Intracrustal complexity in the United States midcontinent: Preliminary results from COCORP surveys in northeastern Kansas

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ABSTRACT

Unusually clear indications of complex structure in the mid-to-lower crust is revealed by seismic reflection surveys in northeastern Kansas. This complexity contrasts markedly with the layer-cake simplicity of both the overlying sedimentary cover and most previous crustal models for the central United States. Seismic sections collected by COCORP (Consortium for Continental Reflection Profiling) as part of a major east-west traverse across the Nemaha Ridge and Midcontinent Geophysical Anomaly indicate that below a thin, relatively flat layered Paleozoic sedimentary section, the deep crust is characterized by numerous dipping and arcuate reflections and diffractions. In many places layered and crosscutting, these reflections suggest convoluted three-dimensional folded, faulted, and intruded structures. Specific identification of these deep features may be possible if future surveys can trace them to accessible depths. The basement above these reflection complexes contains significantly fewer reflections—consistent with, but not necessarily diagnostic of, the granitic terrane that dominates basement drill-hole samples in the region. Among the events at these shallower basement depths are several east-dipping reflections, some of which may be major faults. Travel times corresponding to expected Moho depths (about 36 km) are characterized less by specific reflections than by an apparent decrease in the density and number of reflections. While evidence of crustal heterogeneity is common among deep reflection studies, the Kansas seismic results outlined in this brief report stand out as being unusually clear representations of such.

INTRODUCTION

Hidden by a relatively undisturbed veneer of platform deposits, the underlying craton of the United States midcontinent is little known except for the insight provided by scarce outcrops, shallow drilling, and the often ambiguous or relatively low resolution information gleaned from gravity, magnetic, and seismic-refraction measurements. In 1979 the Consortium for Continental Reflection Profiling (COCORP) began collecting multichannel seismic reflection data along a major east-west traverse in northeastern Kansas (Fig. 1). The traverse was designed to cross several major structural elements including the Nemaha Ridge, a north-northeast–trending basement uplift, and the Midcontinent Geophysical Anomaly. Additional field work was carried out in the late spring and early winter of 1981. Kansas is one of a dozen areas in which COCORP has profiled (see Schilt and others, 1979; Brewer and Oliver, 1980). Previous work in the midcontinent (Fig. 1) includes surveys in northern Texas–southwest Oklahoma (Oliver and others, 1976; Brewer and others, 1981), central Michigan (Brown and others, 1982b), and central Minnesota (A. K. Gibbs and others, in prep.)

It is beyond the scope of this brief report to detail all aspects of the COCORP Kansas surveys. We present here selected initial results that, because of exceptional data quality, illustrate particularly well the complexity that intracrustal structure can exhibit. Special attention is drawn to an unusually pronounced series of arcuate and layered reflection complexes at mid-crustal depths which stand out in stark contrast to the uniformity of the overlying platform sedimentary rocks, the seismically transparent shallow basement, and the simplicity of conventional (refraction) models of crustal structure for such areas. Subsequent papers will deal with other major findings of the Kansas surveys, including those related to the Nemaha Ridge and the Midcontinent Geophysical Anomaly.

GEOLOGICAL AND GEOPHYSICAL SETTING

The COCORP traverse in northeastern Kansas is located within the Central Stable Region of Snyder (1968), where Precambrian basement is buried beneath a thin veneer (less than 1.5 km thick in the vicinity of the traverse) of relatively undeformed Paleozoic strata (Merriam, 1963). Although the Phanerozoic section of the midcontinent is known more for its layer-cake simplicity (for example, King, 1977, p. 23) than its deformational features, the COCORP surveys cross several major structures of both supracrustal and basement affinities. From east to west the COCORP surveys (Fig. 1) traverse from the Forest City Basin, across the Humboldt fault zone and Nemaha Ridge, into the Salina Basin. Beneath the Salina Basin lies Precambrian structure associated with the Midcontinent Geophysical Anomaly.

The geology of the Paleozoic Forest City and Salina Basins, both with maximum stratigraphic sections less than 1.5 km thick, was reviewed by Merriam (1963). The intervening Nemaha Ridge is a north-northeast–trending basement uplift bounded on the east by the Humboldt fault zone. More than 500 km long, the Nemaha Ridge formed during Late Mississippian–Early Pennsylvanian time. West of and subparallel to the Nemaha Ridge is a secondary basement uplift, the Abilene anticline. The Salina Basin is bounded on the west by the Central Kansas uplift, a northwest-trending basement upwarp (Fig. 1).

The most prominent basement structure of northeastern Kansas, however, is inferred largely from geophysical measurements. The Midcontinent Geophysical Anomaly in Kansas consists of a pronounced southwest-trending gravity high (Yarger and others, 1980) with flanking lows, and a corresponding magnetic high

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(Yarger, 1981). Also referred to as the Midcontinent Gravity High or the Central North American Rift System, this feature (Figs. 1, 2) is generally interpreted to represent a buried, late Precambrian (1.1 b.y. old) rift because of lithologic similarity to and geophysical (gravity and magnetic) continuity with exposed Keweenawan stratigraphy in the Lake Superior region (for example, King and Zeitz, 1971). Results across the Midcontinent Geophysical Anomaly are the subject of a future paper (L. Serpa and others, in prep.).

Basement geology in the central midcontinent is inferred primarily from shallow basement samples recovered from boreholes. Natural exposures nearest to the COCORP traverse are xenoliths in the nearby Riley County diatremes (Fig. 2; Brookins and Meyer, 1974) and the Rose Dome granites in Woodson County, Kansas, 200 km to the south (Bickford and others, 1971). Aside from rift lithologies associated with the Midcontinent Geophysical Anomaly, Bickford and others (1981) recognized two distinct basement provinces: a northern terrane (includes COCORP Kansas traverse) dominated by mesozonal granite (typically 1.6 b.y. old, with some 1.3 b.y. old) with minor metasedimentary rocks, and a southern terrane (includes COCORP southern Oklahoma and northern Texas surveys) characterized by epizonal granites and felsic volcanic rocks.

Xenoliths found in kimberlite diatremes located in Riley County, Kansas (Fig. 2), have been used by Brookins and Meyer (1974) to infer a gross crustal and upper-mantle stratigraphy: below the Paleozoic sedimentary rocks and the upper Precambrian Rice and Clay lithologies (arkose and basalt, respectively) may lie as much as 20 km of Precambrian granitic rocks, underlain in turn by amphibolite, schist, diorite, gabbro and norite, metagabbro and metanorite, and, near the base of the crust, granulite. Depth to the base of the crust (Moho) was estimated by Steeples (1976) from refraction and gravity measurements to vary from 45–48 km in eastern Colorado to about 34–38 km in north-central Kansas. Other nearby refraction studies of crustal structure are those of Tryggvason and Qualls (1967) and Mitchell and Landisman (1971) in central Oklahoma, which

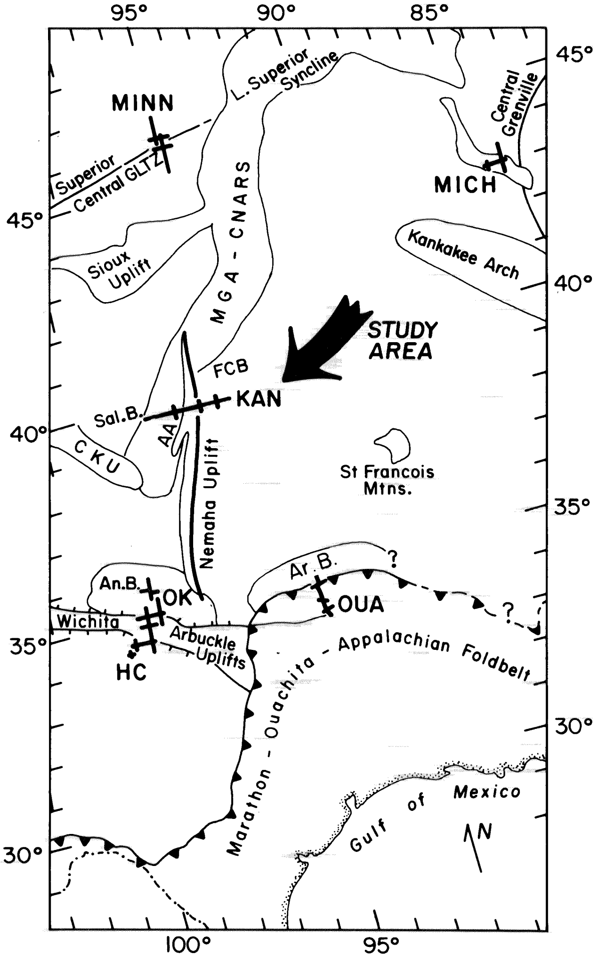

Figure 1. COCORP profiles in United States midcontinent. Basement features from Bayley and Muehlberger (1968). GLTZ = Great Lakes Tectonic Zone, MGA-CNARS = Midcontinent Geophysical Anomaly–Central North American Rift System, CKU = Central Kansas uplift, AA = Abilene anticline, FCB = Forest City Basin, Sal.B. = Salina Basin, An.B. = Anadarko Basin, Ar.B. = Arkoma Basin. Heavy lines indicate COCORP surveys in Michigan (MICH), Minnesota (MINN), Hardeman County, Texas (HC), southern Oklahoma (OK), Ouachitas of central Arkansas (OUA), and northeastern Kansas (KAN). Heavy dashed line represents fault system flanking east side of Nemaha uplift.

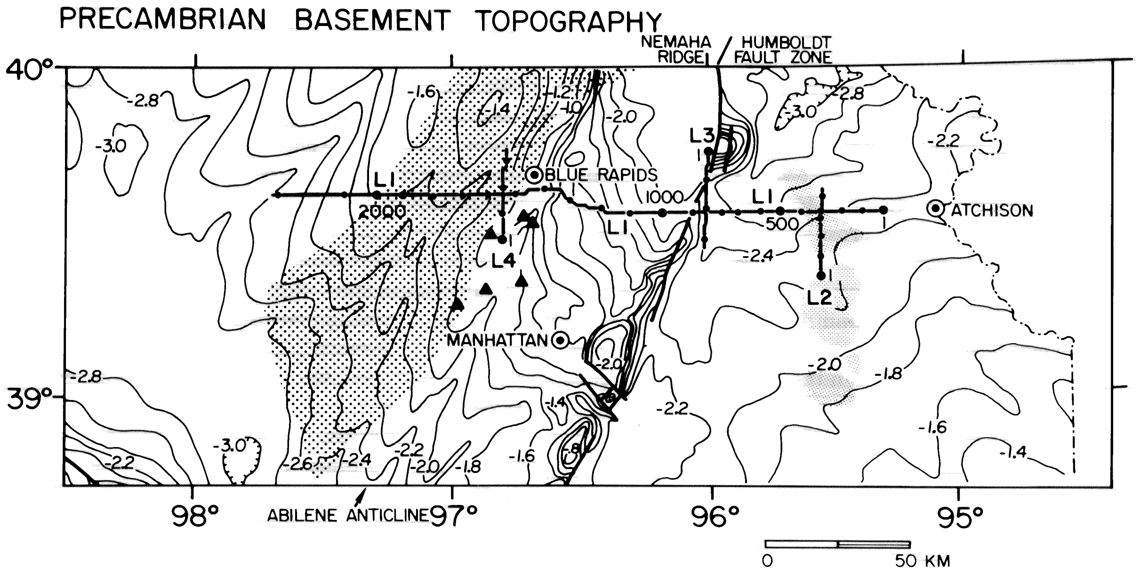

Figure 2. Location of COCORP lines in northeastern Kansas. Basement structure after Bickford and others (1979). Location of Midcontinent Geophysical Anomaly (shaded pattern west of Nemaha Ridge) and Big Springs magnetic anomaly (shaded pattern east of Nemaha Ridge) after Yarger and others (1980) and Yarger (1981). Depth to basement in thousands of feet below sea level. Triangles indicate locations of Riley County kimberlites (from Foley, 1964). Numbers refer to vibration points along seismic lines.

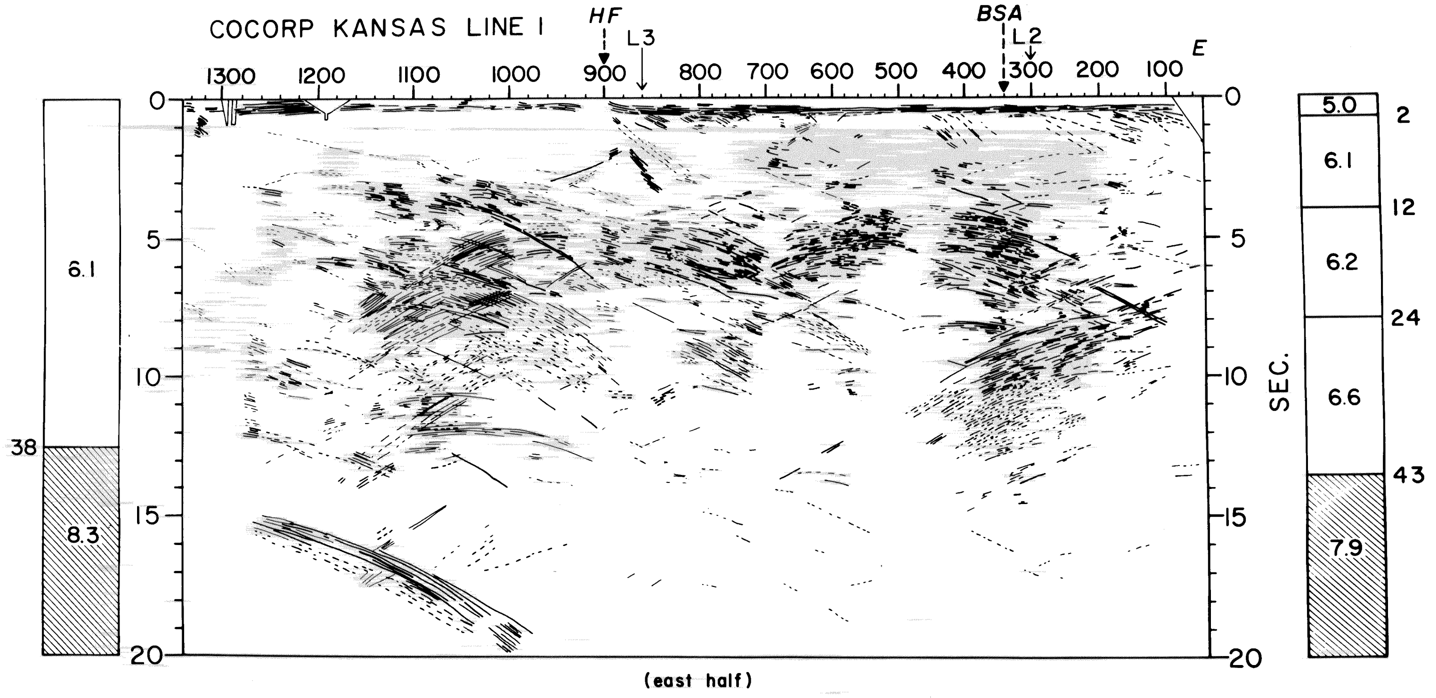

Figure 3. Line drawing of seismic line 1 and 1A. Vibration point (VP) spacing is 67 m. Approximately equal horizontal and vertical distance scales assuming an average crustal velocity of 6 km/s. To convert travel time to approximate depth, multiply by 3. Crustal velocity model on west side of line drawing inferred by Steeples (1976) from refraction measurements; corresponding model on east is from refraction study by Stewart (1968). Numbers inside columns refer to refraction velocities in kilometres per second; numbers outside refer to depth in kilometres of corresponding velocity discontinuity. HF = Humboldt fault, BSA = Big Springs magnetic anomaly.

indicate a flat-layered crust 46 km thick; and those of Stewart (1968) in Missouri, which place the Moho at 43 km (Fig. 3).

COCORP RESULTS

Figure 3 provides an overview of the Kansas seismic sections. Representative parts of the sections for lines 1 and 3 are reproduced in Figures 4 and 5. Standard common-depth-point (CDP) techniques and Vibroseis (trademark of Continental Oil Company) sources were used to profile each line. The seismic sections were similarly processed (see Schilt and others, 1979, for a synopsis of standard COCORP processing). Although seismic sections resemble geologic cross sections in many respects, the reader is reminded that, as is usually the case, proper interpretation requires recognition of migration, three-dimensional, and velocity distortion effects (for example, Fitch, 1976).

In general, numerous strong, coherent reflections and diffractions are evident throughout the range of travel times corresponding to the crust; some even appear at upper-mantle travel times, although these may be reflections from crustal structure out of the plane of the section or diffractions from local intracrustal heterogeneity. Strong reflectors at depth, lack of cultural noise (such as traffic), simple near-surface geology (minimal raypath distortion), and a thin (little-attenuating), sedimentary cover sequence may all have contributed favorably to data quality.

Seismic Homogeneity in the Upper Crust

The upper 0.5 s (about 1 km) on all seismic sections consists of a relatively continuous, undeformed layered sequence of reflections that dip gently to the west, except near the Nemaha Ridge and related Humboldt fault (Figs. 3, 4). These events correspond to the Paleozoic section of the Forest City and Salina Basins. In spite of the overall appearance of uniformity, minor offsets and diffractions indicative of faulting are common, especially at the base of these strata. Several east-dipping events extend down from the sedimentary cover into the basement. Among these are one (Fig. 2), which is near, and thus may be related to, the Big Springs magnetic anomaly, a major series of magnetic highs trending northwest across the east part of line 1. Another (Fig. 3) is a set of weak reflections that can be traced upward to the vicinity of the Humboldt fault and that may therefore represent the deep root of the fault along which the Nemaha Ridge was uplifted; if so, this structure would seem to be a low-angle normal fault at depth. While other possible interpretations of the deep geometry of the Humboldt fault are allowed by the data, the continuity of reflection B (Fig. 4) beneath the Nemaha Ridge would seem to rule out a deeply penetrating vertical geometry, unless B is a side reflection or corresponds to a post-Pennsylvanian structure.

The shallow basement is notable primarily because of the marked decrease in the number and amplitude of reflections relative to both the overlying sedimentary section and deeper reflection complexes (for example, Fig 4; many of the shallow basement events marked in Fig. 3 are actually quite weak, and some may be processing artifacts). The abundance of reflections from below rules out any lack of energy penetration as an explanation. Lateral variations in the "thickness" and character of this subdued reflectivity zone suggest that it is neither an artifact of data processing nor a simple geologic "layer" in the conventional stratigraphic sense. For example, on line 3 (Fig. 5) this depleted reflection zone appears more as a triangular block than a plane "layer." Reflections are by no means absent from this zone; east-dipping events that penetrate down from the near surface have already been mentioned. In addition, some short, typically subhorizontal events are scattered through the upper section.

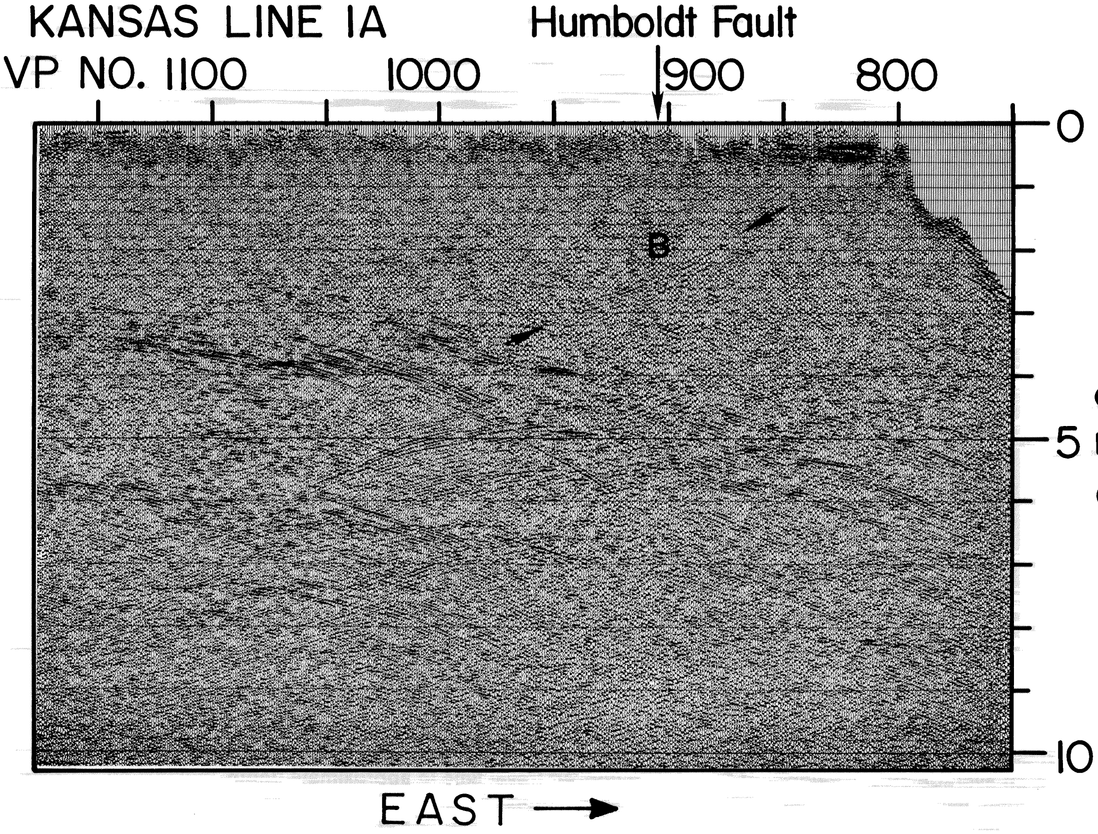

Figure 4. Part of seismic section from line 1. Vibration point (VP) spacing is 100 m.

Lack of reflections from the upper crust has been noted in COCORP results from several areas, including central New Mexico (Brown and others, 1980), the Atlantic Coastal Plain (F. S. Schilt and others, in prep.), the Appalachians (Cook and others, 1979) and the Adirondacks (Brown and others, 1983). The significance of these transparent or quasitransparent zones is not clear. Their identification is often subjective, inherently relative (to other features on a given seismic section), and dependent upon data acquisition and processing factors. Furthermore, given the variety of tectonic histories of the areas where such zones have been noted, it seems likely that several geologic processes could be responsible. For example, granitic intrusions, very highly deformed terranes (where structure has been milled to coherent lengths below the resolution of seismic measurements, typically a few hundred metres or less), and cataclastic fault zones might all be expected to appear seismically homogeneous.

In the case of northeastern Kansas, the simplest explanation may be that relatively homogeneous granite, abundant in drill holes in the region (Bickford and others, 1981), is responsible for the seismic transparency. On the other hand, granites are outnumbered among the xenoliths of the kimberlite pipes by several other intrabasement species, including gabbroic and dioritic materials (Brookins and Meyer, 1974), which could also appear seismically transparent under appropriate conditions. Furthermore, although the depleted reflection zones may correspond to the dominance of granite in the upper crust, it is probably misleading to infer the existence of a simple granitic body or "layer" in view of the evolving recognition of crustal complexity (for example, Oliver, 1978). Composite accumulation of plutons is perhaps more realistic.

Structural Complexity in the Deep Crust

By far the most striking aspect of the COCORP results in Kansas is the abundance of strong, coherent reflections and diffractions at mid-to-lower crustal levels (Figs. 3, 4, 5). These events form a complex series of reflection patterns that contrast markedly with the relative seismic homogeneity of the overlying basement, the structural simplicity of the blanketing sedimentary strata, and the simple, layered geometries of geophysical models inferred from regional refraction measurements (Fig. 3).

The deep events on lines 1 and 3 are commonly dipping, arcuate, and layered. As a whole, the mid-crustal reflection complexes appear to become shallower to the west and north (Figs. 3, 4, 5). If this is not a chance alignment, or apparent alignment, it could be indicative of crustal offset across the Humboldt fault zone or regional upwarping associated with Keweenawan rifting to the west. The arcuate (hyperbolic) geometry suggests diffraction (for example, Schilt and others, 1981), and seismic migration processing does collapse many of the arcuate diffraction "tails" and eliminate many of the crosscutting relations between events. However, it is unlikely with reflection patterns as complex as these that all of the energy visible on the seismic section is due to structure located within the vertical plane beneath the survey line. The cross lines (for example, Fig. 5) confirm significant lateral dip. Thus, two-dimensional migration, which has been performed on these sections although it is not shown here, is probably inadequate—perhaps even misleading. Three-dimensional migration and modeling will probably be necessary before the precise geometry of these deep events can be fully understood.

The arcuate and layered reflection patterns corresponding to the middle crust are undoubtedly due to complex, three-

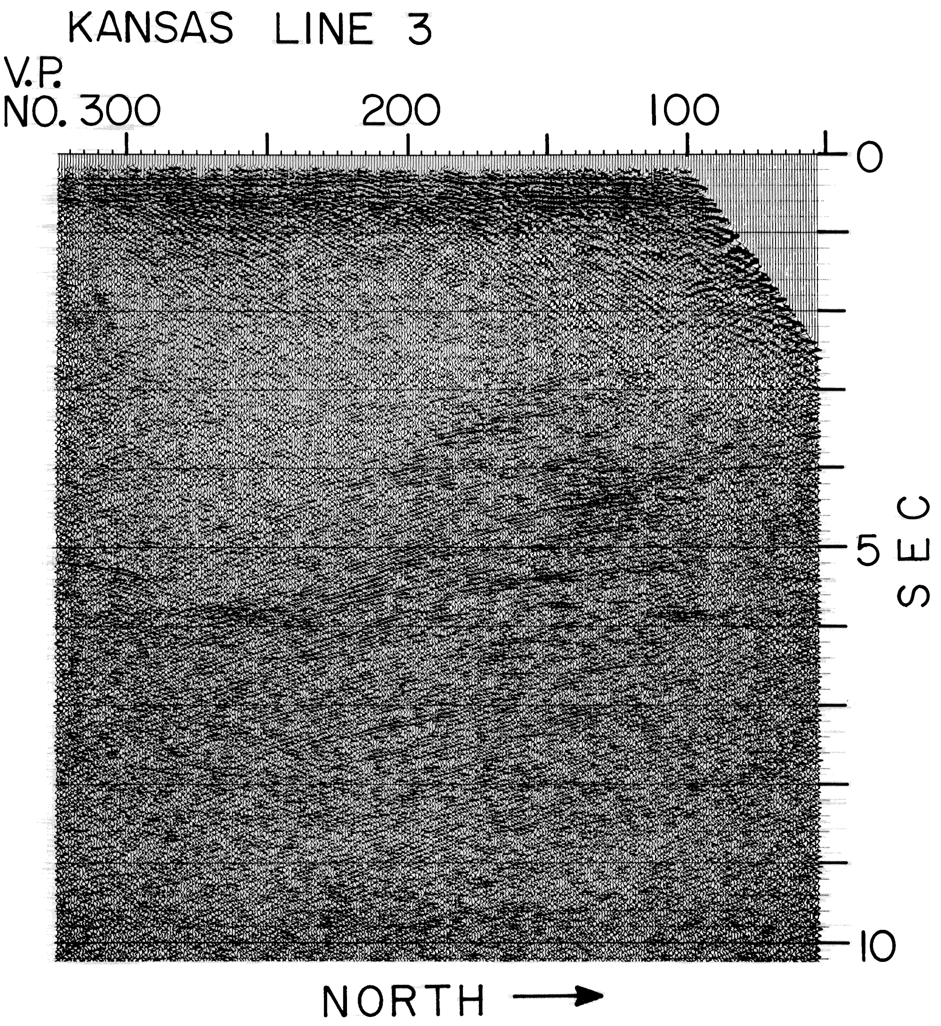

Figure 5. Seismic section from line 3. VP spacing is 100 m.

dimensional structures; diapirs and nappes are but two possible analogues (Smithson and others, 1980; Schilt and others, 1981). The deeper parts of the Kansas section are strongly reminiscent, for example, of the synthetic seismic sections presented by Wong and others (1982) for models of Alpine nappes and the roots of an island-arc complex. Yet, specific identification of the components of such structure is still a matter of poorly constrained speculation. It is tempting to correlate these deep reflectors with the emplacement of the more mafic rock types that Brookins and Meyer (1974) inferred, on the basis of xenolith evidence, to underlie the upper granite complexes. Contacts between granitic and gabbroic rocks may provide the substantial reflection coefficients suggested by the strong reflection amplitudes. Layered mafic complexes may have formed cogenetically with or been deformed by emplacement of the overlying granite complexes.

Deep layered reflection sequences have been noted in other areas, including southern Oklahoma and northern Texas (Brewer and others, 1981), the Adirondacks of New York (Brown and others, 1982a), and the southern Appalachian Piedmont (Cook and others, 1979). Explanations for such layered character include reverberation in the overlying sedimentary cover (Zawislak and Smithson, 1981), igneous layering (Lynn and others, 1981; Meissner, 1973; Brown and others, 1982a), tectonic layering (Berry and Mair, 1977), or relict sedimentary layering (Cook and others, 1979). The possibility that the layered mid-crustal reflections beneath northeastern Kansas may represent mafic underplating of the overlying granite (igneous layering) was mentioned above. Another option worth further comment is the metasedimentary interpretation. Large-scale basement overthrusting such as that found by COCORP profiling in the southern Appalachians (Cook and others, 1979) appears to be a viable means of injecting sediments to mid-crustal depths (for example, Brown and others, 1982a). The presence of metasedimentary xenoliths within the Riley County and other crustal xenolith suites (Kay and Kay, 1981) supports the speculation that at least some layered reflections may correspond to sedimentary protoliths.

An important observation is that the strong, continuous subhorizontal layering so prominent in the upper crust of northern Texas and southern Oklahoma (Oliver and others, 1976; Brewer and others, 1981) is absent in Kansas, although the numerous diffractions at mid-to-lower travel times observed in Texas and Oklahoma (Schilt and others, 1981) are similar in some respects to the mid-crustal complexes observed in Kansas. The flat-layered sequence to the south has been interpreted as a Proterozoic basin (Brewer and others, 1981) and as igneous layering (Lynn and others, 1981). In either case, if this layered sequence, or one of similar origin, once extended into Kansas, it may have been removed during unroofing of the mesozonal granites characteristic of the northern terrane (Bickford and others, 1981). Alternatively, one may speculate whether the arcuate, layered mid-crustal complexes of Kansas represent the deformed (intruded?) equivalents of the undisturbed strata to the south.

Although the mid-crustal reflection complexes are most prominent, clear events are evident at later travel times. For example, east-dipping, laminated diffractions extend to almost 20 s at the west end of line 1A (D in Fig. 3). Although these particular events appear to be diffractions off a structural discontinuity within the crust, they confirm that seismic energy has penetrated distances equivalent to sub-Moho depths. Unambiguous Moho reflections, expected at times of 11 to 13 s (34 to 38 km), are difficult to identify. A broadly arched event at 12 s on line 1A (E in Fig. 3) seems to be at an appropriate depth, but again its three-dimensional location is uncertain. There is a suggestion of an overall change in reflection character at about 12 s, with a rapid decrease in the number of reflections (Fig. 3). If not an artifact of limited energy penetration, this transition in reflection character may represent increased homogeneity (at least in the seismic sense) in the upper mantle.

CONCLUSIONS

In spite of its surficial uniformity, the crust of northeastern Kansas revealed by COCORP seismic sections is dominated by pervasive structural complexity. As these variations are indicated by reflected seismic waves, requiring contrasts in density and seismic velocity, considerable compositional heterogeneity is likewise implied. While evidence of crustal heterogeneity on deep seismic reflection sections is neither new nor unique, the Kansas results provide particularly clear examples. Reflection-poor zones (granitic complexes?) in the upper crust, perhaps dissected by major crustal faults, are underlain by a remarkably well defined series of arcuate-layered reflection complexes. Reflections are evident at times corresponding to lower crustal and even upper mantle depths, although some may correspond to side reflections or diffractions from shallower levels. The observed reflection patterns suggest three-dimensional fold and intrusion structures in the middle crust. The layered character of some of these deep reflection complexes could be indicative of igneous (cumulate) or sedimentary protoliths. Further profiling is needed to trace these reflection complexes to accessible depths where they may be unambiguously identified.

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Reviewer's comment

An excellent paper presenting exciting new COCORP data for a little-studied part of the continental crust.