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STRUCTURE OF THE SOUTHERN KEWEENAWAN RIFT FROM COCORP SURVEYS ACROSS THE MIDCONTINENT GEOPHYSICAL ANOMALY IN NORTHEASTERN KANSAS

L. Serpa, T. Setzer, H. Farmer, L. Brown,
J. Oliver, S. Kaufman, and J. Sharp

Department of Geological Sciences,
Cornell University

Don W. Steeples

Kansas Geological Survey

Abstract. COCORP profiling across the midcontinent geophysical anomaly in northeastern Kansas reveals structural basins and other features of the Precambrian Keweenawan rift buried beneath the Phanerozoic cover. The 40-km-wide main basin is asymmetric, with a maximum depth of 3 km on the east and 8 km on the west. The basin fill is characterized by a lower layered sequence of strong continuous west dipping reflectors which may be correlated with Middle Keweenawan interbedded volcanic and clastic rocks exposed along the MGA in the Lake Superior region. Overlying this layered sequence is a zone of weak, discontinuous reflectors correlated here with the predominantly clastic rocks characteristic of the Upper Keweenawan sequence near Lake Superior. A second tilted but shallower basin lies to the east of the main basin and appears to be filled predominantly with clastic sedimentary rocks. The character of the seismic data, the seismic velocity distribution, and gravity modeling suggest that mafic intrusions lie beneath the main rift basin. Normal faults associated with the rift dip at moderate angles to the east. Palinspastic reconstruction indicates that the rift basin formed by the rotation of fault bounded blocks during crustal extension. Although reactivation of preexisting structures appears to have occurred in many other rifts profiled by COCORP, the evidence is inconclusive on this point in the case of the Kansas data. The structures mapped by COCORP surveys in Kansas and elsewhere suggest that asymmetric sequences of layered reflectors are characteristic, and perhaps diagnostic, of rift basin deposits in general.

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INTRODUCTION

In the fall of 1981, COCORP completed 317 km of deep seismic reflection profiling in northeastern Kansas. The principal purpose of this survey was to investigate the buried structure of the Precambrian Keweenawan rift associated with the midcontinent geophysical anomaly (MGA), and that topic is the focus of this paper. The COCORP Kansas survey also provided information on other aspects of the cratonic basement, such as the structure of the Nemaha ridge and the distribution of major horizons within the deep crust. These subjects are mentioned here but are discussed more thoroughly in the works of Brown et al. [1983a] and T. Setzer [manuscript in preparation, 1984].

The Kansas data are generally of good quality and provide much information on the subsurface. Many seismic events were

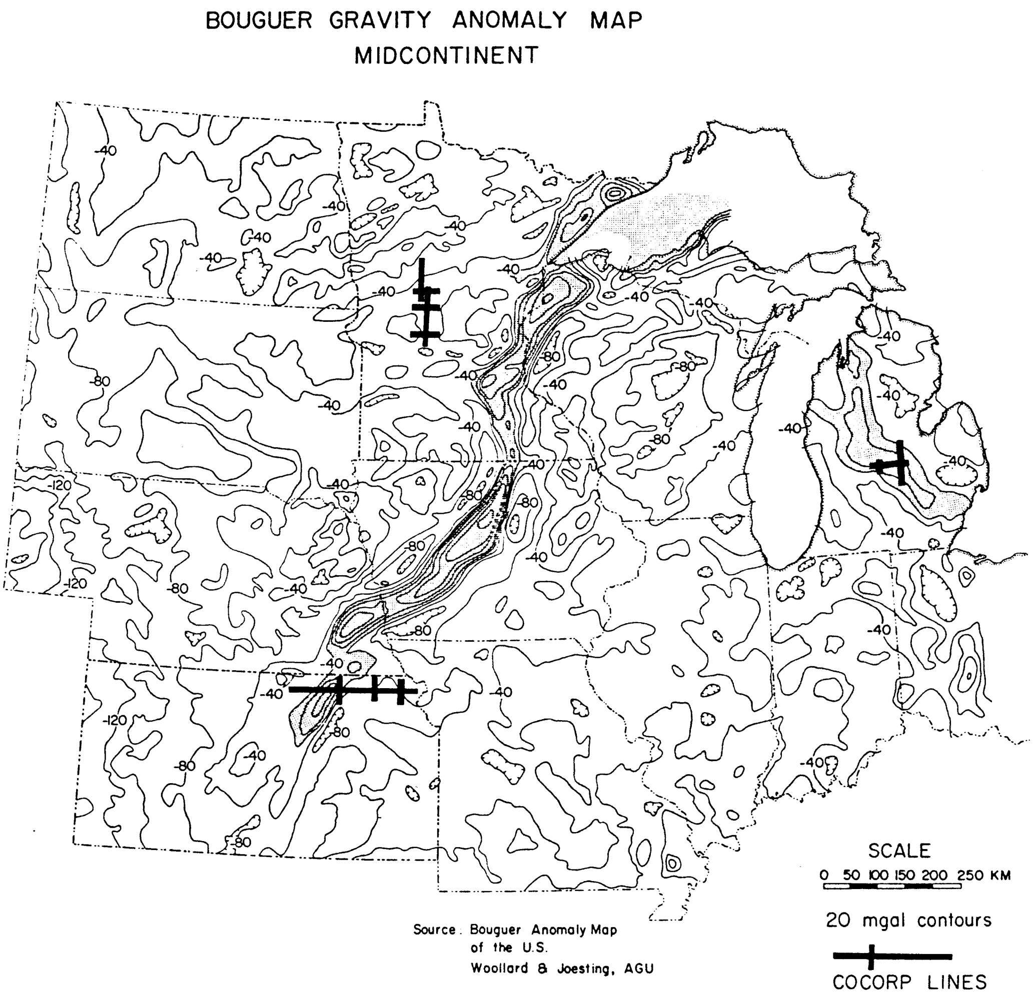


Fig. 1. Bouguer gravity anomaly map of the midcontintent [after Woollard and Joesting, 1964] showing the location of the Midcontinent Geophysical Anomaly (stippled). COCORP profiles indicated by heavy lines.

recorded at times corresponding to lower crustal depths, but these events were not traced to the surface in this survey. Thus there is some ambiguity in the interpretation of the deep events, and there probably will be until such tracing is accomplished.

The Precambrian Keweenawan rift is prominent in the seismic data. The asymmetric nature of the rift is clearly demonstrated by the dip of strong depositional layering within the basin. The rift structure and the gross stratigraphy of the basin deposits imaged in the COCORP data can be compared with Keweenawan rift features exposed near Lake Superior, 1200 km north of the Kansas profile, and with seismic data from other rift systems to provide guidelines for the recognition and interpretation of continental rift features in seismic reflection profiles.

Phanerozoic sedimentary rocks cover the rift system along most of its length but the rift can be traced in the subsurface along the trend of the MGA (Figure 1) from central Kansas to the southern tip of Lake Superior [e.g., King and Zietz, 1971]. Keweenawan igneous and sedimentary rocks crop out along the flanks of Lake Superior where they are correlated directly with the high gravity and aeromagnetic anomalies of the MGA [Thiel, 1956]. In the Kansas seismic profile, prominent west dipping layered reflectors, centered beneath the gravity high of the MGA, are interpreted as Keweenawan basalts and

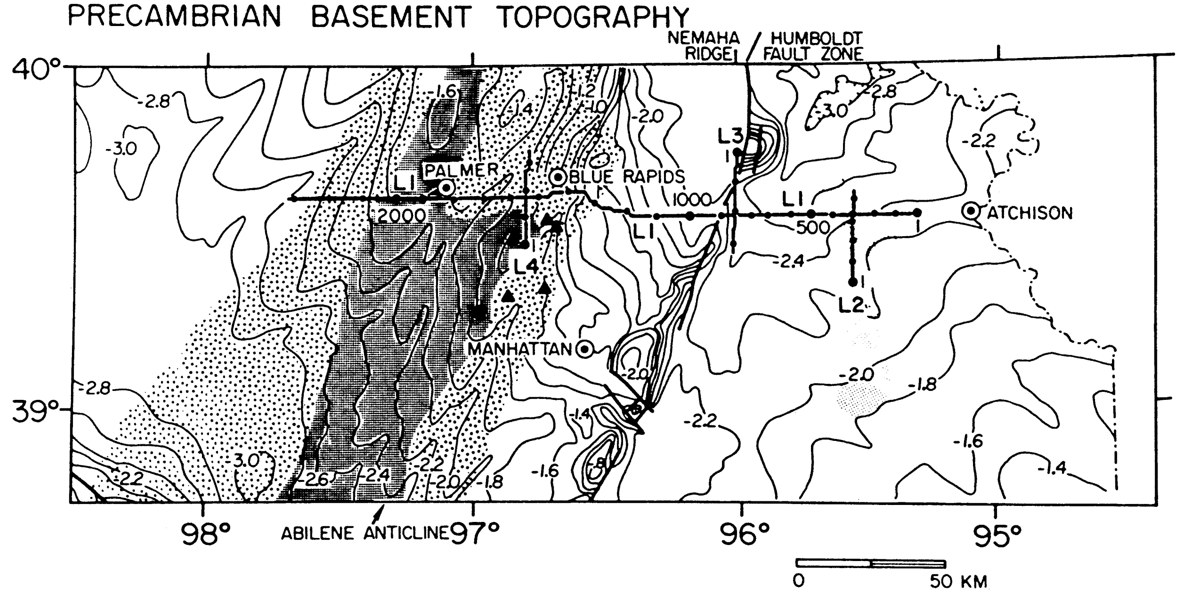


Fig. 2. Structural contours (in thousands of feet) at top of the Precambrian basement in northeastern Kansas [after Cole, 1976] showing the location of COCORP profiles. Numbers refer to VP locations of the surface. Dark shading shows the inferred extent of the mafic Clay formation with dots representing the Arkosic rocks of the Rice formation [Bickford et al., 1979]. The Clay and Rice formations are interpreted as Precambrian rift deposits and indicate the trend of the MGA. Light shading marks the trend of the Big Springs magnetic anomaly [Yarger, 1981].

clastic rocks deposited during the formation of the main rift basin. East dipping planar normal faults appear to truncate or offset basin deposits both in the main basin and in a second flanking basin.

The evolution of the rift basin in Kansas may be traced through a series of palinspastic reconstructions based on the basin stratigraphy imaged in the seismic data. Planar normal faults appear to have formed at relatively high angles (50° east dip) and to have rotated 15° toward the horizontal during crustal extension. This "domino style" of faulting has been observed through geological field studies in parts of the Rio Grande rift [Chamberlin, 1978] and the east African rift [Morton and Black, 1975].

Comparison of the Kansas data with COCORP data from other rifts suggests that asymmetry of basins and fault block rotations are typical. A dipping sequence of layered reflectors overlain by a zone of diffuse reflectors is common, and perhaps diagnostic, of rift basin deposits. The evidence is inconclusive in Kansas but seismic and other kinds of data suggest that reactivation of preexisting structures occurs often in connection with continental rifting.

In the following sections, we present a description of the seismic data and an interpretation of reflections seen in the profiles, particularly in the area of the MGA. This interpretation is used to construct a series of palinspastically restored cross sections which demonstrate a possible evolutionary sequence for the formation of the rift basin. The Kansas COCORP model is also compared to published models of the Keweenawan rift, as well as other continental rifts, to develop both a guide to the recognition of extensional basins in seismic data and a more comprehensive picture of the process of continental rifting.

DATA ACQUISITION AND PROCESSING

The COCORP Kansas survey (Figure 2) consists of 4 seismic profiles recorded during three field seasons between 1979 and 1981. Line 1 was shot in three parts, joined at vibrator point (VP) 810 and VP 1360, and provides 214 km of continuous east-west coverage beginning 18 km west of

TABLE 1. Data Acquisition Parameters

Parameter	Line 2 Line 1 VP 1-810	Lines 3 and 4 Line 1 VP 810 to 2334
Sampling rate, ms	4	8
Signal frequency, Hz	8-40	8-32
Sweep length, s	22	31
Record length, s	42	51
Sweeps per station	16	8
Spacing of vibrator points	every other station	every station
Station spacing	220	330
Spread configuraton	split spread, 12-84	off end
Offset	4	4

the Missouri border and extending to the western edge of the MGA. Three cross lines (103 km total length) provide three-dimensional control at key points along the main traverse. Line 2 intersects line 1 along the trend of the Big Springs magnetic anomaly at VP 300, line 3 intersects at VP 850 near the Humboldt fault zone, and line 4 intersects at VP 1550 along the eastern margin of the MGA. Line 4 and the west end of line 1 lie within the MGA and comprise the most recently completed profiles.

Data acquisition in Kansas was performed for COCORP by Petty Ray Geophysical Division, Geosource Inc. The resulting Vibroseis (TM Continental Oil) data were processed at Cornell University, using a MEGASEIS (TM Seiscom Delta) seismic processing system. After the completion of the first period of profiling (line 2 and VP's 1-810 of line 1), the survey parameters were evaluated and modified. Both the original survey parameters and the modified parameters used for the remainder of the survey are listed in Table 1. The modifications include a change from an asymmetrical split-spread configuration to a standard off-end geometry, an increase in the sampling interval, a decrease in the highest input frequency, and an increase in station spacing. These changes were designed primarily to improve the efficiency of the data acquisition and processing without significant loss of seismic information. However, an effort was also made to redesign the survey parameters to further enhance deep events which were apparent in the initial survey [Brown et al., 1983a]. New field equipment made possible the use of a sweep length longer than that used for the earlier surveying, thus more energy was put into the ground. Vibrating every station, rather than every other station as had been done in the initial part of the survey, increased the stacking fold from 2400% to 4800%. This increase in the stacking fold was to improve noise cancellation and to reduce spatial aliasing in the data. There does appear to be some improvement in the quality of the deep data associated with these modifications.

Routine data processing [e.g., Schilt et al., 1979] included demultiplexing and correlating the field records, sorting the resulting records into common midpoint gathers (CDPs), velocity analysis, muting, application of both elevation static and normal moveout corrections, and stacking to produce the seismic sections (Figure 3). Autocorrelations were examined to identify systematic noise and, as a result, predictive deconvolution was applied to line 2.

The minimum depth for imaging seismic events in the Kansas data is approximately 200 m (0.2 s) because the refracted and surface waves recorded at the near receiver (400 m from the source) appear to have traveled at velocities equal to, or greater than, 2 km/s. When these nonreflected arrivals are muted from the field files, the upper 0.2 s of data are left blank. This muting also reduces the stacking fold for about the upper 2 s of data on all the files.

A detailed analysis of seismic velocities was conducted on line 1 to assess the survey parameter changes (Table 1) and to provide guidelines for the optimum processing of deep crustal seismic data. The velocities resulting from this study are currently being reviewed in conjunction with velocities from several other COCORP sites to determine whether they may provide additional information on the nature of crustal rocks [L. Serpa, manu-

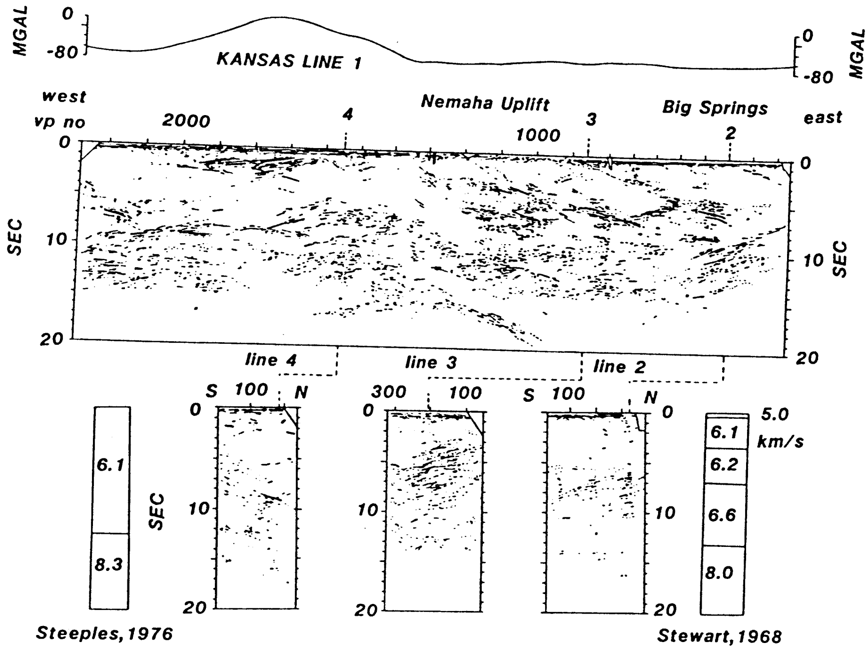


Fig. 3. Line drawings of COCORP lines in northeastern Kansas. Gravity profile across line 1 from Woollard [1958] and seismic refraction models from northwestern Kansas [Steeples, 1976] and northwestern Missouri [Stewart, 1968].

script in preparation, 1984]. This study is not yet complete. However a preliminary evaluation of the data suggests that it is possible to determine statistically consistent velocities from COCORP data to depths of at least 20 km when the 10 km far offset is used during the survey. For the data interpretation presented in the following sections, the stacking velocities are correlated with changes in the character of reflections seen on the final processed sections in an effort to map mafic intrusions in the area of the rift. Interval velocities were calculated [Dix, 1955] from the stacking velocities and these interval velocities were used to prepare migrated time sections (see, for example, Figure 6) and both migrated and unmigrated depth sections for use during data interpretation.

DATA INTERPRETATION

General Characteristics East of the Rift

Figure 3 is a schematic drawing of all the COCORP seismic sections from the Kansas study (see also Brown et al. [1983a] and T. Setzer [manuscript in preparation, 1984]. One of the most prominent features on the seismic sections is a wedge of strong, layered reflections centered beneath the axis of the approximately 70 mGal Bouguer gravity high of the MGA (VP 1760 on line 1). These strong reflectors appear to define the main basin of the Keweenawan rift, which is the focus of this paper.

Other shallow features of interest along Kansas line 1 include the Nemaha ridge, the Humboldt fault zone, and the Big Springs magnetic anomaly. T. Setzer [manuscript in preparation, 1984) analyzed the seismic data in the area of the Nemaha ridge and the Humboldt fault zone and Brown et al. [1983a] described the general character of the seismic data east of VP 1360. The following is primarily a summary of those works.

The flat-lying reflections between 0.2 and 0.6 s in the seismic sections represent the Phanerozoic sedimentary cover. Up to 2 km of Paleozoic shallow marine rocks have been mapped from well data and shallow seismic reflection profiles [Merriam, 1963; Steeples, 1981] in the area of the COCORP survey. On line 1 reflections from these sedimentary layers are truncated at the Humboldt fault zone (VP 910) and are absent directly over the Nemaha Ridge between VP 910 and VP 1300. As a result of the late Paleozoic uplift of the basement ridge, the overlying sedimentary rocks are shallower than the minimum depth of imaging for this survey. The Paleozoic reflectors dip gently to the west without apparent offset on the western side of the Nemaha ridge. Offsets, bifurcations, and lateral variations of reflections in this upper section of the data suggest the presence of minor faults and changes in stratigraphic thicknesses of the order of a few tens of meters. However, the Humboldt fault zone is the only place where there is evidence for major structural disruption of the Phanerozoic sequence.

Within the Precambrian basement, the COCORP profiles reveal regions of similar seismic character which appear to be nearly continuous across all of the lines and which may correspond to major structural or lithological provinces within the cratonic crust. The seismic character of the data changes both horizontally and vertically within these regions, but the most striking changes appear to occur vertically across the boundaries of the regions.

The uppermost boundary within the Precambrian basement occurs at approximately 5 s (15 km) on the COCORP profiles and separates an overlying section containing relatively few continuous or strong seismic events from an underlying zone of numerous reflections and diffractions. T. Setzer (manuscript in preparation, 1984) analyzed the upper, nearly transparent region in detail and identified a series of weak reflectors, interpreted as faults, which appear to dip between 25° and 35° east in the areas of the Nemaha ridge, the Humboldt fault zone, and the Big Springs magnetic anomaly. A few other seismic events are recognized in this upper crustal section, but they have not been traced to identifiable geologic sequences for interpretation [Brown et al., 1983a].

Well samples and basement cores [Bickford et al., 1979, 1981; Cole and Ebanks, 1974; Steeples and Bickford, 1981] combined with geophysical data [Woollard, 1943, 1958; Steeples, 1976; Steeples et al., 1979; Yarger, 1981] provide the only sources of information on the distribution of crystalline basement rocks in Kansas (Figure 2). The diffuse seismic character of this upper basement may be related to the 1.6-b.y.-old granite gneiss encountered in over 80% of the basement wells outside of the MGA (the northern terrane of Bickford et al. [1981]). A relatively transparent seismic sequence is observed in parts of other COCORP profiles where they cross either highly deformed surface rocks, such as in the Adirondacks [Klemperer et al., 1983; Brown et al., 1983b] and the northern side of the Ouachitas [Lillie et al., 1983; Nelson et al., 1982], or large intrusive complexes, such as the Wichita Mountains [Brewer et al., 1983] and the Giant's range batholith [Gibbs et al., 1984]. The basement rocks of the Northern terrane [Bickford et al., 1981] are both intrusive and highly deformed. Thus these observations from other COCORP sites are consistent with the suggestion by Brown et al. [1983a] that the transparent upper zone of the Kansas seismic data may be related to the shallow granite gneisses.

The transparent zone is underlain by a region of complex reflections and diffractions. Prominent events appear to come within 7 km (2.5 s) of the surface at the north end of line 3 and between VP's 1200 and 1300 on line 1 but are still too deep for geologic identification. Possible interpretations for these deeper events, outlined by Brown et al. [1983a], include (1) gneissic banding, (2) interlayering of granite and restites related to anatexis, and (3) diffractions and layering related to mafic intrusions. Xenoliths found in Cretaceous kimberlites [Brookins and Meyer, 1974; Brookins and Wood, 1970] near the southern end of line 4 indicate that amphibolites and granulites derived from both igneous and sedimentary sources exist within the lower crust and the juxtaposition of some of these different lithologic units may produce impedance contrasts sufficient to give the deep reflection patterns.

There are few seismic events below about 15 s (45 km) on any of the profiles (Figures 3 and 4). This change from an overlying section containing many reflections to a lower zone of virtually no reflections appears to occur at a time roughly correlative with the expected base of the crust (i.e., 40 km; Steeples [1976] and Stewart [1968]). This is a common observation on many COCORP profiles [e.g., Oliver et al., 1976; Schilt et al., 1979; Brown et al., 1980; Allmendinger et al., 1982]. In Kansas there is evidence to indicate that this change in seismic character at the expected base of the crust is not due to energy attenuation with depth. Deeper seismic horizons indicate that measureable energy has, in

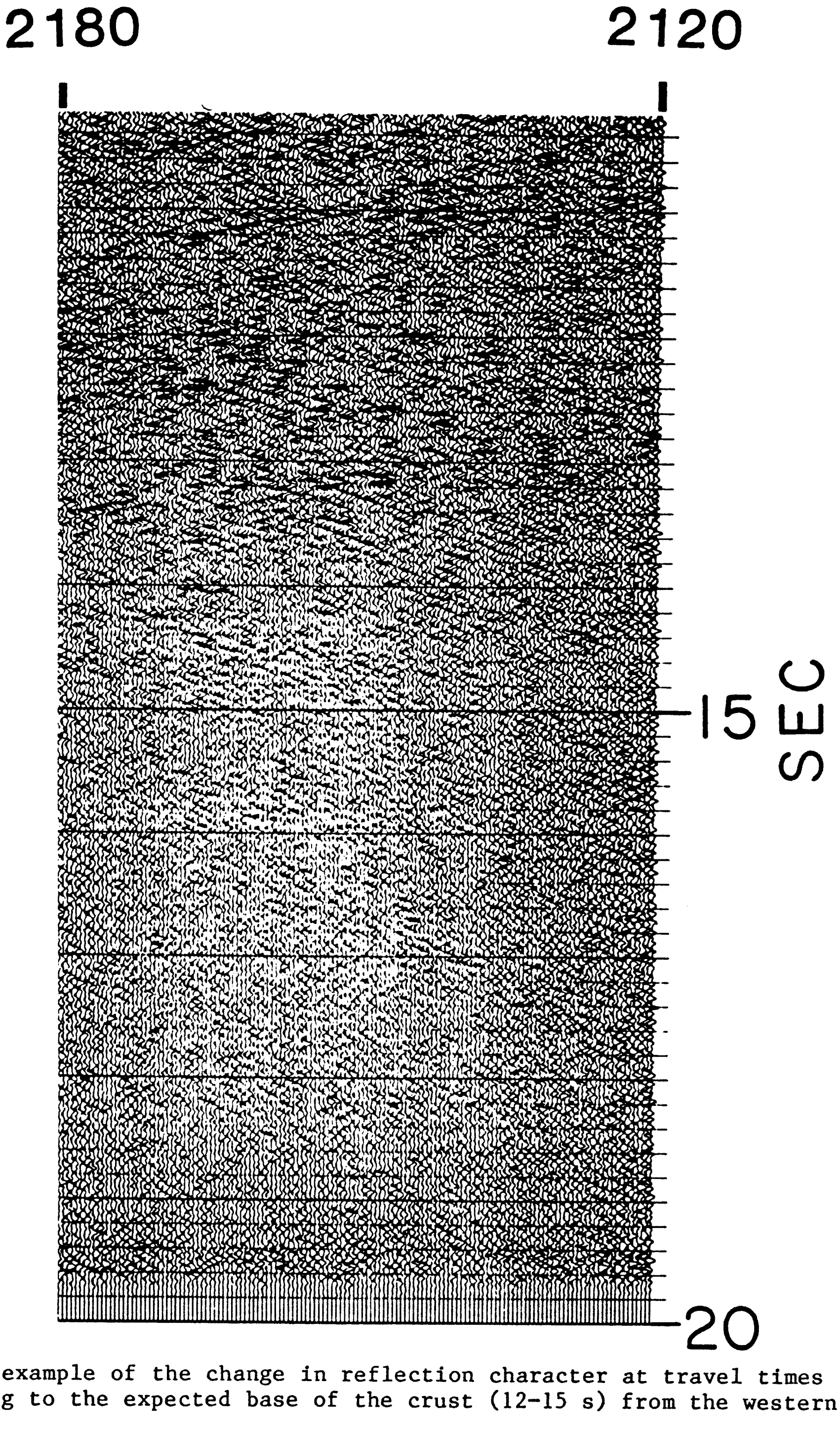


Fig. 4. An example of the change in reflection character at travel times corresponding to the expected base of the crust (12-15 s) from the western end of line 1.

places, penetrated 55-60 km through, or within, the Kansas crust. A prominent event can be identified at 16.5 s on both lines 1 and 4 at their intersection. This event appears to represent energy reflected vertically from an interface 55 km deep within the upper mantle. An apparent diffraction can be traced clearly to 20 s (the length of the data) beneath VP 1000 [Brown et al., 1983a]. This diffraction

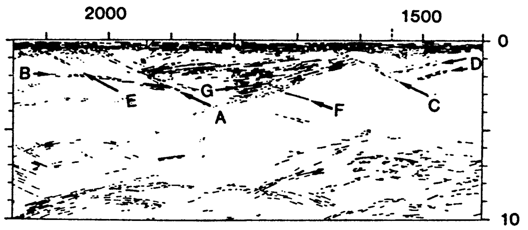


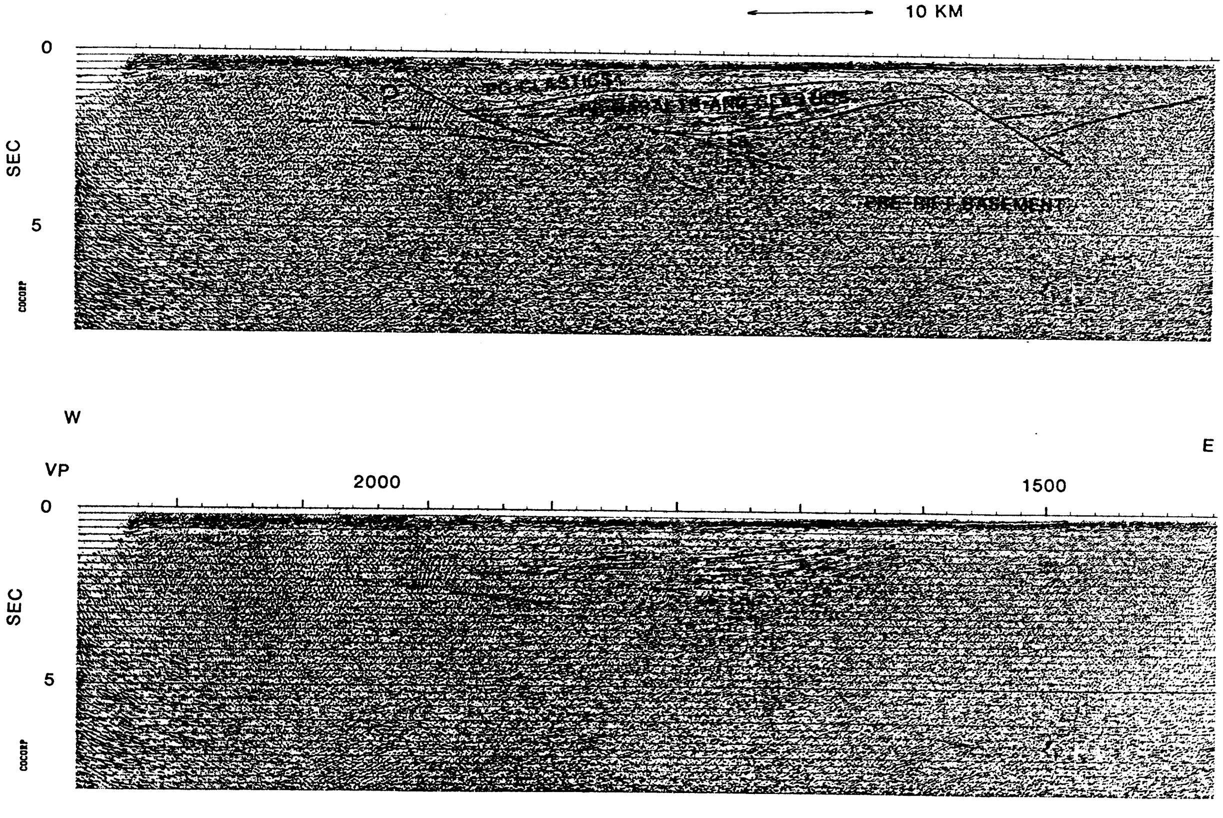
Fig. 5. Line drawing display of the upper section of line 1 in the area of the MGA. Letters are discussed in the text.

source cannot be constrained three-dimensionally by the seismic data but the curvature of the diffraction is consistent with seismic velocities of 6 km/s or greater along the travel path. Thus the energy appears to have traveled from the source a radial distance of at least 60 km through the Kansas crust. In Kansas, it appears that COCORP can normally record events from throughout the crust. The loss of reflections at approximately 15 s may therefore be related to changes in the physical character of the rocks at the transition from the crust to the mantle.

Southern Keweenawan Rift

Perhaps the most prominent feature in the seismic data is the 40-km-wide wedge of layered reflections centered about the axis of the MGA at VP 1760. The location, layered character, and fanlike geometry of these events strongly suggest that they represent strata deposited into the actively subsiding Keweenawan rift basin. These layered reflectors dip approximately 25° west and extend to a depth of 3 km (1.2 s) on the eastern side of the basin and reach a maximum depth of about 8 km (3.0 s) on the western side to define a clearly asymmetric basin.

There are two distinct seismic units within the basin, the layered reflections and an overlying zone of weak reflections (Figure 5). The seismic character of these two units suggests a correlation



KANSAS LINE 1 (WESTERN HALF) MIGRATED

Fig. 6. Migrated seismic data from line 1 in the area of the MGA. The upper section shows the interpretation and the lower section is unmarked.

with the Middle and Upper Keweenawan sequences, respectively, which have been described by Halls [1966] for rocks exposed near Lake Superior. The Middle Keweenawan consists of interbedded basalts and clastic rocks whose contacts might be expected to have high impedance contrasts, thus providing a reasonable explanation for the continuity and the high amplitudes characterizing the lower basin sequence in Kansas. The Upper Keweenawan consists primarily of massive sandstones and conglomerates which are less likely to produce strong reflections [Sangree and Widmier, 1977] and thus are correlated here with the weak reflectors in the upper part of the Kansas basin. Mafic igneous and clastic sedimentary rocks have been encountered in basement wells along the trend of the MGA in Kansas [Bickford et al., 1979] and support the interpretation of the basin fill comprising a lower unit of interbedded basalts and clastic rocks which reach a maximum thickness of approximately 5 km and an upper unit of predominantly clastic rocks reaching a maximum thickness of 3 km (Figure 6).

Two west dipping events (D on Figure 5) appear geometrically similar to the layered events within the main basin and thus are interpreted as mafic rocks deposited in a basin located to the east of the main basin. This eastern rift basin appears to contain significantly fewer reflectors than the main basin, and thus the eastern basin fill is suggested to be a predominantly clastic sequence with some minor basalt flows.

Distinct east dipping reflectors, interpreted as faults, truncate the main basalt sequence on both the eastern and western margins. On the west, fault reflection A (Figures 5 and 7) also truncates a high amplitude event B beneath the basin. On the east, fault reflection C truncates two events D to the east of the basin. A similar east dipping event E is observed in the shallow basement between VP 2030 and VP 2100, which may also represent a fault but it does not appear to offset reflector B.

Migration (Figure 6) of the seismic data appears to steepen and enhance these inferred fault plane reflections; however their appearance does not change significantly. Directly beneath the basin is a prominent east dipping reflection F, which crosses event G and layered reflections below G. Migration does not resolve this crossing relationship which suggests that three-dimensional complexities and/or multiples may be involved. Because it trends subparallel to the other inferred faults (A, C, and E) and appears to truncate layering above G, event F is here interpreted as a fault. The west dipping layers begining at G and extending down to about 5 s in the seismic section appear to occur at twice the travel times of the shallow layered arrivals and to dip at twice the angle of the shallower events. Therefore event G is interpreted as the first direct multiple and the deeper layering is attributed to multiple reflections from the shallow basalts.

The faults dip approximately 30° east in the plane of the migrated section and, if they strike parallel to the MGA, they have a true dip of about 35° east southeast. The sense of displacement across C and F indicate that they are normal faults. The layered reflectors within the basin curve upward along A indicating possible drag folding associated with normal fault displacement on A. The fault reflectors can be traced relatively continuously to depths of 8 to 10 km and occasionally can be projected into discontinuous deeper events at middle or lower crustal levels. The only curvature which can be detected along the faults occurs on fault A (Figure 7) where it passes beneath the layered reflectors in the basin. This curvature of A does not exist on the depth sections and thus appears to be a velocity "pull-up" resulting from the change in material properties above the fault. Seismic energy traveling to the shallow part of the fault only passes through the low-velocity clastic rocks; while the deeper path includes the high-velocity basalt sequence. Such marked changes in velocity do not appear to occur above the remaining faults, and thus the faults can be traced to depths of approximately 10 km without significant curvature, suggesting a planar or domino style of faulting.

Weak east dipping events are observed in the shallow basement across the Nemaha ridge and Humboldt fault zone which T. Setzer [manuscript in preparation, 1983] interprets as normal faults developed during Keweenawan rifting and reactivated during the Paleozoic uplift of the Nemaha ridge. Between VP's 1200 and 1400 a transparent seismic zone extends from beneath the eastern basin into the lower crust. This deep transparent zone lies between the projections of two interpreted faults on the east side of the rift basin

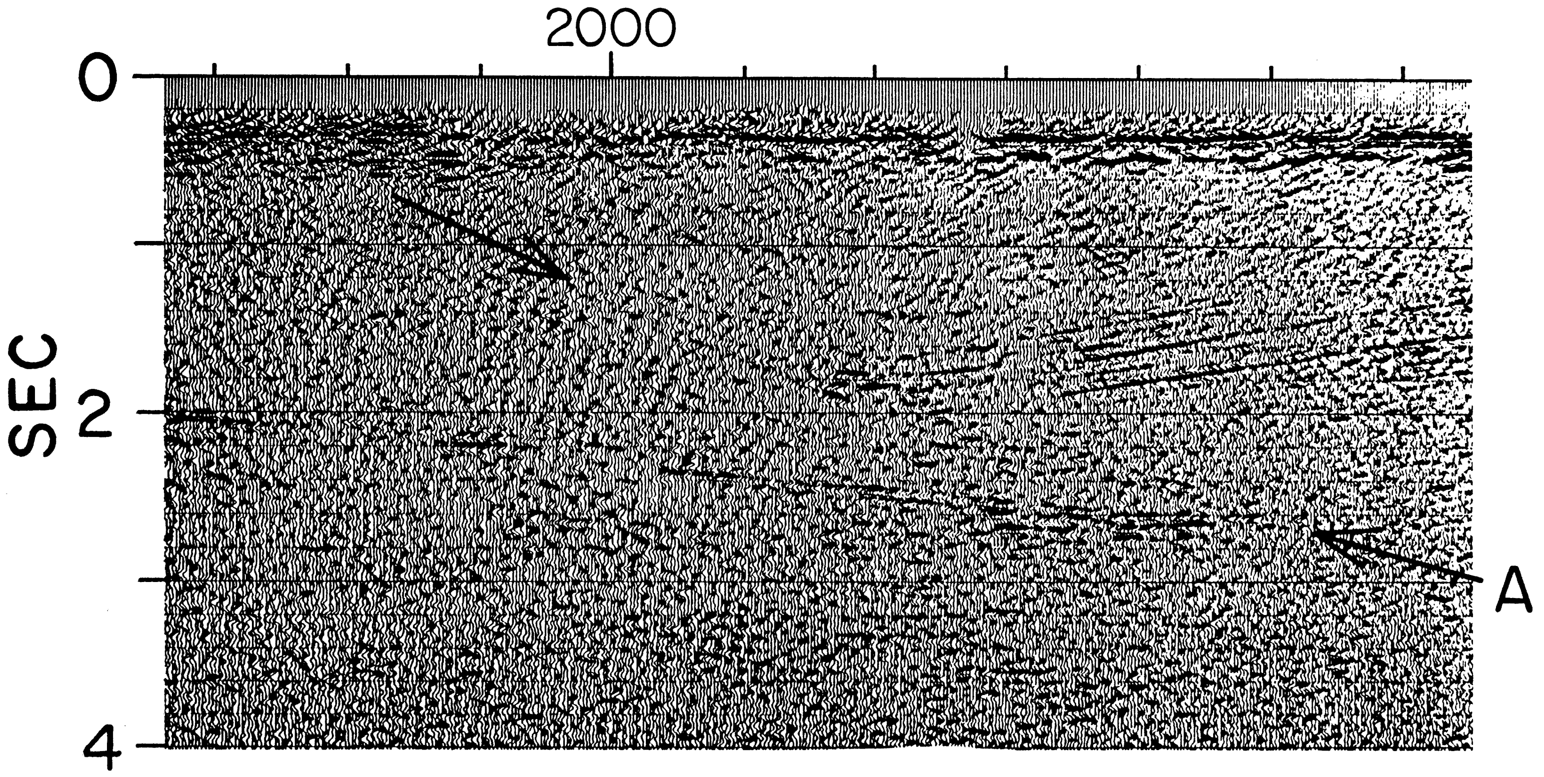


Fig. 7. Large-scale display of migrated seismic data from line 1 on the western side of the MGA. See text for discussion.

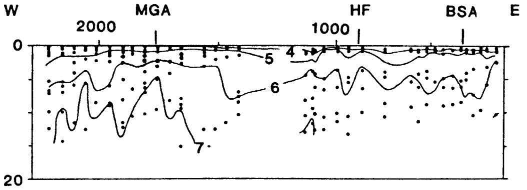


Fig. 8. Contours of stacking velocities across line 1 (contour interval 1 km/s). Dark shading indicates velocities greater than 7 km/s and light shading indicates the location of the layered basin reflections. Dots indicate the location of velocity determinations.

in a manner which suggests that throughgoing crustal faults may be present. However, this zone also coincides with an area of reduced stack fold and crooked line geometry, both of which may cause a deterioration in the quality of the seismic data. Thus the deep geometry of the normal faults in Kansas is not yet clear.

The interpretation of event B to the west of the main basin (Figure 5) is problematic. The prominence and continuity of B suggest that it may have a source similar to the layered reflections to the east. However, to interpret B as a continuation of the basalt sequence, offset by fault A, would require that A be a reverse fault. This interpretation is clearly inconsistent with the sense of drag folding on the eastern side of A and the lack of reverse offset elsewhere in the basin area. If B represents a western continuation of the basin, then, to be consistent with the normal faulting across A, it must have formed prior to the deposition of the layered basalt sequence above it. This interpretation would suggest that the basalts were deposited into a preexisting basin which may have formed prior to or during the earliest stage of rifting. Alternatively, B may represent an intrabasement feature such as (1) a sill, similar to the Duluth gabbro in Lake Superior [Weiblen and Morey, 1980], (2) a low angle detachment similar to those seen in the Basin and Range [Allmendinger et al., 1983; McDonald, 1976], or (3) a coincidental structure which is not related to the rifting event. The proximity of B to the rift basin suggests that it is related to Keweenawan event. There is no evidence that inferred fault E (Figure 5) cuts B thus it seems likely that B did not form prior to the faulting. Although continued data analysis and/or further seismic profiling to the west of the MGA may provide a less ambiguous explanation, at this time the interpretation of event B as either an intrusion or a detachment is preferred.

Beneath the rift basin there is an increase in the measured seismic velocities which may be related to mafic intrusions within the deeper crust. Figure 8 shows the stacking velocities used to process Kansas line 1. There is a considerable amount of variation in the individual velocity picks, but distinctly higher velocities were found to the west of VP 1500. Stacking velocities in excess of 7 km/s are absent above 10 s to the east of VP 1500 and common to the west. The greatest increase in the shallow stacking velocities is observed directly beneath the gravity maxima where midcrustal reflections, which are common to the east of the MGA (Figure 3), appear to die out. This loss of the midcrustal reflections coupled with the apparent increase in stacking velocities beneath the basin suggests the presence of anomalous material within the deep crust.

Analysis of P wave residuals recorded by the Kansas seismological network in the area of the MGA [D. W. Steeples and Miller, manuscript in preparation, 1984] provides additional evidence for high crustal velocities beneath the rift basin. Arrivals which travel through the crust (Pg) across the MGA from earthquakes occuring between 120 and 200 km from the network are consistently early relative to arrivals which do not cross the MGA. Preliminary estimates of these travel time variations indicate an increase in crustal velocity of up to 1 km/s is possible within the MGA.

In the northern Keweenawan rift Ocola and Meyer [1973] have interpreted the presence of mafic intrusions beneath the

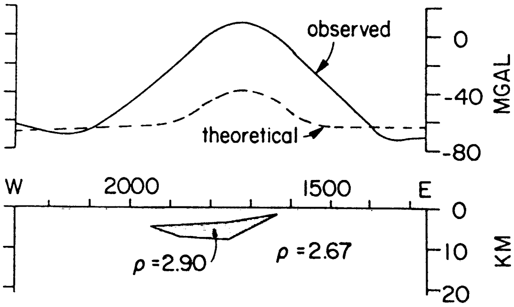
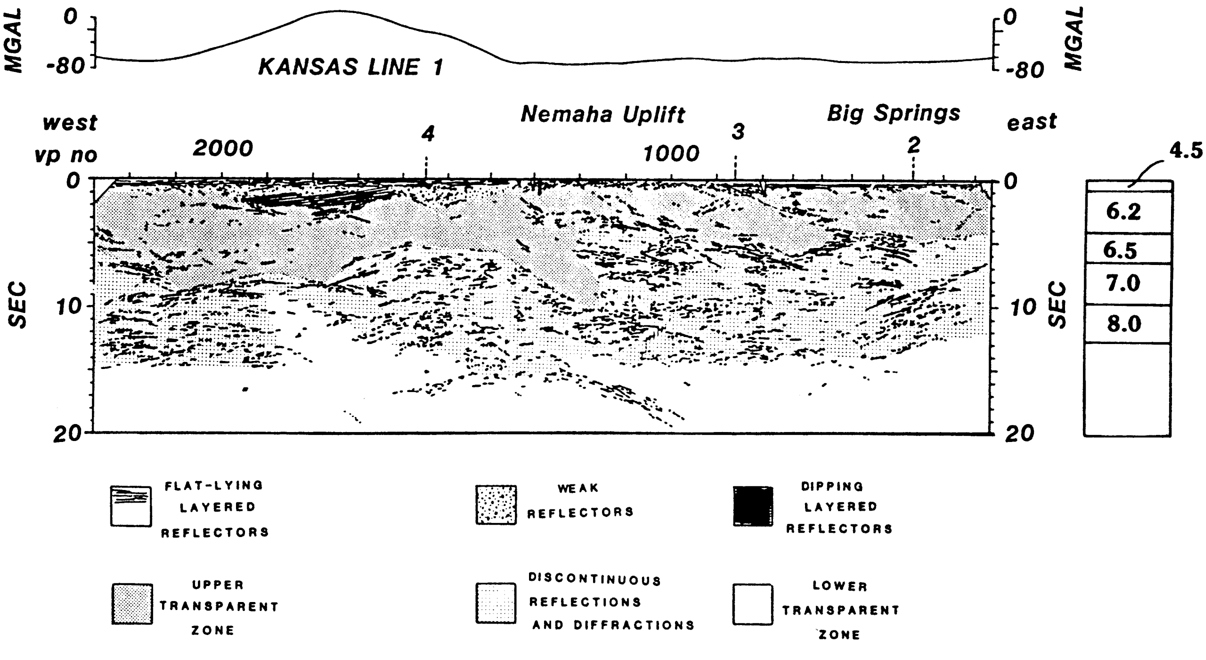


Fig. 9. Gravity model of rift basin showing the contribution of the interpreted basalts to the gravity high.

rift basin and suggested that these intrusions, rather than the basalts within the basin, provide the main source for the gravity high along the MGA. A gravity model (Figure 9) of the interpreted basalt sequence was therefore prepared from the Kansas data to assess the relative contributions of the basalts and the inferred intrusions to the gravity high. A density of 2.90 g/cm^3 was assumed for the basalts in contrast with a surrounding crustal density of 2.67 g/cm^3. The overlying low-density sedimentary material was omitted in order to determine the maximum possible amplitude of the gravity anomaly which can be attributed to the basalts. The results indicate that the basalts within the basin cannot account for more than one third of the nearly 70 mGal relief of the gravity high. If the source of the gravity high is within the basin, it would have to be entirely filled with basalts as has been suggested by King and Zietz [1971]. However, the presence of an entirely basalt filled basin in Kansas is inconsistent with the known Keweenawan stratigraphy [Halls, 1966], the prevalence of Precambrian arkoses in the Kansas well data [Bickford et al., 1979], and the seismic character of the basin fill seen in the COCORP data. The major contribution to the gravity high appears to come from deeper intrusive material beneath the basin. The shape of the gravity anomaly does not appear to reflect either the configuration of the rift basin or the thickness of the basin deposits.

DISCUSSION

The major features of the crust in northeastern Kansas as defined by the COCORP data (Figure 10) appear to be related primarily to either the Precambrian Keweenawan rift or to the older craton surrounding the rift. The only significant Phanerozoic structure identified in the seismic data is the Nemaha Ridge whose formation appears to have reactivated preexisting Keweenawan faults [T. Setzer, manuscript in preparation, 1984]. Within the area of the rift the seismic data are dominated by relatively continuous, moderately dipping events. In contrast, the seismic data from outside the rift are highly complex, containing numerous arcuate diffractions and both dipping and flat-lying reflec-



MAJOR SEISMIC CHARACTERISTICS OF KANSAS LINE 1

Fig. 10. General interpretation of major crustal structures observed in COCORP line 1. Shading indicates areas of similar seismic character as discussed in the text.

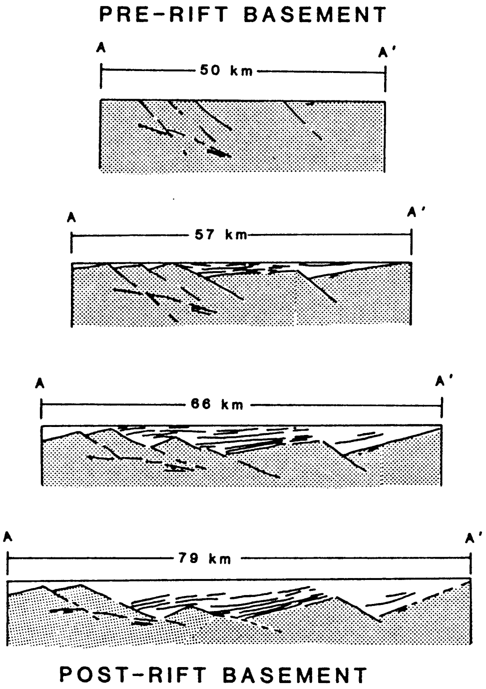


Fig. 11. Geologic model for the present rift structure (bottom) and the interpreted evolutionary history during the opening of the rift basin determined by palinspastic reconstruction.

tions [Brown et al., 1983a]. East of the MGA the seismic character of the crustal rocks appears to change dramatically at about 5 s (15 km). Another major change in the seismic character occurs near the base of the crust at about 15 s (45 km) and appears to mark the transition into upper mantle rocks.

The most striking feature in the seismic data is the sequence of layered reflectors from within the Keweenawan rift basin. This layering appears to define both the shape of the main basin and the attitude of gross stratigraphic units within the basin. Moderately east dipping normal faults which truncate or offset the basin deposits can be traced without apparent curvature to depths of approximately 10 km. The uniform dip direction of the planar faults suggests that crustal extension was accommodated by fault block rotations. To evaluate this hypothesis, a series of palinspastically restored cross sections were prepared across the basin (Figure 11). Each cross section shows a succeedingly deeper layer within the basin rotated back to the horizontal surface where it is believed to have been deposited during the formation of the rift. This reconstruction suggests that the basin faults initially formed with approximately 50° east dip and subsequently rotated 15° during crustal extension to their present position. The estimated 58% extension across the basin appears to have been accommodated by planar normal faulting accompanying the deposition of volcanic and sedimentary rocks into the rift basin.

The results of this COCORP study provide a basis for reanalysis of proposed rift models along the entire Keweenawan system. The seismic reflection data provide a reasonable interpretation for the shallow rift structure, the relative thicknesses of the major depositional units, and the nature of crust beneath the basin. Figure 12 compares the Keweenawan basin in Kansas with models proposed for the northern part of the rift. The model of Ocola and Meyer [1973] attributes the main source of the gravity anomaly to high density material intruding the crust. In contrast, King and Zietz [1971] model the source of the gravity high as mafic material (density of 3.0 g/cm^3) completely filling a shallow basin. The change of reflection character within the Kansas basin and the prevalence of arkosic sandstones in the Kansas wells [Bickford et al., 1979; Cole and Ebanks, 1974] does not support the interpretation of an entirely basalt filled basin in Kansas. Gravity modeling of the interpreted basalt sequence in Kansas indicates a deep source

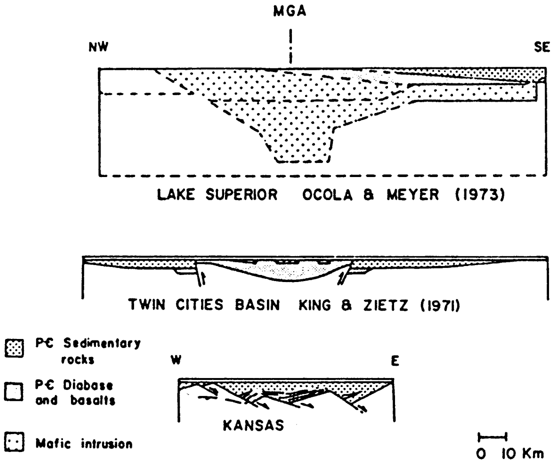


Fig. 12. Comparison of Kansas rift basin (bottom) with models of the northern Keweenawan rift.

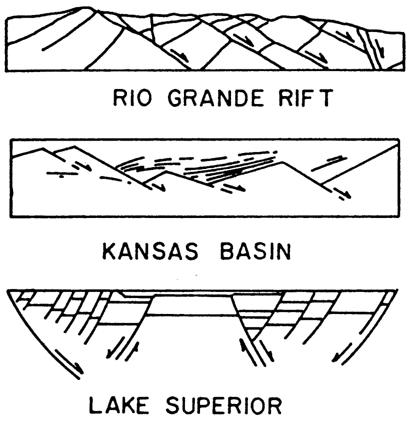


Fig. 13. Comparison of Kansas rift model (center) with proposed rift structure across Lake Superior [Weiblen and Morey, 1980] and mapped structures in the Rio Grande Rift [Chamberlain, 1978; Chapin et al., 1978].

for much of the gravity high similar to that interpreted by Ocola and Meyer.

Fault geometry is not constrained by the potential field and seismic refraction data used for the models of King and Zietz [1971] and Ocola and Meyer [1973]. The model (Figure 13) by Weiblen and Morey [1980], however, is based on petrological and structural analysis in the area of the Duluth gabbro, where they also find evidence for normal fault block rotations. They infer that the normal faults are listric. In the Kansas seismic data the faults do not appear to have any pronounced curvature and are interpreted as planar faults which have rotated (Figure 11) to produce surface structures similar to those observed by Weiblen and Morey [1980] to the north.

Many classical rift models have emphasized graben subsidence along steeply dipping normal faults [e.g., Illies, 1970; Bott, 1976; Stewart, 1971]. However, the structure of the rift seen in the Kansas data may be more typical of continental rifts. Although the faults in Kansas appear to have formed at a relatively high angle, subsequent rotation of the fault blocks produced moderately dipping faults which can be traced to a depth of at least 10 km without measurable curvature. In the Rio Grande rift Chamberlain [1978] mapped planar tilted fault blocks (Figure 13) very similar to those interpreted in Kansas. In the Basin and Range province of the western United States, extension commonly appears to be accommodated by block rotations along low-angle normal faults [e.g., McDonald, 1976; Proffett, 1977; Wernicke, 1981; Allmendinger et al., 1983]. Rotational fault geometries have been observed in the Bay of Biscay [de Charpal et al., 1978] and in the Triassic basins of the eastern United States [Petersen, 1983]. The diversity of observed extensional fault geometries indicates that models [e.g., Bott, 1976] which predict high-angle normal faults and symmetrical grabens are inadequate and, in fact, such simple grabens may be rare. Moderate and low-angle normal faults, as well as rotated blocks, are common in rifts. The reactivation of older structures [e.g., McDonald, 1976; Allmendinger et al., 1983; Petersen, 1983] suggest that normal faults can mimic the complex geometries (i.e., ramps and splays) commonly associated with thrust faulting.

Comparison of the Kansas profile with COCORP data from other rifts indicates that the seismic character of the basin deposits--i.e., a zone of relatively strong and continuous reflections overlain

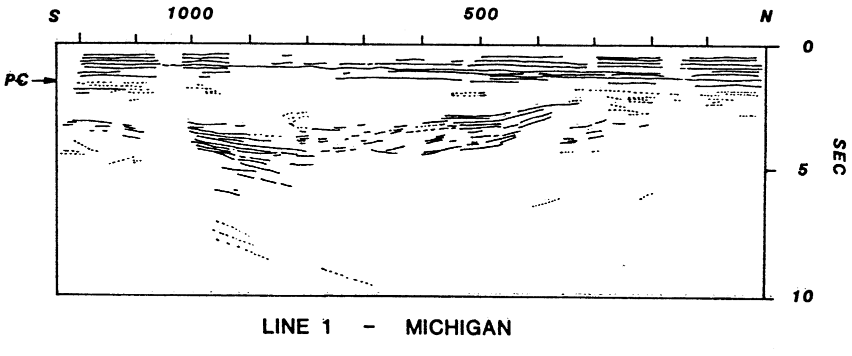


Fig. 14. Line drawing of COCORP profile across the Michigan basin [Brown et al., 1982].

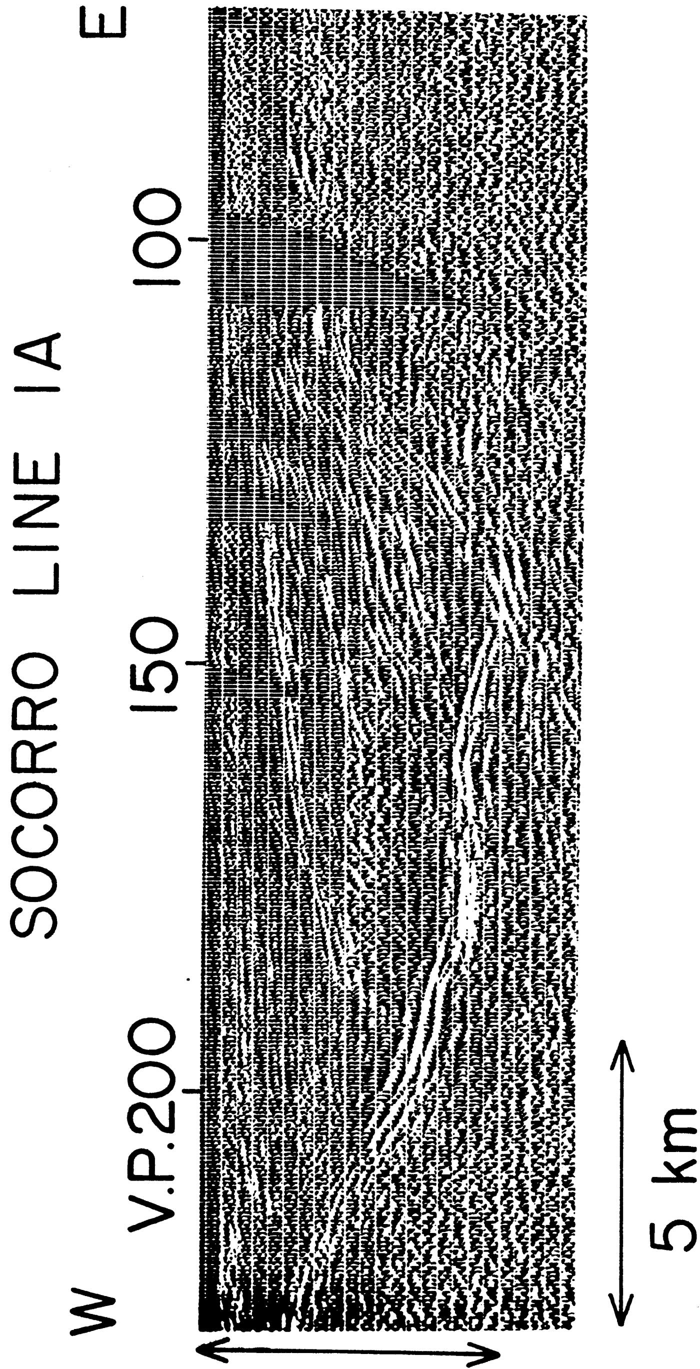


Fig. 15. COCORP data from the eastern side of Soccorro line 1A [Brown et al., 1980].

by a region of weak, discontinuous reflections--and asymmetric basins formed by fault block rotations are common. A tilted basin sequence similar to that observed in Kansas was previously observed in COCORP profiles across a branch of the Keweenawan rift in Michigan (Figures 1 and 14) and similarly interpreted as a clastic unit overlying a basaltic unit [Brown et al., 1982]. A deep well into the upper zone of weak reflectors beneath Paleozoic sedimentary rocks of the Michigan Basin encountered a clastic red bed sequence containing minor volcanic material [Sleep and Sloss, 1978; Fowler and Kuenzi, 1978] similar to the interpreted upper sequence in Kansas.

A striking similarity is also observed between the Kansas basin and COCORP results from the Rio Grande rift [Brown et al., 1980]. An asymmetric, strongly layered sequence on the east side of the Albuquerque basin is overlain by less reflective Tertiary clastics (Figure 15). Although smaller in scale, the geometry of this wedge and its reflection character strongly mimic the Kansas sequence. The New Mexico wedge has also been interpreted as rotated sedimentary deposits with a substantial amount of volcanic material [Brown et al., 1980; Cape et al., 1983]. Mutter et al. [1982] have pointed to similar layered events along rifted margins of the Atlantic, and R. Lillie [manuscript in preparation, 1984] has interpreted similar reflections buried in complexly deformed orogenic belts as possible evidence for an earlier history of rifting.

We suggest that asymmetric basins, fault block rotations, and fanning of layering within the basins as seen in the Kansas data may be characteristics of continental rifting which can be recognized in seismic data and which, the Keweenawan profiles demonstrate, can be recognizably preserved for over one billion years buried within the crust. Indeed the seismic character of the reflection sequences seen in the Keweenawan basin in Kansas and Michigan, as well as in seismic data from other rift basins, may be a key to recognizing buried rifts in seismic sections from a variety of tectonic environments.

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L. Brown, H. Farmer, S. Kaufman, J. Oliver, L. Serpa, T. Setzer, and J. Sharp, Department of Geological Sciences, Kimball Hall, Cornell University, Ithaca, NY 14853.

D. W. Steeples, Kansas Geological Survey, Lawrence, KA 66044.

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