Velocity analysis at CDP 3194

Time (ms)	Root mean square velocity (m/s)	Interval velocity (m/s)	Depth (m)
0.001	1,440.0	1,440.0	0.7
.045	1,300.0	1,896.6	29.2
.145	1,570.0	1,677.4	113.1
.345	1,730.0	1,837.3	296.8
.885	2,315.0	2,621.3	1,004.6
1.000	2,400.0	2,973.9	1,175.6

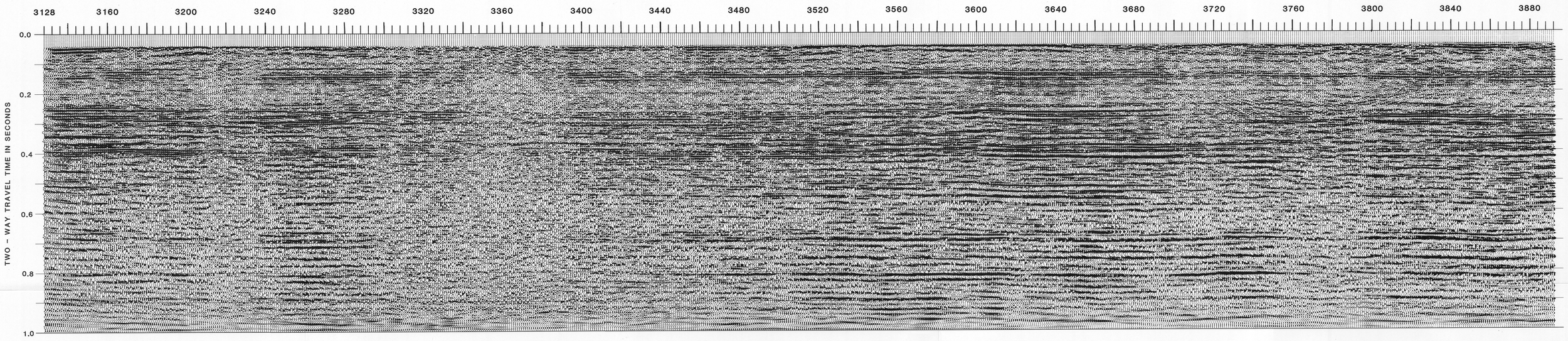
Velocity analysis at CDP 3494

Time (ms)	Root mean square velocity (m/s)	Interval velocity (m/s)	Depth (m)
0.001	1,440.0	1,440.0	0.7
.048	1,335.0	1,332.7	32.0
.170	1,600.0	1,692.9	135.3
.415	1,735.0	1,822.8	358.6
1.000	2,300.0	2,628.2	1,127.3

Velocity analysis at CDP 3794

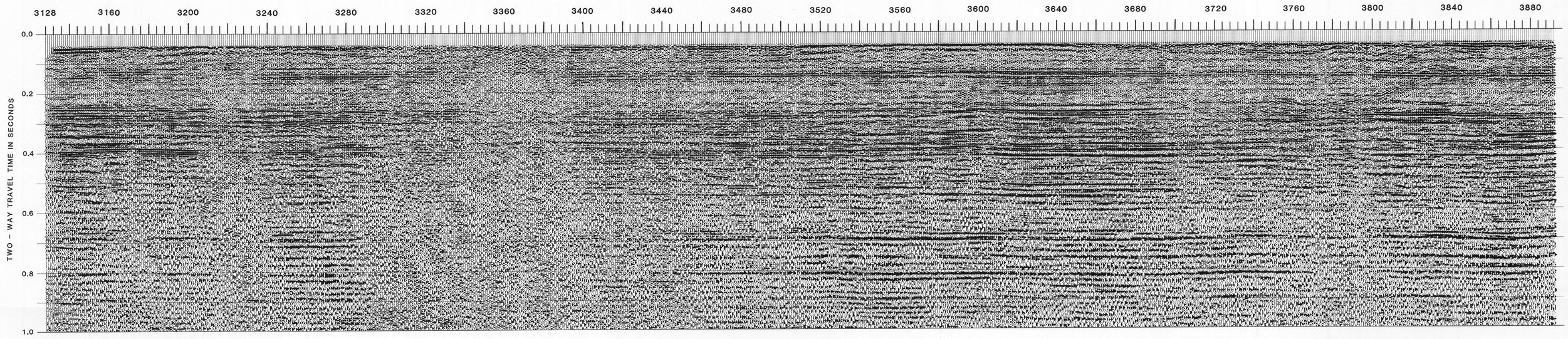
Time (ms)	Root mean square velocity (m/s)	Interval velocity (m/s)	Depth (m)
0.001	1,440.0	1,440.0	0.7
.050	1,340.0	1,337.9	33.5
.175	1,625.0	1,725.9	141.4
.435	1,875.0	2,026.0	404.7
.820	2,465.0	2,994.9	981.3
1.000	2,700.0	3,560.4	1,303.5

COMMON DEPTH POINT



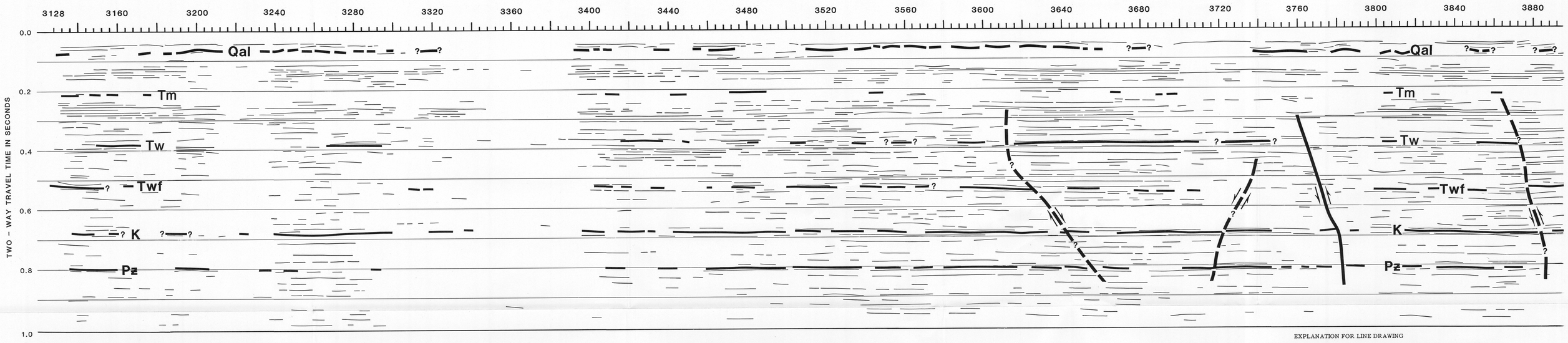
PROFILE A.-- MIGRATED SECTION

COMMON DEPTH POINT



PROFILE A.-- UNMIGRATED SECTION

COMMON DEPTH POINT



PROFILE A.-- LINE DRAWING

EXPLANATION FOR LINE DRAWING

Major regional seismic reflectors; queried where uncertain. Pz, top of the Paleozoic bedrock surface; K, bottom of the Paleocene Midway Group and top of the Upper Cretaceous McNairy Sand; Twf, bottom of the Paleocene Fort Pillow Sand of the Wilcox Group; Tw, bottom of the Eocene Claiborne Group and top of the Paleocene-Eocene Wilcox Group; Tm, top of the Eocene Memphis Sand of the Claiborne Group; Qal, base of the Quaternary Mississippi River alluvium

Locally prominent reflectors

Faults; dashed and queried where subtle or uncertain; arrows show direction of movement

INTRODUCTION

The tectonic setting and the earthquake hazards of the New Madrid seismic zone in the northern Mississippi embayment have been the subject of intensive study the past several years as part of the Earthquake Hazard Reduction Program of the USGS (U.S. Geological Survey). These efforts have improved our knowledge of the geologic history, general tectonic setting, and patterns of modern seismicity (see McKeown and Pakiser, 1982) in the New Madrid seismic zone. Identifying and characterizing the specific structures that may be responsible for the seismicity is the focus of continuing research. Unfortunately, these structures are buried by the veneer of poorly consolidated Upper Cretaceous and Tertiary sediments that overlie competent rocks in the embayment. In such a geologic setting, seismic-reflection profiling is one of the most valuable techniques available to obtain useful information on the distribution of faults, and on the local and regional structure.

Three major seismic-reflection programs have been conducted by the USGS in the New Madrid seismic zone. The first program consisted of 32 km of conventional Vibroseis® profiling designed to investigate the subsurface structure associated with scarps and lineaments in northwestern Tennessee (Zoback, 1979). A second, more extensive Vibroseis® program collected about 250 km of data from all parts of the New Madrid seismic zone in Missouri, Arkansas, and Tennessee (Hamilton and Zoback, 1979, 1982; Zoback and others, 1980). The profiles presented here are part of the third program that collected about 240 km of high-resolution seismic-reflection data from a boat along the Mississippi River between Osceola, Ark., and Wickliffe, Ky. (fig. 1). The data for profiles A, B, C, and D were collected between river miles 839-1/2 and 850-1/2 from near the Interstate-155 bridge to upstream of Caruthersville, Mo. (fig. 2). Profiles on this part of the river are important for three reasons: (1) they connect many of the land-based profiles on either side of the river, (2) they are near the northeast termination of a linear, 120-km-long, northeast-southwest zone of seismicity that extends from northeast Arkansas to Caruthersville, Mo. (Stauder, 1982; fig. 1), and (3) they cross the southwesterly projection of the Cottonwood Grove fault (fig. 1), a fault having a substantial amount of vertical Cenozoic offset (Zoback and others, 1980).

DATA COLLECTION AND PROCESSING

The data were collected by the R/V Neecho, a USGS research vessel based in Woods Hole, Mass., using a 40-in.^{3} air gun towed about 2.4 m below the water surface. The 12-channel data were recorded as the boat traveled upstream against a fluctuating current. The current caused some variation in the distance between shot points; most shots were spaced at 5-m (±1 m) intervals, but, in some parts of the survey, the interval was as much as 10 m. Details of the field parameters are listed in table 1 and discussed by Shedlock and Harding (1982).

The data were processed using a Phoenix® I system; the sequence of processing steps is listed in table 1. Careful monitoring of the data processing reduced the effects of various sources of noise such as streamer oscillation, water-bubble multiples, and electronic and cultural noise (Shedlock and Harding, 1982). However, noise from passing river traffic was a recurring problem; in a few places it overwhelmed the seismic signals and made reflectors indistinguishable (see the area near CDP (common-depth-point) 3365, profile A). One especially noisy segment, between CDP's 6051 and 6610 (profile D), has been deleted from the data presented here because the noise obliterated any useful information.

Between CDP's 5100 and 5300 (profile C), an overlap occurred between the surveys at the end of one day and the beginning of the next day. This overlap has been deleted and the profiles have been spliced together during processing to produce a continuous record section.

GENERAL CHARACTERISTICS OF THE SEISMIC-REFLECTION PROFILES

The seismic-reflection profiles show one second of two-way travel-time data, corresponding to maximum depths of about 1,081-1,397 m depending on the stacking velocities. The data have been divided into four parts (profiles A, B, C, and D) to fit the format of this map. Final-stack unmigrated and migrated record sections are presented. Directly below the unmigrated sections are line drawings showing: (1) the major regional seismic reflectors, (2) less continuous, locally prominent reflectors, and (3) a structural interpretation of the data showing faults.

The major reflections identified on the record sections and labeled on the line drawings are correlated with specific stratigraphic horizons on the basis of data from a nearby research well in southeast Missouri (fig. 1). Geophysical logs and cuttings from the well have provided detailed information on the Late Cretaceous and Tertiary stratigraphy in the area (Crone, 1981). The well logs were also used to generate a synthetic seismogram; the seismogram predicts which stratigraphic horizons are likely to generate seismic reflections on the basis of their physical properties. Thus seismic reflections can be directly related to the stratigraphy. Next, reflections on the synthetic seismogram were correlated with the reflections on a Vibroseis® line that passed within 10 m of the well (Crone and Russ, 1979). This line extended to the river where the reflections could then be correlated with similar reflections on the river data.

[1]Any use of trade names in this report is for descriptive purposes only and does not imply endorsement by the USGS.

The six major reflections on the profiles, labeled on the line drawings, are in ascending order: (1) Pz--top of the Paleozoic bedrock surface; (2) K--bottom of the Paleocene Midway Group and top of the Upper Cretaceous McNairy Sand; (3) Twf--bottom of the Paleocene Fort Pillow Sand of the Wilcox Group; (4) Tw--bottom of the Eocene Claiborne Group and top of the Paleocene-Eocene Wilcox Group; (5) Tm--top of the Eocene Memphis Sand of the Claiborne Group; and (6) Qal--base of the Quaternary Mississippi River alluvium. The K reflection is the strongest, most continuous reflection on both the Vibroseis® and river profiles. The Pz reflection is locally very strong (CDP 3585, profile A), but elsewhere it is obscured by noise or is subtle because of insufficient reflected energy. Reflections from the shallower Tertiary horizons (Twf, Tw, Tm) are very discontinuous, difficult to trace, and, in comparison with the Pz and K horizons, have a relatively low acoustic impedance. Because of their discontinuous nature, the Tertiary reflectors cannot be correlated as confidently as the Pz and K reflectors. In places, very strong reflections within the Tertiary sedimentary rocks help to identify local deformation (for example, 160 ms on profile A).

The Qal reflection, thought to be from the contact between the weakly consolidated Tertiary sediments and the overlying, unconsolidated alluvium, is laterally very discontinuous and varies in depth (two-way travel time) rapidly. During the late Pleistocene glacial cycles, the discharge and sediment load of the ancestral Mississippi-Ohio River system fluctuated greatly, and periodically the river scoured channels into the underlying Tertiary sediments (Saucier, 1974). Thus the base of the alluvium is probably an uneven, scoured contact. Identifying this shallow contact on the profiles was difficult because of its irregularity, and because the signal from the contact had to be distinguished from direct-wave signals and bottom- and side-channel reflections. Where available, U.S. Army Corps of Engineers boring logs along the river levees were used to help identify the base of the alluvium and to estimate the two-way travel time of the reflection. Nevertheless, the identification of Qal on the profiles is generally uncertain and highly interpretative.

STRUCTURAL INTERPRETATION AND DISCUSSION

In the subsequent discussion, all references to unlabeled reflectors and fault offsets will be cited in two-way travel time in ms (milliseconds). We also convert these travel times to metric values using the stacking velocities. However, because of both vertical and lateral velocity changes, these metric values should be regarded as estimates that are subject to significant error. In general, a simple rule that can be used to obtain crude depth estimates for all horizons above the Paleozoic bedrock is that 1 ms of two-way travel time is approximately equal to 1 m of depth.

The Mississippi embayment is a broad, southwest-plunging syncline whose axis approximately follows the modern course of the Mississippi River (Cushing and others, 1964). On the basis of limited drill-hole data, structure contours of the Paleozoic rocks beneath the embayment sediments show that the axis of the syncline lies immediately southeast of the part of the river covered in this map (Stearns and Wilson, 1972; Crone, unpub. data). Therefore, broad, gentle rises and falls in the reflectors on the profiles may not necessarily be caused by local structures; they may be the result of the meandering river course traversing the flank of the syncline.

Faults and upwarps or arches are the most obvious structures on the profiles. The distribution, characteristics, and amount of deformation associated with these structures are important to earthquake hazard studies. The faults that have been interpreted on the profiles have several common characteristics. Perhaps most obvious is the relatively small vertical displacement associated with individual faults, especially considering the relatively abundant seismicity in the region. However, focal mechanisms of earthquakes located between Caruthersville, Mo., and northeast Arkansas show that the fault movements are dominantly right-lateral strike-slip (Herrmann and Canas, 1978; Herrmann, 1979). Lateral displacements are difficult to identify on reflection profiles; for obvious reasons, the vertical component of faulting is the most conspicuous on reflection profiles. Thus, the faults with small vertical offsets noted on these profiles could have a substantially larger total offset much of which is a lateral component.

Another common characteristic is that none of the faults can be confidently traced all the way to the surface (that is, none of the faults displace the Qal reflection). On most of the profiles, there is a strong reflection or group of reflections between about 160 and 200 ms. The upward continuation of faults that offset deeper reflections do not appear to displace these strong reflections where they exist.

Many faults and an obvious upwarp are present between CDP's 4345 and 4800 (profiles B and C). The center of this faulted area (CDP 4560) is exactly on strike with the southwesterly projection of the Cottonwood Grove fault (Zoback and others, 1980), which vertically offsets the K reflection about 80 m at Cottonwood Grove, Tenn., located about 10 km to the northeast. Our profiles do not show a single dominant fault as observed at Cottonwood Grove, but show several faults, each with vertical offsets of 8-12 ms (10-15 m). These faults are associated with a broad arch that has about 44 ms (55 m) of relief on the K reflection. The interpretation presented here shows a series of southeast-dipping high-angle reverse faults on the upriver (northwest) side of the arch and several northwest-dipping, high-angle reverse faults on the downriver (southeast) side of the arch. On the downriver side, a small downdropped block occurs on the K reflection between CDP's 4477 and 4521 (profile B) (Shedlock and Harding, 1982).

The 160-ms reflection that is so prominent downriver (profile A) is weak and poorly developed between CDP's 4345 and 4800, making it difficult to identify the upper termination of faults interpreted in this area. However, some of the faults do not seem to affect shallower reflections (for example, the faults at CDP's 4543 and 4586 on the K reflection, profile B). These relationships may be similar to those observed on land-based high-resolution reflection profiles across the fault at Cottonwood Grove, Tenn., that show the deep faulting terminating below reflections at about 200 ms (Sexton and Jones, 1981).

Another area of numerous faults occurs between CDP's 5760 and 6050 (profile D), directly northeast of Caruthersville. Here, the interpreted major faults have apparent dips downriver to the southeast and several major faults have related antithetic faults. The sense of displacement across the major faults suggests both normal and reverse apparent movements. The location of these faults coincides perfectly with the northeastward projection of the northeast Arkansas to Caruthersville seismic trend (fig. 1). The lateral slip in this trend indicated by focal mechanisms may explain the apparent normal and reverse movements on the faults. Most of the faults in this zone displace the Tw reflection, and several are interpreted to cut the Tm reflection, indicating some post-middle Eocene movement. The lack of distinctive shallower reflections in the Tertiary sediments above the Tm reflection make it difficult to confidently trace the faults upward toward the surface. A reverse fault that dips downriver displaces Tw near CDP 6030 (profile D) and can be traced up to about 200 ms at the end of profile D. The reflection data upriver from the end of the profile are poor, making the projection of this fault above 200 ms speculative.

Other interpreted faults, scattered along the profile, have minor vertical displacements of about 3-5 ms (4-6 m). A cluster of faults and minor warping on the K reflection occurs near CDP's 3881-3911 (profile B). Upriver of this zone, the K reflection is weak, making it difficult to define a specific fault. Reflections as shallow as 350 ms are arched as much as 10 ms (10 m), but the strong 160-ms reflection is unaffected by the deformation. The structural significance of the faulting and warping in this area is unclear, but it is unlikely that these are important earthquake-generating faults because of their small vertical displacement and because they are not spatially associated with the current seismicity.

The gentle rise in the reflections between CDP's 3125 and 3230 (profile A) does not seem to be associated with faulting nor is it related to any regional structure. This minor warping may be an actual structure; conversely, it could be a local velocity "pull-up" caused by a near-surface high-velocity layer, or it could be caused by "edge effects" when the number of traces stacked for each CDP diminishes near the end of a processing run. Regardless of the cause, the deformation is minimal and, if real, it probably has limited tectonic significance.

Subtle warping also occurs between CDP's 3525 and 3605 (profile A) where the 160-ms reflection rises slightly. This subtle deformation may be related to movement along the fault that lies beneath the upwarped area at CDP 3605; the continuity of the doublet reflections at 140-160 ms suggests that the deeper fault does not continue upward with any substantial offset.

A noteworthy feature is the apparent thinning of strata in the Paleozoic rocks (below Pz) immediately downriver from the Cottonwood Grove fault between CDP's 4360 and 4470 (profile B). The doublet reflection at about 860 ms near CDP 4360 gradually rises upriver and converges with the Pz reflection, suggesting either a depositional or an erosional pinch-out toward the structurally high part of the fault. Paleozoic rocks in this area are Cambrian black shale and limestone of the Bonneterre Formation and dolomite of the Elvins Group (Grohskopf, 1955). If the pinch-out is erosional, it suggests a local area of Cambrian uplift; if depositional, it could be related to thinning on the flanks of a reef or carbonate bank. A depositional pinch-out could result from local shoaling that may have been structurally controlled. The coincidence of the pinch-out in Cambrian rocks with the Cottonwood Grove fault, a Tertiary-age feature, may be fortuitous; however, it may be significant and indicate Tertiary reactivation of a Cambrian structure.

Another example of stratigraphic thinning occurs in the Tertiary sediments between CDP's 5520 and 5640 (profiles C and D). Near CDP 5640 a series of three reflections between 60 and 380 ms lies just above the Tw reflection. Although discontinuous, these reflections can be traced downriver where they gradually merge toward the Tw reflection. This pinch-out occurs in the lower part of the Claiborne Group, which was deposited in nonmarine and marginal-marine environments in western Tennessee (Moore, 1965; Parks, 1975). It is unlikely that the pinch-out results from movements on Tertiary-age faults because faulting in the area is minor and questionable. Furthermore, the sense of movement on the possible faults is inconsistent with the direction of thinning. The pinch-out is probably related to depositional facies changes that commonly occur in nonmarine and marginal-marine environments.

Between CDP's 6650 and 6800 (profile D), a group of reflections in the upper 300 ms of the profile forms a broad, complex, channel-like trough whose origin is unclear (Shedlock and Harding, 1982). In detail, the feature appears to be composed of several superimposed channels marked by reflections warped downward to depths of about 275 ms and rising approximately 15 ms (10 m) of structural relief. A shallower channel between CDP's 6675 and 6710 extends to a depth of about 80 ms (54 m). The trough complex is not caused by a local velocity anomaly because the reflection at 380 ms is level and essentially continuous across the area. The trough is probably not caused by infilling of an unusually deep scour channel even though it coincides with a tight meander in the modern river (fig. 2) because, at similar sites along the river that are equally susceptible to deep scouring, the reflection profiles do not show similar troughs. Furthermore, the depth of the trough (250 ms or about 175 m) is likely to be much deeper than the depth to which the river could scour along this part of the Mississippi Valley. A tentative interpretation of the origin of the trough is that a large channel formed, followed by penecontemporaneous sedimentation and local downwarping; however, many details of this interpretation are uncertain.

CONCLUSIONS

These profiles show an area of faulting inferred to be the southwesterly extension of the Cottonwood Grove fault. The fault, which can now be traced a distance of 20-25 km, has the most Tertiary-age vertical displacement of any fault in the New Madrid seismic zone, but its relationship to the modern seismicity is unclear. Near Ridgely, Tenn., the Cottonwood Grove fault consists of a single major fault having considerably more structural relief than at its location below the river where the displacement is distributed on several faults. This may indicate that the fault plays a more active role in the tectonics near Ridgely than near the river, or that the mechanics of faulting near the river are different than they are near Ridgely. The large amount of Tertiary displacement on the Cottonwood Grove fault suggests that it has played an important role in the tectonics of the New Madrid seismic zone in the past, but its current tectonic role and its seismogenic potential are uncertain.

The tectonic significance of the concentration of faults below the river near Caruthersville (CDP's 5760-6050, profile D) and their relationship to the modern seismicity is also not clear. Seismologic and structural data in this area suggest that structural trends have a northeasterly orientation. Southwest of these faults, the seismicity trends approximately N. 45° E. (see Stauder, 1982, fig. 5); and to the northeast, arches and faults strike N. 40° E. (Zoback and others, 1980; Hamilton and Zoback, 1982). Yet, where N. 45° E.-striking projections of the Caruthersville faults intersect nearby Vibroseis® lines, there is no significant faulting. Thus, the strike of the faults near Caruthersville remains undetermined.

The modern seismicity in the New Madrid seismic zone is concentrated along ancient zones of crustal weakness that are associated with a northeast-trending rift (Hildenbrand and others, 1982; Ervin and McGinnis, 1975). Initially, the rift and related structures probably developed in a northwest-southeast extensional stress field, but the modern stress field is dominated by east-west compression (Zoback and Zoback, 1980). Except for the Cottonwood Grove fault, the strikes of the normal and reverse faults interpreted on these profiles are unknown, thus it is difficult to determine their tectonic significance and their susceptibility to movement in the current stress regime.

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Table 1.--Field parameters and processing sequence for the seismic-reflection profiles

Field parameters	
Acquired by: USGS	Date: January 1981
Instruments: DFS V	No. of channels: 12
Energy source: Air guns	Shot interval: 5-10 m
Gun depth: 2.4 m	Average cable depth: 1 m
Near offset: 61 m	Far offset: 171 m
Group interval: 10 m	Sample interval: 0.5 ms
Record length: 1 s	Recording filter: 8-512 Hz
Tape density: 1,600 BPI	Tape format: SEGB

Processing sequence

1. Demultiplex: Gain restore
   Resample to 1 ms
2. CDP sort
3. Deconvolution: Trace equalization
   Deconvolution operator: 80 ms (spiking)
   Design window: 120-920 ms
   Filter: 26-375 Hz
4. Velocity analysis: Constant velocity stacks display
   Contoured display
5. NMO and mute verification
6. NMO application
7. Mute application
8. Scale: 400 ms AGC
9. Bandpass filter: 30-200 Hz
10. Residual statics: 5 trace model
    12 ms max. shift
    Window: 200-800 ms
11. CDP stack
12. Wave equation migration
13. Filter: Gate 1: 40-200 Hz 0-500 ms
    Gate 2: 32-160 Hz 500-1000 ms
14. Scale: 400 ms AGC
15. Datumize to sea level
16. Display: Horizontal scale: 20 traces/in.
    Vertical scale: 7.5 in./s

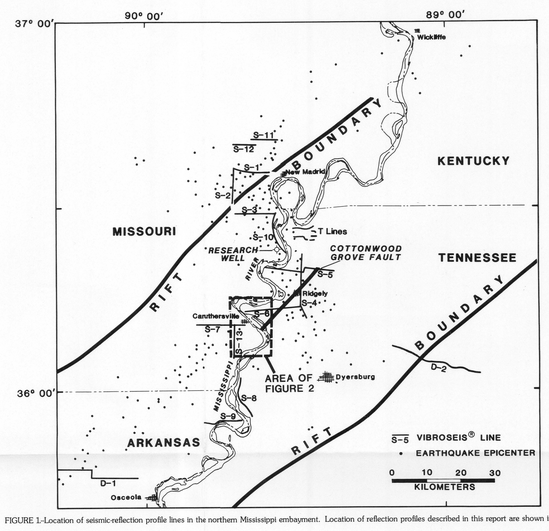

FIGURE 1.-Location of seismic-reflection profile lines in the northern Mississippi embayment. Location of reflection profiles described in this report are shown in figure 2.

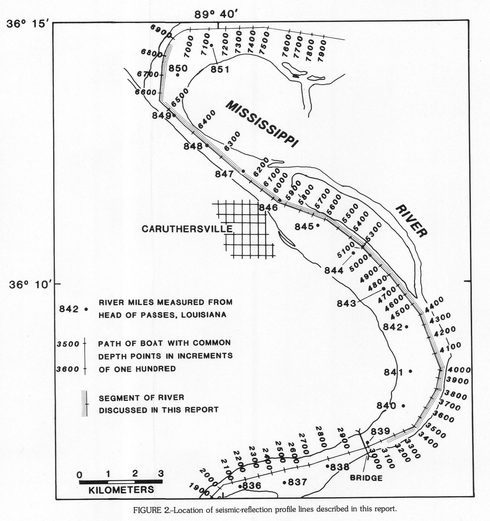

FIGURE 2.-Location of seismic-reflection profile lines described in this report.

SEISMIC-REFLECTION PROFILES OF THE NEW MADRID SEISMIC ZONE—DATA ALONG THE MISSISSIPPI RIVER NEAR CARUTHERSVILLE, MISSOURI

By
Anthony J. Crone, Samuel T. Harding, David P. Russ, and Kaye M. Shedlock

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