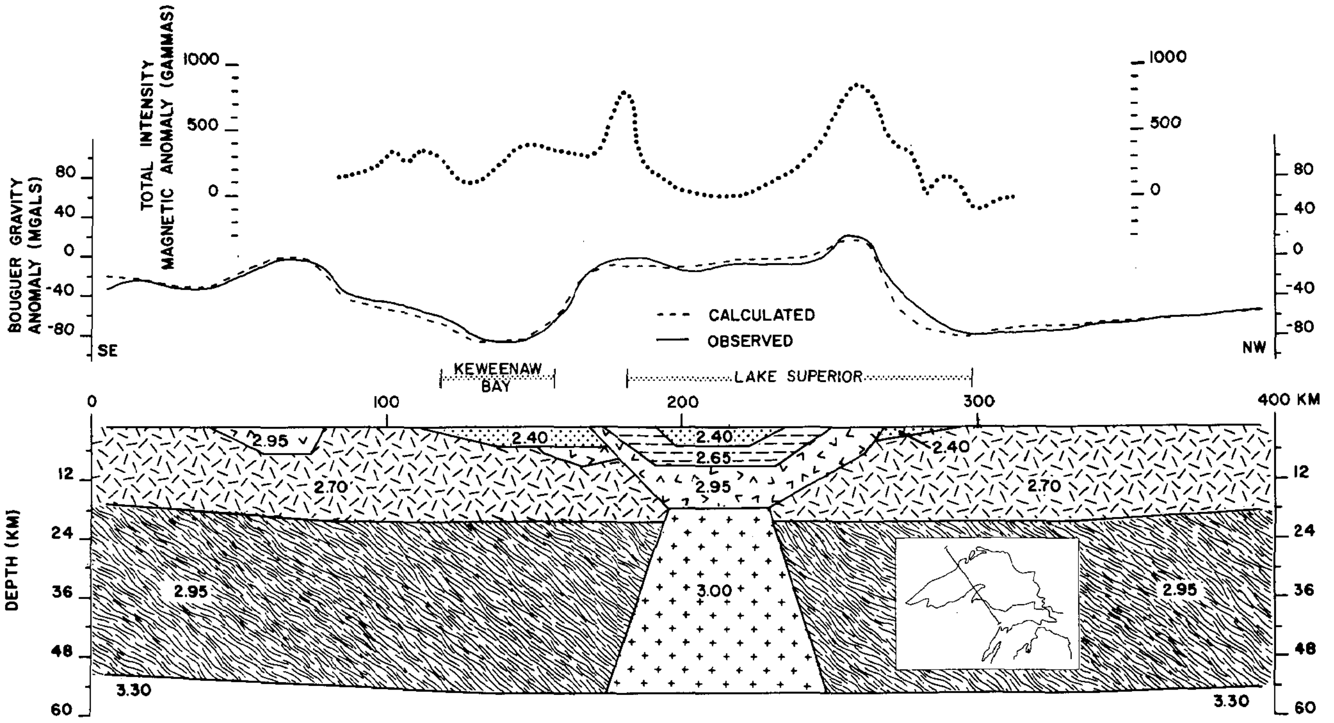

Figure 9 Model of gravity and magnetic profiles across western Lake Superior, showing the inferred deep structure of the rift at this point. Compare with cross sections in Figures 7*b*,*c*. Numbers indicated for geologic units are assumed densities in grams per cubic centimeter. Lithologies are identified by densities as follows: 2.70 = upper crust, 2.95 = lower crust and mafic extrusives, 3.3 = upper mantle, 2.65 = Oronto Group; 2.40 = Jacobsville Sandstone and Bayfield Group, and 3.0–3.05 = "hybrid" introduced crust. After Hinze et al (1982).

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the question of how far the older crust has separated during the rifting event. It is apparent that at the southern end (in Kansas), crustal separation must become negligible. Chandler (1983) has recently analyzed offsets of magnetic anomalies in the western Lake Superior region and concludes that crustal separation was about 60 km, consistent with earlier estimates of 65–75 km (Chase & Gilmer 1973) and 70 km (Sims et al 1980). The width of the anomaly in these areas is comparable with or slightly wider than the rest of the rift system (excluding the Lake Superior basin), which indicates that the rift never opened more than about 60–75 km.

Although many older rift systems show evidence of moderate to extensive reactivation, the midcontinent rift system shows little evidence of such behavior. There are a few minor structures along the rift system (Coons et al 1967, Hinze et al 1975) but no major faults that cut the Phanerozoic cover. In fact, there is very little evidence of a concentration of seismic activity today in the region occupied by the MGA or any other segment of the system (see, for example, York & Oliver 1976).

5. ORIGIN AND EVOLUTION OF THE RIFT SYSTEM

Although the overwhelming consensus is that the MGA, Lake Superior Basin, mid-Michigan anomaly, etc, represent continental rifting, there is much less agreement about the underlying causes for the rifting. In general, a rift can be classified as an active type, in which thermal perturbation of the mantle causes disturbance of the overlying crust, or a passive type, in which plate interaction causes internal tension (Baker & Morgan 1981). Because of the generally large volumes of basaltic magma associated with the midcontinent rift system, an active-type system seems more probable. However, because of the proximity of the Grenville Province, it is possible that extensional forces behind a continental collisional zone (Tapponnier & Molnar 1976, Tapponnier et al 1982) may have contributed significantly to the development of the rift.

In the context of an active model for the formation of the midcontinent rift system, several authors have proposed that the Lake Superior basin is situated over a former hotspot, that a rifting (rrr) triple junction formed, but that only two of the arms (the MGA and mid-Michigan segments) developed extensively. The third, failed arm in this model has not been uniquely identified, but suggestions include the Kapuskasing structural zone northeast of Lake Superior (Burke & Dewey 1973), the Coldwell Alkaline Complex trend north of Lake Superior (Mitchell & Platt 1978), and the Nipigon basin north of Lake Superior (Franklin et al 1980). All three of these possibilities have problems, however. As mentioned above,

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the Kapuskasing structural zone is an Archean crustal feature (Watson 1980, Percival & Card 1983). It is bounded on the southeast by an inferred northwest-dipping thrust fault that brought deep-seated Archean rocks to the surface. The time of uplift is uncertain; Watson (1980) suggested an Archean age, but geochronologic data summarized by Percival & Card (1983) suggest that a more probable time of uplift is Early Proterozoic because the structure is cut by roughly 1800-Myr-old alkaline-carbonatite complexes. In any case, it appears that the Kapuskasing structural zone predates development of the rift system by several hundred million years. Furthermore, since the Kapuskasing structure was apparently formed by thrusting (Percival & Card 1983), it is not a likely candidate for the failed third arm of the rift.

Igneous activity in the Nipigon region and alkaline complex development in general north of Lake Superior could be related to regional tension associated with development of the rift system, but it does not seem to be localized well enough to define a failed third arm of a rift system developing over a hotspot. Mitchell & Platt (1978) pointed out that mafic dike swarms in the Lake Superior region tend to fall into three groups, paralleling the northeast, northwest, and south shores of the lake. They suggested that the dikes may have been emplaced into zones of weakness developed during the start of rifting, and that the three orientations were consistent with the geometry of rifting over a hotspot. Thus, the presence of a well-defined third arm may not be a prerequisite for favoring the former existence of a hotspot in the Lake Superior region.

Models of passive origin, calling on intraplate tensional forces, have been proposed by Donaldson & Irving (1972), Gordon & Hempton (1983), Weiblen (1982), and Baer (1981). These are generally related to the stress field established in the North American plate in conjunction with the development of the Grenville Province, although details vary considerably depending on whether authors accept a plate collision model for the Grenville Province (e.g. Young 1980, Gordon & Hempton 1983) or call on some other mechanisms (e.g. Baer 1981, Weiblen 1982). One of the factors complicating attempts to fit models of this type into development of the Grenville Province is that a detailed understanding of the Grenville Province is still far from complete, and there is still considerable dispute as to whether there is an identifiable suture or what the actual processes were. Therefore, full understanding of the midcontinent rift system may have to await more complete understanding of the Grenville Province.

The midcontinent rift system is a very large crustal feature, comparable in scale with the current East African rift system (Figure 10). The African system is also very complex, with large segments having extensive igneous activity while others have very little igneous activity (Williams 1982), and

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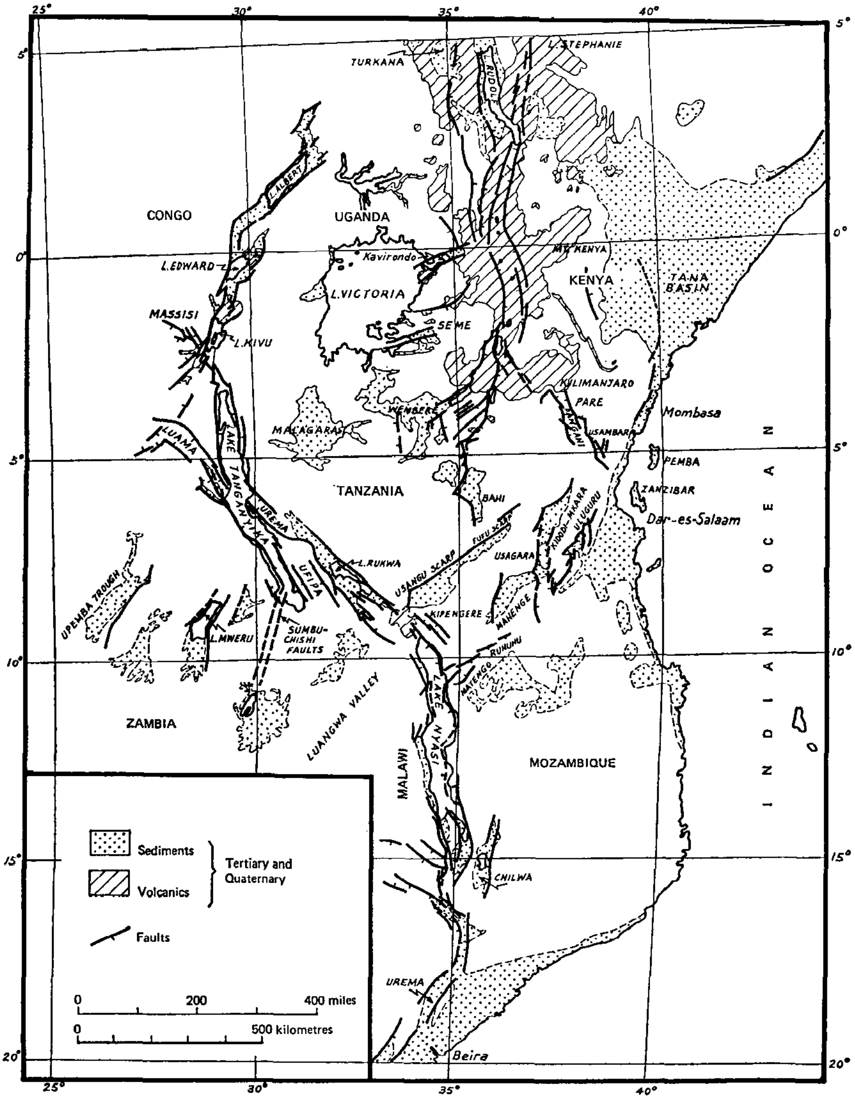

Figure 10 Map of the rift system in eastern Africa (Baker 1971). Note the complexity of the rift system, with numerous branches and satellite rifts. Compare with the midcontinent rift system for scale and complexity.

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with many branches and satellite rifts. There appears to be little doubt that active rifting is a major component of development of the East African system, and we believe that it is also reasonable to attribute much of the development of the midcontinent rift system to active, rather than passive, forces. In this context, several authors have pointed out that the development of the midcontinent rift system occurred at a time during which rifting was prevalent throughout the world (Stewart 1976, Sawkins 1976, Halls 1978), and thus it may be related to a major extensional stress field that developed at this time in continental lithosphere, perhaps as a result of widespread plate movement and breakup.

The proximity in time of the rifting and development of the Grenville system and others like it also suggests strongly that these tectonic regimes must be related to one another in a broad sense. Although there may be no direct connection between formation of the midcontinent rift system and development of the Grenville orogen, there appears to be strong evidence for a connection between later events in the rift system (such as later compression) and in the Grenville Province; full understanding of one probably cannot be accomplished without full understanding of the other.

In summary, the midcontinent rift system is a major feature of the North American continental lithosphere. It began about 1200 Myr ago, probably as an active rift system in conjunction with a period of continental breakup on a global scale. Interpretation of geophysical data suggests that much, if not most, of the rift system contains mafic intrusive rocks in a central root zone, with variable amounts of shallower intrusive mafic rocks, mafic volcanic rocks, and clastic sedimentary rocks. The latter rocks formed both in axial rift basins and (later) in regional basins that formed as the crust subsided along the rift system. Later structural modification of the rift system may have been influenced strongly by development of the nearby Grenville orogen. The rift system has been shown to contain valuable mineral deposits, and exploration along the buried portions of the rift may reveal other occurrences of nonferrous metals. In addition, the rift system is currently being examined by the petroleum industry as a possible source of oil and gas.

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