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A COCORP deep reflection profile across the buried Reelfoot rift, south-central United States

K.D. Nelson and Jie Zhang *

Institute for the Study of Continents (INSTOC), Snee Hall, Cornell University, Ithaca, NY 14850, USA

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ABSTRACT

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A COCORP deep reflection survey across the northern Mississippi Embayment reveals essential features of the late Precambrian (?)/early Paleozoic Reelfoot rift. Stratified reflections delineating the sedimentary fill of the rift basin are of variable thickness, the base ranging from 2.0 to a maximum of 3.5 s twt (~ 4 to 8 km depth). In contrast, the base of Phanerozoic the sedimentary section immediately east of the rift is at 1.4 s (~ 2.8 km depth). Correlation with a basement-penetrating well indicates that the base of the Upper Cretaceous/Holocene Mississippi Embayment Supergroup, base of the Cambrian–Ordovician Knox Group, and the lower Upper Cambrian(?) Bonneterre Formation are basin-wide seismic stratigraphic markers. Clastic sedimentary strata of the Lamotte Formation, which immediately overlie Precambrian basement, show clear angular discordance with the overlying subhorizontal Bonneterre Formation indicating that the base of the Bonneterre marks the transition from active extension to passive subsidence within the Reelfoot rift. Palinspastic restoration of the basement suggests relatively modest extension associated with rift formation (~ 17%). The Blytheville Arch, an axial antiformal feature, as well as a number of lesser structures indicative of multiple episodes of fault reactivation, are also evident on the COCORP profile.

The crystalline basement beneath the Reelfoot rift is relatively devoid of reflections down to ~ 5.0 s (12–15 km depth), beyond which it passes gradationally into a complexly reflective/diffractive middle and lower crust. The lower crust, however, does not exhibit the distinctly laminated character commonly observed in Mesozoic/Cenozoic extensional provinces. The crust–mantle transition beneath the rift is characterized by a gradational downward cessation of crustal reflectivity at 12–13 s (~ 40 km depth), followed by an unreflective zone, which in turn is followed by a distinct horizontal reflection at 14.5 s. The latter is not observed on existing profiles outside the rift. At present it is not possible to determine strictly whether the deep horizon represents Moho or alternatively a discrete feature (sill?) within the uppermost mantle; however, its spatial association with the Reelfoot rift suggests that the two are genetically related.

Regional relations, together with the existence of dipping fabric in the deep crust beneath the rift, suggest the *possibility* that the Reelfoot rift formed along the southern extension of the circa 1 Ga Grenville Front.

Introduction

As part of an ongoing effort to study the deep structure of continental rift zones, the Consortium for Continental Reflection Profiling (COCORP) recently acquired deep seismic reflection data across the late Precambrian(?)/early Paleozoic Reelfoot rift, which lies buried beneath Cretaceous to Holocene sedimentary strata of the northern Mississippi Embayment (Fig. 1). The Reelfoot rift was first delineated on the basis of regional potential field data, and is generally thought to be a late Precambrian aulacogen that formed during the supercontinent rifting event that led to the formation the Paleozoic Iapetus ocean (Ervin and McGinnis, 1975; Kane et al., 1981; Thomas, 1985; Hildenbrand, 1985). The rift is known to have been structurally and magmatically reactivated in late Paleozoic and late Cretaceous time, and is seismically active today as

* Currently at Center for Lithospheric Studies, University of Texas at Dallas, Richardson, TX 75083, USA.

manifest by the destructive 1811–1812 New Madrid earthquakes and contemporary microseismicity (Nuttli, 1973; Herrman and Canas, 1978; Andrews et al., 1985). In recent years the area has been the subject of a number of geophysical/geological investigations aimed at elucidating the large-scale crustal structure of the rift (Mooney et al., 1983; Hildenbrand, 1985), and related to that, controls on modern seismicity (Crone et al., 1985; Andrews et al., 1985). The region has also been subject to intermittent petroleum exploration activity (Howe and Thompson, 1984).

In this paper we describe and interpret the new COCORP deep seismic reflection data within and adjacent to the Reelfoot rift. Our interpretation of the sedimentary section filling the rift follows largely from the work of James Howe (Howe and Thompson, 1984; Howe, 1985) who has interpreted a large body of proprietary seismic reflection data in conjunction with key petroleum exploration wells in the region. Part of that proprietary seismic data has also been purchased and described independently by personnel of the U.S. Geological Survey (Crone et al., 1985; R. Hamilton, pers. commun., 1988) and has been viewed by us. For the basement, we compare and contrast the reflection "image" of the crust and upper mantle given by the new COCORP data with the velocity structure deduced from refraction/wide-angle reflection date (McCamy and Meyer, 1966; Mooney et al., 1983; Ginzburg et al., 1983). We also qualitatively compare the reflection character of the crust beneath the Reelfoot rift with that of extensional and cratonic regions elsewhere for which deep seismic data are available.

Data acquisition and processing

COCORP's Arkansas line 6 (AR-6) and the western part of Tennessee line 3 (TN-3) traverse the buried Reelfoot rift, which in the region crossed by the survey is approximately 70 km wide. AR-6 begins 20 km east of Newport, Arkansas, over the northwest boundary of the rift as defined by

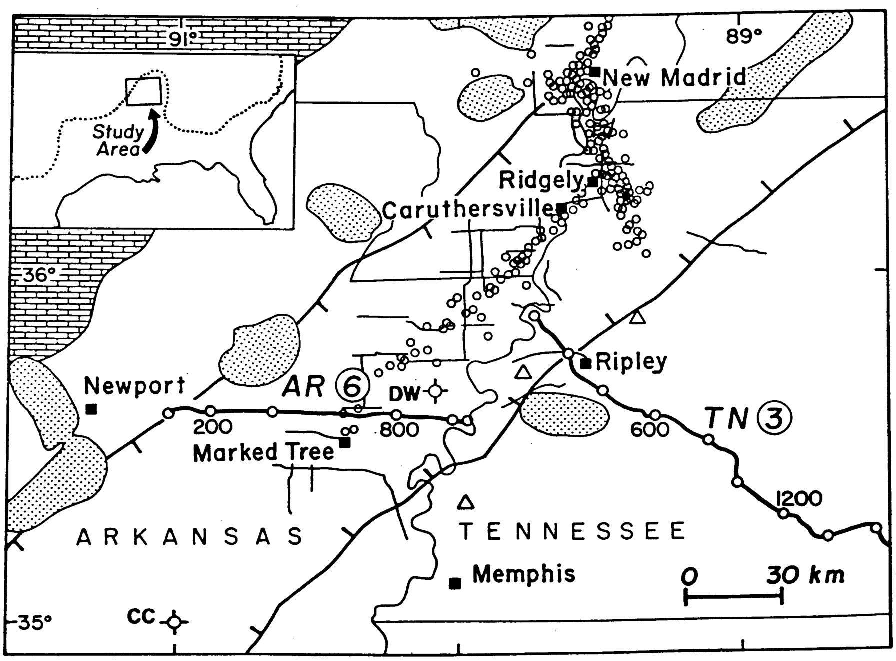


Fig. 1. Location map of COCORP profiles crossing the Reelfoot rift (AR-6, TN-3). Heavy barbed lines show rift boundaries as inferred from potential field data (Hildenbrand, 1985). Fine lines: U.S.G.S. and Dow Wilson seismic lines in U.S.G.S. collection. Open circles: earthquake epicenters (Andrews et al., 1985). White: area covered by Upper Cretaceous/Holocene Mississippi Embayment Supergroup. Brick pattern: area of exposed Lower Paleozoic strata. Stipple: mafic/ultramafic plutons in subsurface inferred from potential field and drill data (Hildenbrand, 1985). DW = Dow Wilson well.

Hildenbrand (1985) on the basis of gravity and magnetic data. From there it continues 100 km east to the Mississippi River. The beginning of TN-3 is offset 40 km north from the end of AR-6 along the Mississippi River. (due to logistical constraints). From there it extends southeastward crossing the southeast boundary of the rift at vibrator point (VP) 200 near Ripply, Tennessee. From there it continues southeastward beyond the rift.

All of the data comprising the COCORP survey are nominal 60-fold vibroseis deep seismic reflection data collected with a 120-channel recording system and 100 m station spacing. Near and far offsets for the recording spread were nominally 0.3 and 12.3 km respectively, and a 10–48 Hz upsweep was employed throughout.

Processing of the reflection data included the normal sequence of demultiplex, Vibroseis correlation, elevation statics, trace amplitude balance, pre-stack deconvolution, frequency–wavenumber (F-K) filter, CMP-gather, velocity analysis, normal moveout correction (NMO), mute, CMP stack, and post-stack coherency filter. The stacked sections contain 20 s of data, though due to space limitations only 16 s are displayed in Fig. 3. Wave equation migrations of the entire data set, as well as the shallow sedimentary part specifically, were also produced.

As is typical of many deep seismic reflection profiles, the stacked sections exhibit several vertically bounded "panels" extending downward through the entire section within which the crust appears relatively less reflective than in the surrounding regions (most notably between VPs 380 and 610 on AR-6). Amplitude decay plots generated for the entire data set demonstrate that these less reflective panels correlate with regions of high ambient noise encountered recording (traffic and/or poor source/receiver coupling), and hence are not of geologic significance.

Rift basin

Stratigraphic interpretation of the major reflectors within the Reelfoot rift basin (Fig. 4) is based on correlation with the section penetrated in the Dow No. 1 Wilson well, which lies 14 km northeast along regional strike from VP 820 on AR-6 (Fig. 1). To facilitate correlation of the seismic data with the penetrated stratigraphy, a synthetic seismogram was derived from an integrated velocity log of the well (Fig. 2). The stratigraphic assignments of the principal reflections generated by the synthetic follow those of Howe (1985). Despite the fact that the Dow Wilson well lies at a considerable distance from the COCORP profile, there is excellent correlation between the major reflections generated by the synthetic and those observed on the seismic profile. In particular the reflections associated with the base of the Upper Cretaceous/Holocene Mississippi Embayment Supergroup, base of the Cambrian Ordovician Knox Group, and the Bonneterre Formation are prominent basin-wide seismic stratigraphic markers. The prominent reflection associated with the base of the Embayment Supergroup results from a large positive impedance contrast produced by low-velocity, poorly consolidated, Upper Cretaceous clastic sediments of the Embayment Supergroup lying unconformably on high-velocity Lower Ordovician dolomites of the Knox Group. The reflection associated with the base of the Knox Group is produced by the transition from high-velocity carbonates above to lower-velocity shales of the Upper Cambrian Elvins Formation below. The prominent reflection associated with the Bonneterre Formation results from constructive interference of reflections from the top and bottom of the Bonneterre dolomite, which is a relatively thin high-velocity unit sandwiched between lower-velocity Elvins shale above and Lamotte arkosic sandstone below. In general, the top of the Precambrian basement does not produce a prominent reflection because of the lack of significant impedance contrast between it and the immediately overlying Lamotte arkoses. The interpreted top of basement shown in Fig. 4 is placed at the base of obviously stratified rocks. Question marks indicate areas where the interpretation of the top of basement is ambiguous due to the obscuring effect of multiple reflections produced in the overlying strata.

The seismic data reveal that the pre-Cretaceous fill of the Reelfoot rift basin is grossly divisible into a lower "syn-rift" unit assigned entirely to

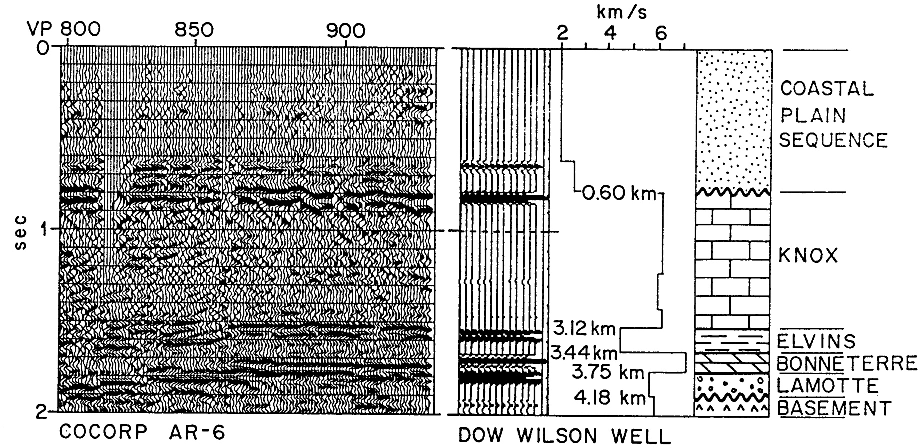


Fig. 2. Comparison of synthetic seismogram produced from velocity log of Dow Wilson well and nearby portion COCORP seismic profile. Stratigraphic assignments follow those of Howe (1985).

the Lamotte Formation, and an upper "post-rift" unit composed of the overlying Bonneterre and Elvins Formations and Knox Group.

Syn-rift sequence

The syn-rift unit is characterized by locally thick assemblages of gently dipping strata lying beneath the basinwide Bonneterre reflection. These assemblages appear to define two asymmetric half-grabens lying beneath the east and west flanks of the rift, respectively. The deepest of these occurs beneath the east flank of the rift where stratified sub-Bonneterre reflections extend as deep as 3.5 s (~ 8 km total depth, VP 100 on TN-3). The terminations of these reflections against unreflective basement to the southeast implies that this sub-basin is bounded on the southeast by several steep normal faults having an aggregate throw of about 5 km, down to the northwest. The location of these normal faults corresponds approximately with the southeast boundary of the Reelfoot rift defined previously from potential field data (Fig. 1). The northwestern feather edge of this half-graben, or an analogous one occurring along-strike to the southwest, is visible beneath the east end of AR-6 where a westward thinning assemblage of gently east-dipping reflections pinches out beneath the Bonneterre reflection (VPs 800–1050). At this locality there is clear angular discordance between the graben-fill (Lamotte) reflectors and the overlying flat-lying Bonneterre reflector, implying that the base of the Bonneterre is a regional seismic stratigraphic boundary marking the transition from active crustal extension, with attendant basement block rotation and localized deposition within the rift, to regional basin-wide subsidence ("rift–drift transition"). As noted by Howe (1985), and discussed subsequently, some movement on the rift-bounding faults clearly continued through deposition of the Knox Group; however, the major episode of crustal extension apparently occurred prior to deposition of the Bonneterre Formation.

The northwest boundary of the rift is also underlain by an inward facing normal fault. On the west end of AR-6 a gently east dipping reflection beneath the Bonneterre Formation is traceable to about 3.8 s (~ 9 km depth) beneath VP 380 (Figs. 3, 4). Stratified reflections lying above this feature and beneath the overlying Bonneterre reflection imply that this is a reflection from a southeast dipping normal fault with a half-graben in the hanging wall. Correcting for the obliquity of the seismic profile to the local strike of the rift boundary (Fig. 1), implies that the true dip of the fault is between about 18 and 24 degrees to the southeast. Local downward flexing of the Bonneterre Formation (VP 140–260, AR-6) above this normal fault implies that it continued to be active subsequent to deposition of the Bonneterre Formation.

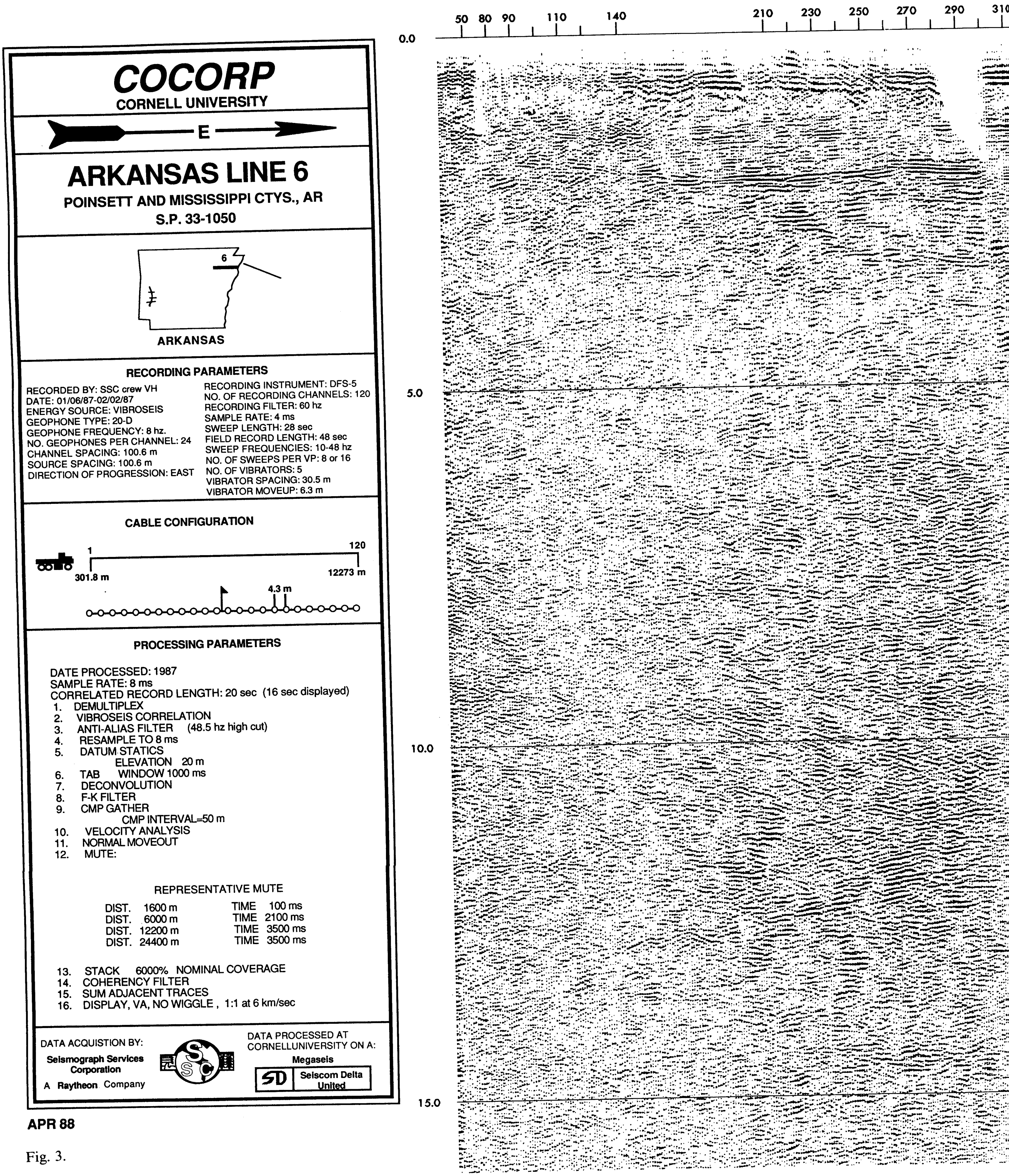
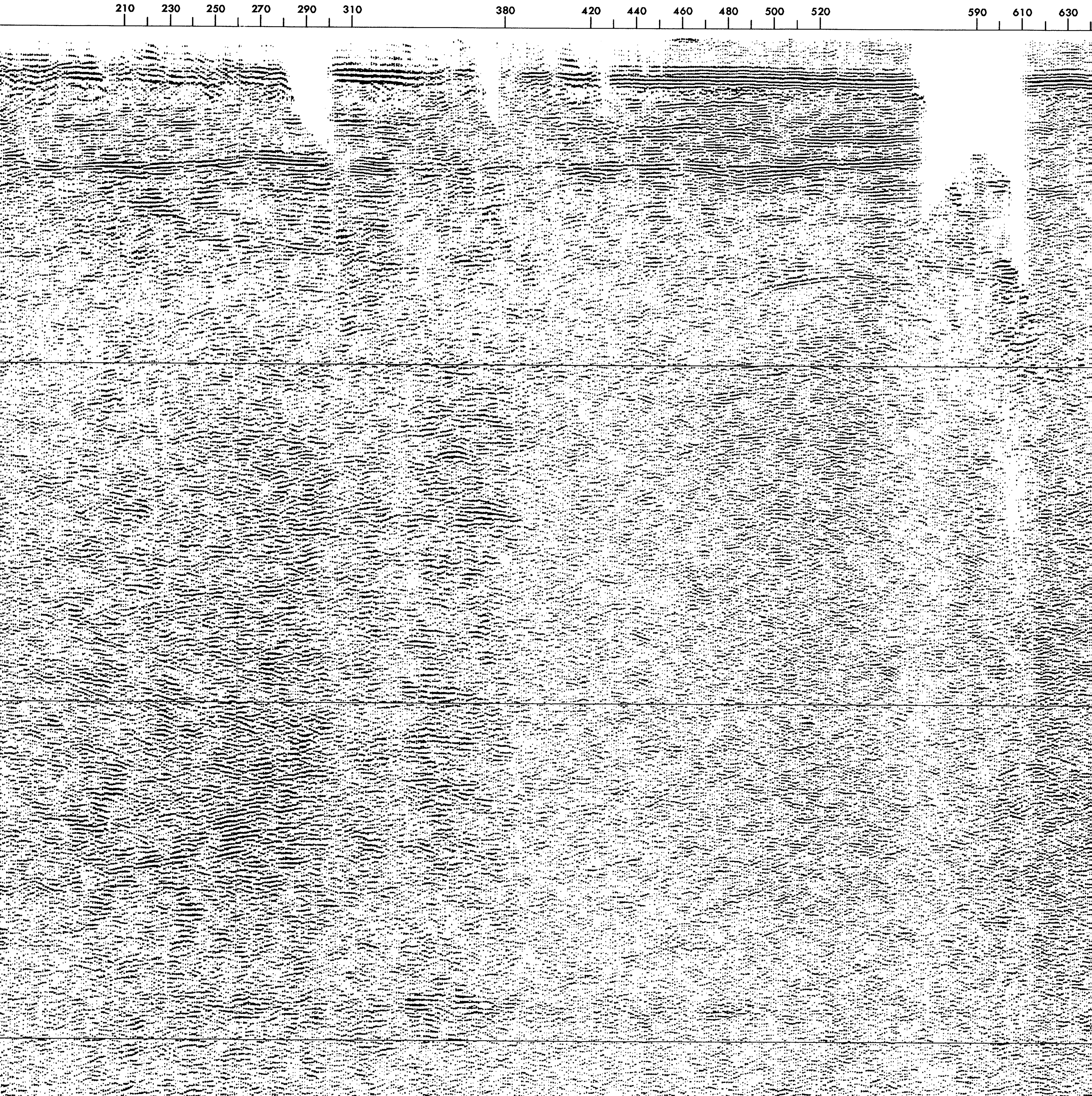
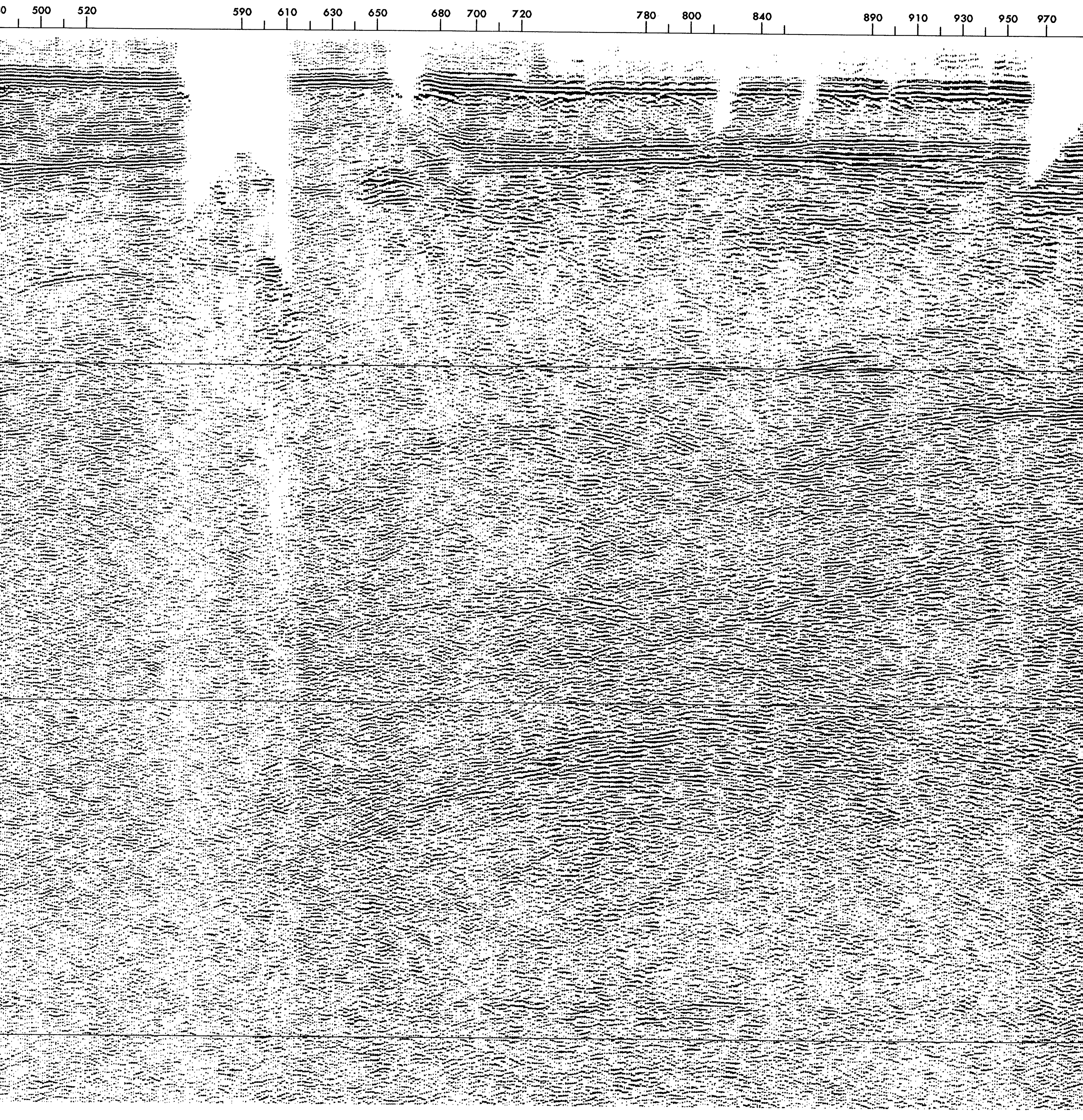
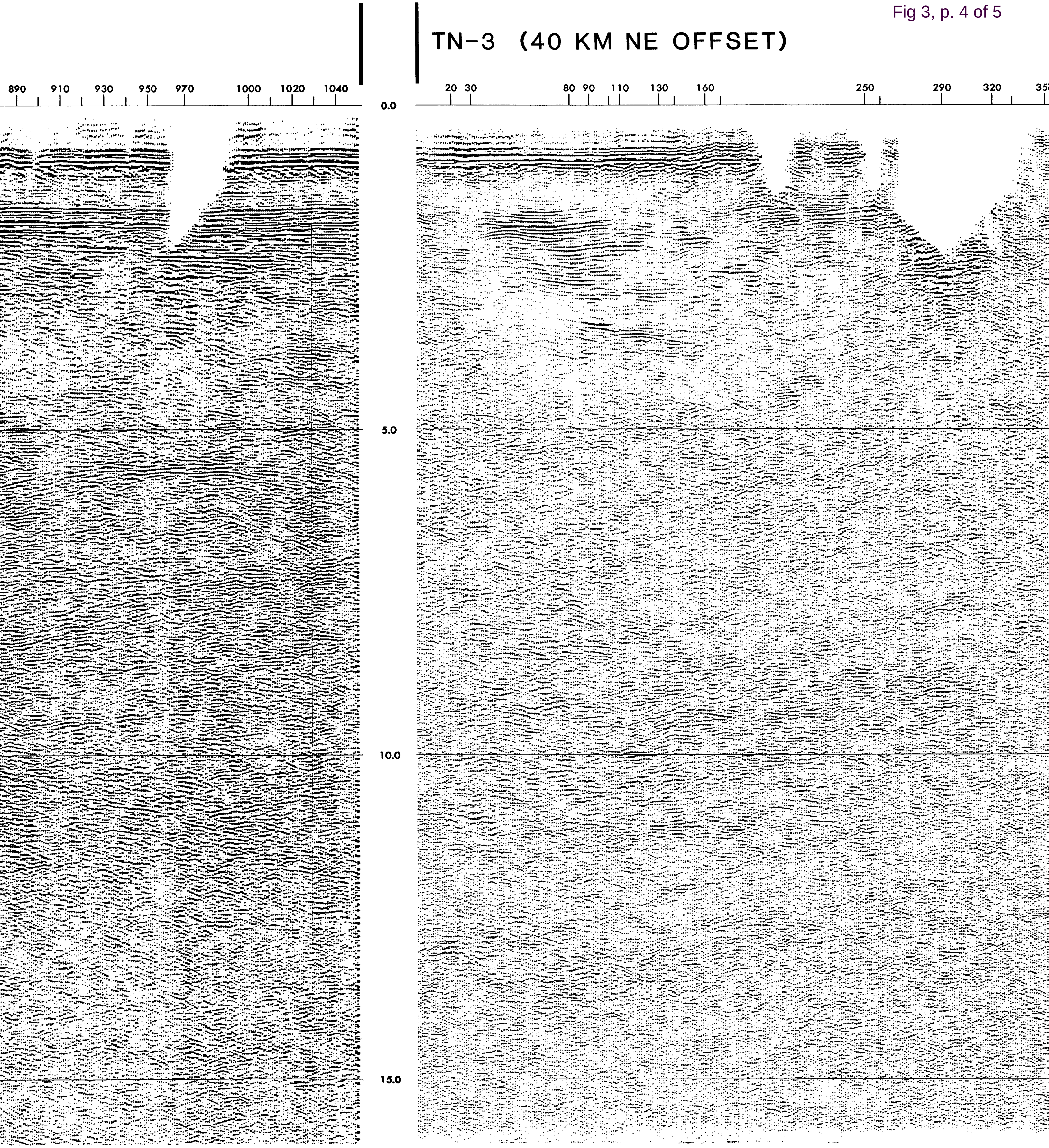

COCORP
CORNELL UNIVERSITY
E
ARKANSAS LINE 6
POINSETT AND MISSISSIPPI CTYS., AR
S.P. 33-1050
6
ARKANSAS
RECORDING PARAMETERS
RECORDED BY: SSC crew VH
DATE: 01/06/87-02/02/87
ENERGY SOURCE: VIBROSEIS
GEOPHONE TYPE: 20-D
GEOPHONE FREQUENCY: 8 hz.
NO. GEOPHONES PER CHANNEL: 24
CHANNEL SPACING: 100.6 m
SOURCE SPACING: 100.6 m
DIRECTION OF PROGRESSION: EAST
RECORDING INSTRUMENT: DFS-5
NO. OF RECORDING CHANNELS: 120
RECORDING FILTER: 60 hz
SAMPLE RATE: 4 ms
SWEEP LENGTH: 28 sec
FIELD RECORD LENGTH: 48 sec
SWEEP FREQUENCIES: 10-48 hz
NO. OF SWEEPS PER VP: 8 or 16
NO. OF VIBRATORS: 5
VIBRATOR SPACING: 30.5 m
VIBRATOR MOVEUP: 6.3 m
CABLE CONFIGURATION
1
120
301.8 m
12273 m
4.3 m
PROCESSING PARAMETERS
DATE PROCESSED: 1987
SAMPLE RATE: 8 ms
CORRELATED RECORD LENGTH: 20 sec (16 sec displayed)
1. DEMULTIPLEX
2. VIBROSEIS CORRELATION
3. ANTI-ALIAS FILTER (48.5 hz high cut)
4. RESAMPLE TO 8 ms
5. DATUM STATICS
ELEVATION 20 m
6. TAB WINDOW 1000 ms
7. DECONVOLUTION
8. F-K FILTER
9. CMP GATHER
CMP INTERVAL=50 m
10. VELOCITY ANALYSIS
11. NORMAL MOVEOUT
12. MUTE:
REPRESENTATIVE MUTE
DIST. 1600 m TIME 100 ms
DIST. 6000 m TIME 2100 ms
DIST. 12200 m TIME 3500 ms
DIST. 24400 m TIME 3500 ms
13. STACK 6000% NOMINAL COVERAGE
14. COHERENCY FILTER
15. SUM ADJACENT TRACES
16. DISPLAY, VA, NO WIGGLE , 1:1 at 6 km/sec
DATA ACQUISTION BY:
Seismograph Services Corporation
A Raytheon Company
DATA PROCESSED AT CORNELLUNIVERSITY ON A:
Megaseis
Seiscom Delta United
APR 88
0.0
5.0
10.0
15.0
50 80 90 110 140 210 230 250 270 290 310

Fig. 3.

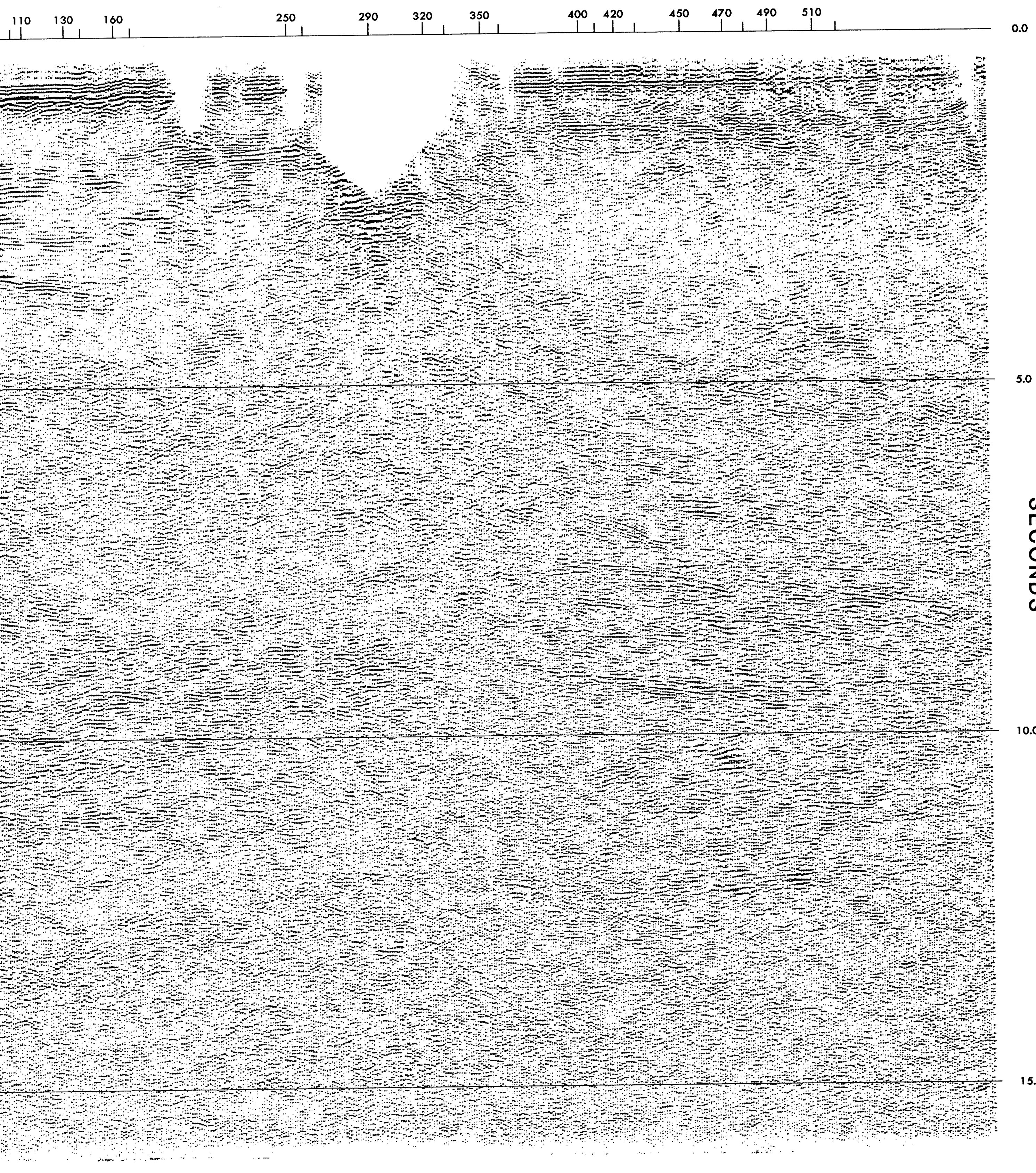

210
230
250
270
290
310
380
420
440
460
480
500
520
590
610
630


500
520
590
610
630
650
680
700
720
780
800
840
890
910
930
950
970


TN-3 (40 KM NE OFFSET)
890
910
930
950
970
1000
1020
1040
20
30
80
90
110
130
160
250
290
320
0.0
5.0
10.0
15.0

pp. 275–279

M NE OFFSET)



pp. 280–284

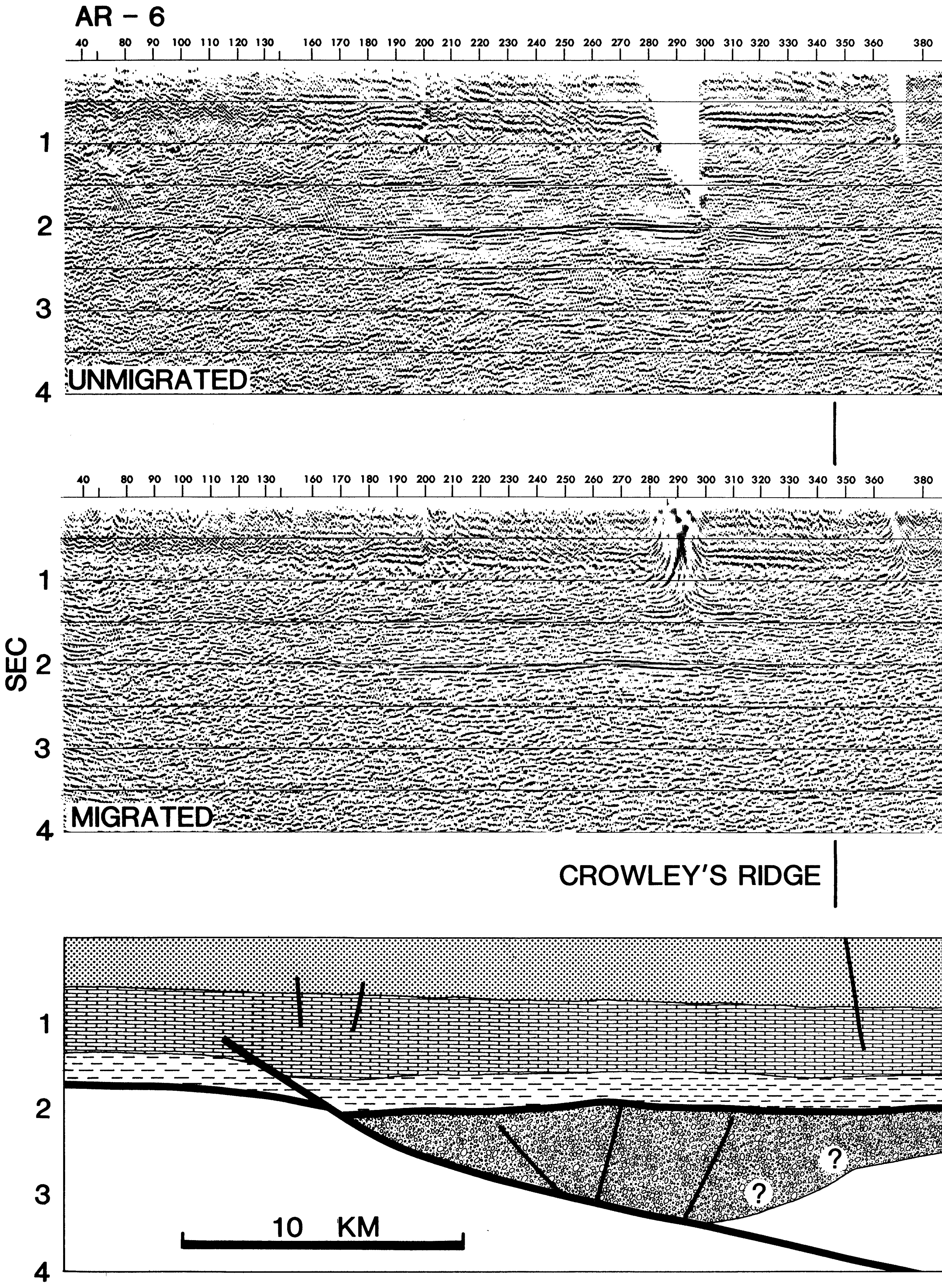
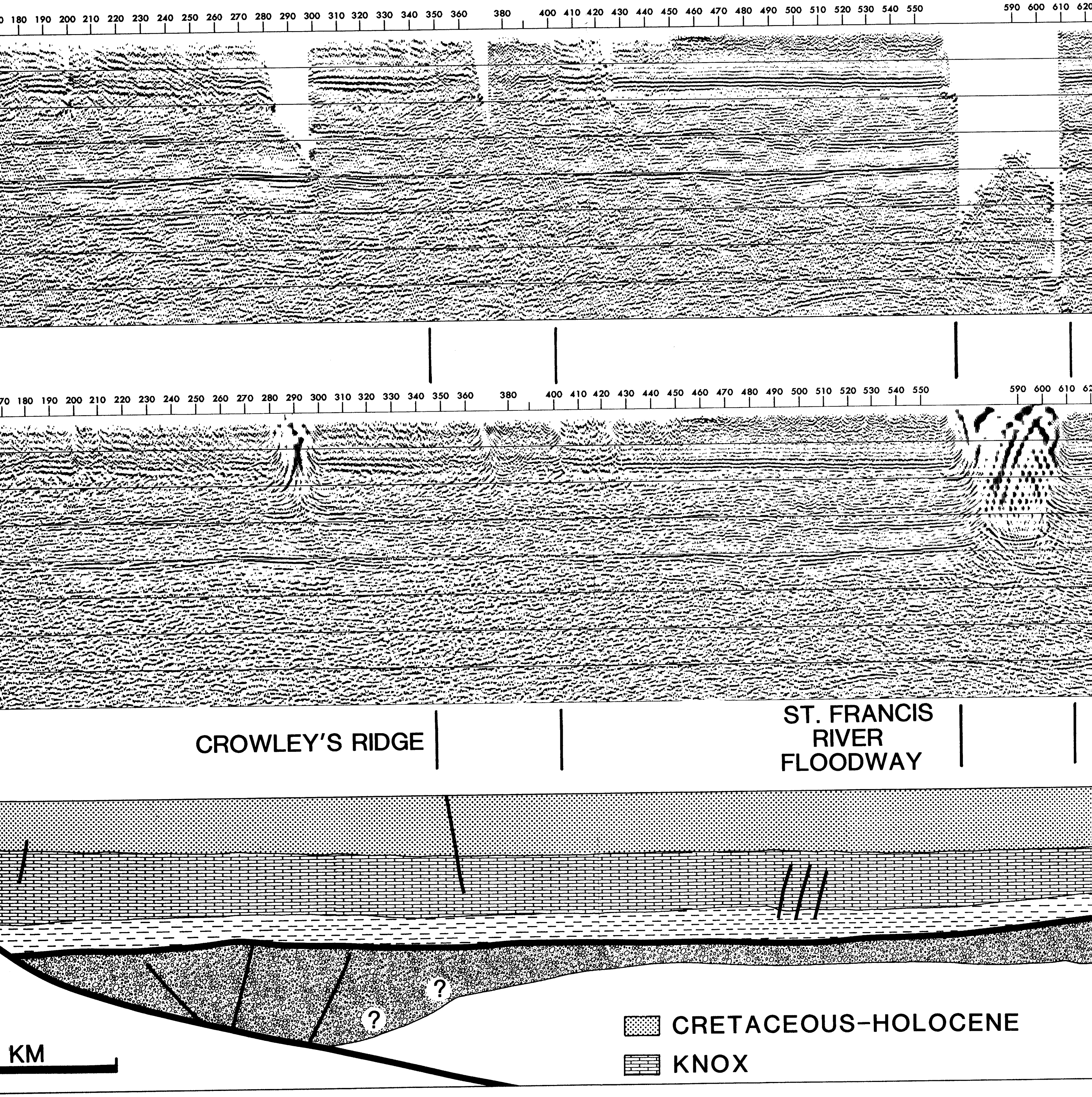
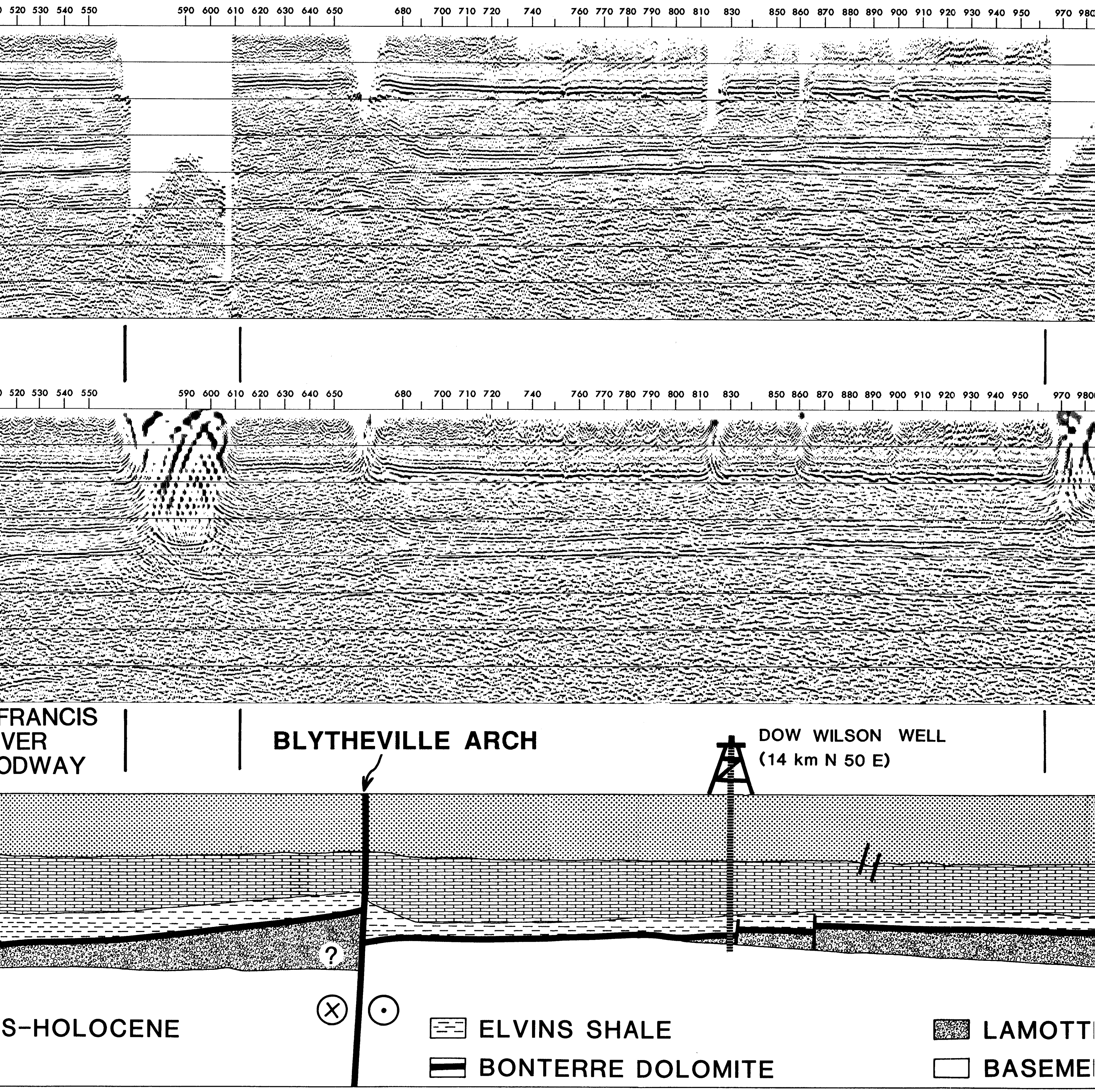
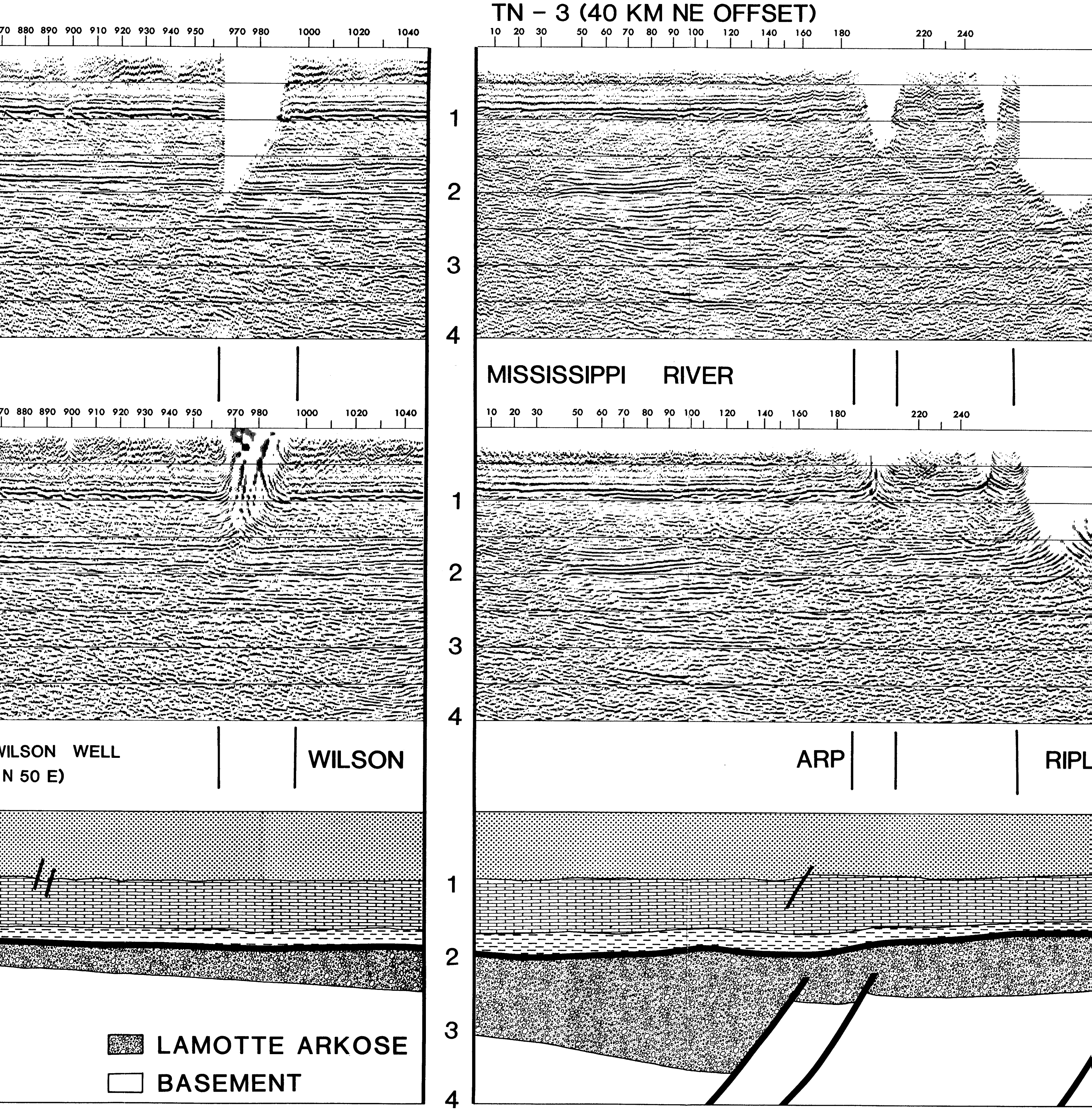


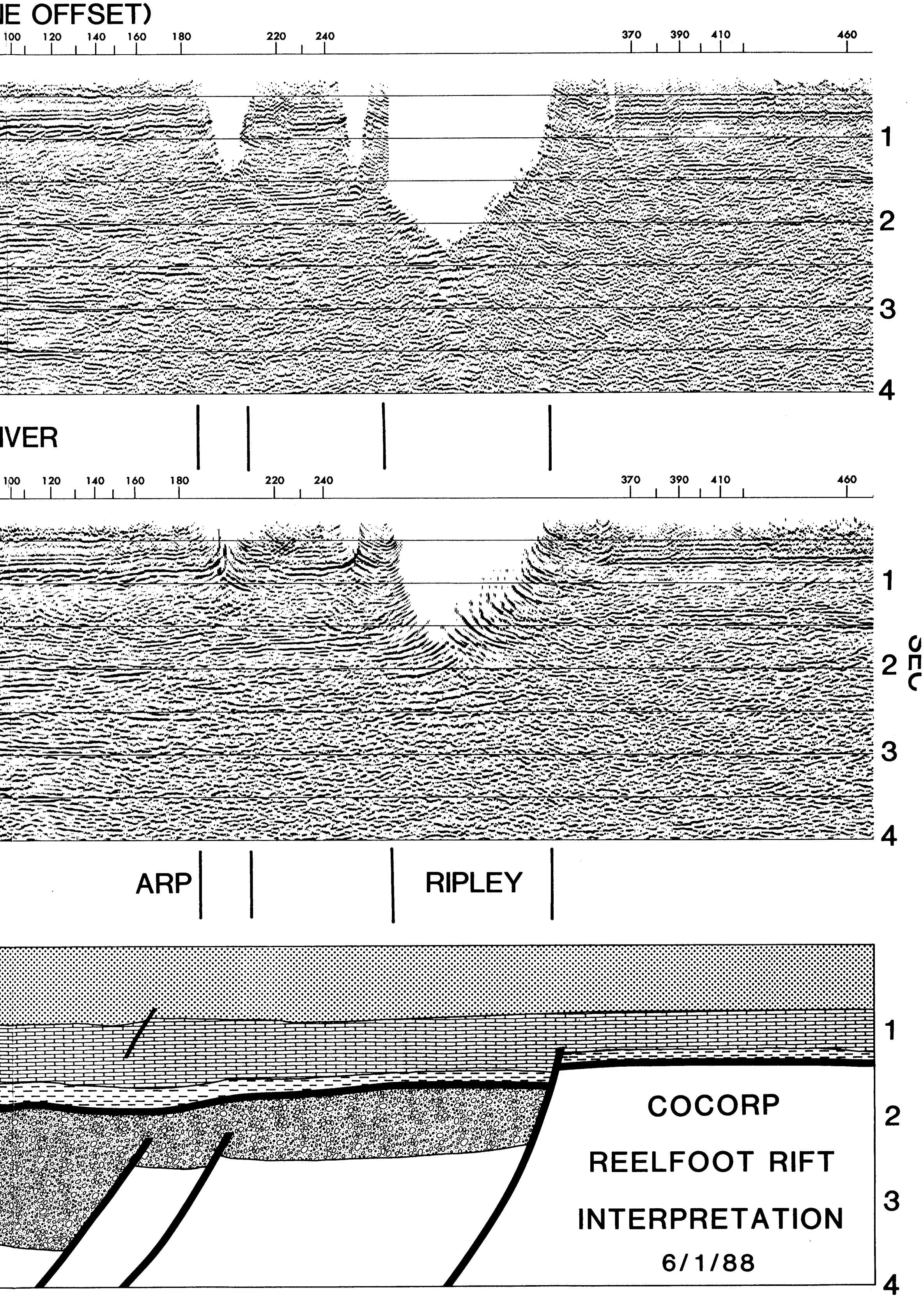
Fig. 4.


CROWLEY'S RIDGE
ST. FRANCIS
RIVER
FLOODWAY
KM
CRETACEOUS–HOLOCENE
KNOX



520 530 540 550 590 600 610 620 630 640 650 680 700 710 720 740 760 770 780 790 800 810 830 850 860 870 880 890 900 910 920 930 940 950 970 980
520 530 540 550 590 600 610 620 630 640 650 680 700 710 720 740 760 770 780 790 800 810 830 850 860 870 880 890 900 910 920 930 940 950 970 980
FRANCIS
VER
ODWAY
BLYTHEVILLE ARCH
DOW WILSON WELL
(14 km N 50 E)
?
S-HOLOCENE
ELVINS SHALE
BONTERRE DOLOMITE
LAMOTT
BASEME


TN – 3 (40 KM NE OFFSET)
70 880 890 900 910 920 930 940 950 970 980 1000 1020 1040
10 20 30 50 60 70 80 90 100 120 140 160 180 220 240
1
2
3
4
MISSISSIPPI RIVER
WILSON WELL
N 50 E)
WILSON
ARP
RIPL
LAMOTTE ARKOSE
BASEMENT


IE OFFSET)
100 120 140 160 180 220 240 370 390 410 460
1
2
3
4
IVER
ARP
RIPLEY
COCORP
REELFOOT RIFT
INTERPRETATION
6/1/88

Post-rift sequence

The post-rift sequence, consisting of the Bonneterre and Elvins Formations and Knox Group, is grossly conformable across the entire rift, except in the immediate vicinity of the Blytheville Arch (discussed subsequently). The entire post-rift sequence is considerably thicker within the rift basin than on the flanking shoulders (2.7–3.0 km within the rift vs. 2.1 km on the SE shoulder), and both the Elvins Formation and Knox Group appear to thicken slightly from east to west across the rift, implying some ongoing tilting of the basin floor during Elvins–Knox deposition. The reflection character of the Elvins–basal Knox interval also changes somewhat from east to west across the rift, suggesting that some lateral facies variation within the rift was produced in association with tilting of the rift floor. Thickening of the post-rift sequence across the rift boundaries, warping of the Bonneterre reflection in the hanging wall of the northwestern border fault, and the observation of several minor offsets of the Bonneterre reflection within the rift that appear to die out upsection (e.g. VPs 810, 135, AR-6), constitute the primary evidence for continued normal faulting in the rift during deposition of the Bonneterre–Knox succession. As noted, the magnitudes of normal-sense displacements during this period were apparently considerably less than that which occurred during deposition of the underlying Lamotte Formation.

Axial antiform

The Blytheville Arch (Hamilton and McKeown, 1988), a large antiformal upwarp of the Knox Group and underlying sedimentary strata extending along the axis of the Reelfoot rift, constitutes the principal evidence for post Early Ordovician–pre Late Cretaceous compressional deformation affecting the rift. ** This structure coincides with the locus of modern seismicity within the rift implying that it is active today (Zoback et al., 1980; Andrews et al., 1985) (Fig. 1). However, the major episode(s) in its formation must have occurred prior to Late Cretaceous time, as manifest by the pronounced erosional truncation of the Knox Group along the crest of the antiform. Northeast of the COCORP survey, pre-Knox shale subcrops along the axis of the antiform beneath the Cretaceous unconformity, implying that in that area erosion entirely removed the Knox Group (Howe, 1985).

On the COCORP profile the axis of the Blytheville Arch occurs beneath VP 670 on AR-6. Immediately east of this position, reflections defining the Knox Group can be seen to bend sharply upward toward the axis of the structure, diverging from the Bonneterre reflection beneath. The latter appears to step down toward the west and then be offset(?) across the axial fault. Structural relief on the base of the Knox Group at this position is approximately 1.0 km. The more gentle northwest limb of the Blytheville Arch, though partially obscured by a vibrator skip (VP 560–610), is also discernable on the seismic section (VP 490–670)

The axial antiform was first imaged on "shallow" seismic reflection profiles collected within the rift by the U.S. Geological Survey (Zoback et al., 1980; Hamilton and Zoback, 1982), and was originally suggested by Survey workers to have resulted from emplacement of an igneous intrusion (laccolith) along the axis of the rift, beneath the Knox Group (e.g. Crone et al., 1985). Subsequently Howe (1985), interpreting proprietary seismic and well data, interpreted the axial uplift as resulting from late Paleozoic compressional reactivation of a syn-rift normal fault. We favor the latter interpretation because (1) a well drilled on the axial antiform encountered an overthickened section of shale beneath the Knox Group, rather than igneous rocks (Dow Garrigan well, Howe, 1985), and (2) there is no obvious gravity or magnetic anomaly associated with the axial antiform, such as are associated with known igneous intrusions along the margins of the rift (e.g. Hildenbrand, 1985). The pronounced stratal divergence between the Bonneterre and basal Knox reflections, which typifies Blytheville Arch, is characteristic of a "flower structure" (Harding et

** This structure has also been referred to as "Charlie's Ridge" (Howe and Thompson, 1984; Howe, 1985). However, that terminology is probably inappropriate in that there is no positive topographic relief associated with the structure. Indeed, along most of its length it is overlain by a swamp.

al., 1983), implying that there may have been significant transcurrent motion associated with formation of the axial antiform. At present we have no way of evaluating this possibility.

Post-Late Cretaceous faulting

Minor offsets of the reflection from the basal Cretaceous unconformity of a few tens to ~ 100 ms (~ 30–100 m), indicative of post-Late Cretaceous faulting within the rift, are a common feature of seismic sections in the region (e.g. Hamilton and Zoback, 1982). Examples visible on the COCORP profile (Fig. 4) occur at VP 890 on AR-6, above the crest of the axial antiform (VP 670, AR-6), and beneath the west flank of Crowley's Ridge (an actual topographic ridge of ~ 50 m height trending NNE within the embayment; VP 345, AR-6). The latter is notable because it suggests that Crowley's Ridge is structurally controlled, rather than simply being an erosional remnant.

Sub-rift crust

Although several discrete high-amplitude reflections occur in the shallow basement beneath the Reelfoot rift basin (e.g. 3.5 s beneath VP 500–550), in general the upper part of crystalline crust beneath the basin appears *relatively* unreflective down to roughly 5 s (12–16 km depth), beyond which it passes gradationally into a complexly reflective middle and lower crust (Fig. 3). Processing with several alternative parameter sets and processor combinations indicates that this is not a data processing effect (e.g. "AGC shadow").

Close examination of the seismic reflection pattern in the middle and lower crust indicates that it is composed of superposed arcuate events (probable diffractions), discontinuous subhorizontal reflections, and two opposed sets of dipping reflections (Figs. 3, 5). Examples of prominent arcuate events visible on AR-6 occur at 4.5 s beneath VPs 850–910, at 5.8 s beneath VPs 900–1000, and 8 s beneath VPs 650–770. Upon migration these arcuate events collapse into bright subhorizontal reflections, which have a maximum lateral extent of a few kilometers.

Superimposed on the subhorizontal features of the middle and lower crust are two sets of inwardly dipping reflections that occur beneath the east and west flanks of the basin, respectively (Figs. 3, 5). These are best imaged on the migrated section (Fig. 6). The eastern, west-dipping (15–25° migrated apparent dip) reflections are visible beneath VPs 700–1000 on AR-6 in the depth range 5–11 s. The lowermost reflections in this suite (10–11 s beneath VPs 780–850) appear to terminate against a set of horizontal reflections below, suggesting that the horizontal features may be younger. The east-dipping reflections (20–30° migrated apparent dip) beneath the west flank of the basin are visible beneath VPs 50–300 on AR-6 in the depth range 6–12 s. Neither set of dipping reflections is traceable to the top of the basement, and hence their interpretation is equivocal. However, their symmetric inward-facing arrangement beneath the rift roughly mimics the inward-facing

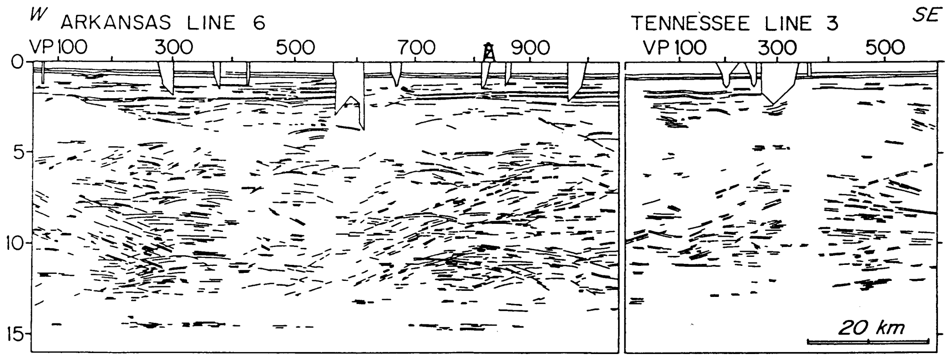


Fig. 5. Simplified line drawing illustrating major reflection features of the crust beneath the Reelfoot rift (unmigrated).

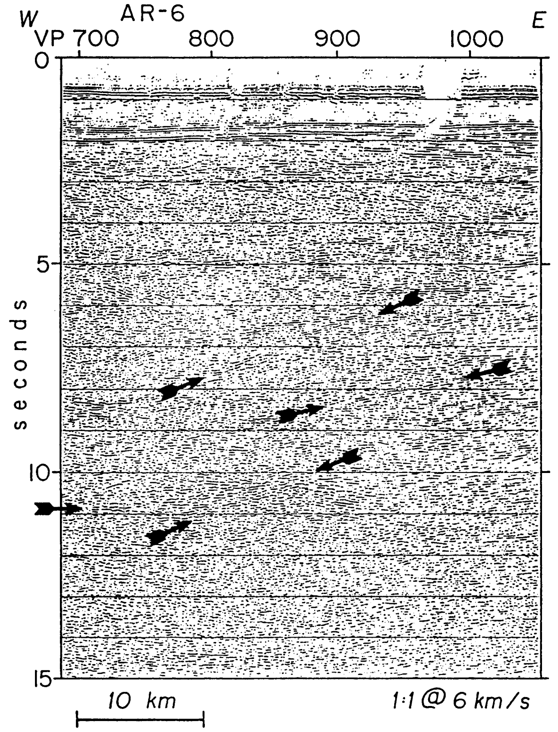


Fig. 6. Migrated portion of AR-6 showing dipping reflections in the deep crust beneath the rift.

geometry of the basin-bounding normal faults above, implying that they might represent the down-dip "ductile" continuation of the basin-bounding normal faults. This might be entirely an extensional fabric produced at the time of rifting, or alternatively might represent a preexisting structural fabric that controlled the subsequent development of the rift-bounding faults.

The complexly reflective crust, both beneath the rift and outside the rift to the east, grades downward between about 12 and 13 s (~ 35–40 km depth) into a nonreflective zone beneath. This downward decrease in crustal reflectivity is generally similar in appearance to the gradational "Moho" observed on many deep seismic reflection sections in cratonic regions (Brown et al., 1983), Allmendinger et al., 1987). However, beneath the rift on AR-6, the nonreflective zone is itself bounded below by a distinct horizontal reflection at 14.5 s (~ 45 km depth) (Fig. 3). This reflection is not visible on TN-3 beneath the eastern flank of the rift, or outside the rift to the east.

The apparent continuity of the 14.5 s reflection suggests that it represents an essentially continuous geologic "horizon" that extends beneath most of the rift. Internally the reflection consists of several wavelets with a total time thickness of 0.2–0.3 s, implying that the horizon is likely to be a composite of a number of layers having an aggregate thickness of about 1 km.

Comparison with refraction / wide-angle reflection results

A reversed long-range refraction profile shot parallel to and immediately west of the Reelfoot rift (McCamy and Meyer, 1966), and a series of wide-angle reflection profiles shot by the U.S. Geological Survey within and across the rift (Ginzburg et al., 1983; Mooney et al., 1983) constitute the primary sources of information on the velocity structure of the deep crust in the vicinity of the COCORP survey (Figs. 7, 8). Comparison of these data with the COCORP profile indicates the following:

(1) There are no simple first-order boundaries imaged on the COCORP profile within the crys-

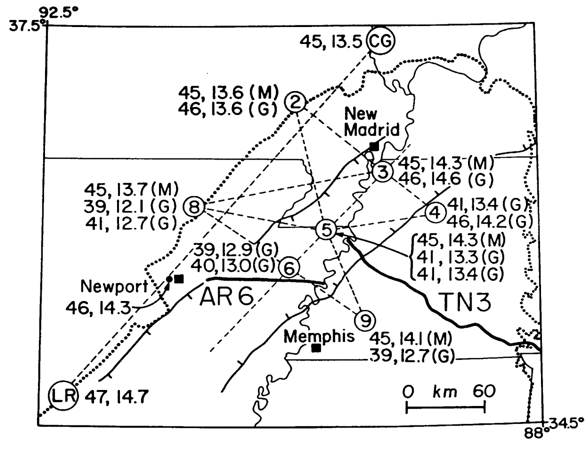


Fig. 7. Map showing locations of regional refraction and wide-angle reflection profiles in the vicinity of the Reelfoot rift. Line LR/CG: reversed refraction profile between Cape Girardeau, Illinois and Little Rock, Arkansas (McCamy and Meyer, 1966). Circled numbers: shot points in U.S.G.S. wide-angle reflection study. Number pairs give Moho depth and corresponding vertical incidence travel time for each shot point, as modelled by Mooney et al. (1983) (M), and Ginzburg et al. (1983) (G).

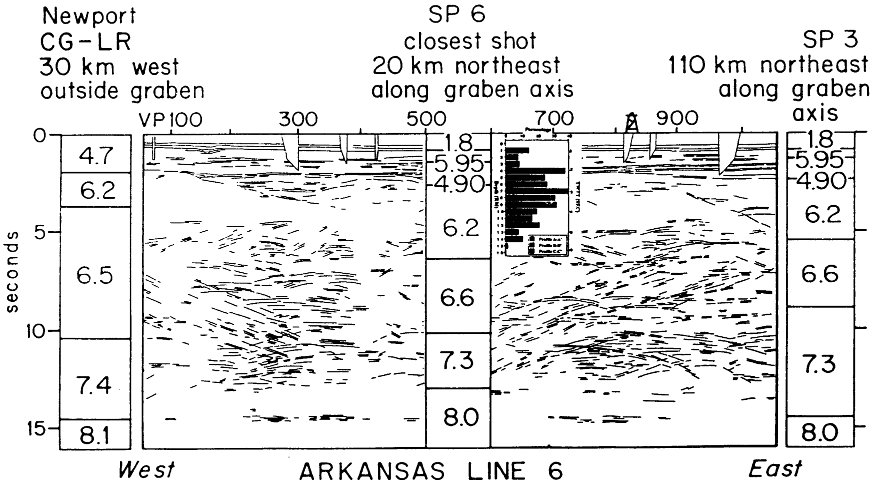


Fig. 8. Comparison of COCORP seismic reflection image of the crust beneath the Reelfoot rift with velocity structures interpreted from refraction/wide-angle reflection data. Note that velocity column for SP 3, like Sp 6, corresponds to the axis of the rift, not the east side. Histogram shows depth distribution of earthquakes along rift axis composed from profiles *AA'*, *BB'* and *CC'* of Andrews et al. (1985).

talline basement that correspond to the velocity "boundaries" derived from interpretation of the refraction and wide-angle reflection data. With the exception of the top of the basement, all of the velocity transitions in the crust beneath the rift must be gradational at the scale imaged by the seismic reflection profile.

(2) The above caveat aside, the less reflective upper part of the crystalline basement observed on the COCORP profile corresponds approximately with that part of the crust within which an average velocity of 6.2 km/s has been interpreted both inside and outside the rift. This is also the depth range of virtually all of the seismicity associated with the axial zone of the rift (Andrews et al., 1985) (histogram in Fig. 8).

(3) The complexly reflective middle and lower crust observed on the COCORP profile includes the depth range where intermediate average velocities of 6.5 to 6.6 km/s have been interpreted, and part or all of the depth range beneath where velocities of 7.3 to 7.4 have been interpreted ("rift cushion"). There is no obvious feature visible on the COCORP section that corresponds to the transition between these two velocity domains (Fig. 3).

(4) The crust–mantle transition, as deduced from the refraction/wide-angle reflection data, occurs in the vicinity of the deepest reflections visible on the COCORP profiles. However, because of ambiguities discussed subsequently it is not possible at present to determine *strictly* whether the Moho (transition to velocities > 8 km/s) beneath the rift corresponds to the downward disappearance of reflections at 12 to 13 s or the deep reflection at 14.5 s, or lies somewhere in between.

The ambiguity in interpretation of Moho stems in part from the fact that none of the wide-angle profiles in the U.S.G.S. study coincide precisely with the COCORP profile, and in part from the limited precision of the Moho depths derivable from the wide-angle data. Two different velocity–depth models calculated for U.S.G.S. shot point 6, which lies closest to the COCORP survey, both place the Moho at approximately 40 km depth, corresponding to a vertical travel time of about 13 s (Fig. 7). This would appear to correspond well with the downward cessation of reflections visible on the COCORP profile between 12 and 13 s. However, the range of Moho depths determined for the several wide-angle shot points within the rift varies by as much as 5 km, as does the Moho depth for different models determined for several of the same shot points, both within and outside the rift. This implies that the precision of the Moho depth determinations from the wide-angle data is not better than several kilometers, which is comparable to the separation between the downward cessation of reflections at 12 to 13 s and the deeper reflection at 14.5 s on the COCORP profile.

The limited precision of the Moho depths determined from the wide-angle data stems largely from the fact that the wide-angle profiles were not long enough to record Pn as a first arrival, which is crucial for precise Moho depth determination. Lacking P_n, the derived depths were based entirely on modeling P_mP, the identification of which is ambiguous in some areas (see for example Fig. 8 of Ginzburg et al., 1983). Furthermore, without being able to trace PmP unambiguously to zero-offset on these profiles, it is not possible to compare the Moho travel times on the wide angle profiles directly with the COCORP profile. An expanding spread experiment centered on the COCORP profile, with an aperture large enough to record P_n, might well resolve this issue.

Discussion

Figure 9 illustrates two alternative interpretations of the deep structure of the Reelfoot rift corresponding to the two possible positions of Moho discussed above. Both interpretations presume that the magnitude of crustal extension associated with formation of rift was relatively small ($\beta = 1.1$–1.2). While we cannot account quantitatively for the effects of late Paleozoic transpression, simple line-length restoration of the basement in Fig. 4 suggests that the total extension across the rift in the vicinity of the COCORP survey is only about 17% (10 km). This relatively modest figure is consistent with the observation that crustal thickness varies by at most a few kilometers from outside the rift to inside, regardless of which of the two Moho interpretations is chosen. Minimal extension is also qualitatively consistent with the lack of prominent subhorizontal lamination in the lower crust beneath the rift. Such lamination is a distinctive feature of seismic sections from a number of extended terranes (e.g. Basin and Range province, North American and European Atlantic margins), and while its precise origin is problematic, it is generally thought to be produced during crustal extension (e.g. Allmendinger et al., 1987; McCarthy and Thompson, 1988). Both of the interpretations in Fig. 9 also incorporate the presumption that lower crustal rocks of > 7 km/s average velocity represent mafic magmatic additions to the crust during rifting (underplate and/or "inplate" e.g. Furlong and Fountain, 1986). Similar anomalously high-velocity units have been found in the lower crust of several continental rifts (Mooney et al., 1983), and at a number of localities at the base of transitional crust beneath Atlantic-type margins (LASE Study Group, 1986; White et al., 1987; Trehu et al., 1989).

In both interpretations, Moho outside the rift is placed at the downward cessation of reflectivity at 12–13 s visible on TN-3. This is consistent with

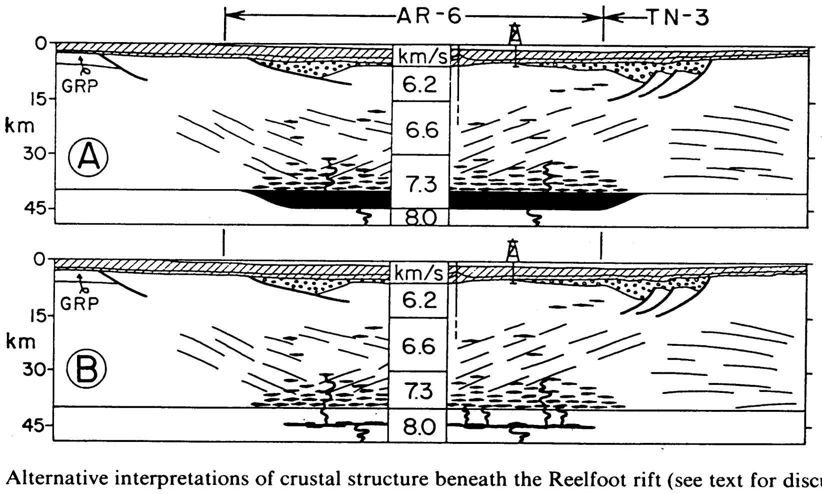


Fig. 9. Alternative interpretations of crustal structure beneath the Reelfoot rift (see text for discussion).

the interpretation of Moho from many cratonic regions throughout the world (Allmendinger et al., 1987). In the "A" interpretation, however, Moho inside the rift is considered to be an entirely new (early Cambrian) feature, corresponding to the deeper reflection visible at 14.5 s on AR-6. In this scenario the ~ 7.3 km/s material deduced from the wide-angle studies is suggested to be composed of a massive magmatic underplate (unreflective material between 12–13 s and 14.5 s), which passes upward into heavily injected preexisting crust (reflective upper portion of the 7.3 km/s zone). The top of the 7.3 km/s "layer" is suggested to represent a gradual upward decrease in the proportion of high-velocity magmatic material in the crust, which would not have expression on the near vertical incidence COCORP profile.

In the alternative "B" interpretation Moho, both inside and outside the rift, is placed at the downward cessation of reflectivity at 12–13 s. The deeper 14.5 s reflection is suggested to represent some discrete feature, perhaps a sill complex, within the upper mantle beneath the rift. While relatively rare, discrete mantle reflections are known from several areas (e.g. Flannan "fault", Warner and McGeary, 1986). The Moho in this interpretation, while perhaps modified somewhat during the rifting event, essentially coincides with the pre-rift Moho, and the 7.3 km/s lower crust is composed only of magmatically injected preexisting crust, with no massive underplate beneath.

Superimposed on both these scenarios is the possibility that the magmatic material represented by the 7.3 km/s layer beneath the rift is currently in the garnet granulite or eclogite facies, and the transition to lower-velocity material above marks the transition to amphibolite facies in these rocks.

A major uncertainty in both interpretations depicted in Fig. 9 is the age of the magmatic addition(s) to the crust. While the preceding discussion ascribes these to the rifting event, in reality no igneous rocks of late Precambrian or Cambrian age have been found in the vicinity of the Reelfoot rift, and hence the existence of such rocks in the deep crust is entirely conjectural. Conversely, mafic/ultramafic plutonic rocks of Permian and Late Cretaceous age are well known from boreholes in the region (Zartman, 1977; Hildenbrand, 1985), and therefore part or even all of the magmatic material hypothesized in Fig. 9 could have been added during these subsequent reactivation events. Lacking a method to "date" deep reflectors, this issue will remain unresolved.

Time of initial rifting and rift / drift transition

While the Reelfoot rift is generally thought to have initiated in late Precambrian/Early Cambrian time (e.g. Braile et al., 1986), in fact the time of both the initiation of rifting and the rift–drift transition are poorly constrained. A K/Ar whole-rock age of 845 ± 42 m.y. has been reported for the basement in the Dow Wilson well (Howe, 1985). Although the interpretation of this date is problematic, it presumably places a lower limit on the time of the initiation of rifting. The Elvins Formation, from which trilobite fragments of early Late Cambrian age have been recovered (Grohskopf, 1955; Howe, 1985), is the oldest overlying biostratigraphically dated unit in the rift. Hence, at this time it can only be inferred that the initiation of rifting occurred sometime between 845 Ma and early Late Cambrian time. The rift–drift transition, while necessarily postdating the initiation of rifting, is similarly poorly constrained to lie between these bounds. While lacking tight constraints, the relatively small thickness of the Bonneterre Formation and lack of evidence for a significant time gap at its base suggests to us that the rift–drift transition probably occurred in late Medial to early Late Cambrian time. If correct, this would be some 30 to 50 m.y. younger than the rift–drift transition of the Iapetus margin preserved in the Appalachian miogeocline to the east (Bond et al., 1984; Williams and Hiscott, 1987).

Relationship to preexisting structure

Prominent zones of dipping reflections penetrating deeply into the crust have been observed on seismic sections across a number of major crustal-penetrating high-strain zones (e.g. several Appalachian terrane boundaries, Nelson et al., 1987; Penninic zone of the Alps, Pfiffner et al., 1988; Grenville Front Tectonic Zone, Green et al., 1988). Hence the presence of the two zones of dipping reflections extending into the deep crust beneath the Reelfoot rift suggests the possibility that the rift formed along a preexisting crustal high strain-zone, This inference is at least circumstantially supported by regional magnetic anomaly data, which show opposing anomaly trends across the rift (Hildenbrand et al., 1982; Hildenbrand, 1985). Here we suggest that the Reelfoot rift may have formed along the southern extension of the Grenville Front.

The Grenville Front, extending from northern Canada to Mexico, is arguably the most extensive Precambrian tectonic feature in North America. It is both a structural and metamorphic boundary that separates rocks on the east and south, deformed and metamorphosed in the circa 1.0 Ga Grenville orogeny, from older terranes to the west and north (Hoffman, 1988). Within the eastern United States it lies hidden beneath Phanerozoic sedimentary strata; however, its position is reasonably well known as far south as north-central Tennessee on the basis of borehole penetrations, magnetic field data, and seismic reflection studies (Lucius and Von Frese, 1988; Lidiak and Hinze, 1992; Pratt et al., 1989). South of north-central Tennessee, however, the magnetic signature of the Front becomes indistinct, and borehole penetrations unequivocally constraining its location are lacking. Previous interpreters have tended to extend it southward, more or less along trend with its better located segment to the north, thus placing the Reelfoot rift well within the 1.4–1.5 Ga Eastern Granite Rhyolite Province, which bounds the Grenville Province to the west (e.g. Denison et al., 1984; Bickford et al., 1986). This was done at least in part because silicic igneous rocks have been encountered in several basement penetrations in northern Alabama and western Tennessee (Thomas, 1988). However, this is not a compelling constraint because silicic igneous rocks also occur within the Grenville Province to the north (Lucius and Von Frese, 1988) and crystallization ages requiring these rocks to lie within the older Granite/Rhyolite Province are lacking. More critically, this position for the Front is not easily reconciled with the recent observation that the Reelfoot rift is floored by amphibolite-grade metamorphic rocks (basement in Dow Wilson well, Denison, 1984), not unmetamorphosed granite or

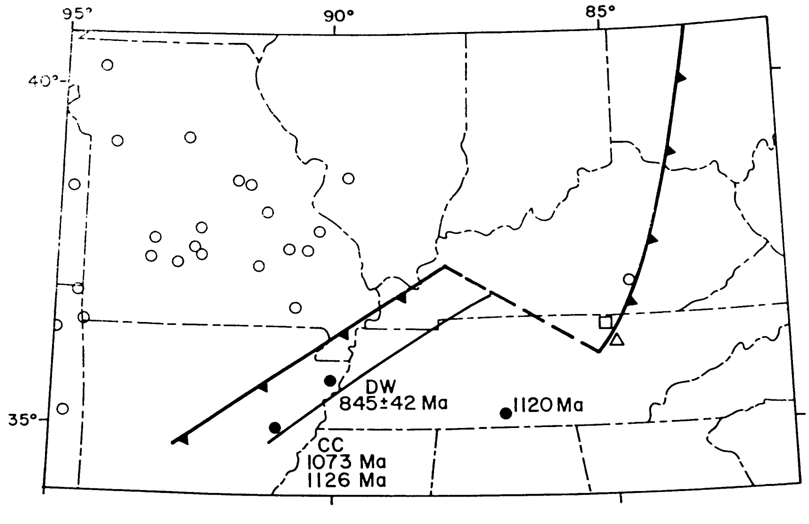


Fig. 10. Proposed southern extension of the Grenville Front beneath the Reelfoot rift. Heavy barbed line: Grenville Front. Solid line: east side Reelfoot rift. Dashed line: Rough Creek fault zone. Open circles: wells penetrating unmetamorphosed granites and rhyolites yielding ages of 1.38–148 Ga (Bickford et al., 1986). Solid circles: wells yielding "Grenville-like" basement ages. *DW* = Dow Wilson well (Howe, 1985); *CC* = Cockrell Consolidated No. 1 Carter Well (J.R. Howe, written commun., 1987). Closed circle in south-central Tennessee from Wasserburg et al., (1962). Square: unmetamorphosed silicic volcanic. Triangle: granite gneiss defining location of Grenville Front in north-central Tennessee (Lidiak and Hinze, 1989).

rhyolite. As noted, this metamorphic basement has yielded a suspiciously Grenville-like K/Ar whole-rock uplift age.

As an alternative we suggest that the Grenville Front does not continue southward across central Tennessee and northern Alabama, but rather is offset westward, perhaps along the Rough Creek fault zone, and continues southward along the Reelfoot rift (Fig. 10). This would provide a ready explanation for the occurrence of metamorphic rocks in the floor of the rift, and for the dipping fabrics observed in the deep crust beneath. It is also consistent with the fact that prominent stratification of the upper basement, which is characteristic of much of the Granite/Rhyolite Province to the north (Pratt et al., 1989), is not observed on COCORP seismic sections within or southeast of the rift in Tennessee or northern Alabama. More basement penetrations in the region, coupled with appropriate radiometric age studies are needed to test this hypothesis. If correct, it would lend support to the view that continental rifts commonly nucleate along preexisting crustal weakness, and would yield insight into the shape of the pre-Grenville margin of southern North America.

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