Structure of the Reelfoot–Rough Creek Rift System, Fluorspar Area Fault Complex, and Hicks Dome, Southern Illinois and Western Kentucky—New Constraints from Regional Seismic Reflection Data

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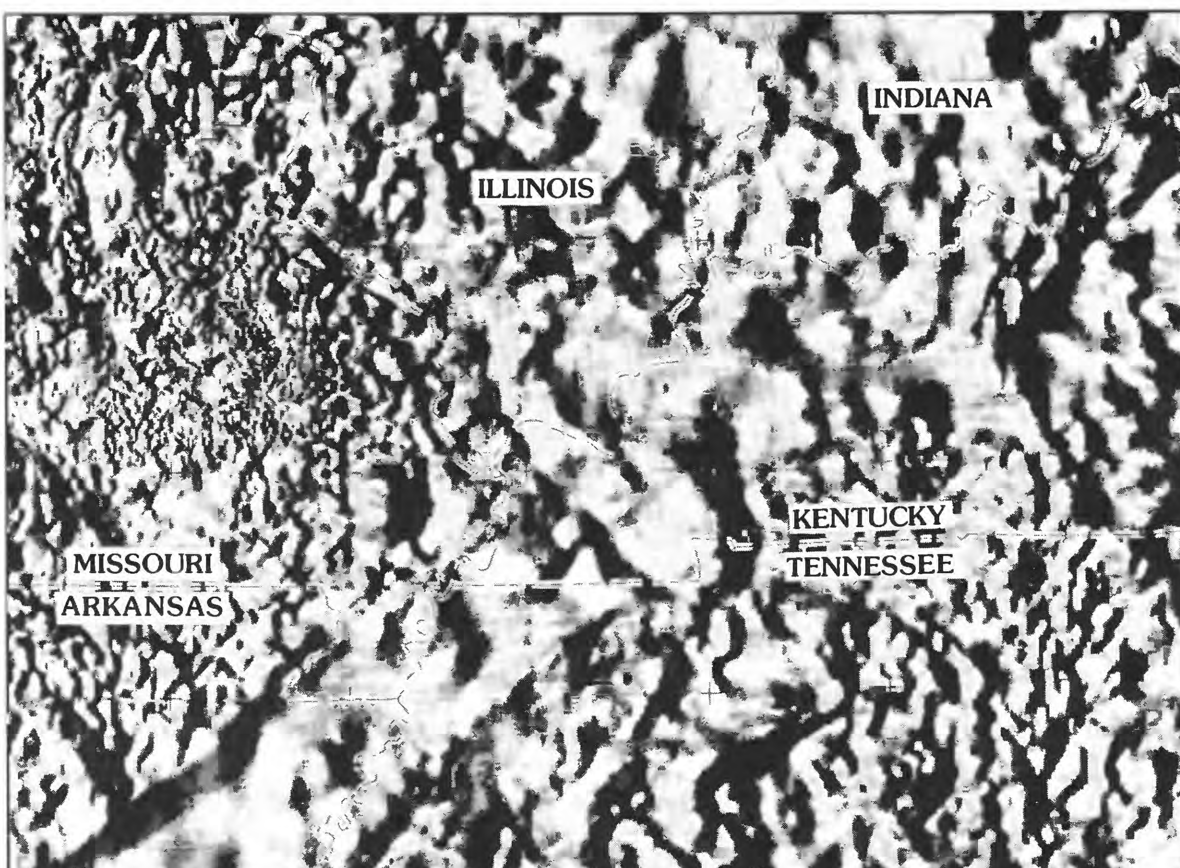
U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1538–Q



Cover. Gray, shaded-relief map of magnetic anomaly data. Map area includes parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, and Arkansas. Illumination is from the west. Figure is from *Geophysical setting of the Reelfoot rift and relations between rift structures and the New Madrid seismic zone*, by Thomas G. Hildenbrand and John D. Hendricks (chapter E in this series).

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By Christopher J. Potter, Martin B. Goldhaber, Paul C. Heigold, *and* James A. Drahovzal

INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE
Edited by Kaye M. Shedlock *and* Arch C. Johnston

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By Christopher J. Potter,[1] Martin B. Goldhaber,[2] Paul C. Heigold,[3] *and* James A. Drahovzal[4]

ABSTRACT

Because the New Madrid seismic zone coincides spatially with a segment of the Cambrian Reelfoot rift (RFR), regional studies of subsurface Cambrian rift structures may provide important insights into the structural fabric of the New Madrid seismic zone. High-quality seismic reflection data examined in this study show that, north of the New Madrid seismic zone within the major dogleg bend in the rift system in southern Illinois and western Kentucky, the geometry of the Cambrian rift system is that of a half-graben that thickens to the southeast. This contrasts with the northward-thickening half-graben observed to the east, in the Rough Creek graben in Kentucky, and with the more symmetric graben to the south, in the seismogenic part of the RFR.

The 83-km segment of seismic reflection data examined here is oriented northwest-southeast within the major bend in the Cambrian rift, in southeastern Illinois and western Kentucky. The margins of the 110-km-wide rift (as determined by aeromagnetic data) lie beyond the ends of the seismic line. The data show that, near Hicks dome (southeastern Illinois), Lower and Middle Cambrian syn-rift sedimentary rocks occupy about 0.4 s two-way travel time on the seismic reflection section (corresponding to a thickness of about 1.1 km). This stratigraphic interval thickens to the southeast within the rift. The syn-rift sedimentary sequence occupies about 0.76 s (2.1 km) near the Ohio River and is thickest against basement-cutting normal faults in the area of intersection of the Tabb and Pennyrile fault systems in western Kentucky, where it occupies 1.13 s (3.1 km). Near the southeast margin of the rift, the Cambrian syn-rift sequence thins markedly to the southeast across steep basement-cutting normal faults in the Tabb-Pennyrile zone; these northwest-dipping faults appear to have been the dominant faults in this part of the Cambrian rift. Post-Mississippian reverse displacements are also evident in the Tabb-Pennyrile fault zone.

Comparison of these seismic reflection data with other published reflection data in the Cambrian rift system reveals several major along-strike changes in the cross-sectional geometry of the rift, similar to other rift systems. We propose that the localization of New Madrid seismicity within a discrete segment of the Reelfoot rift is inherited from Cambrian rift structure; the zone of seismicity appears bounded on the north and south by Cambrian accommodation zones that linked segments with differing rift geometry.

The seismic data also provide new information on the late Paleozoic development of Hicks dome (southeastern Illinois) and the surrounding Fluorspar area fault complex (FAFC) in southeastern Illinois and western Kentucky. Near Hicks dome (a center of carbonatitic intrusions), strong Mississippian reflections are relatively continuous, whereas the Cambrian-Ordovician section is greatly disrupted. This disruption is probably related to the combination of intrusive and explosive processes that formed the dome. The entire section of Paleozoic rocks and the top of the Precambrian basement are domed, demonstrating that the uplift originated in the basement rather than within the sedimentary section. Southeast of Hicks dome in western Kentucky, a series of grabens and horsts in the FAFC document a late Paleozoic

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reactivation of the Cambrian rift. Beneath two of the FAFC grabens, the bounding faults meet within the Knox Group and do not continue to depth. This requires that extension was locally accommodated laterally within the Knox. Other normal faults in the FAFC clearly offset the top of Precambrian basement.

The broad FAFC disappears to the southwest beneath Cretaceous and Tertiary sedimentary rocks of the Mississippi Embayment; the strike of these faults is collinear with the Reelfoot rift and the principal zone of New Madrid seismicity to the southwest. It is not known how far the FAFC continues beneath the Cretaceous and Tertiary cover in the embayment. It is possible that the FAFC terminates northeast of the well-defined cluster of New Madrid earthquake epicenters and that strain transferred from the New Madrid seismic zone is distributed in the much wider FAFC so that no individual fault accumulates sufficient stain energy for a major earthquake within the FAFC. This may help explain the abrupt northward decrease in seismicity in the northernmost Mississippi Embayment.

INTRODUCTION

Recurring historic seismicity in the New Madrid and Wabash Valley seismic zones has focused attention on the tectonic history of the midcontinent region. These seismic zones lie in a structurally complex part of the North American Midcontinent. A Cambrian rift complex comprised two major structures, the Reelfoot rift and Rough Creek graben, which intersect to form a "dogleg" map pattern centered roughly on the junction of the Mississippi and Ohio rivers (fig. 1). Late Paleozoic reverse, normal, and strike-slip faulting and Mesozoic normal faulting affected the region, probably as an intracratonic response to Alleghanian-Ouachita orogenesis and subsequent continental breakup. In many cases, these later movements occurred along older Cambrian rift structures (Nelson and Lumm, 1984; Nelson, 1991). Because the well-established zones of modern seismicity occur within the Cambrian Reelfoot rift and near its northwest margin, it is important to understand the regional patterns of Cambrian extensional structures and the subsequent history of faulting in and near the rift complex. The vast majority of New Madrid earthquakes occur within the Precambrian basement; only a small percentage have shallow focal depths within the Paleozoic sedimentary rocks (Chiu and others, 1992). Thus, comparison of the style of faulting within the Paleozoic section with that in the Precambrian basement is another important goal of structural studies in the rift complex.

This study is based on interpretation of an 82.8-km segment of a northwest-southeast-trending dynamite-source seismic reflection profile that lies along the axis of the major bend in the Cambrian rift system in southern Illinois and western Kentucky (fig. 1). This survey produced high-quality data that effectively image the regional structure and stratigraphy. The area has historically been nearly aseismic, and it lies in a transitional area between the well-defined New Madrid seismic zone and a more diffuse area of seismicity in southern Illinois and Indiana. The study area contains major structures that are critical to understanding the regional tectonic context of this transition in seismicity.

Acknowledgments.—We are grateful to James W. Baxter of the Illinois State Geological Survey for his contributions to our understanding of the geology of Hicks dome and environs. J.P. Fagin of the Illinois State Geological Survey prepared two synthetic seismograms, which provided crucial constraints for seismic interpretation. M.C. Noger of the Kentucky Geological Survey provided valuable insights that improved our discussion of the western Kentucky part of the seismic profile. Cliff Taylor of the U.S. Geological Survey contributed to the early stages of geologic interpretation of the seismic line. Formal and informal collaborations between the U.S. Geological Survey and the Illinois Basin Consortium were instrumental in this study. The study was jointly supported by the U.S. Geological Survey's Evolution of Sedimentary Basins Program and Paducah CUSMAP (Conterminous United States Mineral Assessment Program) Project, as well as the Earthquake Hazards Reduction Program.

GEOLOGIC SETTING

The seismic reflection profile crosses numerous faults that originated during Cambrian rifting (fig. 1). These include the Herod fault (an extension of the Lusk Creek fault zone) near the northwest end of the profile in southern Illinois, the Tabb and Pennyrile fault systems near the southeast end of the profile in western Kentucky, and several unnamed faults. The north-trending Shawneetown fault system, also crossed by the seismic line in southern Illinois (fig. 1) did not originate in Cambrian time (as seen in the data in this study), although it merges into the east-trending Rough Creek fault, which was clearly a major Cambrian rift-bounding fault. In western Kentucky, the Rough Creek fault system defines the northern boundary of the Cambrian Rough Creek graben (Nelson, 1991; Bertagne and Leising, 1991), and the Pennyrile fault system (in the broad sense used by Lumm and others, 1991) forms the graben's southern boundary. (Lumm and others' use of "Pennyrile fault system" includes the "unnamed faults to the south" referred to as part of the rift boundary by Nelson, 1991.) East of the study area, displacement along the northern boundary greatly exceeds that along the southern boundary (Bertagne and Leising, 1991). Within the study area, Nelson (1991) has identified the Lusk Creek fault zone as the northwest boundary of the Reelfoot rift near its intersection with the Rough Creek graben; Hildenbrand and others (1992, in press) present potential-field data that suggests that this rift boundary is about 30 km to the northwest of the Lusk Creek fault zone. In this paper, we present

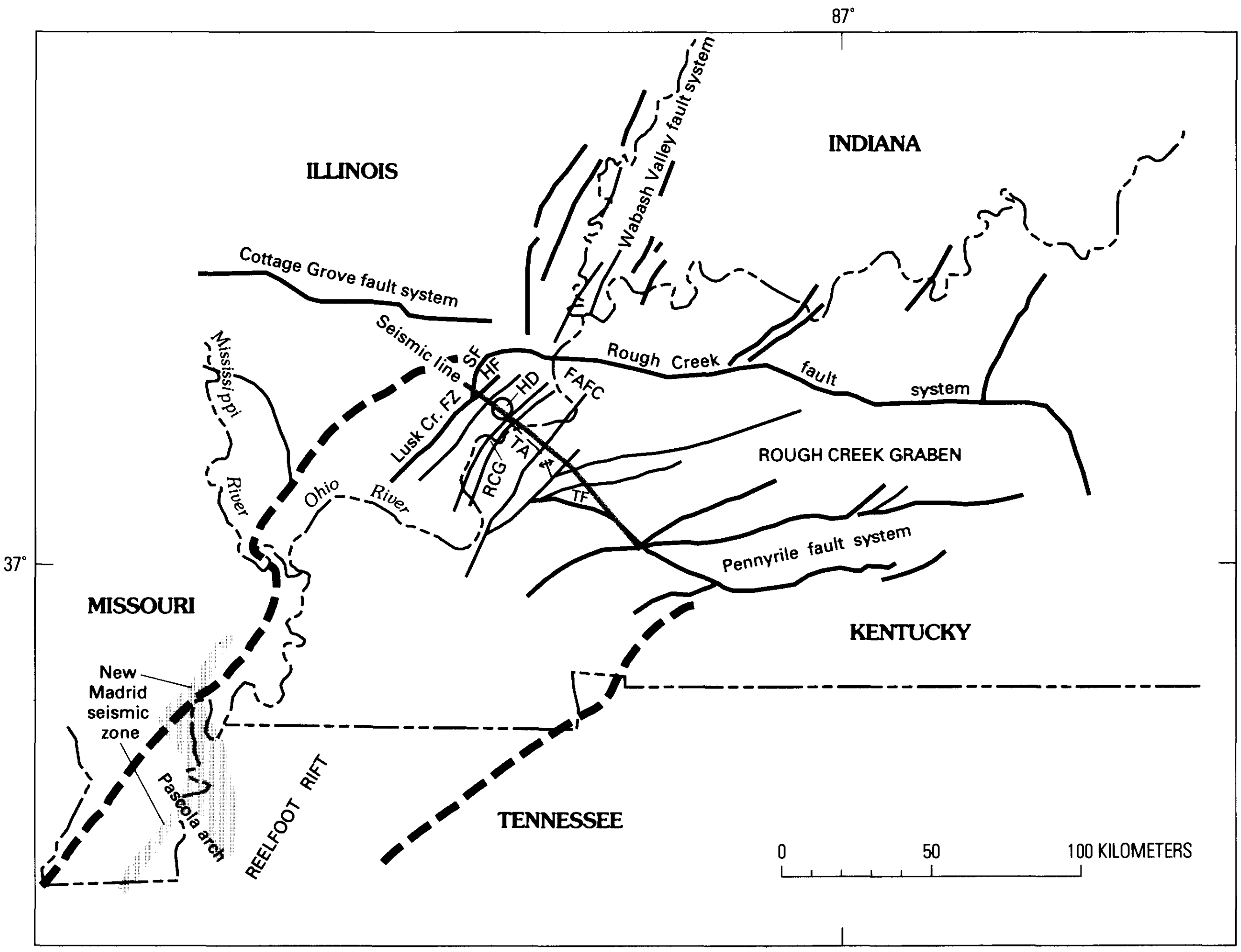

Figure 1. Map of the southern Illinois, southern Indiana, western Kentucky and adjacent States showing location of the seismic line and geologic features near the bend in the Reelfoot–Rough Creek rift system. Bold dashed lines are the boundaries of the Cambrian rift system based on the depth to magnetic basement (Hildenbrand and others, 1992). Light stipple is the northern part of the New Madrid seismic zone. Heavy solid lines are faults. Lusk Cr. FZ, Lusk Creek fault zone; HF, Herod fault; SF, Shawneetown fault; HD, Hicks dome; FAFC, Fluorspar area fault complex (shown schematically only—the number of faults is too large to illustrate at this scale); RCG, Rock Creek graben; TF, Tabb fault system; TA, Tolu arch.

evidence that the Lusk Creek and related faults were active during Cambrian rifting but probably did not form the rift margin. The seismic data also demonstrate that the Cambrian rift sequence thickens to the southeast and that the greatest Cambrian displacement occurred along faults at the southeastern edge of the rift (Tabb and Pennyrile fault systems) within this major bend in the rift system. This contrasts with the structural pattern to the east in Kentucky, where the Cambrian rift sequence is thickest along the northern rift margin, and contrasts with the more symmetric graben to the south in the Reelfoot rift.

The seismic profile also crosses the Fluorspar area fault complex (FAFC) and Hicks dome (fig. 1), major structures that originated in late Paleozoic time. The FAFC is a complex zone of mineralized northeast-trending faults in southern Illinois and western Kentucky that offset rocks as young as mid-Pennsylvanian (Nelson, 1991). Normal faults are most abundant, and the FAFC also includes reverse and strike-slip faults. Fluorspar area faults commonly displace Permian alkalic dikes that are part of a regional system of dikes that radiate from Hicks dome in southern Illinois along a northwest-trending axis (Nelson, 1991). A component of the fluorspar mineralization along the faults appears related to the Permian magmatism (Plumlee and Goldhaber, 1992; Plumlee and others, in press); thus, Fluorspar area faulting must have begun prior to the end of hydrothermal activity that accompanied this Permian intrusive event.

Hicks dome is an asymmetric northwest-southeast elongate structure that lies at the northwestern terminus of the northwest-trending Tolu arch. Devonian through

Pennsylvanian strata crop out around the dome, which is steepest on its northeast flank. Hicks dome is thought to have an igneous origin (Trace, 1974; Heyl, 1983; Nelson, 1991) because igneous dikes, pipes, and several stock-like bodies of peridotite, lamprophyre, and carbonatite breccia (Bradbury and Baxter, 1992) radiate from the dome. Snee and Hayes (1992) report a Permian age (272 Ma) for an intrusion in this suite. In addition to the carbonatite breccia, in which fragments of igneous rocks and Paleozoic sedimentary rocks are entrained in an altered carbonate matrix, shatter breccias and vent breccias made up of fragments of Paleozoic country rock crop out near Hicks dome (Bradbury and Baxter, 1992). The dome lies on the flank of a major positive magnetic anomaly that strongly suggests the presence of an intrusion at depth (McGinnis and Bradbury, 1964). This inferred intrusion is not centered beneath Hicks dome; however, the dome does not appear to overlie a local laccolithic body. The prevailing model calls on a "cryptovolcanic" origin related to igneous vapors or ground water flashing to steam within the Paleozoic section (Brown and others, 1954; Nelson, 1991). The seismic reflection data discussed herein demonstrate that the entire Phanerozoic section and top of Precambrian basement are domed. We examine the origin of Hicks dome and the FAFC in the context of seismic reflection patterns and the overall tectonic evolution of the region.

DATA ACQUISITION AND PROCESSING

The seismic data discussed in this paper were collected as part of a regional exploration effort undertaken in the southern Illinois Basin by a private corporation. An 83-km segment of a northwest-southeast-oriented seismic reflection profile (fig. 1) through southern Illinois and western Kentucky was purchased by the U.S. Geological Survey with limited publication rights. The data were collected in 1989 using a dynamite source, 2-ms sample rate, and a 120-channel geophone spread. Geophone and source arrays were spaced at 46-m (150-ft) intervals, producing a stacking fold of 60. The recording time was 8 seconds; 5 seconds of data were processed. Processing (performed by a private contractor) included surface-consistent deconvolution, refraction static corrections, velocity analysis, automatic surface-consistent static corrections, wave equation migration, and noise-reduction filtering. The data acquisition and processing techniques employed in this survey were standard oil-industry techniques that provide a level of resolution that is appropriate for investigating the regional geologic framework. They are distinctly different from high-resolution, shallow, seismic reflection surveys carried out in some other U.S. Geological Survey investigations of the New Madrid seismic zone (e.g., Luzietti and others, 1992; Schweig and others, 1992; Sexton and others, 1992), which image smaller areas and shallower depths in greater detail.

The data were not reprocessed after purchase by the U.S. Geological Survey. Because the authors did not participate in processing of the seismic data, care was taken to avoid over-interpreting geologic structure and stratigraphy. In general, seismic reflection data commonly contain artifacts of data-acquisition problems and signal-processing algorithms that can produce offset reflections that do not correspond to geologic breaks. Other processing artifacts can produce "reflection" events that are more continuous than the actual reflectors. In interpreting the seismic data, we examined the pre-migration and pre-noise-reduction stacked sections, as well as the final migrated sections. This allowed us to evaluate the effects of the post-stack processing and helped ensure that our interpretations of strata and structures were not based on processing artifacts. Specific familiarity with the static corrections, filters, and other processing steps would be necessary for interpretation of very small scale structural and stratigraphic effects. For this reason, the interpretations in this paper focus on major structures and stratigraphic trends.

CORRELATION OF REFLECTIONS WITH REGIONAL STRATIGRAPHY

Mississippian (and locally Pennsylvanian) rocks are exposed at the surface along the seismic line. In most areas, reflections are clearly identifiable down to the top of Precambrian basement; therefore, reflections on the seismic line generally correspond to the Cambrian through Mississippian stratigraphic section. Five segments of the regional seismic data are shown in figures 2–6; these are keyed to reflection patterns along the entire profile in plate 1. Major reflections have been identified based on synthetic seismograms produced from sonic logs in two deep exploration wells (Texas Pacific Streich 1 well, Pope Co., Illinois, less than 1 km northwest of the Shawneetown fault, and the Sun 1 Stephens well, Caldwell Co., Kentucky, about 13 km northwest of the southeast end of the profile) and by correlation with other published seismic reflection profiles from the area (Bertagne and Leising, 1991; Heigold and Oltz 1991). Reflection patterns are reasonably consistent, with the exception of structurally complex zones in the vicinity of Hicks dome, Rock Creek graben, and the Tabb and Pennyrile fault systems, where it is difficult to trace Paleozoic reflections (plate 1; figs. 2, 6). Where such complexities are absent (figs. 2, 4, and 5), the following major reflections or reflection patterns are mappable (generally corresponding to boundaries between clastic and carbonate strata, as summarized elsewhere in the Illinois Basin by Heigold and Oltz, 1991): (1) a reflective Devonian and Mississippian sequence that generally occupies the upper 0.2–0.3 s (two-way time) across the seismic line, with a strong reflection at the top of the Middle Devonian to Lower Mississippian New Albany Shale; (2) the boundary between the New Albany and the underlying thick

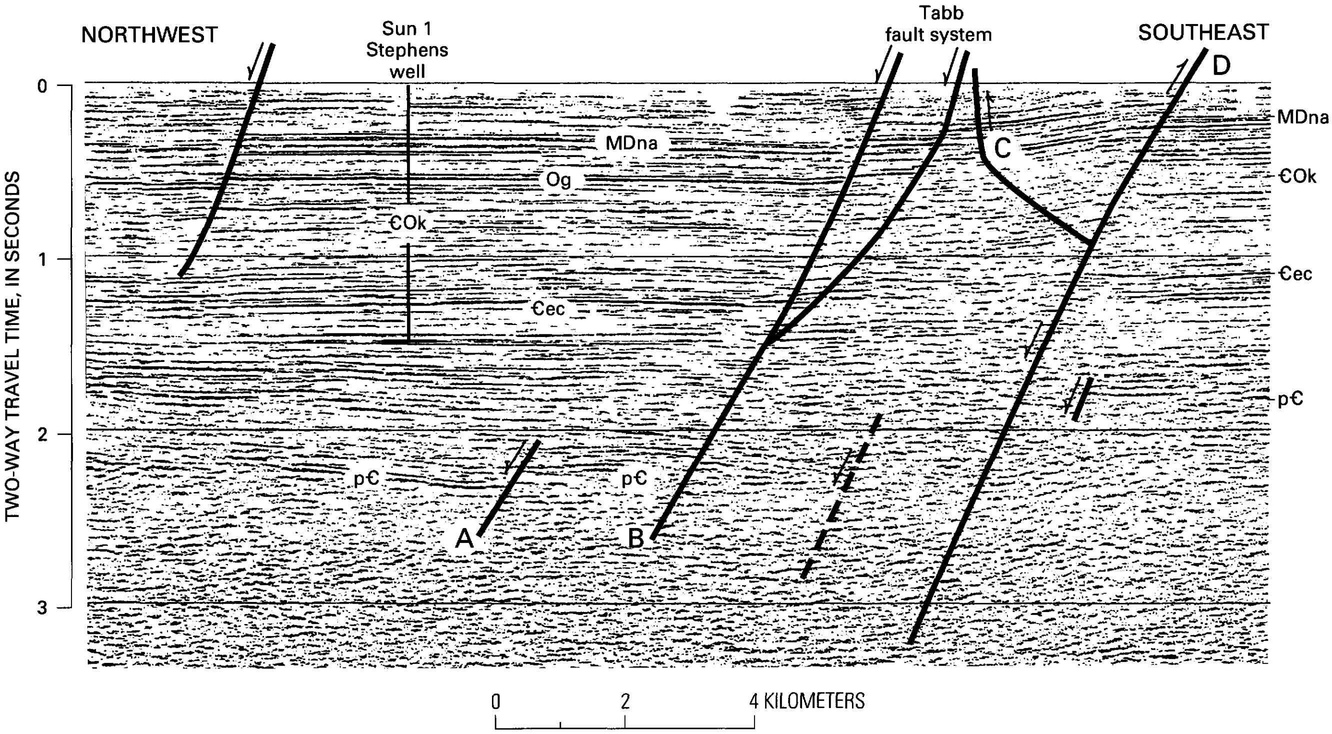

Figure 2. Segment of seismic reflection data, Caldwell Co., Kentucky, in the vicinity of the Tabb fault system. DMna, top of Middle Devonian to Lower Mississippian New Albany Shale; Og, top of Upper Ordovician Galena Group; €Ok, top of the Knox Group; €ec, top of Upper Cambrian Eau Claire Formation; p€, top of Precambrian basement. Sun 1 Stephens well (Caldwell Co., Kentucky) drilled to a total depth of 3,952 m (12,965 ft) and bottomed in the Eau Claire. A, B, C, and D denote faults that are discussed in the text.

carbonate section in the Silurian and Devonian Hunton Group; (3) the top of the Upper Ordovician Galena Group carbonates (Shaver, 1985); (4) the boundary between the Middle Ordovician St. Peter Sandstone and the underlying Upper Cambrian and Lower Ordovician dolomite of the Knox Group; and (5) the Upper Cambrian Eau Claire Formation. The tops of the New Albany, Galena, Knox, and Eau Claire are generally traceable, but there are a few places (even outside of the structurally complex zones noted above) where the reflections lose continuity and interpretation of the seismic reflection section becomes difficult. Although the Knox is generally less reflective than the rest of the Paleozoic section, there is a strong, persistent reflective horizon about 0.2 s below the top of the Knox across most of the seismic profile, and in some parts of the profile (Crittenden County, Kentucky) there are many strong reflections in the Knox. The pre-Knox Cambrian clastic section (consisting of the Upper Cambrian Eau Claire Formation, the Upper Cambrian Mount Simon Sandstone, and an unnamed Lower and Middle Cambrian shale and sandstone rift sequence) (Sargent, 1991) contains several very strong continuous reflections and is, in general, much more reflective than is the Knox throughout most of the region. The top of Precambrian basement is marked in places by a strong reflection; elsewhere it is picked at or near the base of an acoustically transparent interval that generally corresponds to the basal part of the rift-related clastic section. The study area is south of the widespread Precambrian reflective sequence that underlies the center of the Illinois Basin (Pratt and others, 1989, 1992). The Precambrian in this area does not contain well-organized, regionally continuous reflections or sequences of reflections.

VELOCITY ASSUMPTIONS

In the interpretations that follow, we use velocity assumptions based on sonic logs from two deep wells along the seismic line (Texas Pacific Streich 1, Pope Co., Illinois; Sun Stephens 1, Caldwell Co., Kentucky) to convert two-way-travel-time intervals to thicknesses and to estimate true dips for structures. For interpretive purposes, it was most useful to establish representative velocities for the Paleozoic section in three parts: (1) the pre-Knox Cambrian clastic sequence (5.55 km/s or 18,200 ft/s); (2) the Knox Group (dominantly carbonates) (6.47 km/s or 21,227 ft/s); (3) the post-Knox Upper Ordovician through Mississippian carbonate and clastic strata (5.35 km/s or 17,552 ft/s). The Knox and post-Knox velocities are averages of the velocities measured in the Streich and Stephens wells; the pre-Knox velocity is based on the Streich well only because the sonic log for the Stephens well passed through only 110 m (361 ft) of this sequence. The velocities used here are somewhat faster than those reported by Heigold and Oltz (1991) for the Union Oil Company 1 Cisne Community well (Wayne Co., Illinois).

INTERPRETATION OF THE SEISMIC PROFILE

Because both ends of the seismic profile include numerous structural complexities and stratigraphic questions, the discussion of the data begins with a well-constrained, straightforward area 10–15 km from the southeast end of the line (plate 1; fig. 2). We then trace reflections from this relatively simple area into more complex areas; first, to the faulted southeast end of the line and then to the Fluorspar area and Hicks dome to the northwest. The discussion emphasizes interpretations of fault patterns.

STEPHENS WELL AND VICINITY

About 13 km from the southeast end of the line, reflections can be tied to a synthetic seismogram generated from a sonic log in the Sun 1 Stephens well (Caldwell Co., Kentucky), which was drilled to a total depth of 3,952 m (12,965 ft) and bottomed in the Cambrian Eau Claire. In this area, the Cambrian through Mississippian reflections can be traced laterally with reasonable confidence, with a few exceptions (fig 2). Strong continuous reflections occur in the Mississippian, as well as at tops of the New Albany, Galena, Knox, and Eau Claire (fig. 2). The reflection at the top of the Knox loses definition to the east. The top of Precambrian basement is marked by a strong reflection that dips gently to the southeast. The depth to basement beneath the Stephens well is about 6,400 m (21,000 ft). (This figure is calculated using the position of the Eau Claire top at 3,490 m (11,239 ft) in the Stephens well and the 1.09 s (two-way time) occupied by the pre-Knox Cambrian clastic interval on the seismic section. We assumed an interval velocity of 5.55 km/s (18,200 ft/s).) The Stephens well is near the deepest part of the basin along this line of section. The greatest two-way travel time to Precambrian basement (2.3 s) along the seismic line occurs 1.4 km to the southeast. The corresponding depth to basement is about 6,600 m (21,600 ft).

TABB FAULT SYSTEM

In a 15-km segment of the seismic line to the northwest of the Tabb fault system (TFS), the entire pre-Knox section defines a southeast-thickening wedge. Within this wedge there is a gentle angular unconformity at about 1.7 s beneath which reflectors dip more steeply to the southeast than those above the unconformity (plate 1). The pre-Knox Cambrian clastic sequence thickens to the southeast to a point where the top of Precambrian basement, and reflectors below the angular unconformity, are clearly offset by northwest-side-down normal faults in two locations (A, B on plate 1 and fig. 2) northwest of the TFS. The interval beneath the unconformity thins abruptly across fault A and, to a lesser degree, across fault B; thus, we interpret A and B as Cambrian normal faults, and the unconformity is interpreted as the upper boundary on a sequence of strata that accumulated in an early phase of rifting during which faults A and B were active. We do not interpret significant reactivation to have occurred along fault A because it does not offset the upper part of the Cambrian clastic section or the Eau Claire reflector.

Above the faulted basement along fault B (plate 1; fig. 2), the Cambrian through Mississippian reflectors are offset in a normal sense along a northwest-dipping zone that projects to the surface location of the TFS. We interpret the TFS as a post-Mississippian normal fault that has reactivated a basement-cutting Cambrian normal fault (B). Another post-Mississippian normal fault that strikes obliquely to the TFS intersects the seismic line 1 km to the southeast of the TFS. This fault has clearly offset post-Eau Claire reflections in a northwest-side-down normal sense and appears to merge with the TFS near the top of the Eau Claire.

Southeast of the TFS, strong reflections within the Mississippian section are offset by two oppositely dipping reverse faults (C, D, plate 1; figs. 2, 3). Although the pre-Devonian part of the section southeast of the TFS is very difficult to interpret, it appears that these two reverse faults meet at about 0.8 s (two-way travel time) within the Knox and isolate a rotated keystone block in which Ordovician through Mississippian reflectors have a northwest component of dip. Faults C and D can be correlated with mapped faults (Trace and Kehn, 1968; Rogers and Trace, 1976) that strike northeasterly and east-west, respectively, oblique to northwest trend of the TFS. As discussed below, fault D (the north-dipping reverse fault) reactivates a Cambrian normal fault.

The poor data quality immediately southeast of the TFS makes it difficult to confidently correlate pre-Galena reflections at the extreme southeast end of the seismic line with those to the northwest of the TFS. The Galena and New Albany can be correlated through the fault-bounded blocks southeast of the TFS at consistent stratigraphic positions. The top of the Knox is difficult to identify at the southeastern end of the line—its position was picked on the basis of stratigraphic position with respect to other reflections. At the southeastern end of the line, the Eau Claire was picked on the basis of reflection character; the top of the Eau Claire (at about 1.1 s) is near the top of the particularly distinctive set of high-amplitude reflections that occur at this level across much of the seismic line. The top of Precambrian basement was picked at 1.8 s, corresponding to the base of a 0.3-s-long interval of semi-continuous strong reflections below which the rocks are essentially unreflective.

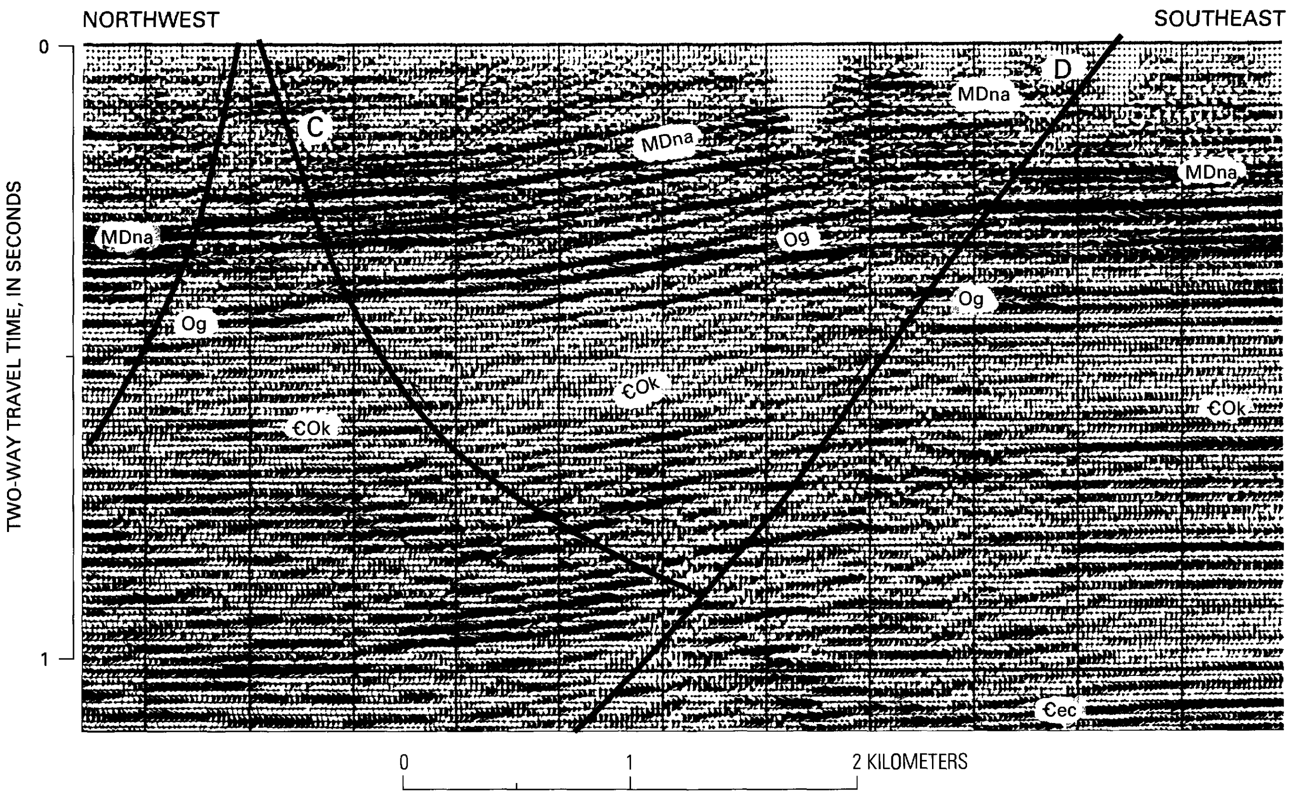

Figure 3. Detail of part of the data shown in figure 2 showing faulting southeast of the Tabb fault system. DMna, top of Middle Devonian to Lower Mississippian New Albany Shale; Og, top of Upper Ordovician Galena Group; ꞒOk, top of the Knox Group. C and D denote faults that are discussed in the text.

Correlation of reflections at the extreme southeast end of the profile with faulted reflection segments immediately to the northwest, and with reflections northwest of the TFS, shows that Eau Claire and younger reflectors are offset in a reverse sense along fault D (plate 1; figs. 2, 3). At lower stratigraphic levels, this reverse displacement is replaced by northwest-side-down normal displacement, evidenced by normal displacement of the top of Precambrian basement, and by abrupt northwestward thickening of the pre-Knox Cambrian clastic sequence. Thus, one can interpret fault D as a Cambrian normal fault that was reactivated by post-Mississippian north-side-up reverse faulting. The latter movement had a dip-slip component of about 350 m.

Strike-slip faults commonly exhibit opposite senses of apparent dip-slip displacement at different stratigraphic levels (Harding, 1983); thus, it is possible to interpret fault D as a post-Mississippian strike-slip or oblique-slip fault. Several geologists interpreted dominant dip-slip displacement on late Paleozoic and younger faults in this region and found a lack of evidence for significant strike-slip displacement (Trace, 1974; Hook, 1974; Trace and Amos, 1984). Heyl and Brock (1961) suggested that strike-slip displacements in the region were significant. The map pattern along fault D (which corresponds to an east-west-striking fault zone mapped at the surface near the southeast end of the seismic line) (Trace and Kehn, 1968; Rogers and Trace, 1976) could have been produced by several kilometers of late Paleozoic or younger strike-slip displacement or by several hundred meters of dip-slip displacement. Regardless of the kinematic interpretation for late Paleozoic faulting here, there must have been a major Cambrian normal-fault zone that encompassed faults A, B, and D and other unnamed faults, as evidenced by the 1,200 m of thickening of the pre-Knox section across this zone.

FLUORSPAR AREA FAULT COMPLEX

Between the TFS and the Ohio River, there is a general northwestward thinning of the pre-Knox Cambrian clastic section and, to a lesser extent, of the Cambrian-Ordovician Knox Group. (This regional trend is only locally interrupted by structures such as fault E (plate 1), a northwest-side-down, minor Cambrian normal fault in Crittenden Co., Kentucky, just northwest of the younger Moore Hill graben.) Numerous FAFC normal faults cut the Paleozoic section (plate 1); these faults are post-Pennsylvanian structures that do not appear to have had an earlier history. The FAFC normal faults

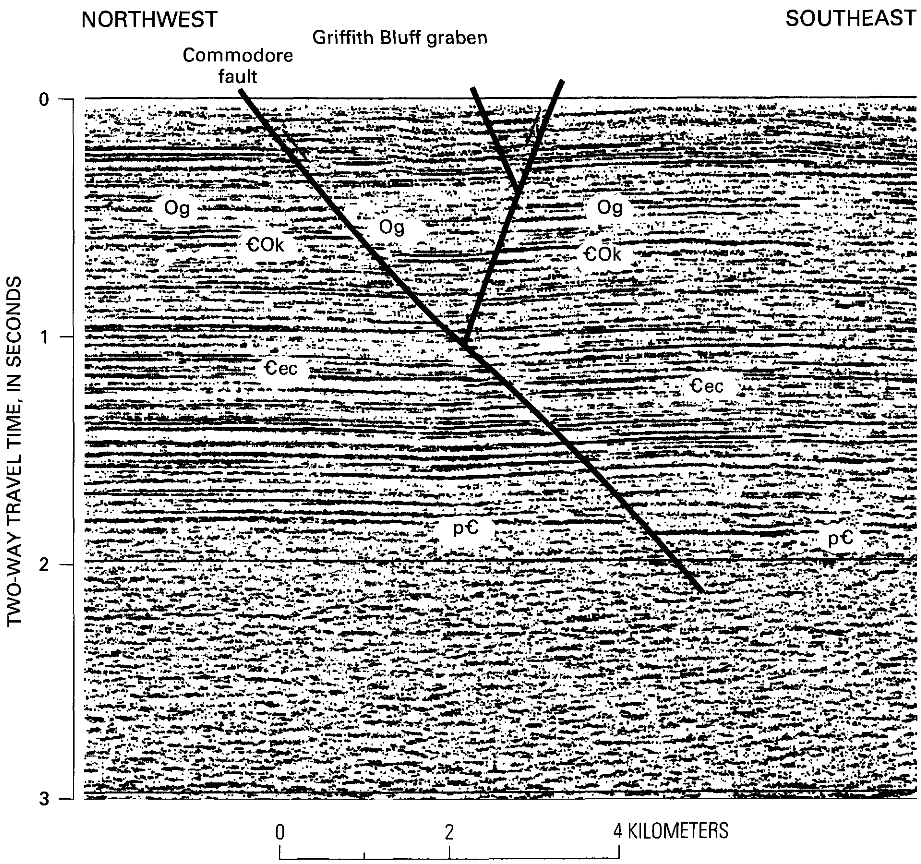

Figure 4. Segment of seismic reflection data across the Griffith Bluff graben, Crittenden Co., Kentucky. Og, top of Upper Ordovician Galena Group; ꞒOk, top of the Knox Group; Ꞓec, top of Upper Cambrian Eau Claire Formation; pꞒ, top of Precambrian basement.

generally define a series of grabens. Some graben-bounding faults clearly cut basement. Beneath other grabens, bounding faults lose displacement downward in the Paleozoic section, requiring lateral accommodation of deformation. Geologic relations (e.g., lack of significant lateral offset of older dikes) indicate that there were not major strike-slip components of displacement in the FAFC (Trace and Amos, 1984).

Beneath both the Shady Grove and the Griffith Bluff grabens (plate 1), one of the bounding faults cuts basement. In both of these grabens, the bounding faults have dips of about 50°–70° (after correcting for seismic velocities) and the opposing normal faults intersect within the Knox. Beneath this level of intersection in each of the two cases, displacement is accommodated along a southeast-dipping normal fault that offsets the top of Precambrian basement. Figure 4 shows reflection data from the Griffith Bluff graben, beneath which the bounding faults splay upward in Silurian and younger strata forming subsidiary fault blocks within the larger graben. Figure 4 also shows the southeast-dipping Commodore fault offsetting basement. The seismic data show an apparent decrease in fault dip within Knox and deeper strata for the "master" faults beneath the Griffith Bluff and Shady Grove grabens. In the case of the Griffith Bluff graben, this is an effect of "velocity pull-up" produced by fast velocities in Knox carbonates; the true fault geometry is planar, after correcting for the variation of velocity with depth. In the case of the Shady Grove graben, the true fault geometry does flatten (using velocity assumptions stated previously for depth conversion) by about 15°.

Examples of grabens that are confined to the Paleozoic section include the Mexico and Moore Hill grabens (plate 1; fig. 5). In both cases, the Knox and younger reflectors are clearly offset along normal faults with 60°–75° dips, whereas the Eau Claire and older reflectors are not. Beneath the Mexico graben, the reflections between the base of the Knox and base of the Cambrian are somewhat disrupted, but not clearly offset. Conceivably, this disruption could be an expression of strike-slip faulting at depth—in such an interpretation, the Mexico graben would be a transtensional structure. Beneath the Moore Hill graben, the Eau Claire and lower reflections are absolutely continuous and do not appear affected at all by the faulting that cuts younger strata.

Immediately southeast of the Shady Grove graben, a narrow horst block (F, plate 1) is apparent. It is bounded on the southeast by a southeast-dipping normal fault (mapped as

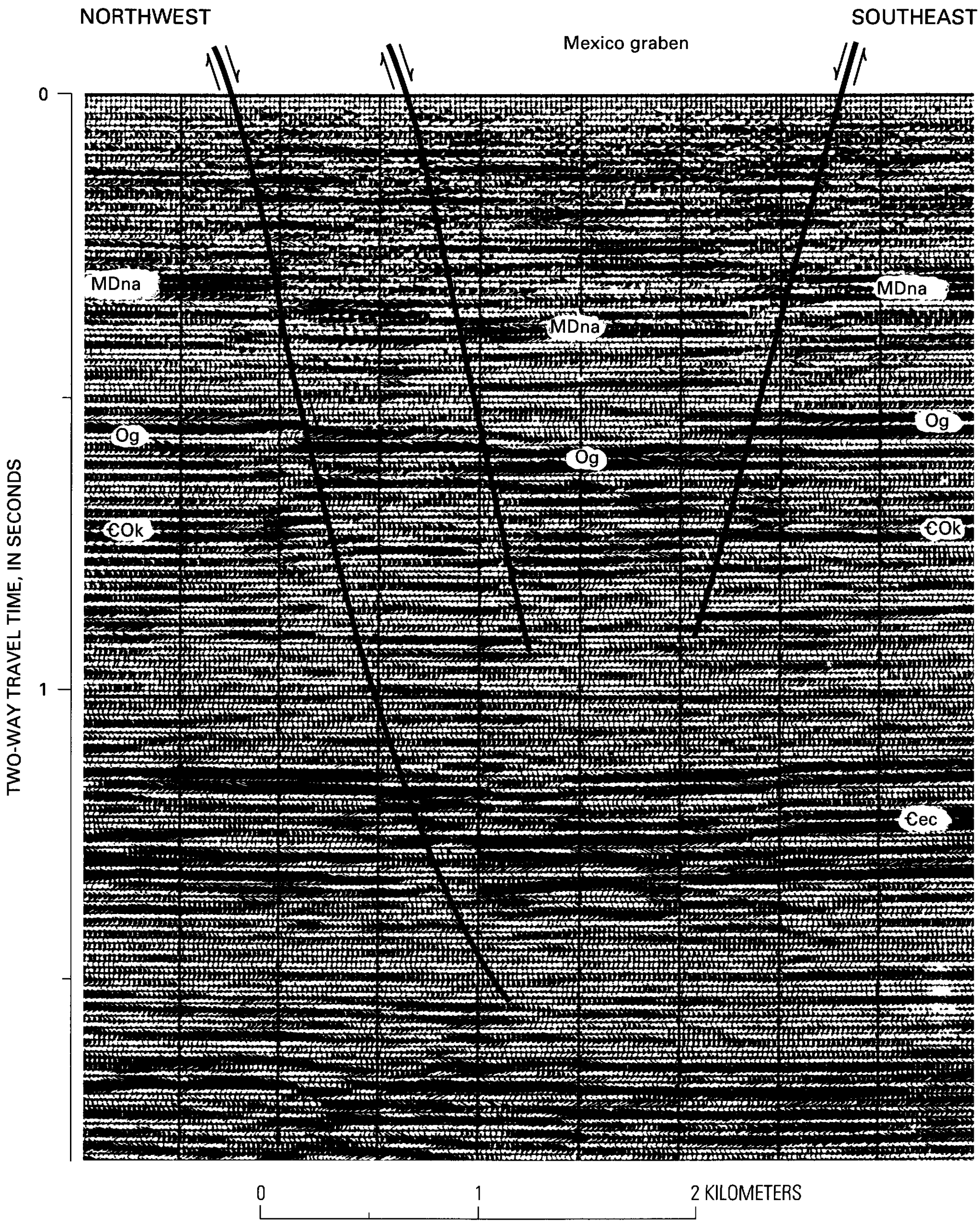

Figure 5. Segment of seismic reflection data across the Mexico graben, Caldwell Co., Kentucky. DMna, top of Middle Devonian to Lower Mississippian New Albany Shale; Og, top of Upper Ordovician Galena Group; €Ok, top of the Knox Group; €ec, top of Upper Cambrian Eau Claire Formation.

a northwest-dipping normal fault by Trace and Palmer, 1971). This fault is also the northwest boundary on an unnamed, 1.5-km-wide graben immediately to the southeast. The faults bounding this graben cut upper Knox and younger strata, but deeper reflectors continue without discernible offset beneath these faults.

The structural style of the Moore Hill and Mexico grabens, and of the unnamed graben just described, strongly suggests that the extension accomplished by the shallow grabens in the upper and middle Paleozoic part of the section is accommodated laterally along a detachment horizon in the Knox. Because there are only about 100 m of extension associated with any of these grabens, the lateral displacement required along this detachment horizon would be of the same order, and this displacement could be transferred to basement-cutting faults such as those noted above.

Because displacement along both the Moore Hill and Mexico grabens increases to the southwest, it is possible that the bounding faults pass into basement-cutting structures along strike to the southwest of the seismic line. For example, about 10 km southwest of its intersection with the seismic line, the southeastern bounding fault on the Mexico graben merges with the Tabb fault, which clearly cuts basement as discussed previously. The Claylick fault system, which bounds the southeast side of the Moore Hill graben, has 105–120 m (350–400 ft) of stratigraphic throw where it intersects the seismic line; the stratigraphic throw increases to about 150 m (500 ft) near the Lucile mine (about 2 km along strike to the southwest) and to 150–185 m (500–600 ft) in the vicinity of the Mineral Ridge mine complex (about 20 km southwest of the seismic line's intersection with the fault) (Trace and Amos, 1984). The presence of significant (basement-derived?) mineralization to the southwest, in conjunction with the increase in fault displacement, suggests that basement may become involved in faulting southwest of the seismic line.

In the horst block between the Griffith Bluff graben and the Moore Hill graben, there is broad arching of Paleozoic reflectors—this corresponds to a gentle anticline delineated by structural contours on the geologic map of the western Kentucky Fluorspar district (Trace and Amos, 1984). This broad arching appears to represent local flexure in response to the impingement of the two bounding normal-fault systems within this southward-tapering horst (geologic map pattern shown in Trace and Amos, 1984). About 1.5 km southeast of the Griffith Bluff graben, the line crosses the 2-m-wide Howard Stout lamprophyre dike (Trace and Amos, 1984), which is too narrow to have expression on the seismic data. Paleozoic reflectors pass uninterrupted beneath the dike, demonstrating that the dike is not connected to a sizable intrusive body at depth in the Paleozoic section.

Northwest of the Griffith Bluff graben, near the axis of the Tolu arch (between the Commodore fault and the Ohio River), the seismic line crosses several faults, each of which has at most a few meters of displacement. These faults have no expression on the seismic data.

OHIO RIVER–ROCK CREEK GRABEN AREA

The character of the reflection data changes dramatically across a 2.75-km gap in the data at the Ohio River (plate 1). On the southeast side of the river, in Kentucky, continuous reflections can be identified throughout the Paleozoic section from the near-surface Mississippian strata to the top of Precambrian basement at about 1.9 s (two-way time). On the northwest side of the river, in Illinois, reflections beneath the Upper Devonian are discontinuous, and very few coherent reflection segments occur below 1.4 s (two-way time). Even though problems with geophone coupling along this part of the line may have contributed to the discontinuity of reflections (P. Scaturro, Seismic Specialists, Inc., oral commun., 1991), the closely spaced faulting and associated structural complexities in the Rock Creek graben–Hicks dome area (fig. 1) were certainly an important factor in the degradation of reflections. There may be other significant geologic changes across this zone, as suggested below in the discussion of the Cambrian section and basement reflections.

The northwest-trending Rock Creek graben is about 3.2 km wide where it is crossed by the seismic line in Hardin Co., Illinois (fig. 1). This is an intensely faulted area, and the graben boundaries consist of complex fault zones. Both bounding fault zones have several hundred meters of displacement on them. Some of the faults (including both normal and reverse faults) can be traced through the Devonian and Mississippian section on the seismic data (plate 1). Some small-displacement, mapped faults are not resolvable. Although complex structure in the graben makes it very difficult to correlate individual reflectors across this area, some major structures are resolvable throughout the Paleozoic section beneath the graben (plate 1).

To the west, the Devonian and Mississippian section (as a whole) can be traced with relative ease across Hicks dome and across the faults and folds northwest of Hicks dome (plate 1, fig. 6), although there are places where individual reflections within this part of the section are discontinuous. The underlying Paleozoic section is quite well defined where the seismic line crosses the southwest flank of Hicks dome and in the area northwest of there where these reflections tie to a synthetic seismogram produced from a sonic log in the Texas Pacific Streich 1 well (plate 1), drilled to a total depth of 4.55 km (14,942 ft) into the Cambrian Mount Simon Sandstone. The pre-Devonian section is very difficult to trace through the projected axis of Hicks dome and the area between Hicks dome and the Ohio River because reflections are discontinuous. Our interpretations of the stratigraphy in this area (plate 1, fig. 6) rely to a large degree on plausible ties to the well-constrained parts of the seismic section to the southeast and northwest and also on some aspects of the character of the reflections in this zone.

Correlation of lower Paleozoic and basement reflections across the Ohio River is somewhat speculative. The pre-Knox Cambrian clastic section occupies about 0.75 s (two-way time) on the seismic section immediately southeast of the Ohio River, and a strong, continuous, two-cycle reflection (X) at or near the base of this section occurs at 1.80–1.85 s (plate 1). On the northwest side of the river (plate 1), a prominent reflection at about 1.8 s can be traced for about 1.5 km to the northwest; we interpret this as the continuation of reflector X. A band of strong but discontinuous reflections (Y, plate 1) at about 1.4 s is traceable (with some minor offsets) for 6.5 km northwest of the Ohio River. We correlate this band of reflections with a strong, continuous set of reflections that occurs in the Cambrian clastic sequence at about the same two-way travel time on the southeast side of the river. We interpret the top of the Eau Claire at the top of a semi-continuous, relatively prominent, three-cycle reflection that is traceable for 2.8 km on the northwest side of the river, at 1.1–1.2 s. It is present at about the same two-way travel time on the southeast side of the

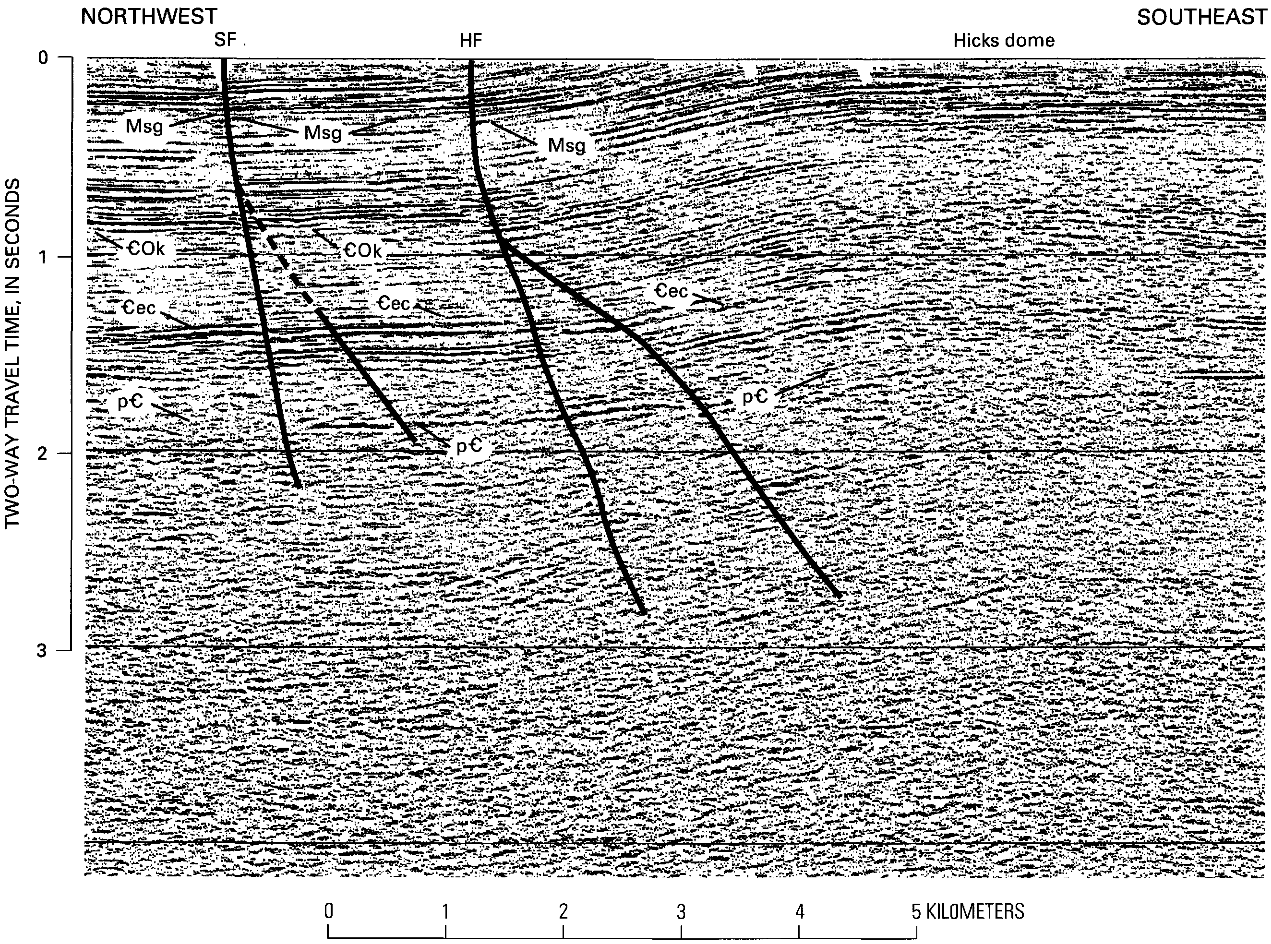

Figure 6. Segment of seismic reflection data across the southwest flank of Hicks dome, Pope Co. and Hardin Co., Illinois. Msg, top of Upper Mississippian Ste. Genevieve Limestone; €Ok, top of the Knox Group; €ec, top of Upper Cambrian Eau Claire Formation; p€ basement, top of Precambrian basement. SF, Shawneetown fault; HF, Herod fault.

river, where it marks the top of a prominent reflective zone (the typical seismic signature of the Eau Claire). The Galena on the northwest side of the Ohio River corresponds to a faint, continuous reflection that occurs at the same two-way travel time as the Galena reflection of the southeast side of the river; the top of the Knox was inferred on the basis of stratigraphic position with respect to other reflections and on the tie to the Knox on the southeast side of the river.

On the northwest side of the Ohio River, reflection Y (plate 1), within the Cambrian at 1.4 s, is broken by small offsets along its 6.5-km span, but there appear to be larger offsets in the deeper (near-basement) reflection patterns. Variations at deeper levels across this area are produced by: (1) a major Early Cambrian structure (masked by poor data quality) at the Ohio River or within a few kilometers to the northwest, or (2) degradation in data quality related to acquisition problems and structural complexity. In spite of serious problems with data quality here, we interpret a southeast-side-down Cambrian normal fault (G, plate 1) about 1.5 km northwest of the Ohio River data gap. Correlations with basement picks northwest of here (see below) suggest a step of about 0.1 s (two-way time, corresponding to about 275 m) on the top of Precambrian basement. Fault G offsets reflection Y and reflection Z (within the Knox—plate 1) with a reverse sense of displacement (two-way time offset of 0.04 s, or about 120 m on reflection Y and about 0.08 s or 245 m on reflection Z). Displacement on other key horizons, such as the tops of the Eau Claire, Knox, and Galena, are not known because these tops do not correspond to strong reflections in this area of poor data quality. Fault G projects to the surface into a zone of intense faulting along the southeast margin of the Rock Creek graben and probably splays upward into several strands within the Devonian and Mississippian section, but its specific configuration within these upper strata is not clear from the seismic data.

From the above observations, we interpret the southeast boundary of the Rock Creek "graben" as a post-Mississippian (Permian?) reverse fault zone (G, plate 1) that experienced about 245 m of displacement where crossed by the seismic line. This reverse fault reactivated a

Cambrian normal fault. The lesser reverse displacement on reflector Y (within the pre-Knox Cambrian strata) relative to that on reflector Z (within the Knox) suggests that some of the Cambrian normal faulting was younger than reflector Y (presumably Middle Cambrian). Our interpretation suggests a total Cambrian normal displacement of about 500 m. Alternatively, the differing amounts and conflicting senses of displacement at different stratigraphic levels along this fault may indicate a post-Mississippian strike-slip displacement history.

Bouguer gravity data show a distinct break of 4 mGal in the area just northwest of the Ohio River, consistent with the idea that there is a significant Cambrian structure there. More negative values occur toward the southeast, compatible with a downward stepping of basement to the southeast and consequent infilling of clastic sediments (T. Hildenbrand and R. Kucks, written commun., 1990). A gravity anomaly of this magnitude could have been produced by Cambrian thickening and basement offset on the order of several hundred meters, as shown by the gravity modeling of the Pennyrile fault system (Lumm and others, 1991).

About 6 km northwest of the Ohio River data gap, reflection Z (plate 1) is offset (down to the east) by about 0.07 s (215 m) across a broad fault zone (H) that underlies the northwestern margin of the Rock Creek graben. This fault zone appears to be nearly 1 km wide within the Knox. We interpret a broadening of the zone, at shallower levels, into the several-kilometer-wide zone of faults mapped along the northwest margin of the graben (Baxter and Desborough, 1965). Along fault H below the Knox, reflection Y is disrupted but is not offset more than a few milliseconds across this fault zone; we speculate that the post-Mississippian east-side-down displacement across this fault reversed early Paleozoic west-side-down displacement here in order to produce this pattern or that the displacement on the eastern boundary of the Rock Creek graben (fault H) was largely accommodated laterally within the lower Knox and Eau Claire. One possibility is that the Rock Creek graben formed in response to Hicks dome-related magmatism and explosive processes that affected the lowermost Paleozoic section—this would explain the faulting of reflectors within the Knox, above pre-Knox reflectors that are disrupted but not offset. This idea is discussed in a later section of this paper.

About 7 km northwest of the Ohio River data gap, just west of fault H, reflection Y (plate 1) is displaced by about 0.06 s (two-way travel time; corresponding to about 200 m of throw) along a gently east-dipping normal fault (J, plate 1). Fault J displaces basement and may continue to shallower depths, as suggested by possible normal drag on reflectors within the Knox (plate 1). The average dip on fault J from the Knox to the top of the basement is about 27°, assuming an average velocity of 5.8 km/s for the interval between the top of the basement and the middle of the Knox. The fault cannot be traced above the Knox due to the poor data quality in the Hicks dome area, but it may be the deep continuation of a normal fault seen in the reflective Devonian-Mississippian section (plate 1).

Directly west of fault J (plate 1), the lowermost Cambrian interval is reflective, and an intermittent reflection at 1.63 s marks the top of Precambrian basement. Beneath this horizon, the basement is characterized by short segments of reflections that do not define continuous stratigraphic or structural patterns. East of fault J, strong reflections are not present at the top of basement or in the lowermost part of the Cambrian. Instead, there is a subtle change in reflection character from an opaque, nonreflective zone in the lowermost Cambrian to short, disorganized reflections in the basement.

Reflections from the Cambrian and Ordovician are very disrupted within a 3-km zone that coincides with the projection of the crest of Hicks dome (plate 1, fig. 6). One cannot trace any individual reflections through this zone. The general reflective character of the Cambrian clastic sequence is preserved, but short discontinuous reflections are present, in contrast to the well-defined continuous reflections within this interval to the west and to the somewhat continuous reflections (discussed above) between Hicks dome and the Ohio River. Short, disrupted, reflection segments also occur in the Knox, in contrast to the adjacent continuous reflections seen on the west flank of Hicks dome. The top of Precambrian basement is not readily discernible beneath this 3-km zone. Reflections in the basement beneath this zone are also disrupted; coherent west-dipping basement reflections at 2–3 s beneath the west flank of Hicks dome terminate and do not continue beneath the zone where Paleozoic reflections are disrupted.

In a west-dipping panel on the heavily faulted west flank of Hicks dome (plate 1, fig. 6), all Paleozoic reflections (lower Cambrian through Pennsylvanian) have an apparent dip of 13°–15° in the plane of the seismic line, using velocity assumptions stated previously. Dips of the near-surface reflections correspond to dips mapped at the surface, and velocity analyses demonstrate no strong lateral velocity gradients within the Paleozoic section; thus, we interpret the dipping reflections to represent the true geologic structure of the Paleozoic strata. Because near-basement Cambrian reflectors are domed, the top of the basement must also be involved in doming. Displacements on most of the mapped faults in this area are too small to be resolved on the seismic data.

The west edge of the west-dipping panel corresponds to the Herod fault, which is the northward continuation of the regionally important Lusk Creek fault system. The seismic data (plate 1, fig. 6) demonstrate that Cambrian through Pennsylvanian strata are displaced in a normal sense across the Herod fault. This post-Pennsylvanian normal fault has produced about 230 m (0.1 s) of displacement of uppermost Knox and younger strata. The fault appears to bifurcate downward within the Knox; the westerly strand continues at a steep (70°–75°) dip to depth. The easterly strand has less dip. There also appears to have been some eastward thickening of the Cambrian clastic section (by about 0.1 s or 280 m) across this easterly strand, suggesting that it was active during Cambrian rifting.

To the west, the seismic line crosses the steeply east-dipping Shawneetown fault (plate 1, fig. 6), which strikes north-northeast. Knox and younger reflectors are offset by about 0.03 s in a reverse sense. The fault appears to bifurcate downward, and it is difficult to resolve any net displacement of Eau Claire and older reflectors, but the position of the fault zone can be easily identified on the basis of disrupted reflections throughout the Paleozoic section. The Cambrian clastic section retains a constant thickness across the fault zone, demonstrating that the Shawneetown fault in this place was not active during Cambrian rifting. Geologic map patterns (Baxter and others, 1967) along this part of the Shawneetown fault require either: (a) major late Paleozoic reverse faulting followed by younger normal faulting (Nelson, 1991), or (b) a single phase of post-Pennsylvanian strike- or oblique-slip faulting. The seismic data demonstrate that cumulative displacements on this fault zone produced little net dip-slip displacement. Nelson (1991) also noted that this part of the Shawneetown fault was not a Cambrian rift boundary and that post-Cambrian movements have produced small net dip-slip.

Northwest of the Shawneetown fault, the seismic line crosses the McCormick anticline (plate 1), a northeast-trending asymmetric structure that is steeper on the northwest limb. Folding affects strata from the Mississippian (exposed at the surface) down through the Knox. Nelson (1991) interpreted this folding to be driven by west-directed horizontal movement along a decollement in the Knox. The seismic data show that the folding is cored by a basement-cutting(?) blind thrust fault (K, plate 1). This fault cuts the Eau Claire 2 km northwest of the position where the Shawneetown fault cuts the Eau Claire (plate 1) and dips easterly at about 30°. Both the Shawneetown fault and fault K almost certainly penetrate the top of the basement, although the seismic data do not explicitly show this because the net offset is small and there is not a strong reflection marking the top of basement here.

About 1.5 km northwest of the west flank of the McCormick anticline (plate 1), there is an east-dipping fault (L) that produced minor reverse movement at the Eau Claire level (and the top of basement?) and at the top of the Knox; this fault appears to have transferred displacement into a gentle monocline in the upper Paleozoic. The interpretation of fault L in the Upper Ordovician through Devonian interval is problematic, however, because there is normal offset of these strata in contrast to the reverse sense of offset above and below this interval. Such contradictory dip-slip displacements are indicative of strike-slip displacement on this fault, although these observations do not provide information on the sense of strike-slip displacement (Harding, 1983). At the extreme northwest end of the seismic line, folding and displacement of the Upper Ordovician reflectors suggest the presence of another reverse or thrust fault (M) that may splay from fault L (plate 1).

Within the Cambrian clastic sequence to the west of fault L, there are apparent offsets of reflections; this may have been a zone of southeast-side-down normal faulting near the northwest flank of the Cambrian rift. Hildenbrand and others (1992, in press) place the rift boundary about 9 km to the northwest, based principally on their interpretation of the depth to magnetic basement and the coincidence of positive magnetic and gravity anomalies in Johnson Co., Illinois.

DISCUSSION

The study area has experienced only diffuse historic and modern seismicity, yet it shares many of the geologic characteristics of the most active part of the New Madrid seismic zone, 140 km to the southwest. A comparison of structural patterns in the southeast Illinois–western Kentucky Fluorspar area (this study) with those in the seismically active New Madrid area should provide some perspective on the geologic controls on New Madrid seismicity. The following section provides such comparisons along with a discussion of significant geologic relations in the vicinity of the seismic line.

REELFOOT–ROUGH CREEK RIFT

The segment of seismic data examined in this paper lies entirely within the Cambrian rift, which is about 110 km wide in this "bend area" (fig. 1) (Hildenbrand and others, 1992, in press). The northwest end of the seismic line is about 5 km southeast of the northwest rift boundary, and the southeast end of the seismic line is about 25 km northwest of the southeast rift boundary as defined by depth to magnetic basement (Hildenbrand and others, 1992, in press). Because the data cover a distance of 83 km across the strike of the rift in the "bend area," we feel that the main aspects of the rift structure are imaged. At the northwest end of the line (in the vicinity of the McCormick anticline), the pre-Knox Cambrian clastic sequence is about 1.1 km thick (corresponding to a 0.4-s two-way-travel-time interval). This sequence thickens to the southeast as the basement steps down across several Cambrian normal faults and achieves its maximum thickness of 3.1 km (1.13 s) in a southeast-thickening wedge that terminates against the Tabb-Pennyrile fault zone. Southeast of this fault zone, at the southeast end of the line, the pre-Knox Cambrian clastic section is about 1.9 km thick (0.7 s). In the Dupont 1 Fee well, situated in Davidson Co., Tennessee (about 100 km southeast of the Cambrian rift), the pre-Knox Cambrian clastic sequence is 0.2 km (737 ft) thick. In the Union Oil Company 1 Cisne Community well, situated in the central Illinois Basin outside of the Cambrian rift (in Wayne Co., Illinois, 80 km north of the Rough Creek fault system), the pre-Knox Cambrian clastic sequence is 0.4 km (1,312 ft) thick. If we assume that normal thicknesses for this sequence outside of the rift are 0.2–0.4 km, the true rift boundaries must lie beyond the limits of the seismic line, as suggested by Hildenbrand and others (1992, in press). It is reasonable to expect that Hildenbrand's magnetically defined rift boundaries correspond to rift-bounding normal-fault zones. The presence of 1.9 km of pre-Knox Cambrian clastic rocks at the southeast end of the seismic line implies that an additional 1.5–1.7 km of thinning of this sequence occurs between there and the true rift boundary, 25 km to the southeast. The 1.2 km of Cambrian displacement across the Tabb-Pennyrile fault zone is by far the most significant rift-related faulting seen on this seismic section. It is likely that another Cambrian normal-fault zone with similar offset (or several zones with as much as 1.7 km combined offset) occurs to the southeast of the seismic line. Candidate fault zones include the "central branch" and "southern branch" of the Pennyrile fault system (5 and 25 km to the southeast of the seismic line, respectively) as defined by Lumm and others (1991). Gravity data and modeling discussed by Lumm and others (1991) strongly suggest that the "southern branch" of the Pennyrile fault system is the southern edge of the Rough Creek graben near its intersection with the Reelfoot rift and that the Cambrian clastic sequence thickens northward by about 1 km, within 10 km (map distance) north of this rift edge. The available geologic and geophysical data support the idea that a broad Pennyrile fault system (more than 30 km across strike), rather than a more localized fault zone, formed the southern margin of the Rough Creek graben in Cambrian time.

The major Cambrian fault zone inferred from the seismic data occurs beneath the area where the Tabb and Pennyrile fault systems intersect at the surface. These two fault systems (mapped on the basis of post-Pennsylvanian displacements) differ in strike by about 45° (fig. 1). The seismic data provide no information on the strike of the Cambrian fault zone that is imaged here. The gravity modeling of Lumm and others (1991) suggests that, about 20 km due south of the southeast end of the seismic line (east of Lake Barkley), the rift margin swings from an east-northeast (Rough Creek graben) orientation toward the northeasterly orientation of the Reelfoot rift. This overall pattern seems inconsistent with significant Cambrian normal displacement along the northwesterly Tabb trend, and we favor the east-northeast (Pennyrile) trend for the major Cambrian fault zone that we interpreted from the seismic data.

The overall geometry and genesis of the Reelfoot rift, Rough Creek graben and Rome trough (a northeasterly trending Cambrian basin that extends from eastern Kentucky to western Pennsylvania in the subsurface) have been briefly addressed by several authors. Thomas (1991) considered these zones of anomalously thick Cambrian strata to be linked segments of a "failed" intracratonic rift system of Early and Middle Cambrian age that was contemporaneous and compatible with a northwest-trending Alabama-Oklahoma transform that coupled Ouachita rifting with mid-Iapetus spreading. Thomas' (1991) view of the Reelfoot, Rough Creek, and Rome basins was based on their map-view geometry and on available paleontological control on rift fill. While conceding that the proposed Rome–Rough Creek connection in eastern Kentucky is not well understood, Thomas (1991) suggested that the Rough Creek graben was an "oblique transfer zone" between the Reelfoot and Rome rift segments. The geometry is essentially that of a right-stepping rift offset as defined by Nelson and others (1992), who stress that an oblique rift offset segment (the Rough Creek graben, in this case) would be a zone of complex strain and that bounding faults (Cambrian Rough Creek and Pennyrile fault systems, in this case) would have undergone oblique displacement with a significant strike-slip component. Chandler and others (1989) illustrated a higher angle rift offset zone in the southern Minnesota part of the Proterozoic Midcontinent rift system, and rift offsets have been documented in many other rift systems worldwide (Nelson and others, 1992). Walker and others (1991) attributed the development of the Rome Trough–Rough Creek graben system to extensional failure resulting from subsidence and flexure of the passive continental margin to the east. Drahovzal and others (1992) suggested that the Early and Middle Cambrian Rome trough and Rough Creek graben were separated by a stable block in central Kentucky that corresponds to the pre-Grenville East Continent rift basin. Goetz and others (1992) postulated that the Rough Creek graben and Rome trough originated in the Precambrian, before the initiation of the Reelfoot rift, and that the Reelfoot rift became linked with these earlier structures in Cambrian time, but Goetz and others (1992) provided no data to substantiate this idea.

The seismic line discussed here clearly records a major transition in rift polarity within the major bend in the Cambrian rift system; such transfer zones between oppositely dipping half-grabens are common in rift systems (Rosendahl and others, 1986; Morley and others, 1990). Other major transfer zones, in which regional extensional strain is conserved between zones of differing fault configuration, can be inferred in the rift system. The seismically active part of the Reelfoot rift appears to have had a different Cambrian geometry than that of adjacent segments, as discussed below. In considering structural controls on seismicity, one should consider (a) the effects of the major change in strike of the rift system, (b) the effect of the variations in cross-sectional geometry of the rift, and (c) mechanical effects of lateral variations in crustal rheology. These are evaluated below.

In examining old fault zones as planes of weakness in the modern stress field, the dogleg-shaped Cambrian rift system includes a wide range of fault orientations that may (or may not) be exploited for strain release in the modern stress field. The Reelfoot rift is controlled by steeply dipping, northeast-striking faults that originated as Cambrian normal faults and have, in many cases, been reactivated as late Paleozoic reverse faults. A northeast-trending linear cluster of

New Madrid epicenters coincides with the central part of the Reelfoot rift, but northeast-trending Cambrian and younger faults continue to the southwest and northeast of the seismic zone (for example, the Lusk Creek–Herod fault system of the study area). The present-day maximum compressive stress is oriented about N. 60° E. (Zoback, 1992); the steeply dipping fault system, trending N. 30° E., would be susceptible to right-lateral strike-slip reactivation in such as stress field. Andrews and others (1985) relocated epicenters and analyzed fault-plane solutions for microearthquakes in the New Madrid seismic zone; they found that the dominant northeasterly trend of the cluster of epicenters is associated with right-slip in a discrete zone along the rift axis (now the Blytheville arch), south of the Pascola arch and along the northwest margin of the rift for a short segment north of the Pascola arch (fig. 7). Chiu and others (1992) found that the central cluster of New Madrid hypocenters in the vicinity of the Lake County uplift define two planes, dipping moderately to the southwest, and they infer that these have undergone reverse movement consistent with the modern stress field. It is not clear why these clusters of seismicity are confined to one 150-km zone along the 350-km-long Reelfoot rift. The Rough Creek graben contains east-striking faults, such as the Rough Creek system, east-northeast-striking faults, such as the Pennyrile system, and northeast-striking faults of the Fluorspar area fault complex that are essentially on trend with faults of the Reelfoot rift. The east-northeast-striking faults would have low resolved shear stress because they are nearly parallel to a principal stress axis. The east- and northeast-striking faults would appear to be candidates for strike-slip seismic activity if fault orientation were the controlling parameter. That is apparently not the case. The FAFC is strongly faulted at all scales and may be too weak to support appreciable strain energy.

The regional variation in the overall structure of the Reelfoot–Rough Creek rift system, obvious from comparison of the present study with other seismic reflection studies in the rift system, may contribute significantly to the localization of New Madrid seismicity. This study of the Cambrian rift establishes the presence of a strongly southeast-tilted graben in the "dogleg bend" area, in contrast with the strongly north tilted asymmetric graben in the main part of the Rough Creek graben to the east. The major transfer zone that must exist between these areas of opposing rift polarity is one of several transfer zones inferred in the rift system. To the south, in the area of maximum New Madrid seismicity, the seismic reflection data across the Blytheville arch (Howe and Thompson, 1984; Howe, 1984) clearly show that there was an axial Cambrian rift zone that contained a locally thickened section (a medial graben). This axial zone underwent later reverse faulting that is obvious in a seismic reflection section from northeast Arkansas (Howe, 1984), and this zone (the seismogenic part of the Blytheville arch) contains the most complex structure in this part of the rift. In contrast, profiles to the south (P1 from McKeown and others, 1990; COCORP data, Nelson and Zhang, 1991) show that, near the southern end of the well-defined line of epicenters, the rift consists of simple half-grabens that appear to change polarity along the rift axis with no pronounced axial thickening. The Blytheville arch at that latitude is a structurally simple gentle antiform. The along-strike transitions between full- and half-graben structural styles, although insufficiently imaged in studies of this rift system, are almost certainly examples of major transfer zones, as described in the East African and other rift systems by Morley and others (1990). These inferred Cambrian transfer zones closely coincide with geographic limits of the most active part of the New Madrid seismic zone, as defined by tightly clustered epicenters of the northern Mississippi Embayment (fig. 7).

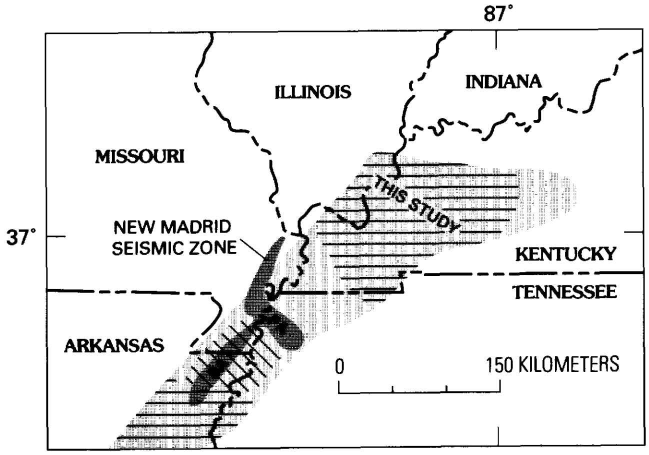

Figure 7. Generalized diagram showing the along-strike variation of structural patterns within the Reelfoot–Rough Creek rift system. The New Madrid seismic zone is shown in dark stipple; the Reelfoot–Rough Creek rift system is shown in a lighter stipple. BA, Blytheville arch; PA, Pascola arch. Horizontally ruled pattern denotes parts of the rift system characterized by major half-grabens with alternating directions of polarity. Diagonally ruled pattern denotes the part of the Reelfoot rift that is characterized by a more symmetric geometry, with an axial maximum of Cambrian rift-related sedimentary rocks ("axial thick"). See text for further discussion.

Howe (1984) and McKeown and others (1990), among others, have emphasized that New Madrid seismicity is localized in a weak zone corresponding to the structurally complex Blytheville arch. The body of published seismic data from the Cambrian rift system, including the present study, indicates that this seismically active area has a geometry that is unlike other parts of the rift system. We hypothesize that the downdropped, structurally complex axial rift zone is the weakest part of the northeast-oriented rift system, and it fails most readily in response to intraplate stresses. The well-defined line of rift-axis seismicity dies out southeast of Blytheville, Ark., because of the along-strike change in character from structurally complex "axial thick" to a gentle antiform; this transition is a consequence of the preexisting

Cambrian transfer zone that separated the axial graben from the half-graben style to the south. Seismicity declines dramatically north of the Pascola arch, probably because the axial rift zone gave way to the strongly asymmetric graben seen in the present study (fig. 7). (Seismicity within the Pascola arch, and along the northwest rift margin north of the Pascola arch, represents a dissipation of accumulated strain at the north end of the axial zone.) In the present study, we identified aseismic northeasterly striking faults that originated as Cambrian normal faults in the Hicks dome area and the Fluorspar area of western Kentucky; however, they are not associated with a discrete axial graben, so their aseismic nature fits the regional pattern.

Rheological contrasts in the basement may also affect seismicity. The possible mechanical effects of pluton boundaries, and of thermal metamorphism surrounding plutons, were addressed by Ravat and others (1987). A long-lived northwest-southeast crustal boundary that crosses our study area was discussed by Heigold and Kolata (1993); this broad boundary crosses the nearly aseismic part of southern Illinois and western Kentucky and lies between the New Madrid and Wabash Valley seismic zones. As Heigold and Kolata (1993) suggest, the quite different characteristics of these two seismic zones may be related to the fact that they lie in different basement provinces that have different mechanical properties.

FLUORSPAR AREA FAULT COMPLEX

The nature of the Fluorspar area fault complex may provide another possible explanation for the abrupt northward decline in seismicity in the northernmost Mississippi Embayment. The Fluorspar area faults, which are probably not older than Permian, follow the same trend as the seismogenic Blytheville arch but occupy a zone that is several times broader. The Fluorspar area faults disappear to the southwest beneath Cretaceous and Tertiary sedimentary rocks of the Mississippi Embayment, and their extent beneath the embayment is unknown. It is possible that a significant amount of "New Madrid" strain is transferred from the well-defined axial zone of the Reelfoot rift to the covered southwestward extension of the FAFC, where it is distributed throughout a much broader zone—sufficient strain energy would not accumulate on any single fault in the FAFC to produce a large-magnitude earthquake. This postulated transition, northeast of the Pascola arch, may be governed by either a northeasterly termination of the axial zone of the Cambrian Reelfoot rift, or by the southwesterly limit of the Permian and younger FAFC, or by both.

HICKS DOME

Although Hicks dome is aseismic, it has many characteristics in common with the seismically active Pascola arch. Like the Pascola arch, Hicks dome is a late Paleozoic structural high forming the northern terminus of an elongate arch (Tolu arch) within the Reelfoot rift (compare McKeown and others, 1990, and Kolata and Nelson, 1991). A well drilled near the crest of the Pascola arch (the USGS New Madrid test well) contained extremely high concentrations of Be, Nb, Th, and La in Paleozoic non-carbonate strata (Goldhaber and others, 1993); these authors interpreted these elements to be metasomatically introduced. This group of elements is characteristic of alkalic igneous processes (e.g., Mariano, 1989), similar to the igneous activity at Hicks dome. Because of these geologic and geochemical similarities between Hicks dome and the Pascola arch (although Hicks dome is considerably smaller), it is instructive to examine the subsurface characteristics of Hicks dome.

The seismic data provide new information on the origin of Hicks dome and on the nature of subsurface rocks (and processes) in the vicinity of Hicks dome. It is clear from the data that the entire Paleozoic section is domed. Thus, contrary to one popular hypothesis (Brown and others, 1954; Nelson, 1991), the doming originated in the basement, rather than being produced by explosive processes within the Paleozoic section. Hicks dome is situated on the southwest flank of a large, northwest-trending positive magnetic anomaly, the maximum intensity of which occurs near Karbers Ridge, 9 km northeast of the center of the dome (McGinnis and Bradbury, 1964). McGinnis and Bradbury (1964) interpreted the source of this anomaly to be a mafic intrusive body at depths of 3.35 km (11,000 ft) and greater, which would place the top of the intrusion in lower Paleozoic strata or Precambrian basement. Although there are no major potential-field anomalies centered on Hicks dome, it is clearly an intrusive center and is likely a product of explosive magmatism fed by the Karbers Ridge intrusion. Previous workers (e.g., Heyl, 1983; Baxter and others, 1989; Bradbury and Baxter, 1992) concluded that mantle-derived volatiles were involved in the genesis of Hicks dome and its associated mineralization, based in part on the presence of intrusive breccias (including carbonatitic breccias) and an "alkalic suite" of elements. As these workers suggested, brecciation at Hicks dome may be explained by an explosive release of igneous volatiles; if so, this must have occurred in the Precambrian basement beneath the dome. The doming was probably not produced by a single large intrusion near the top of the basement, unless this intrusion was pervasively altered during the proposed explosive processes and related fluid flow to erase a "typical" potential-field signature of an intrusive body.

The disruption of lower Paleozoic and intra-basement reflections in a 3-km-wide zone, beneath the projection of the crest of the dome, and the discontinuous nature of reflections between Hicks dome and the Ohio River may be the signature of: (1) myriad small alkalic and carbonatitic intrusions genetically related to those at the surface near Hicks dome, (2) anomalous physical properties due to alteration of the original lithologies by processes such as silicification, (3) brecciation and fracturing of these layers, perhaps during the explosive event that has been invoked to explain Hicks dome, (4) closely spaced minor faults, as mapped at the surface in this area (too closely spaced to show on quadrangle maps, according to Heyl, 1983), or (5) a combination of these. Goldhaber and others (1992) and Plumlee and others (in press) presented fluid-inclusion and geochemical evidence that igneous activity at Hicks dome (and presumably the much larger buried Karbers Ridge intrusion) was a heat source during Permian Fluorspar area mineralization and that hydrofluoric acid-rich fluids related to Hicks dome magmatism were a significant component of the mineralizing fluids in the Fluorspar area. We hypothesize that these strongly acidic fluids, released during Hicks dome magmatism, pervasively altered parts of the Paleozoic section and that this is one of the principal causes of the discontinuous nature of the reflections beneath and southeast of Hicks dome. This postulated flow appears to have been highly directional because the southwest flank of Hicks dome has not been affected similarly.

The term "cryptovolcanic," which has repeatedly been applied to Hicks dome, implies that subaerial explosive activity occurred at Hicks dome. Devonian and Mississippian reflections across Hicks dome and the Rock Creek graben have a quite coherent signature (although it is difficult to trace them continuously because of complex faulting) that argues against the "cryptovolcanic" interpretation for the origin of Hicks dome, unless all volcanic vents were outside the plane of the seismic section.

Reflection patterns beneath the northwest boundary of the Rock Creek graben (discussed in a previous section of this report) may shed light on the role of Hicks dome magmatism in the structural evolution of the region. The obvious fault offset of reflections in the Knox is not seen in the underlying pre-Knox reflections, although the latter are disrupted. Perhaps faulting of Knox and younger layers occurred in response to pervasive intrusion and brecciation of deeper strata. The latter processes, even though they did not produce discrete offsets of individual layers, would have produced a bulk dilatation of the lower Knox, pre-Knox, and uppermost basement(?) rocks in the area between Hicks dome and the Ohio River. Overlying strata were faulted in response to this. In some areas (presumably over the top of the intruded and brecciated zone), overlying faults were extensional, as along the northwest boundary of the Rock Creek graben. One might expect the lateral boundary of the intruded and brecciated zone to be characterized by shortening, as seen in the reverse faulting identified along the southeast boundary of the Rock Creek graben. Thus, the Rock Creek graben may have originated in Permian time as a result of Hicks-dome-related magmatism and pervasive brecciation.

CONCLUSIONS

1. Seismic reflection data demonstrate a major along-strike transition in the geometry of the Cambrian Reelfoot–Rough Creek rift system in the vicinity of the dogleg bend that connects the RFR and the Rough Creek graben. The highly asymmetric, southeast-dipping graben in the bend area (southern Illinois and western Kentucky), controlled by a major northwest-dipping Cambrian normal fault zone near the southeastern edge of the rift, contrasts with the north-dipping half-graben to the east in Kentucky, controlled by the south-dipping Rough Creek fault system.
2. The overall style of rifting changes to the south of the bend area from one of highly asymmetric grabens and half-grabens (Rough Creek graben and bend area) to one characterized by a structurally complex zone of axial thickening (main part of the RFR).
3. The localization of historic New Madrid seismicity as a discrete zone within the RFR may be inherited from Cambrian rift structure—the northern and southern ends of the strongly seismogenic zone appear to correlate with major transfer zones that accommodate along-strike changes in Cambrian rift geometry.
4. The seismic data demonstrate that the top of Precambrian basement is domed beneath Hicks dome, in Hardin Co., Illinois, and that reflectors in the pre-Devonian section near the dome are pervasively disrupted. We interpret the doming to have occurred as a result of a combination of intrusive and explosive processes in the basement during Permian alkalic magmatism, and we interpret the disruption of lower Paleozoic reflectors as the product of alteration by acidic fluid flow and intense faulting. Both the acidic fluids and the faulting appear to be genetically related to alkalic magmatism. There are several geologic similarities between the aseismic Hicks dome and the seismogenic Pascola arch.
5. Fluorspar area Permian and younger normal faulting that reactivated the RFR is well-imaged on the seismic data; some grabens are bounded by faults that cannot be traced below the Knox and must be accommodated laterally within the Knox, whereas other faults clearly offset basement.
6. The broad FAFC may absorb strain from the narrow New Madrid seismic zone; this strain may be distributed aseismically in the FAFC. This would help explain the nearly aseismic nature of the northernmost Mississippi Embayment north of the New Madrid seismic zone.

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