# SEISMIC REFLECTION STUDY

# IN RICE COUNTY, KANSAS

by

Nelda L. Roehl
B.S. University of Kansas, 1983

Submitted to the Department of
Geology and the faculty of the
Graduate School of the University
of Kansas in partial fulfillment
of the requirements for the degree
of Master of Science.

Professor in Charge

Anthony W. Walton
Committee Members

Ernest E. Angino
For the Department

# ABSTRACT

A seismic reflection study conducted in Rice County, Kansas reveals local geology related to regional Kansas stratigraphic and structural features. The geological history includes periods of deformation during the Ordovician, Devonian, and Mississippian with alternating uplift and subsidence, followed by cyclic sedimentation through the Pennsylvanian and Permian. Regional tilting to the south in the Pennsylvanian, to the west in the Permian, and to the northwest in the Cretaceous produces a composite northwesterly dip. Erosion during pronounced unconformities of the Devonian, Mississippian, and Cretaceous, and intercyclic hiatuses create further alterations of parallel strata. Applications of seismic stratigraphic principles indicate regional features of dipping divergent reflections associated with development of the Central Kansas Uplift and the Salina Basin. Superimposed upon these features of the Early Paleozoic are related local geologic expressions, which are observed on the seismic section as discordant dipping and arcuate reflections and diffractions characteristic of eroded folds and upthrown fault blocks. The Early Paleozoic sequence underlies a thick series of continuous, parallel, high to low amplitude

reflections characteristic of cyclic shelf facies. Seismic expressions, constrained by previous geological and geophysical studies, generate the most informed interpretation of the geology of Rice County.

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## ACKNOWLEGEMENTS

The thesis was thoroughly reviewed by Professors R.W. Knapp, A.W. Walton, and D.W. Steeples. I am grateful for their guidance and patience. The research was funded by the Kansas Geological Survey, and the data were collected by the Kansas Geological Survey seismic crews during the summer of 1983: Ralph Knapp, Rick Miller, Greg Neely, Mitch Hall, Dave Newell, Talat Abdullah, Xiaozhong Gu, Young Chung, Don Steeples, Jeff Treadway, Brian McNiece, and Steve Smith. Both seismic crews were concientious, hard working, and amazingly heat-tolerant, and I sincerely appreciate their 1200% effort. I thank Jacobo Quesada for assistance in processing the data. Much appreciation goes to Dave Newell and Kevin Blair for insight into the area geology and for suggestions about the seismic interpretation. Without the cooperation of the geologist and the geophysicist the correct interpretation has yet to be considered. I am grateful for the hours of programming advice from Bradley Kaufman and Eldon Roehl. Credit for the survival of this student's sanity goes to all these people.

This work is dedicated to Eldon.

# INTRODUCTION

The Salina Basin, the Central Kansas Uplift, and the Sedgwick Basin Precambrian basement features intersect near Rice County, Kansas (Figures 1 and 2). Since the Middle Ordovician Kansas has undergone five periods of deformation (Lee, 1956; Merriam, 1963). In Rice County, along the southeasternmost flank of the Salina Basin, deformation has resulted in complex folding and faulting. In general, thickening and thinning of formations as encountered in wells indicates the deformational events. Through reflection seismology a continuous geologic cross-section can be constructed to reveal the particular erosional and depositional sequence, boundary relationships, folding, and faulting for this area.

# PURPOSE OF STUDY

The purpose of this study is to identify local structural and stratigraphic features and to interpret structural history associated with the southeastern edge of the Salina Basin using reflection seismology and the methods of seismic stratigraphy. Ongoing analysis of well logs has resulted in questions about the subsurface geology (K.D. Newell, K.P. Blair, pers. comm., 1984). Early Paleozoic stratigraphic and structural relation-

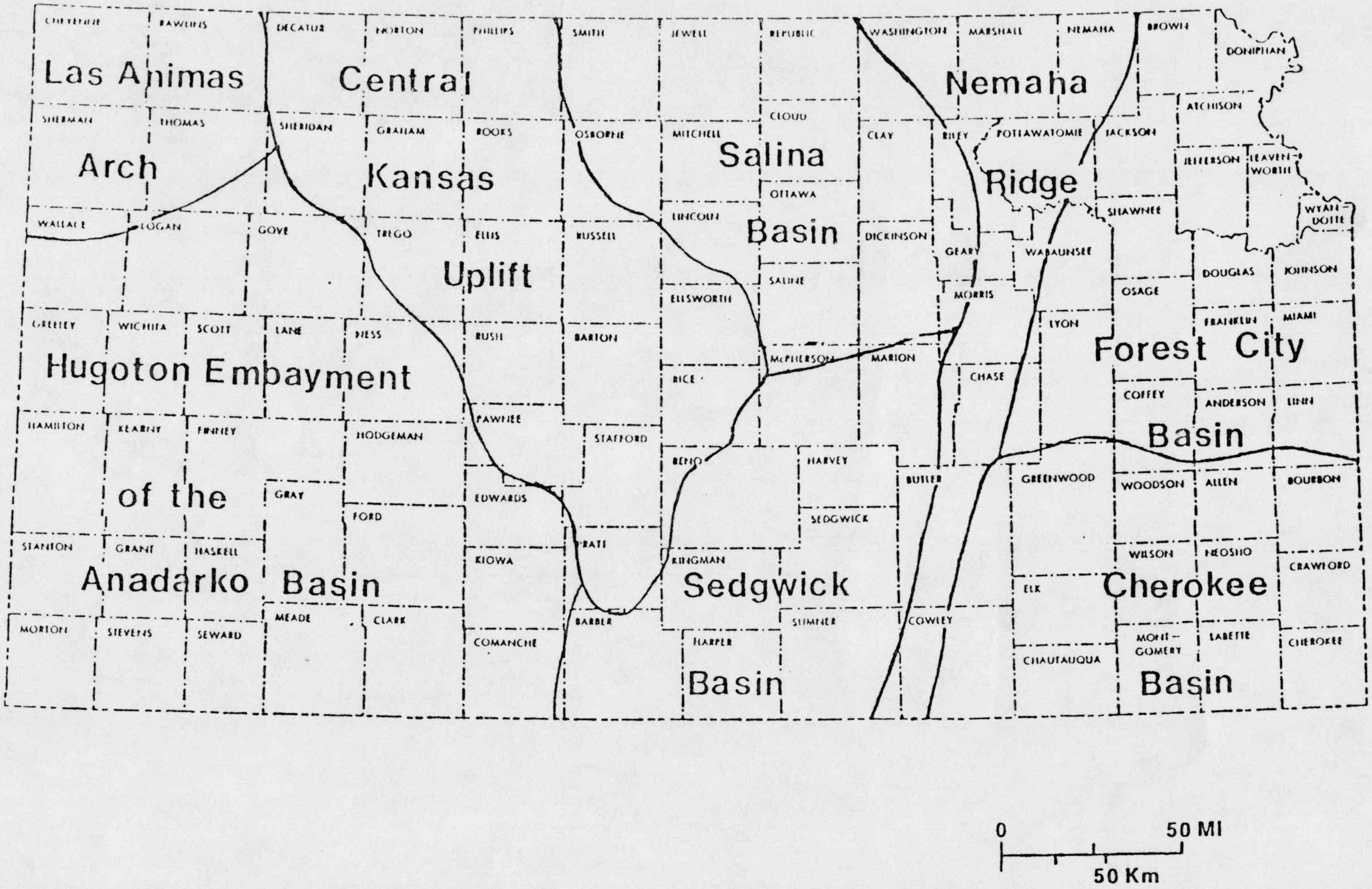


Figure 1 - Present generalized structural features of Kansas basement topography (after Paul, 1979).

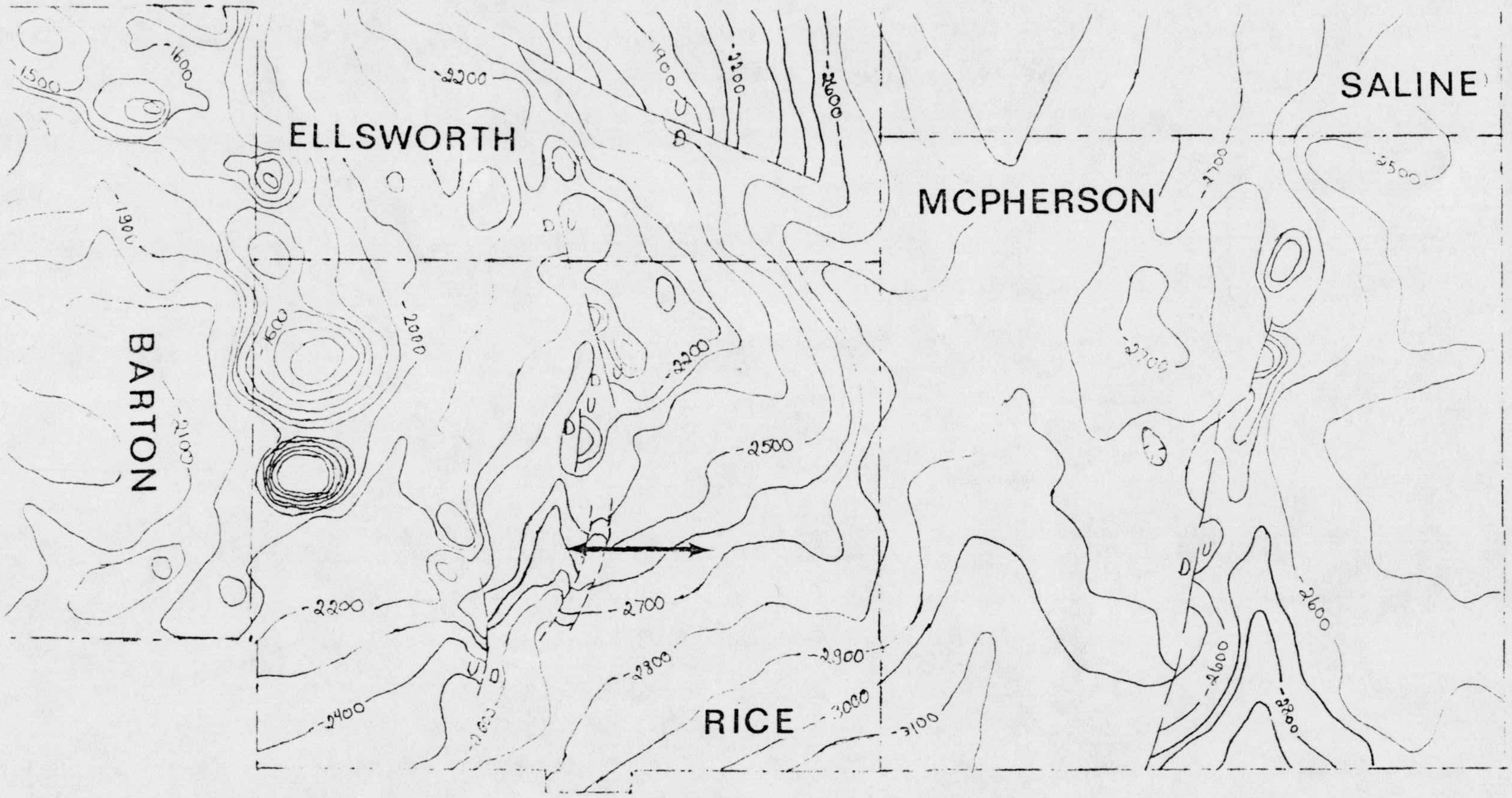


Figure 2 - Elevation of the top of the Precambrian basement (after Cole, 1976), with location of Rice County seismic section (arrow). Topography indicates portions of the Central Kansas Uplift in Barton, Ellsworth and Rice Counties, and portions of the Salina Basin and the Sedgwick Basin in Saline and McPherson Counties, respectively. Scale 1:500,000.

ships within the Salina Basin, the Sedgwick Basin, and the Central Kansas Uplift vary over much smaller distances than well control illuminates. The lateral continuity of a seismic section, controlled by the well data, is needed for a more correct interpretation.

Of particular interest is the extent and character of a limestone within the Mississippian-Devonian Chattanooga Shale. Wells have encountered the limestone at a depth averaging 1,050 meters below ground surface, and show a maximum thickness for the unit of 21 meters at the western edge of the seismic section. Well log data indicate thinning or faulting out of this Chattanooga limestone (Figure 3). The seismic reflection survey conducted in Rice County for this study is located over the limestone unit. It is known (Newell, in prep.) that the limestone thins to the east and is missing under the eastern edge of the seismic section. Modeling using synthetic seismograms, and interpretation using seismic stratigraphic analysis, have helped to define this and other subsurface features in the area.

## SEISMIC STUDY LOCATION AND ACQUISITON PARAMETERS

In an effort to better understand the structure of the southwestern flank of the Salina Basin, MiniSOSIE (Barbier et al., 1976) reflection seismic data were

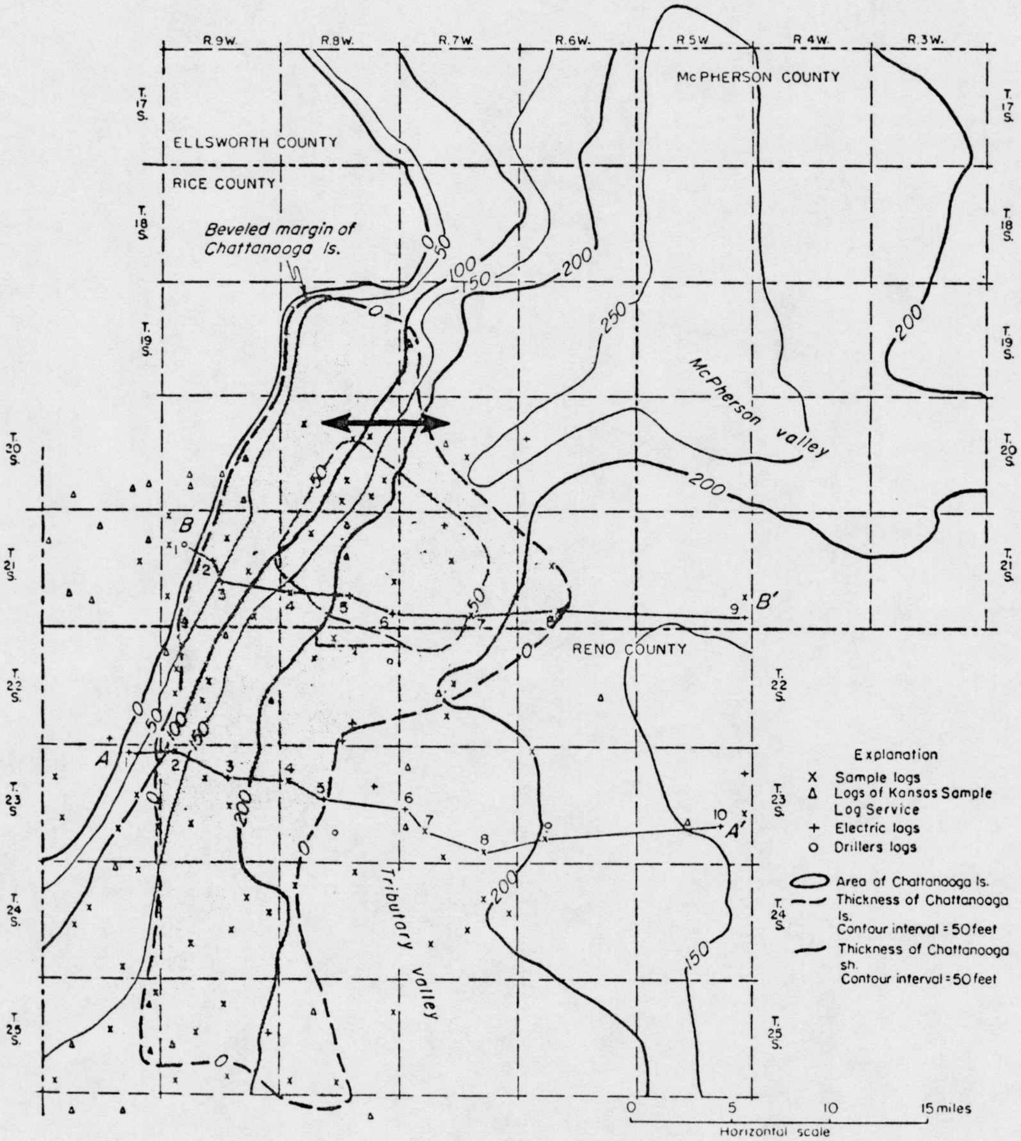


Figure 3 - Topography of pre-Chattanooga McPherson Valley with thickness contours and estimated extent of Chattanooga limestone unit in stippled area (from Lee, 1956). Rice County seismic line is shown in T21S, T7-8W.

acquired by the Kansas Geological Survey (KGS) Geophysics and Geochemistry Section under the supervision of Ralph Knapp during the summer of 1983. The east-west line, located 3.2 km (2 miles) south of U.S. Highway 56 (Lyons, Kansas), extended 11.2 km (7 miles) from 1.6 km (1 mile) west to 9.6 km (6 miles) east of Kansas Highway 96 (Figure 4). An earth compactor energy source provided the input signal. End-on common depth point (CDP) geometry with twelve-fold coverage (Table 1) was used. The reflected seismic energy was sensed by a linear array of geophones on the earth's surface, and recorded by an I/O DHR 2400 24-channel recording system.

## GEOLOGICAL AND GEOPHYSICAL BACKGROUND

The area for this study lies on the southeastern margin of the Salina Basin and is flanked to the southeast by the Central Kansas Uplift. The stratigraphy and structure, therefore, differ significantly from regional Salina Basin geology. Studies to date (Lee, 1956; Ehm, 1965; Bayne and Ward, 1974) have relied on well cuttings, cores and electrical logs, and have at times interpolated over spatial gaps of several square miles. Ongoing research (Newell, in prep.; Berendsen and Blair, in press) is based primarily on the larger present database of electrical well logs, although gaps in

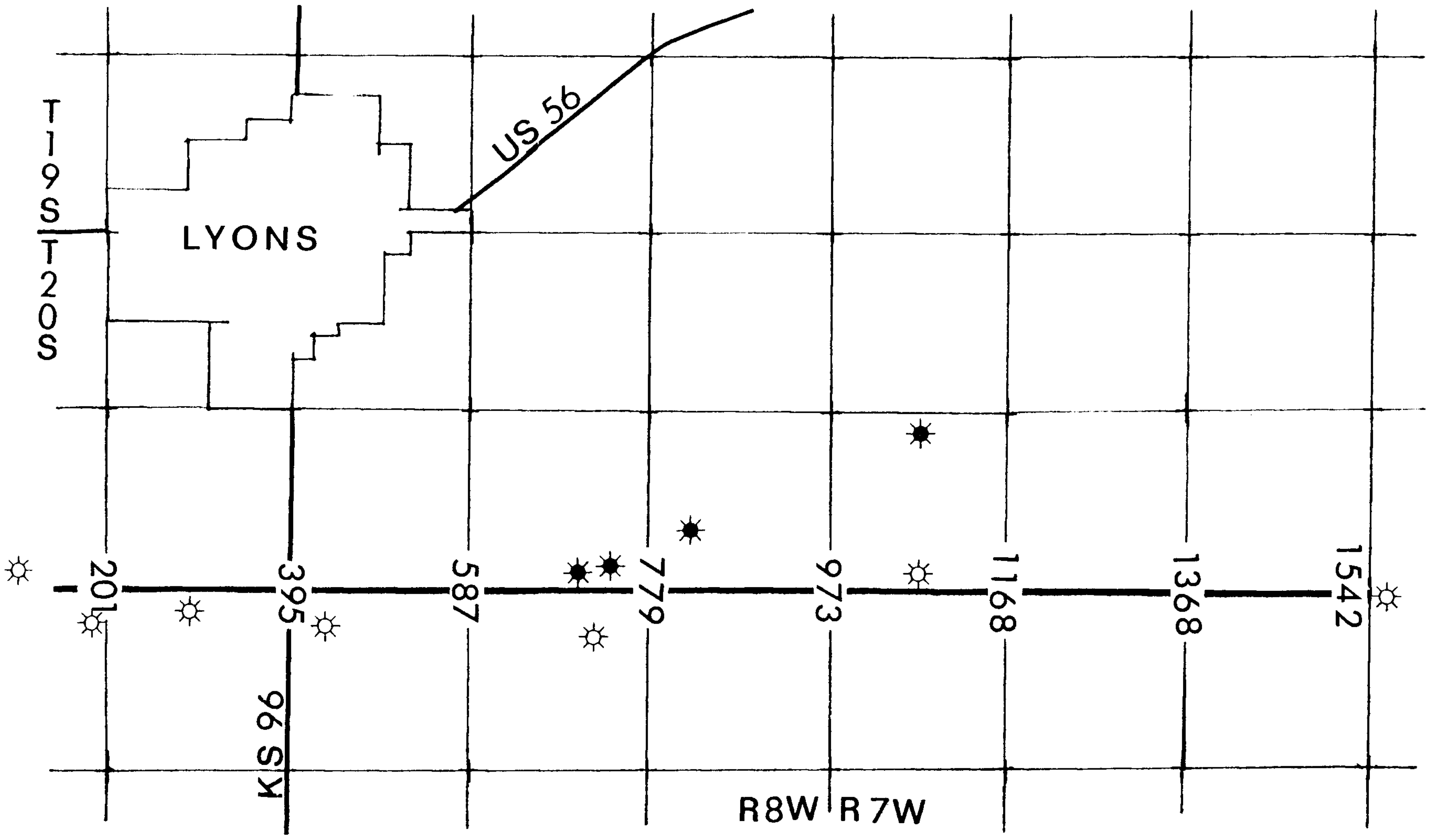


Figure 4 - Location of Rice County reflection seismic section. Common depth point numbers are shown for each mile. Well log availability shown by the well symbols:
✸ = sonic logs; ☼ = gamma ray - neutron logs.

# Table 1 - RICE COUNTY REFLECTION SEISMIC LINE
## DATA ACQUISITION PARAMETERS

| | | |
|---|---|---|
| Record length | | 1 second |
| Sampling interval | | 2 milliseconds |
| Source | | MiniSOSIE earth compactor |
| Vertical stack | | 2,000 pulses/shotpoint |
| Dominant frequency | | 80 Hz |
| Source interval | | 17 m. (55 ft.) |
| Source array | | Linear, continuous |
| Receiver interval | | 17 m. (55 ft.) |
| Receiver array | | 17 m. (55 ft.), linear 10 receivers, equally spaced |
| Recording geometry | | End on, 24-channel, CDP |
| Near offset | | 226 m. (742.5 ft.) |
| Far offset | | 612 m. (2,007.5 ft.) |
| Filters: | lowcut | 55 Hz (24 dB/octave rolloff) |
| | highcut | 125 Hz (24 dB/octave rolloff) |
| | notch | 60 Hz (60 dB/octave rolloff) |

control must still be extrapolated according to current geological models.

## STRATIGRAPHY - Regional and Local

Shown in Figure 5 is the Type Log for Rice County. For this study only gross stratigraphic features that can be seismically expressed will be described. Primary stratigraphic references for the Precambrian are from Bickford, et al. (1981), and Van Schmus and Bickford (1981); for the Cambrian through Mississippian are from Lee (1956) and Zeller (1968); for the Pennsylvanian through Cretaceous are from Lee (1956), Zeller (1968), and Merriam (1963).

### Rocks of Precambrian Age

Through core samples and cuttings the upper ten meters of the Proterozoic crust of Kansas has been dated by U/Pb and Rb/Sr methods and correlated to exposed Precambrian rocks outside the state (Bickford, et al., 1981; Van Schmus and Bickford, 1981). Their map of compiled basement rock types for the mid-continent (Figure 6) shows an older northern terrane formed about 1630 Ma and composed primarily of sheared mesozonal granite to granodiorite with smaller amounts of metasedimentary rocks, primarily quartzite. The northern terrane extends from northern Kansas and Missouri

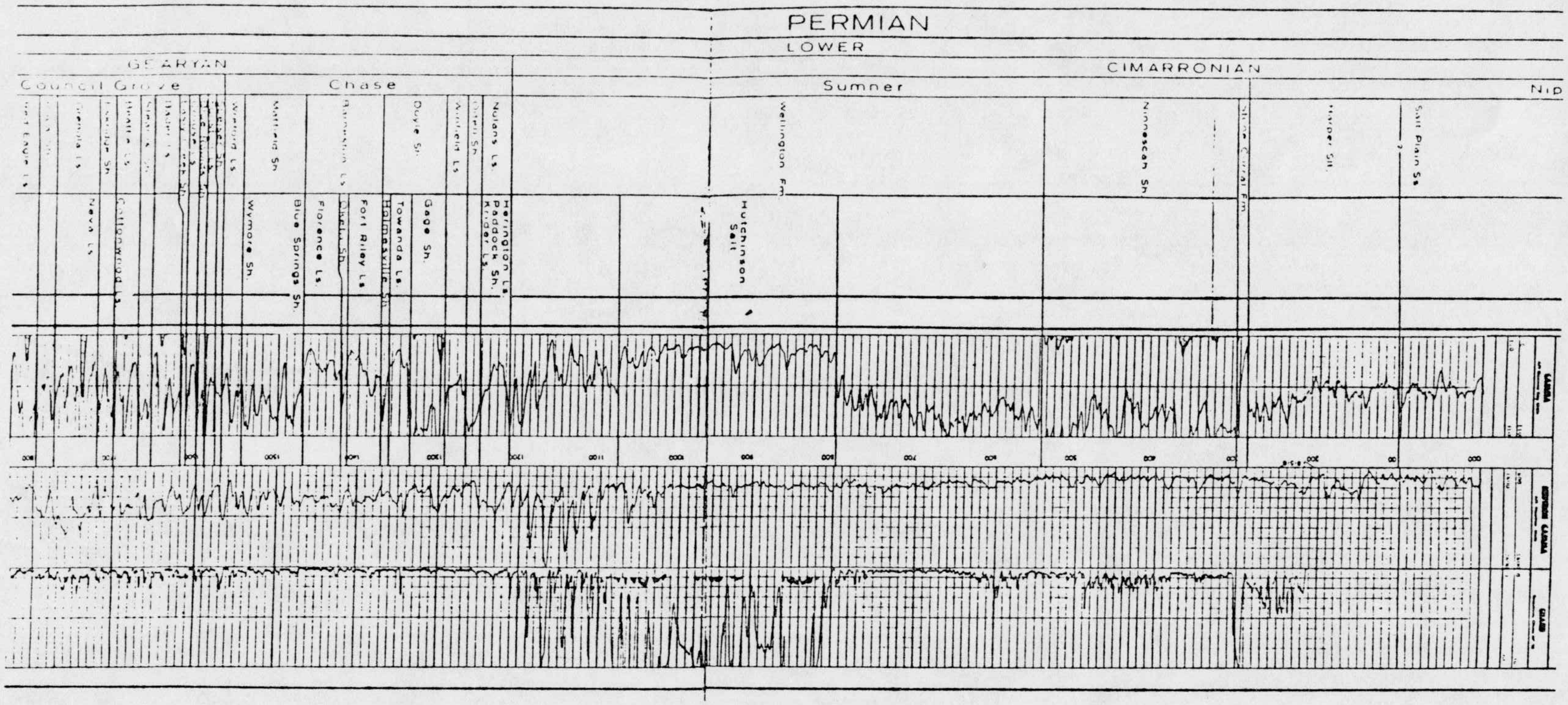


Figure 5 - Kansas Type Log for Rice County, Kansas, Sec. 20, T19S, R8W, (from Harriss, et al., 1966).

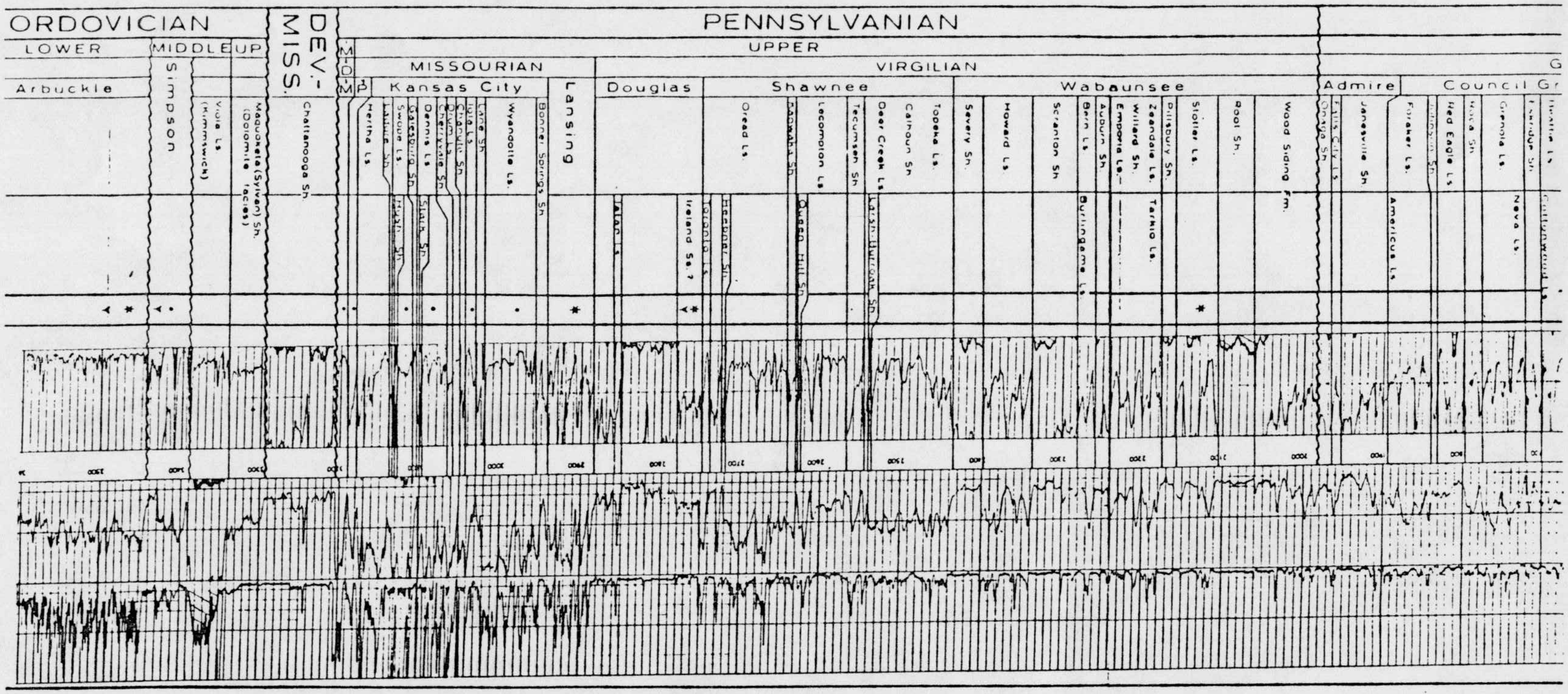


Figure 5 (continued) - Kansas Type Log for Rice County, Kansas, Sec. 20, T19S, R8W, (from Harriss, et al., 1966).

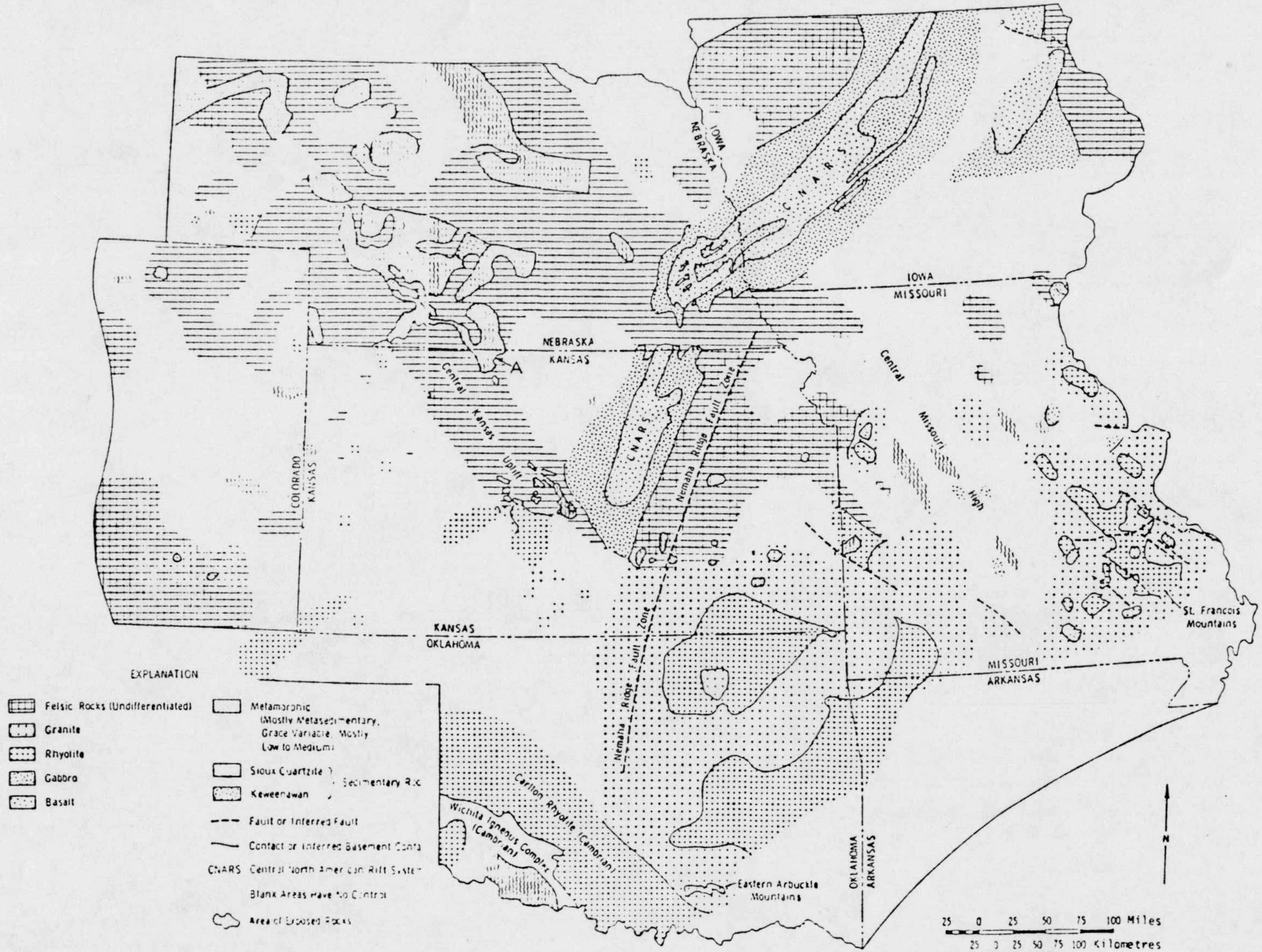


Figure 6 - Basement rock types for the Midcontinent (from Bickford, et al., 1981)

through all of Nebraska. None of the rocks contain minerals indicative of medium- or high-grade metamorphism, although extensive shearing has occurred. A number of anorogenic granitic plutons intruded the northern terrane between 1380 and 1480 Ma, and can be correlated with the epizonal granites of the southern terrane. Two cores recovered from intrusions were analysed as part of a scientific drilling program (Steeples and Bickford, 1981). Gravity and magnetic modelling of the intrusions indicate that they are each roughly 15 km in diameter and extend down from the Precambrian surface approximately 10 km.

Extending from northern Ohio through Indiana and Illinois, cutting down across southern Missouri and Kansas, through Oklahoma and into the Texas panhandle, the southern terrane dates from 1470 ± 20 Ma in the exposed St. Francois Mountains of southeastern Missouri to 1380 ± 20 Ma in basement cores from southern Kansas and northeastern Oklahoma, and exposures in the Arbuckle Mountains of southern Oklahoma. The southern terrane is composed of epizonal granitic plutons and extensive rhyolitic to dacitic volcanic rocks, primarily ash flow tuff. Metamorphism is non-penetrative, consisting only of slight recrystallization of groundmass. Intermediate and mafic igneous and sedimentary rocks are absent from both terranes.

From statewide gravity surveys (Yarger and Lam, 1982) the southern terrane shows a broad 30- to 40-milligal positive anomaly (Figure 7). This is contrary to the low-density rhyolites obtained from core samples, and suggests an extensive high-density body at depth (Yarger and Lam, 1982). The aeromagnetic survey of the State (Yarger, 1983) indicates an abrupt northwest-trending boundary between the northern and southern terranes (Figure 8). A prominent magnetic low under Wichita is shown in Figures 9 and 10. The low is assumed to be connected to a transition zone between the southern and northern terranes, but shows greater than usual depth in the area of Wichita. The magnetic low extends into Rice County suggesting that the Precambrian granites in that area are from a transitional or combined source.

The Consortium for Continental Reflection Profiling (COCORP) has recently finished a series of deep seismic reflection lines, using a Vibroseis source, across northeastern Kansas (Serpa, et al., 1984; Brown, et al., 1983) (Figure 11). Below the sedimentary section the upper 10 km of Precambrian crust shows few reflectors, giving the appearance of a thick homogeneous layer. Considering the presumed mechanics of crustal formation,

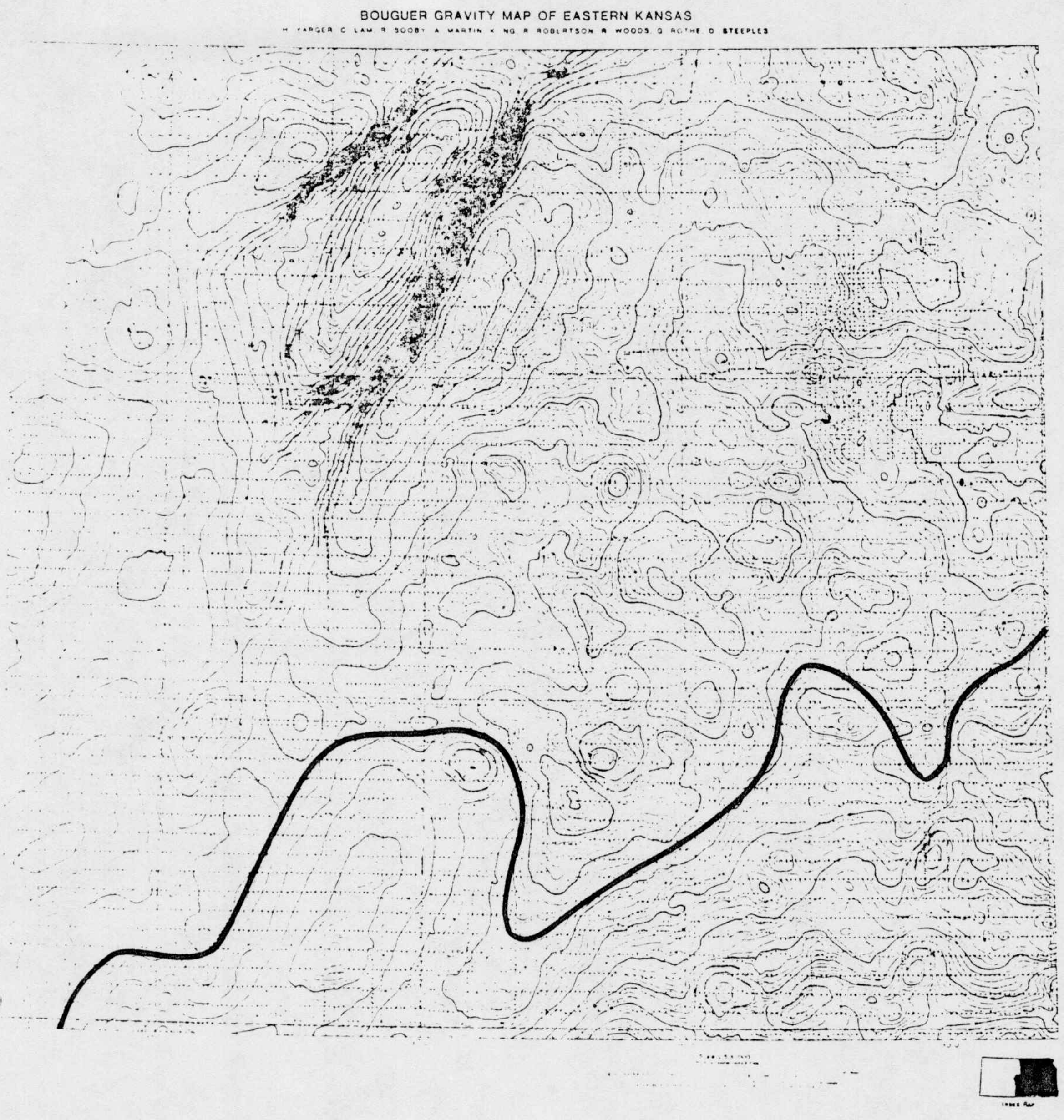


Figure 7 - Bouguer gravity map of eastern half of State of Kansas (after Yarger, et al., 1983), with .1-milligal resolution. High-density anomaly associated with the southern terrane is shown in the southeastern corner. Scale 1:500,000.

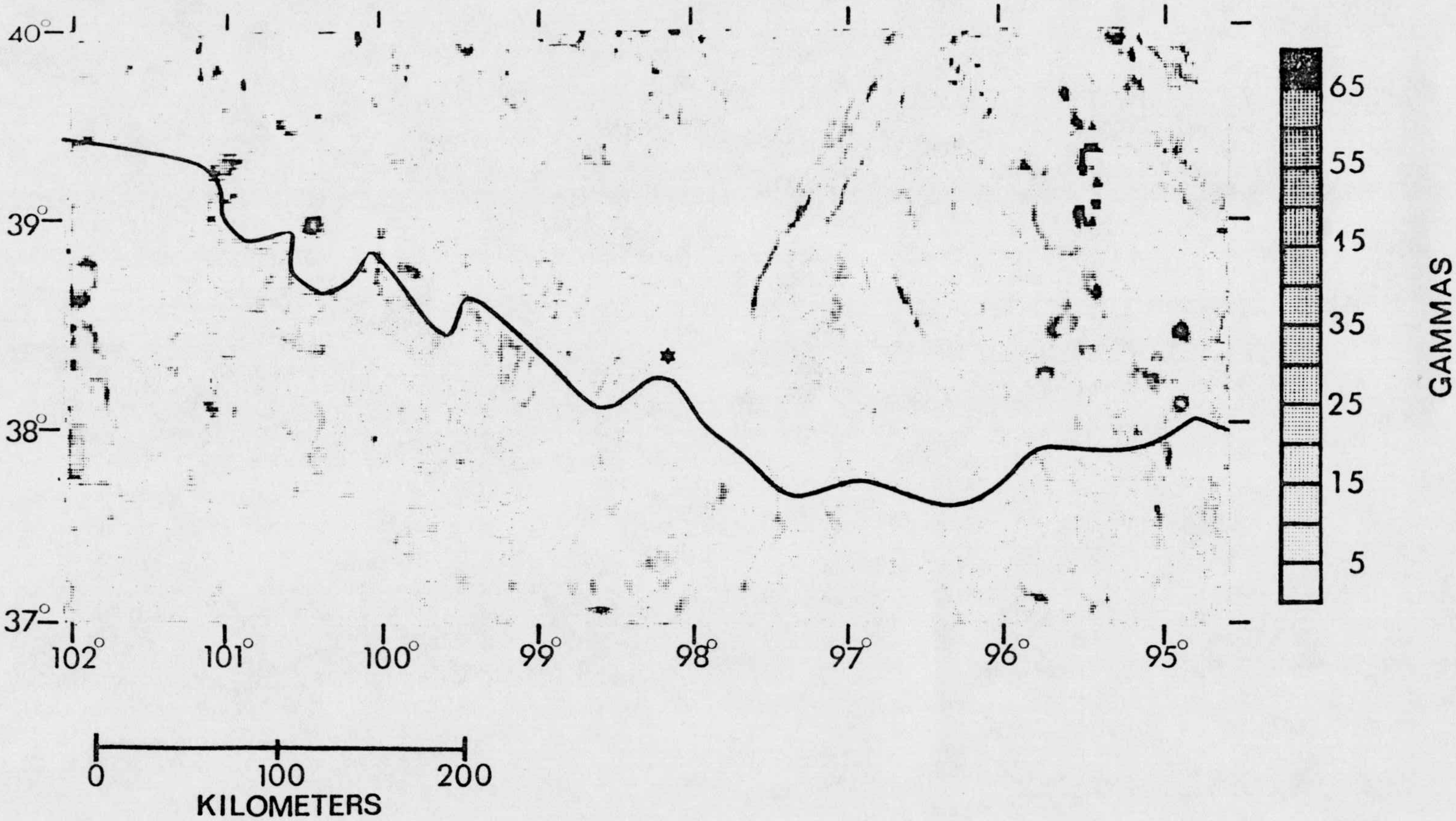


Figure 8 - Aeromagnetic map of Kansas (from Yarger, 1983), reduced to pole and high frequency pass filtered. Abrupt change in frequencies suggests contact between the northern and southern terranes. The solid line interprets this contact. Location of Rice County seismic section is shown in center of the State.

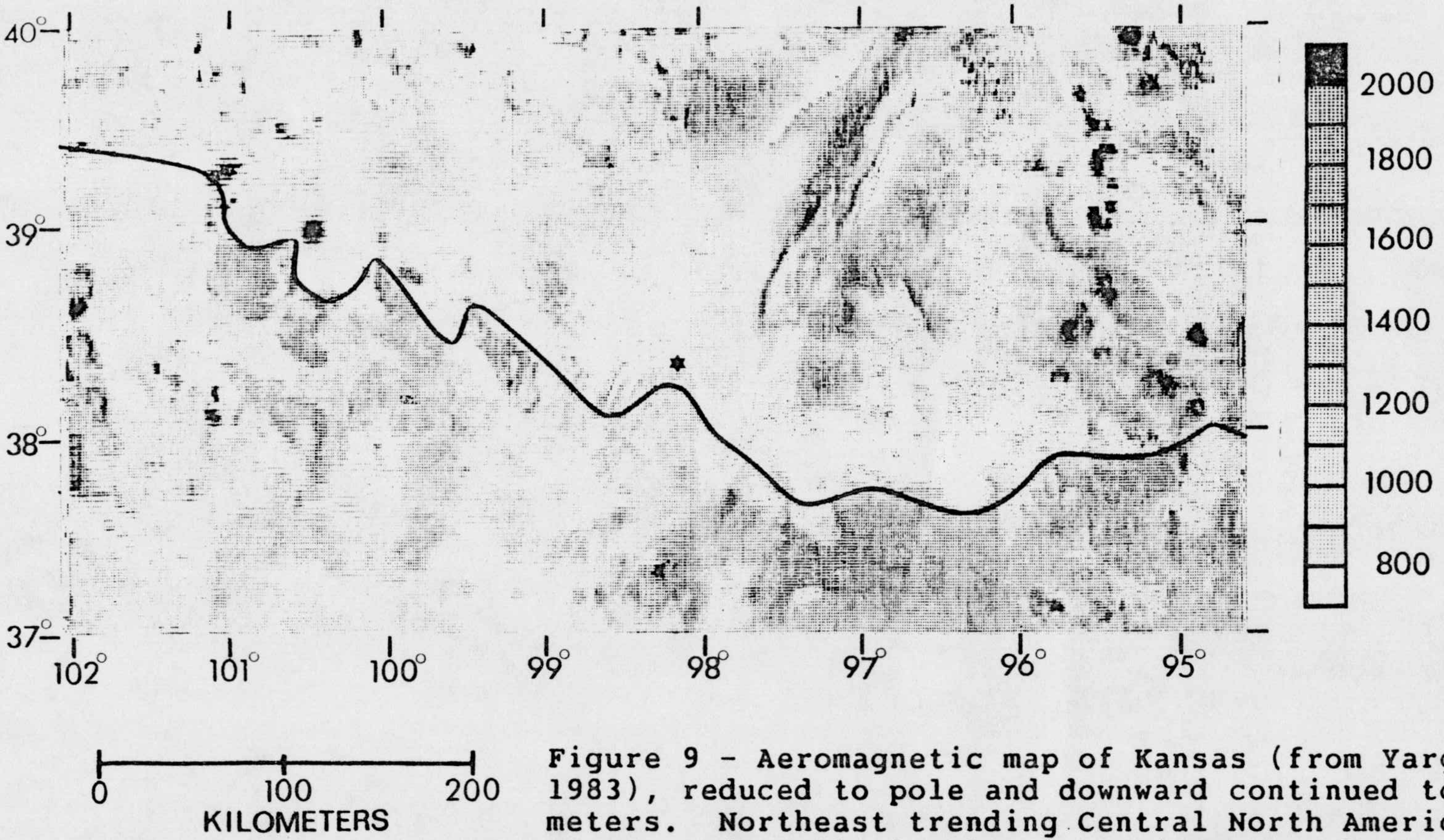


Figure 9 - Aeromagnetic map of Kansas (from Yarger, 1983), reduced to pole and downward continued to 850 meters. Northeast trending Central North American Rift System and small circular intrusives are shown as positive magnetic anomalies; Rice Formation arkoses and large area of transition zone granites in southeastern Kansas are shown as negative magnetic anomalies. Location of Rice County seismic section is shown in center of the State.

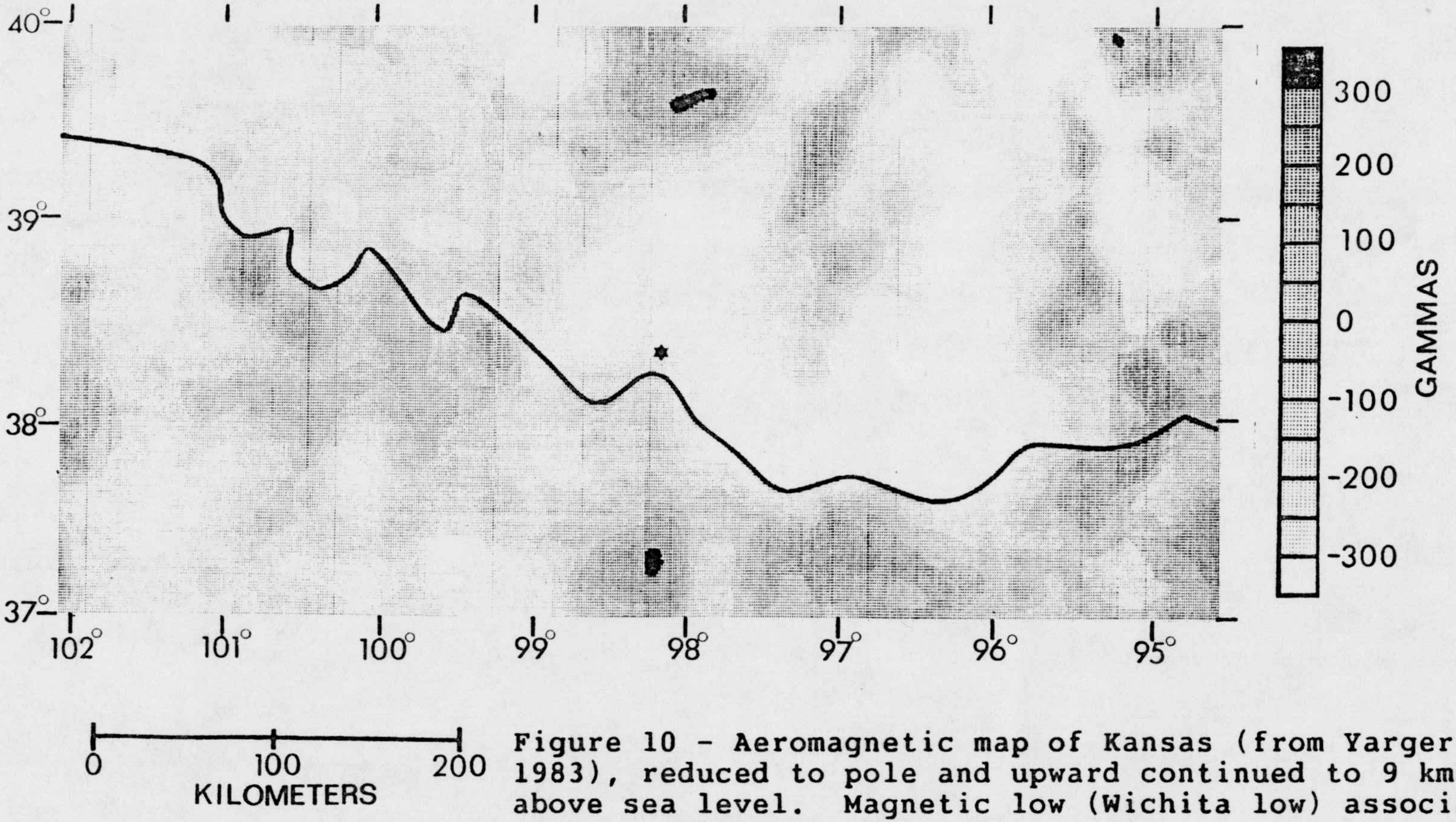


Figure 10 - Aeromagnetic map of Kansas (from Yarger, 1983), reduced to pole and upward continued to 9 km above sea level. Magnetic low (Wichita low) associated with transition zone granites defines terrane boundary in southeastern Kansas. Magnetic highs under Salina and Forest City Basins suggest mafic intrusions which may have caused zones of weakness and subsequent basin foundering. Location of Rice County seismic section is shown in center of the State.

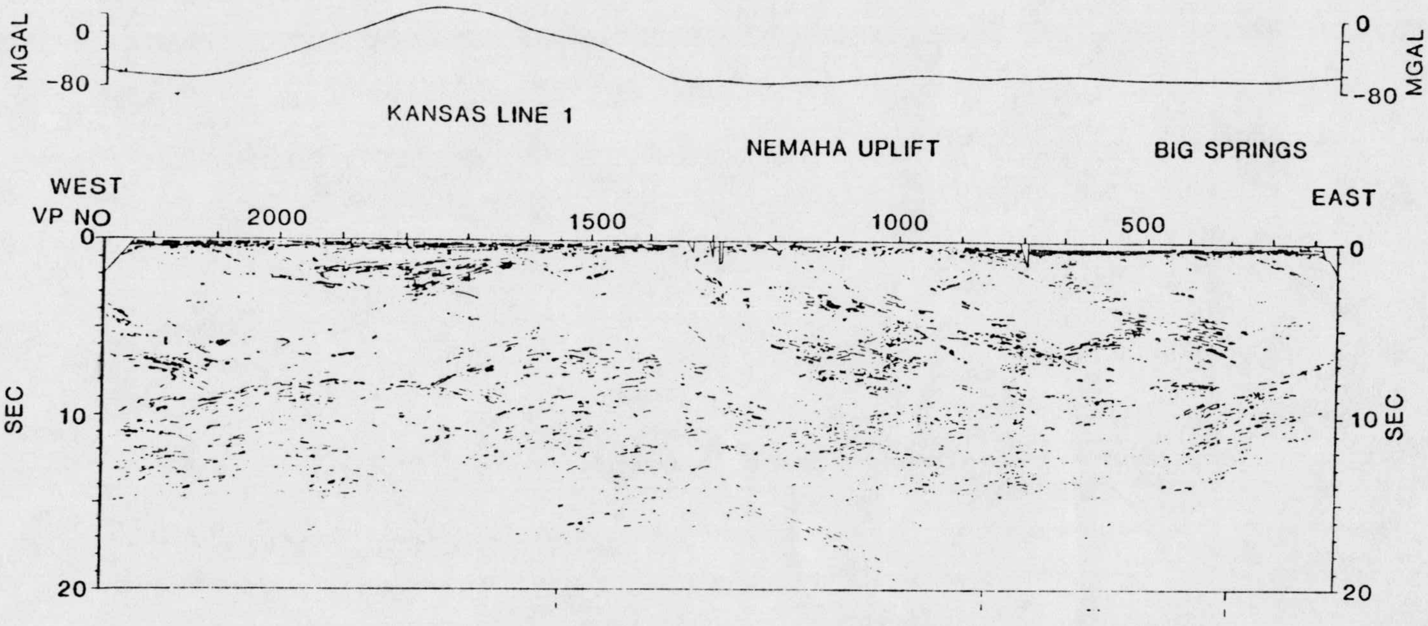


Figure 11 - Line drawing of COCORP seismic reflection line and coincident gravity profile across eastern Kansas (after Serpa, et al., 1984). Granites in the upper 10 seconds display very few reflections.

this "layer" is interpreted as a predominance of granitic materials emplaced as composite plutons (Brown, et al., 1983).

Keweenawan rifting, an aborted breakup of the North American continental crust, occurred between 1000-1200 Ma from the western side of Lake Superior to central Oklahoma (King and Zeitz, 1971). The rift, designated the Central North American Rift System (CNARS), does not rest on older continental crust, but is a separation of the crust, as evidenced by an abundance of interstratified thick basalt flows and arkosic sandstones (Figure 12) (Brown, et al., 1983; Serpa, et al., 1984; Ocola and Meyer, 1973) which overlie mafic intrusions (Somanas, 1984). In Kansas the rift is flanked by the Rice Formation arkosic sandstone. A deep well in Michigan (Sleep and Sloss, 1978) is thought to penetrate a southeastward extension of the rift. Samples of Precambrian redbeds and gabbro were recovered from the well and suggest subsidence and sedimentary deposition coeval with rifting and mantle diapirism. From aeromagnetic data, the rifting is shown to continue to the later stages of vulcanism, crustal foundering, and terrigenous sediment deposition only in the northcentral part of the state (Yarger, 1983). The Rice Formation, indicated by the white magnetic low and the gravity low around the

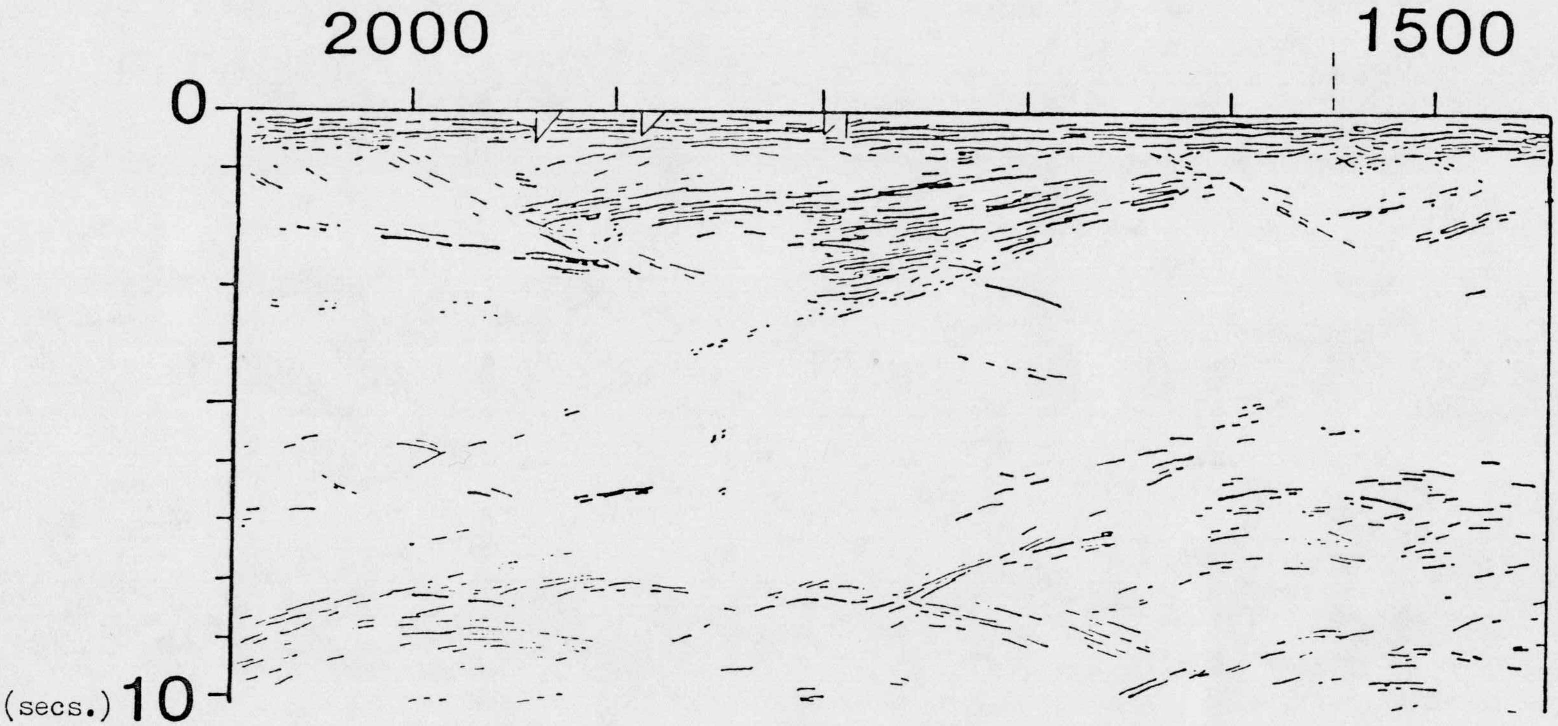


Figure 12- Line drawing of COCORP seismic reflection line (after Serpa, et al., 1984). Enlargement of section across the Central North American Rift System shows the asymmetric basin of layered basalts and arkoses (CDP's 1600-2000, 1-3 sec.). The basin underlies associated graded arkoses which lap out onto massive reflectionless granites.

CNARS (Figures 7, 9, and 13), is a thick deposit of nonmagnetic, low-density sediments (Yarger, 1983) (Yarger and Lam, 1982). The western margin of the Rice Formation intersects the Rice County seismic section (Figure 13; Yarger and Lam, 1982).

## Rocks of Cambrian and Ordovician Age

The Late Cambrian Lamotte Sandstone and Bonneterre Dolomite Formations, like the Precambrian rocks, are described from wells on the Central Kansas Uplift (Lee, 1956). The Lamotte grades from arkose to sandy dolomite with an average thickness of 30 meters. Above it the Bonneterre is a glauconitic non-cherty dolomite which is often erroneously associated with the Arbuckle dolomites (Zeller, 1968). Due to erosion it feathers out on the Central Kansas Uplift, and may be as thick as 50 meters in basin areas.

The Arbuckle Group spans the time between Late Cambrian and Middle Ordovician to include all units up until Simpson. Gas and oil accumulations at the top of the Arbuckle make it one of the major producing horizons in the State. The Arbuckle is also used for gas storage in the area of the Rice County seismic section. The Arbuckle consists of six dolomite formations for a total thickness of 200 meters. Many Arbuckle formations contain chert, and the Roubidoux, in

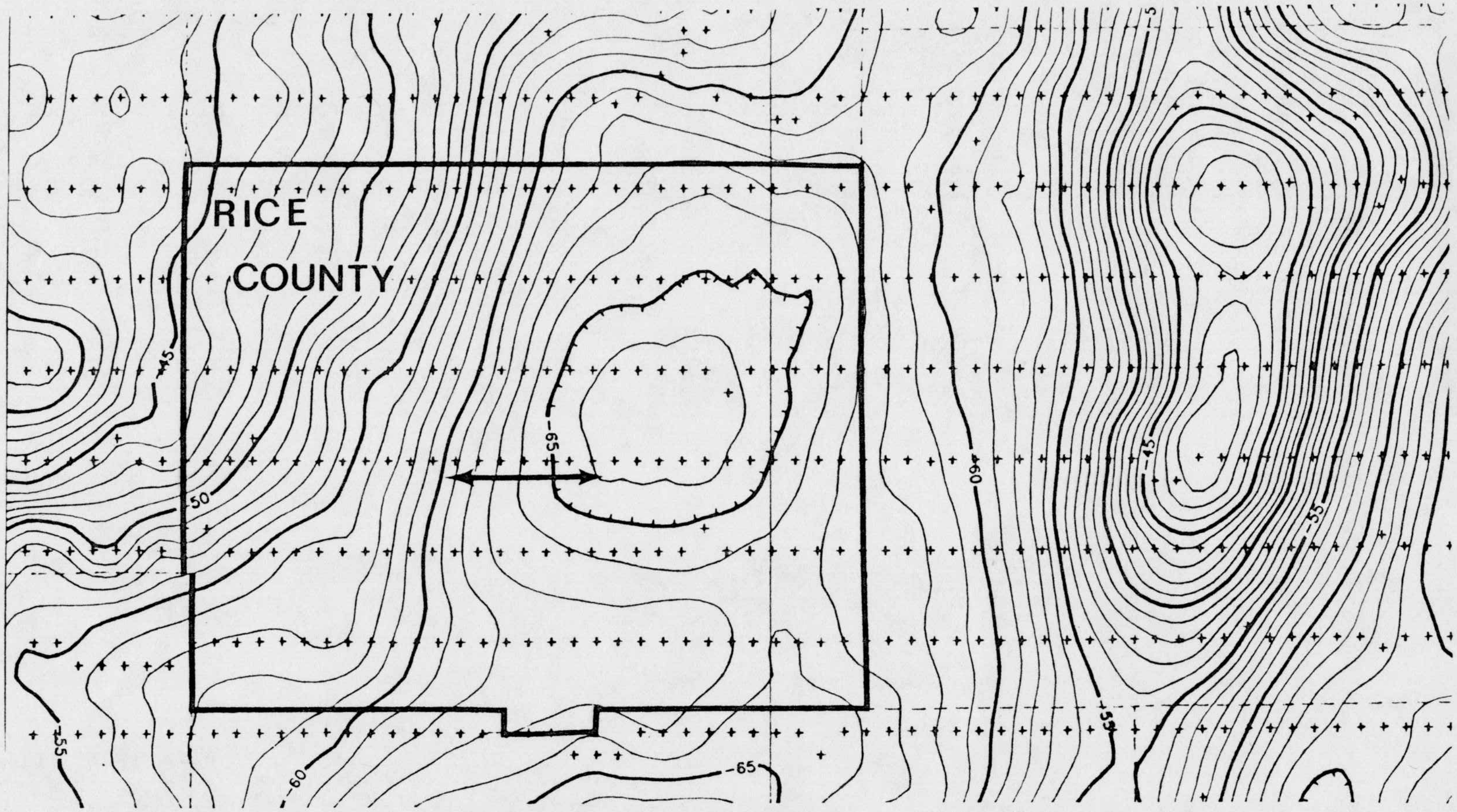


Figure 13 - Bouguer gravity map of central Kansas (after Yarger, et al., 1983). Enlargement of area surrounding Rice County showing gravity low of eastern Rice County between the gravity highs of the Central North American Rift System to the east and the Central Kansas Uplift to the west. The gravity low is associated with low density Rice Formation arkosic sandstones. Contour interval = 1 milligal. Location of seismic line is shown near the center of Rice County.

particular, contains sandstone. Continuous layers of sandstones and chert may give the Arbuckle the layered appearance reflected in the seismic section.

The Middle Ordovician Simpson Group consists, in ascending order, of unnamed beds of sandstones and shales, the St. Peter Sandstone Formation, and the Platteville Formation (Zeller, 1968). In Rice County the Simpson is composed of undifferentiated sandstones and shales, and thin sandy limestones and dolomites (Lee, 1956). Unconformities define both boundaries of the Simpson. The interval thickness locally is relatively constant at 18 meters. The Simpson thickens toward the center of the North Kansas Basin, the basin which formed in the area of the Salina and Forest City Basins from Middle Ordovician to Middle Mississippian time (see section on Structural Background).

The Middle Ordovician Viola Limestone Formation is a variable sequence of limestones and dolomites and discontinuous chert zones with unconformities existing at both upper and lower boundaries. The Viola also thickens, although irregularly due to erosional and structural relief, northeastward from Rice County into the North Kansas Basin. Thickness ranges from 0 to 15 meters along the Rice County seismic section.

The Upper Ordovician Maquoketa Shale Formation in Rice County includes a basal dolomite and an upper dolomitic shale. The top of the Maquoketa is unconformable with the Devonian-Mississippian Chattanooga Shale Formation as a consequence of the erosion of the pre-Chattanooga McPherson Valley and its tributaries. The McPherson Valley is a local erosional feature extending through parts of McPherson, Marion, Reno, and Rice Counties (Figure 3). Thickness for the Maquoketa ranges from 0 to 12 meters along the Rice County seismic section, and regionally ranges from 10 to 40 meters, the variation due primarily to relief on the surface underlying the Viola.

### Rocks of Silurian and Devonian Age

The Hunton Group consists of limestones and dolomites deposited during the Silurian and Devonian, before deposition of the Chattanooga. Although these rocks reach a thickness of 150 meters in the center of the North Kansas Basin, pre-Chattanooga erosion of the McPherson Valley has resulted in their complete removal in the area of the Rice County seismic section.

### Rocks of Devonian or Mississippian Age

The Chattanooga Formation lies between rocks of definite Devonian age and definite Mississippian age

(Zeller, 1968). It consists of the basal Misener Sandstone Member, over which the black-to-grey sequence of Chattanooga Shale effectively fills in pre-Chattanooga erosional features. The Misener appears to be thickest near where the Chattanooga laps onto the Simpson Group, and is probably derived from the Simpson (K.D. Newell, pers. comm., 1984). The Chattanooga limestone unit separates the lower and upper shale units and is limited to the western margin of the tributary to the McPherson Valley (Figure 3). It thins as it extends into the valley and may either wedge out or terminate abruptly. Thickness of the Chattanooga limestone ranges from 0 to 20 meters across the Rice County seismic section, and reaches 75 meters in the deepest parts of the McPherson Valley and North Kansas Basin.

## Rocks of Mississippian Age

Episodically during Late Mississippian time and continuing until Late Pennsylvanian, the Central Kansas Uplift and the Nemaha Anticline rose, creating between them the Salina Basin (Rascoe and Adler, 1983; Kluth and Coney, 1981; Lee, 1956). Mississippian formations present in the Salina Basin consist in ascending order of the Boice Shale Formation, and carbonate rocks of the Kinderhookian, Osagian, and Meramecian Stages. Thickness in the center of the Salina Basin averages 100 meters, although in the area of the Rice County seismic section, erosion after the uplift of the Central Kansas Uplift caused removal of the Mississippian formations and bevelled the top of the Chattanooga.

## Rocks of Pennsylvanian Age

Both Pennsylvanian and Permian rocks consist of complete and partial sequences of cyclothems. Composed primarily of alternating limestones and shales, each intact cyclothem represents a transgression and regression of the sea (Merriam, 1963). Subaerial exposure of limestone units resulted in intercyclic erosion (Lee, 1956), creating channels within the limestone which were filled in with fluvial sandstones and transgressive deposits of shales. Many of the Pennsylvanian limestones are argillaceous and interfinger with shales in southern Kansas.

Throughout the Early Pennsylvanian, episodes of folding similar in trend to those at the end of Mississippian time deepened the Salina Basin and raised the Nemaha Anticline and Central Kansas Uplift above sea level. As a result during the Middle Pennsylvanian only the Pennsylvanian basal conglomerate was deposited over the pre-Pennsylvanian unconformity in the area of the Rice County seismic section (Lee, 1939), although the

Cherokee and Marmaton Groups of the Middle Pennsylvanian Desmoinesian Series average 120 meters in thickness in the center of the Salina Basin. The Pennsylvanian basal conglomerate ranges in thickness from featheredge to 30 meters across the Rice County seismic section.

Missourian Stage--The Pleasanton Group begins the Late Pennsylvanian (Zeller, 1968) and is composed in Rice County of undifferentiated shales and sandstones (Lee, 1956). The group average thickness in Rice County is 15 meters, and is slightly less in the center of the Salina Basin. It thickens toward southeastern Kansas and wedges out over the Central Kansas Uplift.

Above the Pleasanton, the Kansas City and then Lansing Groups include cyclothems, and are composed primarily of thick limestones separated by thin shales that show a frequent occurrence of intercyclical erosion. Thickened limestone lenses and oolitic shoals, representing a marine slope environment, are scattered throughout the Upper Kansas City and Lansing. As do all the Late Pennsylvanian groups, the Kansas City and Lansing Groups thicken to the southeast in response to the Ouachita Orogeny and the related subsidence of the Anadarko Basin. Movement along the Nemaha Anticline and Central Kansas Uplift slowed during the Missourian. The upper units of the Kansas City and all units above succeeded in covering the tops of both features. The thickness of the Kansas City Group averages 70 meters in the center of the Salina Basin and in the area of the Rice County seismic section, and is 100 meters at the saddle to the south between the Salina Basin and the Sedgwick Embayment. The Lansing attains a thickness of 20 meters in Rice County, compared to 12 meters in the center of the Salina Basin and 40 meters in southeastern Kansas.

Virgilian Stage--The first group of the Virgilian, the Douglas Group, consists of several thick shale members often with interbedded sandstones and coal beds, and minor amounts of limestone. An unconformity separates the two formations of the group, the Stranger below and the Lawrence above. Considerable topographic relief resulted from the depositional hiatus, which was filled in by the shales and sandstones of the Lawrence Formation. Due to the erosional relief, thickness for the Douglas ranges from 30 to 130 meters throughout eastern Kansas, and averages 50 meters along the Rice County seismic section (Lee, 1956).

The Shawnee Group consists of four limestone formations separated by three shale formations, each containing multiple cyclothems. The Shawnee is similar in lithology to the Kansas City and Lansing Groups, having thick limestones with shales interstratified. The shales are black and radioactive and a pattern exists of dense fusulinid limestone beneath each shale and fossiliferous cherty limestone above. The Oread Limestone Formation at the base of the Shawnee Group contains four cyclothems and is easily identified in electrical logs and cores by the 3-meter Heebner Shale Member. The shales within the Shawnee Group, and to minor extent the limestones, thicken to the southeast. The thickness of the Shawnee Group ranges from 90 to 100 meters in the Salina Basin. Thickness is 80 meters on the crest of the Central Kansas Uplift, and averages 110 meters along the Rice County seismic line. By Virgilian time the Salina Basin had developed into a structural embayment, opening to the north, with all units thickening to the southeast (Lee, 1956).

Cyclothems of the Wabaunsee Group, the top group of the Virgilian, are separated into twenty-eight formations composed of alternating, nondistinctive, thin limestones and thicker shales. Limestones form only twenty percent of the group, averaging 2 meters each in thickness. The shales commonly contain discontinuous sandstone and coal beds. Many of the thinner units appear discontinuous due to intercyclical erosion or depositional patterns. Overall thickness of the Wabaunsee is 110 meters in the central Salina Basin, 100 meters on the crest of the Central Kansas Uplift, and 140 meters along the Rice County seismic line.

## Rocks of Permian Age

Cyclothems composed of alternating limestones and shales continue into the Lower Permian. Shale units undergo a transition from black and grey to red, and cyclothems yield to siltstone redbeds and evaporite deposits in the upper two stages of the Lower Permian. The Permian in Kansas is divided in ascending order into the Wolfcampian, Leonardian, and Guadalupian Stages, and is separated from the Pennsylvanian below and the Quaternary above by angular unconformities.

Wolfcampian Stage--The Admire Group, the lower in the Wolfcampian, is dominated by shales with few thin limestones, similar to the Wabaunsee below. Formations below the Falls City Limestone Formation serve to fill in the minimal erosional relief resulting from the post-Pennsylvanian unconformity. Thickness of the Admire is a relatively constant 30 meters across the Central Kansas Uplift, the Salina Basin and the Rice County seismic section, indicating little uplift or subsidence through Wolfcampian time.

The Admire is overlain by the Council Grove Group, which consists of alternating thin shales and limestones in equal proportions. Shales are grey to red and often calcareous. Some limestones are argillaceous and interstratified with thin shales. Average thickness for Kansas and across the seismic section is 100 meters.

The Chase Group is composed of thicker (10-30 meters) limestones and shales in equal proportion and represents the last of the Kansas cyclothems. Limestones are commonly cherty and, where they crop out, provide the flint of Kansas' Flint Hills. Shales are variegated, but predominantly red, indicating the transition from cyclothems to redbeds. Average thickness for the Chase in Kansas and along the seismic line is 110 meters.

Leonardian Stage--The lower of the Leonardian groups, the Sumner Group, contains interstratified anhydrite and shale beds under a salt unit, the 100-meter-thick Hutchinson Salt Member. The Hutchinson Salt underlies very thick beds of red and grey siltstones and shales of the Ninnescah Shale Formation. A thin anhydrite unit, the Stone Corral Formation, tops the Sumner Group. Where the salt exists, group thickness averages 365 meters in southern Kansas and 300 meters in Rice County. Thickness where Hutchinson Salt has been dissolved, to the north and east of the study area, averages 200 meters.

The Nippewalla Group, above the Sumner, is represented by the lower formations only, as the hiatus before the Cretaceous stripped away upper Nippewalla as well as the entire Guadalupian Stage in Rice County. Left below the unconformity, red sandstones and shales of the Nippewalla average 50 meters in the area of the Rice County seismic line.

### Rocks of Cretaceous to Quaternary Age

Cretaceous rocks up to 300 meters thick cover the western margin of the Salina Basin, although the rest of the Permian in the basin is covered in part by Tertiary and Quaternary alluvium to depths of up to 50 meters. Quaternary alluvium covers the Rice County seismic section to 5 meters in the Cow Creek floodplain.

## STRUCTURE - Regional and Local

Structural history of Rice County and Kansas requires a general overview of the entire North American midcontinent tectonic sequence of events. Epierogenic movements, as well as periods of no movement, within the State were often related to tectonic events that took place at the boundaries of the North American continent.

During the Middle Proterozoic, at about 1380 Ma (Figure 14), emplacement of southern terrane plutons occurred in the northern terrane in Kansas. 1380 Ma is the age of the southern terrane in Kansas and may be the age of accretion to the northern terrane (Van Schmus and Bickford, 1981). Gravity and aeromagnetic data suggest the delineation of the terrane boundary through Kansas (Yarger and Lam, 1982; Yarger, 1983) (Figures 7 and 10).

During the Late Proterozoic, 1100 Ma, (Figure 15), Keweenawan rifting occurred from the Superior Basin into Kansas along the Central North American Rift System (CNARS) (King and Zeitz, 1979). Related deposition of basalts and of Rice Formation arkosic sandstones filled and surrounded the rift zone (Yarger and Lam, 1982; Yarger, 1983).

During the Cambrian through the Early Ordovician, (Figures 16 and 17), a stable craton with subsiding shelves and aulacogens developed in the midcontinent area (Sloss, 1980). The Cambridge Arch and Central Kansas Uplift emerged as a southeastern extension of the Transcontinental Arch (Merriam, 1963). The Anadarko Basin, considered a Precambrian aulacogen (Brewer, et al., 1983), extends into Kansas as the Southwestern Kansas Basin (Sloss, 1980). The Anadarko Basin at this time was possibly a flexural subsidence (Sloss, 1980),

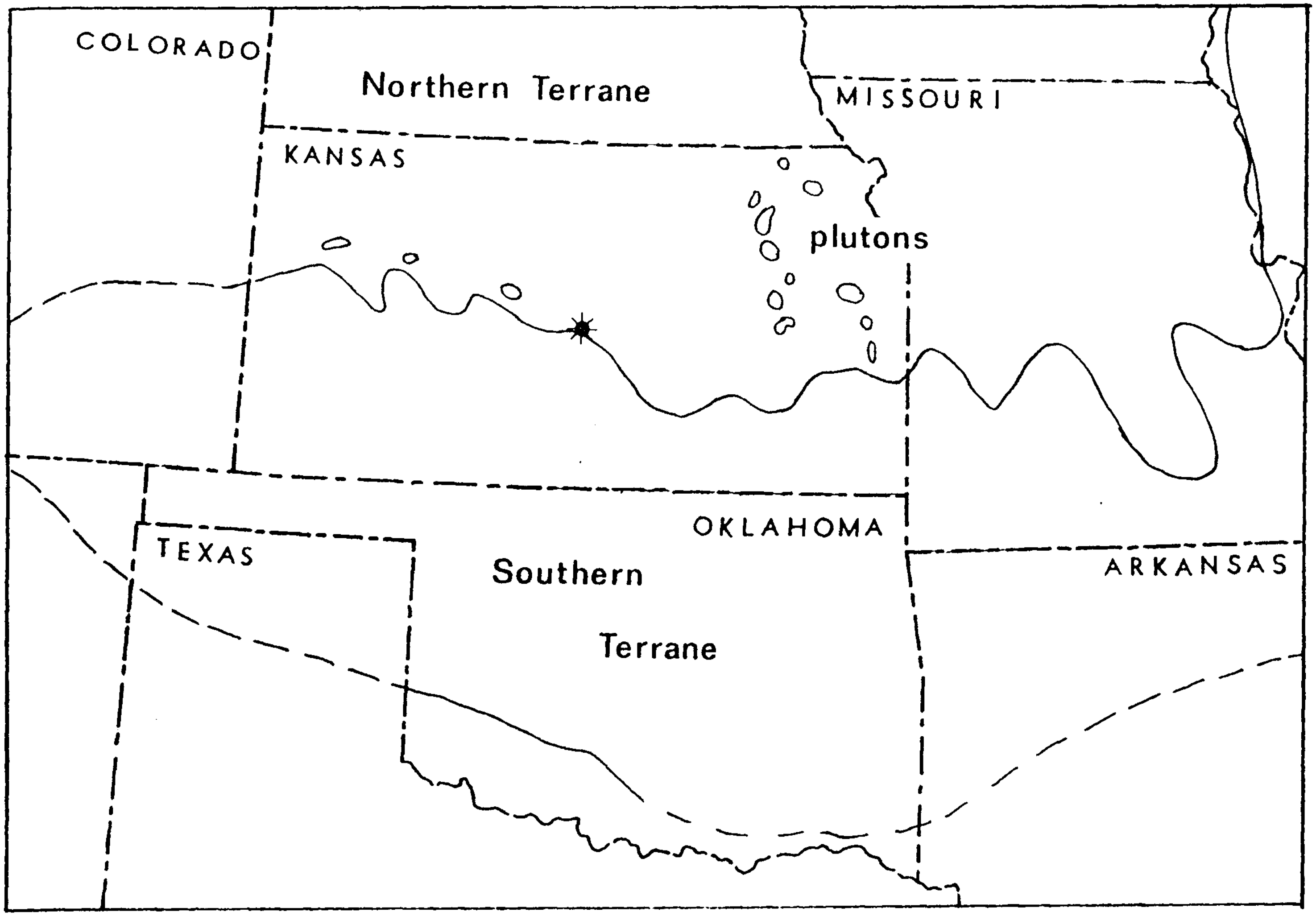


Figure 14 - Structural features of the Midcontinent: Middle Proterozoic (1380 Ma).
✵ = location of Rice County seismic section.

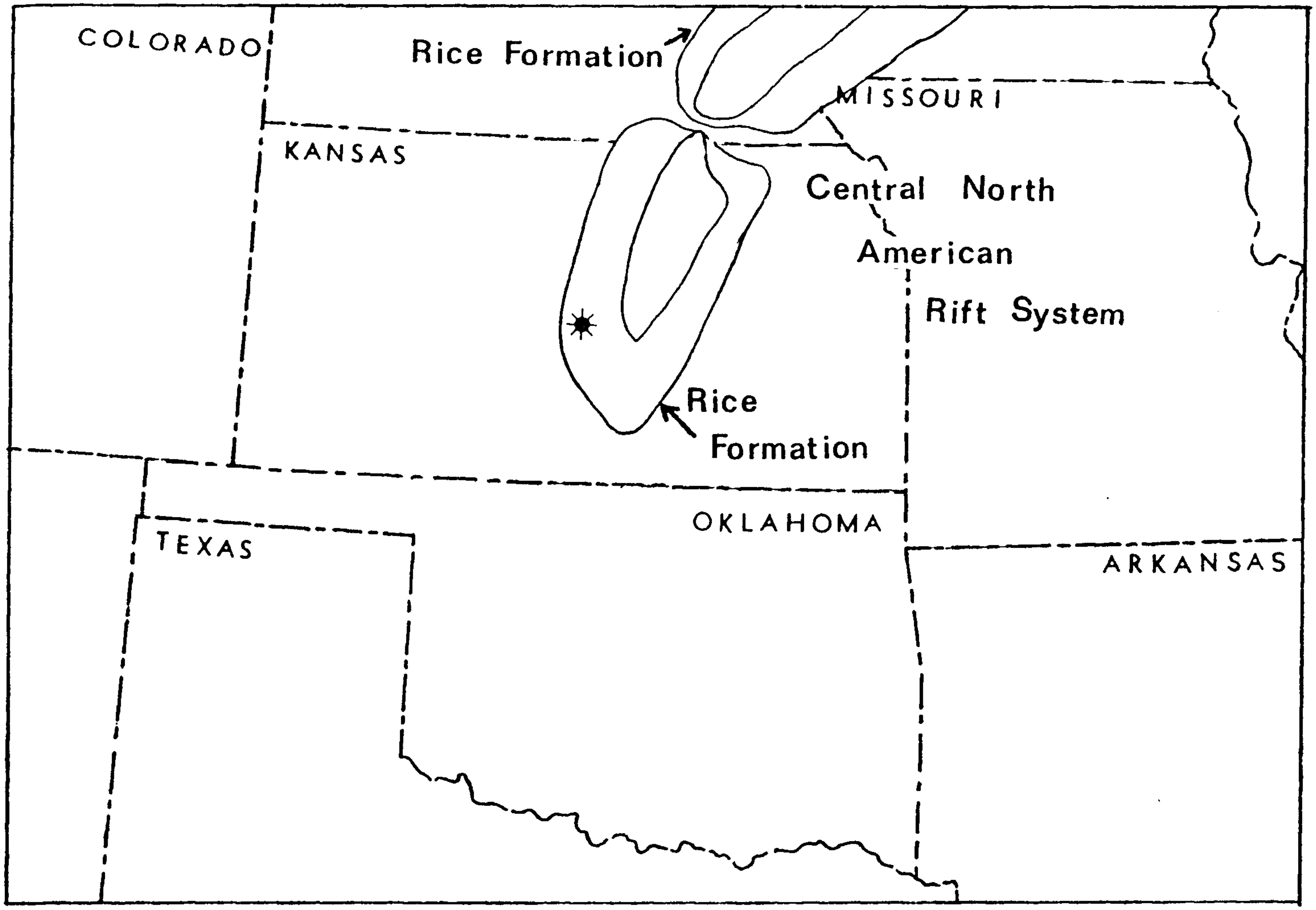


Figure 15 - Structural features of the Midcontinent: Late Proterozoic (1100 Ma).
✷ = location of Rice County seismic section.

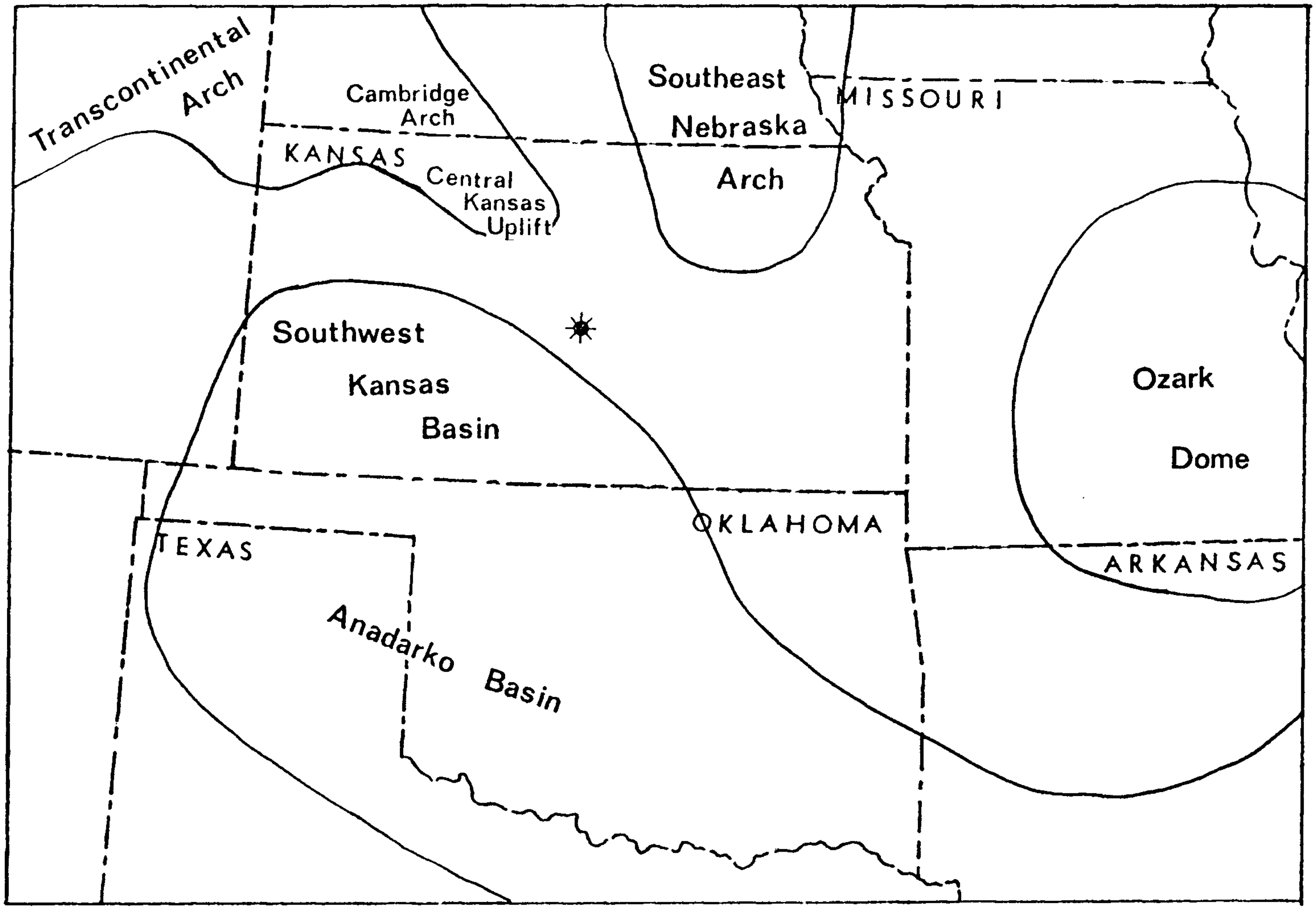


Figure 16 - Structural features of the Midcontinent: Cambrian through Early Ordovician.
✸ = location of Rice County seismic section.

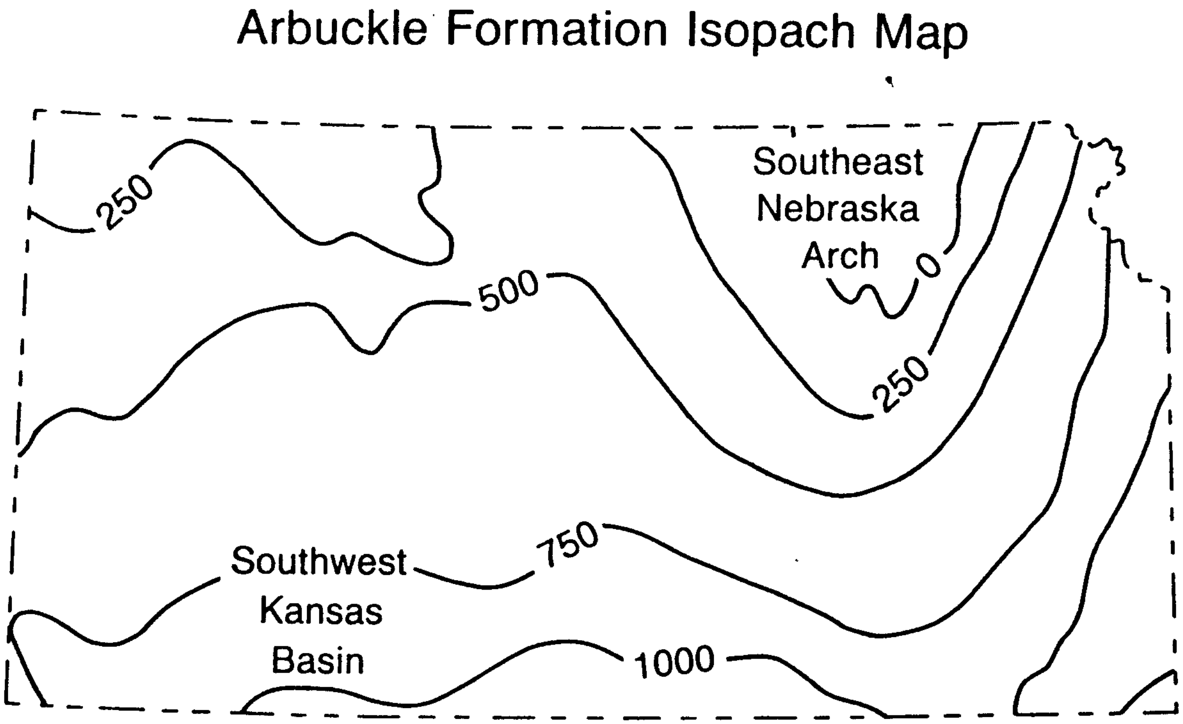


Figure 17 - Isopachous map of top of Precambrian to top of Arbuckle Group (after Merriam, 1963). Countour interval is 250 feet. Structure of Southeastern Nebraska Arch is indicated by thinning in northeast Kansas, and structure of Southwestern Kansas Basin is indicated by thickening in southwestern Kansas.

which might account for contemporaneous uplift of the Southeast Nebraska Arch. Erosion remnants of granite porphyry of Proterozoic age formed the Ozark Dome (Sloss, 1980).

From the Middle Ordovician to the Middle Mississippian (Figures 18A and 19), intracratonic basins and domes developed. The earlier positive features of the Transcontinental Arch and Ozark Dome subsided, and the Anadarko Basin continued to subside (Sloss, 1980). The Chautauqua Arch was an extension of the Ozark Dome during the Middle to Late Ordovician (Jewett, 1951). Episodic uplift from the Middle Ordovician through the Middle Mississippian extended the area of the Central Kansas Uplift southeastward (Lee, 1956). Subsidence of the Southeast Nebraska Arch into the North Kansas Basin started in Middle Ordovician time. The Ozark Dome subsided to form the Ozark Basin during Devonian time. The area was again uplifted in the Mississippian as the Ozark Uplift (Lee, 1956).

During the Late Mississippian through the Early Pennsylvanian (Figures 18B and 20), collision of South America-Africa into the southern margin of North America produced epeirogenic uplift in Kansas of the Central Kansas Uplift and Nemaha Anticline, and associated subsidence of the Salina and Forest City Basins. Related

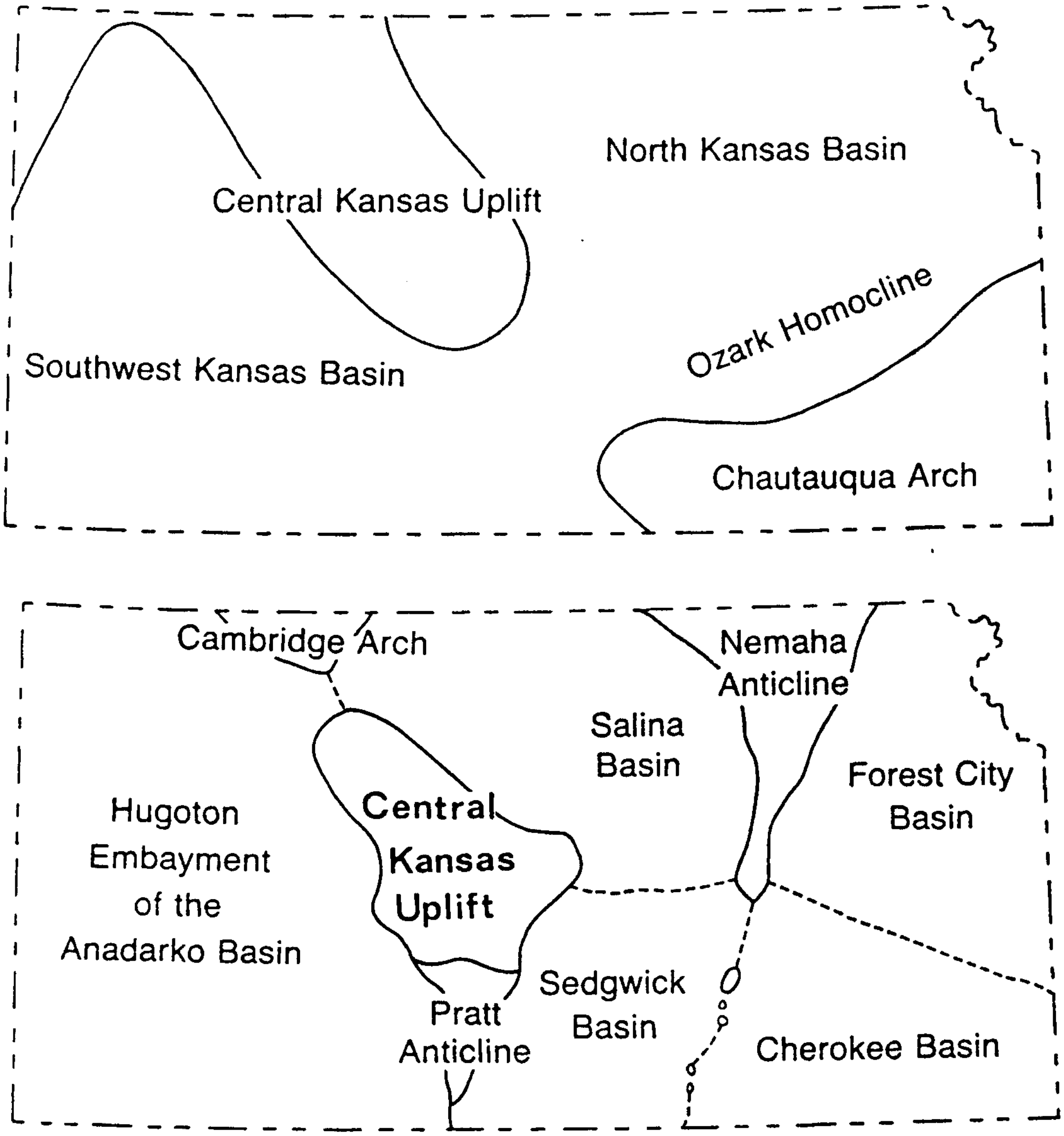


Figure 18 - Major structural features of Kansas (after Merriam, 1963). A) pre-Mississippian features indicate subsidence of Southeastern Nebraska Arch into North Kansas Basin and initial uplift of joint Central Kansas Uplift-Cambridge Arch; B) post-Mississippian features indicate emergence of Nemaha Anticline and Salina and Forest City Basins and further uplift of Central Kansas Uplift.

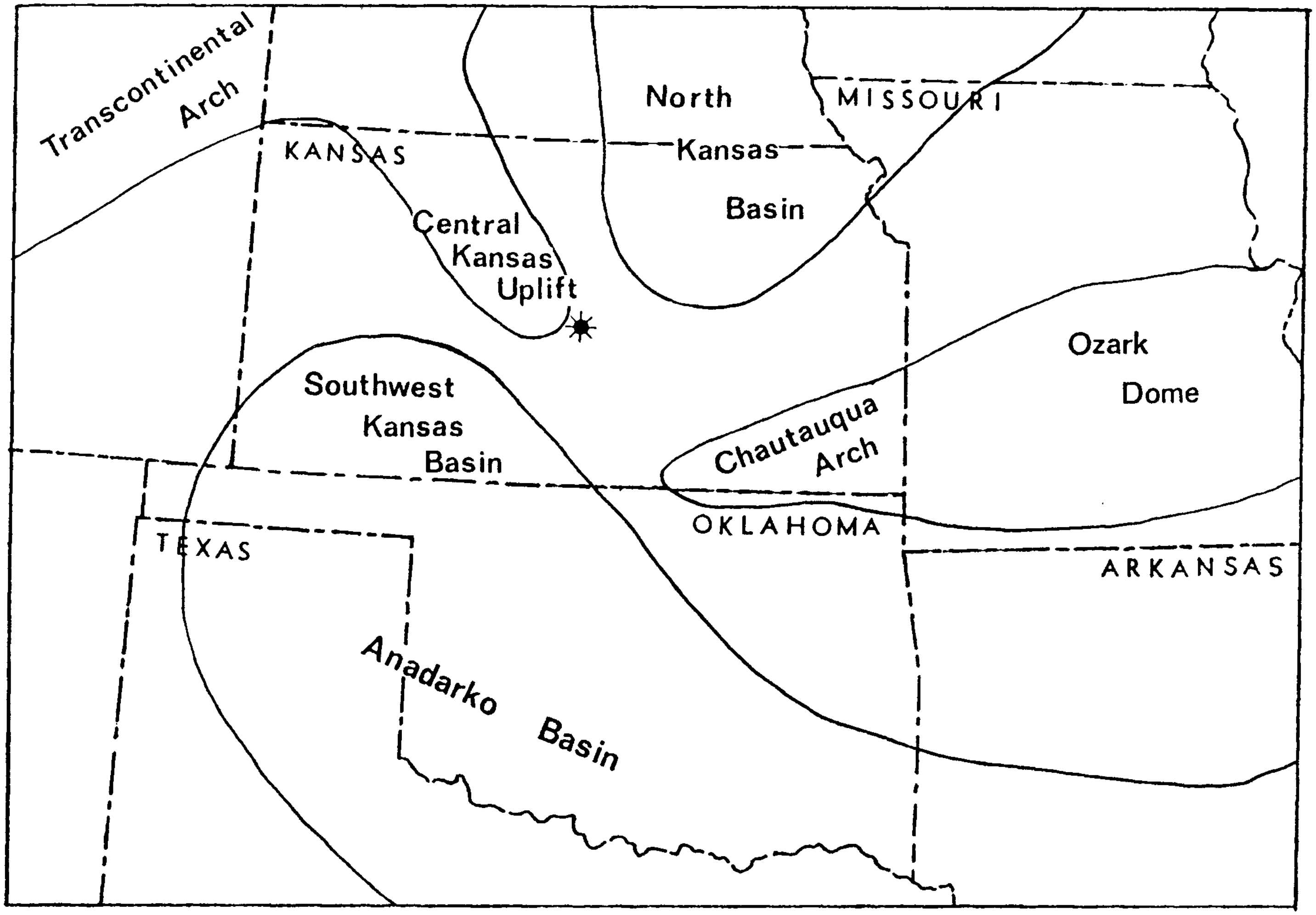


Figure 19 - Structural features of the Midcontinent: Middle Ordovician through Middle Mississippian.
✸ = location of Rice County seismic section.

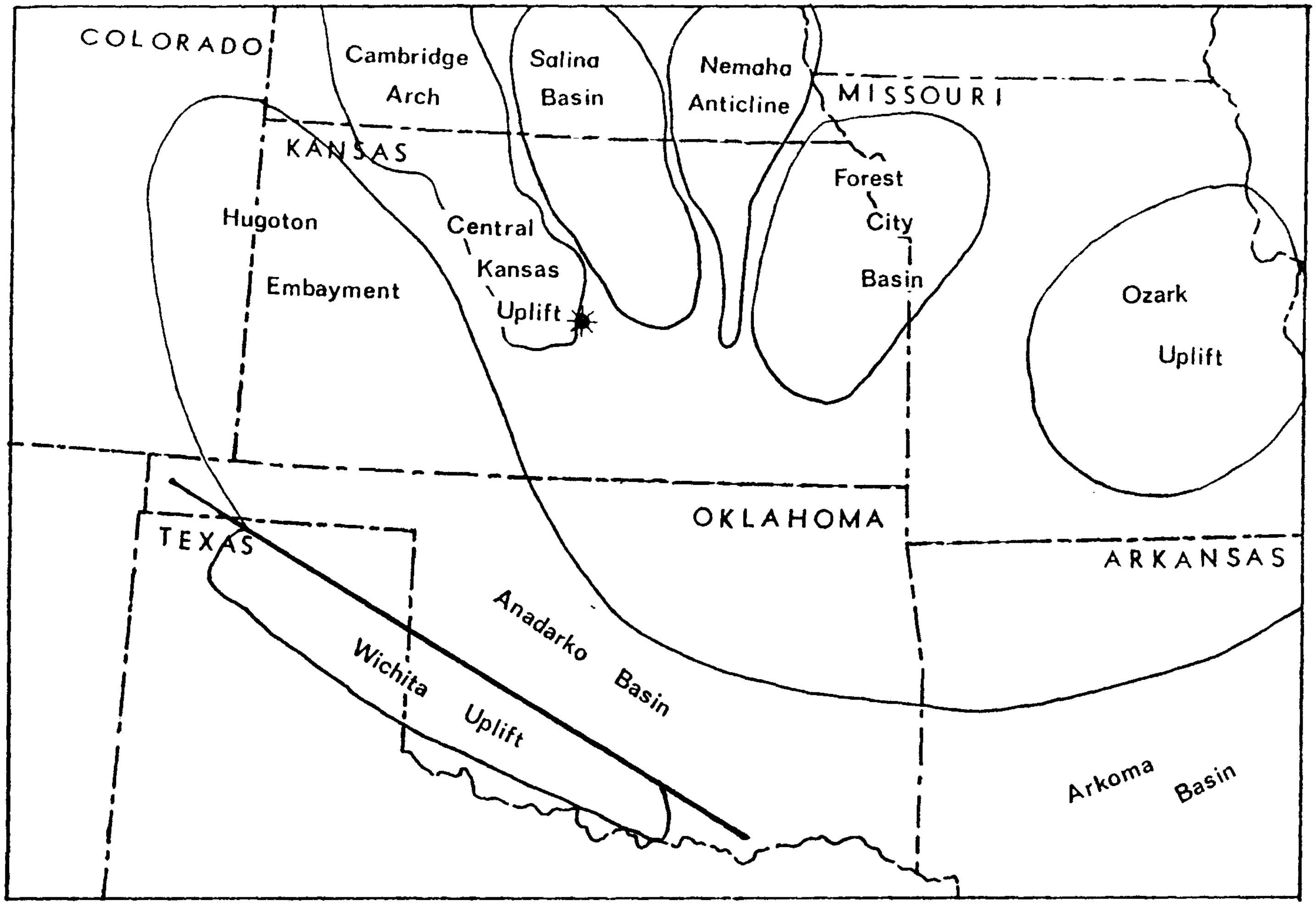


Figure 20 - Structural features of the Midcontinent: Late Mississippian to Early Pennsylvanian.
✱ = location of Rice County seismic section.
╲ = high angle fault zone

orogenic activity along the Ouachita fold and thrust belt began in Late Mississippian and reached a climax in Early Pennsylvanian (late Atokan) or Middle Pennsylvanian (early Desmoinesian) time. Rapid subsidence of the Anadarko Basin and uplift along the nearby Wichita Uplift were caused by shearing along the earlier aulacogenic fault zone. Continental margin subsidence produced the Arkoma Basin and its extension into Texas, the Fort Worth Basin (Kluth and Coney, 1981).

From the Middle Pennsylvanian through the Early Permian, (Figure 21), southwestward migration of orogenic activity in response to the collision of South America-Africa into North America resulted in continued thrusting in the Ouachita belt and initial thrusting in the Marathon fold and thrust belt in southwestern Texas. During the Middle Pennsylvanian activity slowed in Kansas as upthrusting of the Ancestral Rocky Mountains developed rapidly. From Late Pennsylvanian to Early Permian, movement slowed along the Ancestral Rocky Mountains and Ouachita fold and thrust belt (Kluth and Coney, 1981). Movement along the Central Kansas Uplift and Nemaha Anticline ceased by Late Pennsylvanian, and regional tilting into the Anadarko Basin began (Lee, 1956). Development of the Wolfcampian Hugoton Embayment, as a northward extension of the Anadarko

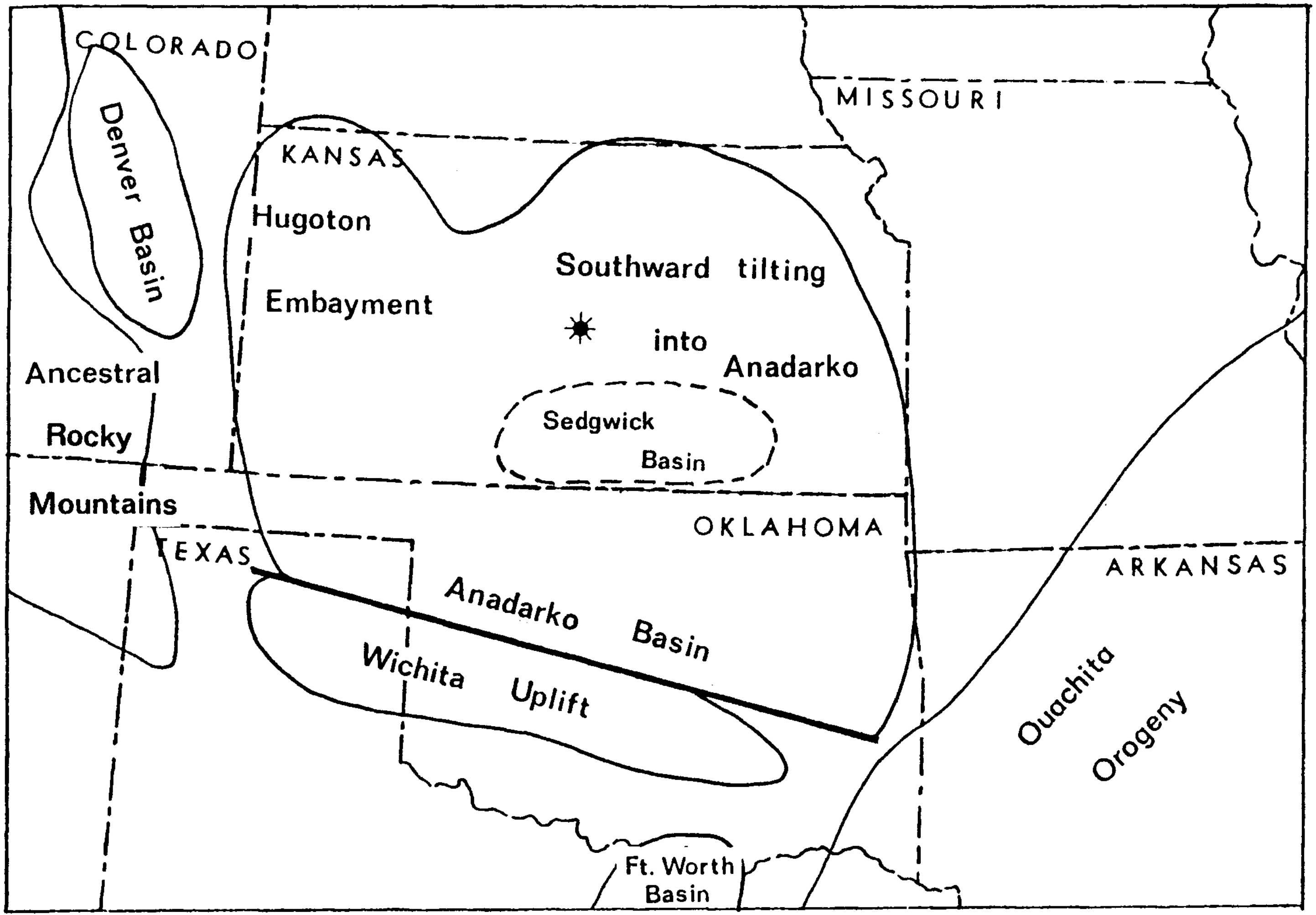


Figure 21 - Structural features of the Midcontinent: Middle Pennsylvanian through Early Permian.
✱ = location of Rice County seismic section.
╲ = high angle fault zone.

Basin (Rascoe and Adler, 1983) caused regional tilting of Kansas strata to the west (Merriam, 1963; Lee, 1956).

During the Cretaceous, (Figure 22), the Denver Basin, a foreland basin formed during the Sevier Orogeny, caused regional tilting of Kansas strata northwestward (Merriam, 1963; Lee, 1956).

## SUMMARY - LOCAL GEOLOGY

The area of the Rice County seismic line contains complex flank structure between the Central Kansas Uplift and the Salina Basin (Figure 2). Superposed upon this, the local geology reveals trends similar to those regional. Formation thicknesses are generally intermediate of those reported for the Central Kansas Uplift and the Salina Basin, although unconformable basal conglomerates, which are locally flank deposits, are thicker, as expected. The Chattanooga Misener and the Pennsylvanian basal conglomerate, in particular, are thick flank deposits, thinning to featheredge in the Salina Basin and terminating due to nondeposition against the Central Kansas Uplift.

Although no wells along the reflection profile penetrate the Precambrian, aeromagnetic and gravity data suggest the presence of shallow gradational arkosic sandstones of the Rice Formation under the eastern one-

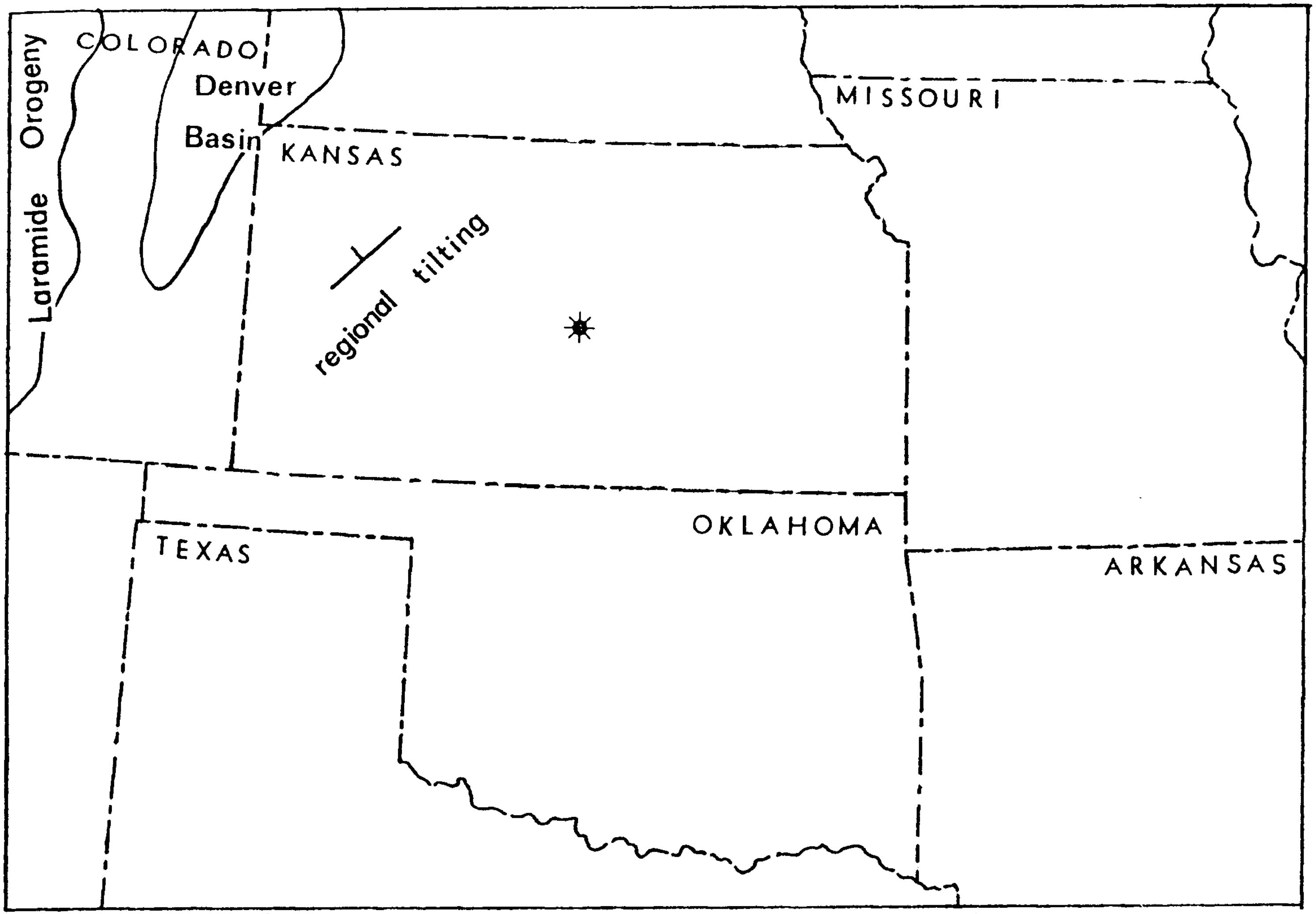


Figure 22 - Structural features of the Midcontinent: Cretaceous.
✷ = location of Rice County seismic section.

half of the seismic line (Figures 9 and 13). A magnetic low, indicating a much deeper, and less magnetic source in the Precambrian underlies the entire line (Figure 10). This material is considered a transition zone between the rocks of the northern and southern terranes of Van Schmus and Bickford (1981) (Yarger, 1983) and a deeper seismic investigation may give a greater understanding of the Precambrian mechanics involved in this type of suture zone.

Through Ordovician and Devonian time uplift of the Central Kansas Uplift, and erosion of the McPherson Valley, resulted in erosion of the Hunton Group. The crest of the Central Kansas Uplift begins just west of the cross-section in Figure 23, and the McPherson Valley begins east of the unnamed anticline located between CDP's 600 and 700 in Figure 23. From the pre-Chattanooga subcrop map (Figure 24) a few of the series of en echelon anticlines parallel to the Central Kansas Uplift expose the Viola beneath the Chattanooga. Further to the west Maquoketa Shale crops out against the Central Kansas Uplift. In the extreme eastern part of the map the Viola is also exposed due to erosion of the McPherson Valley (Lee, 1956).

Accelerated tectonic activity in Mississippian time produced continued folding on the unnamed en echelon

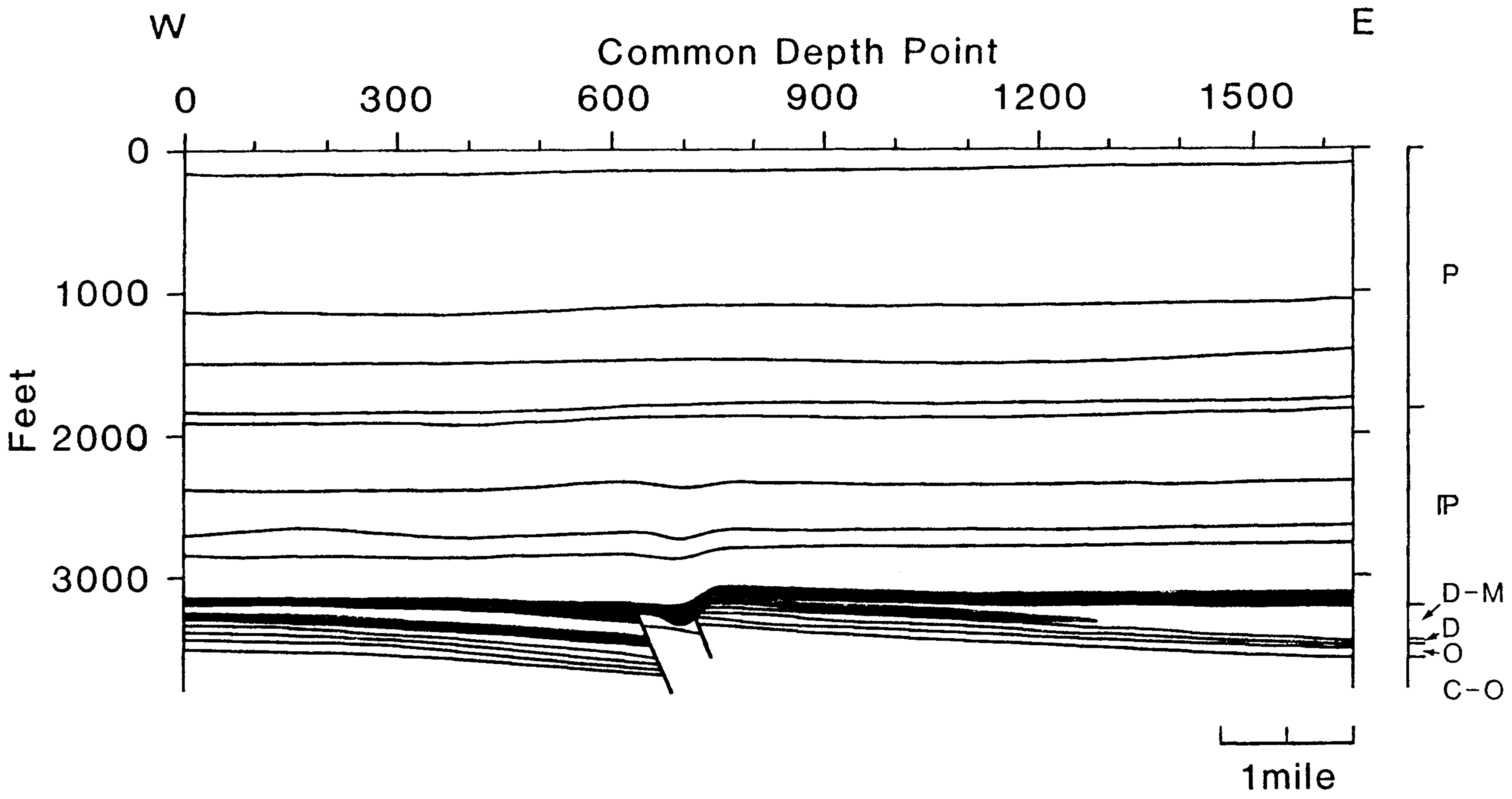


Figure 23 - Geologic cross-section along Rice County seismic section. Wells used are shown in Figure 4. Unnamed anticline is shown as major structural feature of Early Paleozoic. Layers in black are Pennsylvanian Basal Conglomerate above and Chattanooga Limestone Member below.

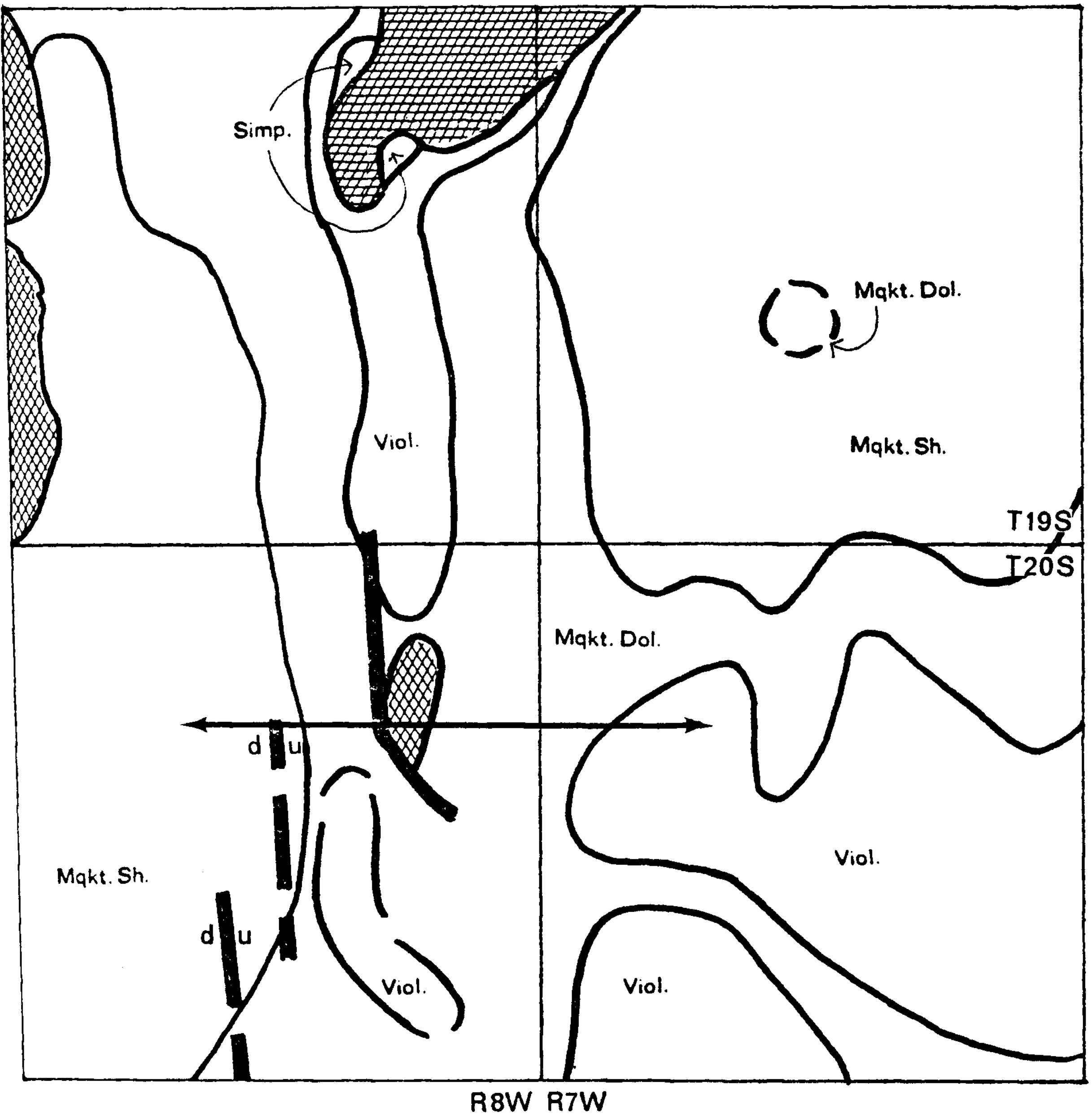


Figure 24 - Subcrop map of pre-Chattanooga unconformity (after Newell, 1984). Erosion of Chattanooga valley in east half, uplift of unnamed anticline to expose Viola, and nondeposition of Chattanooga on Central Kansas Uplift are illustrated. Location of the seismic line is shown in T20S. No deposition of Chattanooga Shale in hachured area.

anticlines. In the subcrop map of the pre-Pennsylvanian unconformity (Figures 25 and 26) a regional outcrop pattern of progressively older strata from east to west shows the extent of the flank of the Central Kansas Uplift.

A closer look at the unnamed anticline (Figure 27) indicates variable dip to the east of less than two degrees of all beds below the Pennsylvanian basal conglomerate. Reverse faulting on the west side of the anticline (Dan Rush, pers. comm., 1984) forms a cuesta. The nose was eroded along the fault plane into the Simpson to form a river valley. During the Middle Pennsylvanian folding had ceased and the valley was filled with Pennsylvanian basal conglomerate. Thinning above the nose is evident from Middle through Late Pennsylvanian time and indicates differential compaction and the probable existence of a river valley from Middle to Late Pennsylvanian time.

Also shown on the pre-Pennsylvanian subcrop map (Figure 26), the Chattanooga limestone unit crops out onto the Central Kansas Uplift and reveals a pattern of folding parallel to the Central Kansas Uplift. An approximate location of where the Chattanooga limestone ceases to exist to the east below the pre-Pennsylvanian unconformity is shown. The exact original extent of

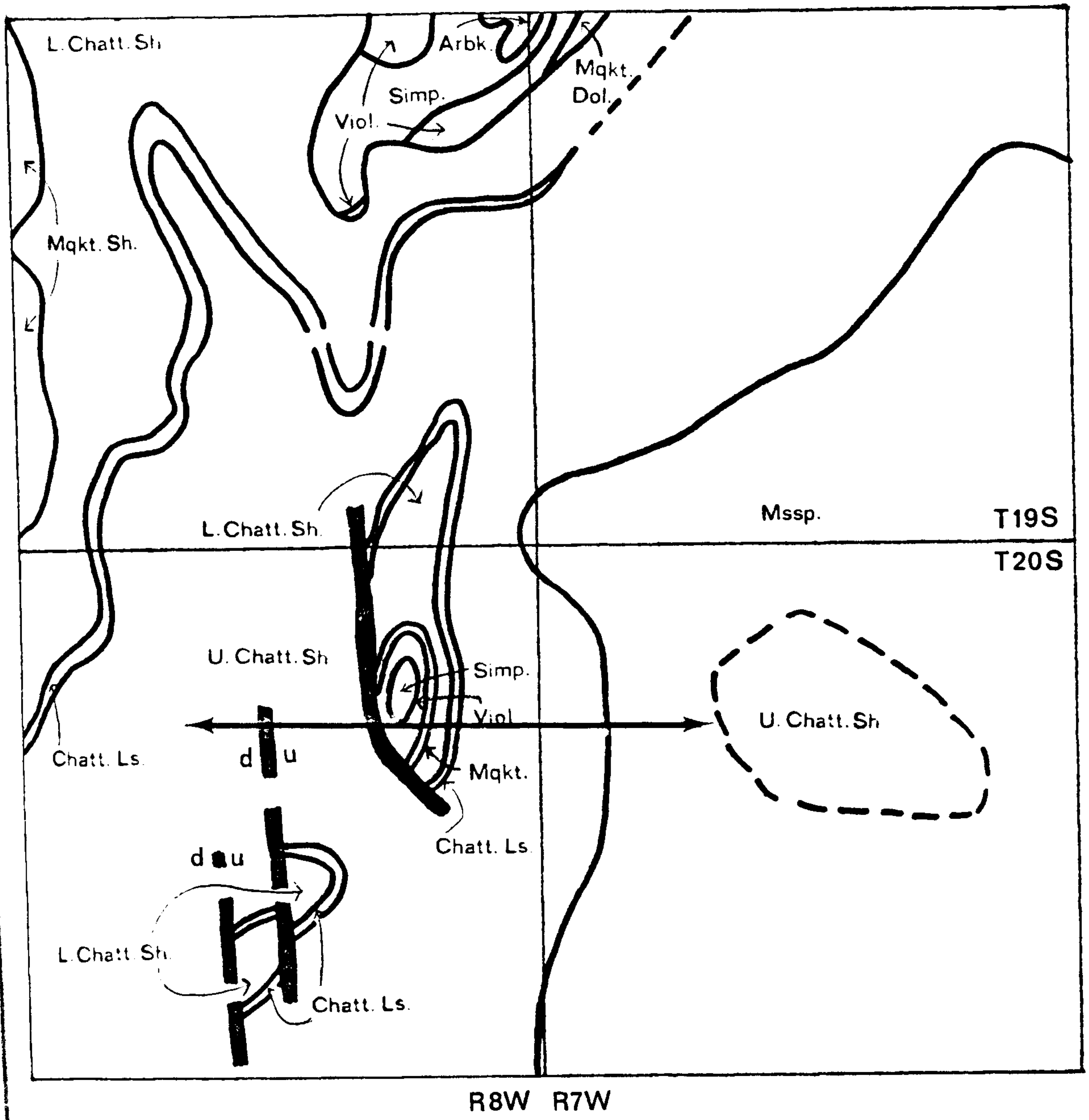


Figure 25 - Subcrop map of pre-Pennsylvanian unconformity (after Newell, 1984). Progressively older formations crop out from east to west indicating extent of flank of Central Kansas Uplift. Folding in flank structure is shown of en echelon series of three anticlines. Rice County seismic section crosses the middle anticline.

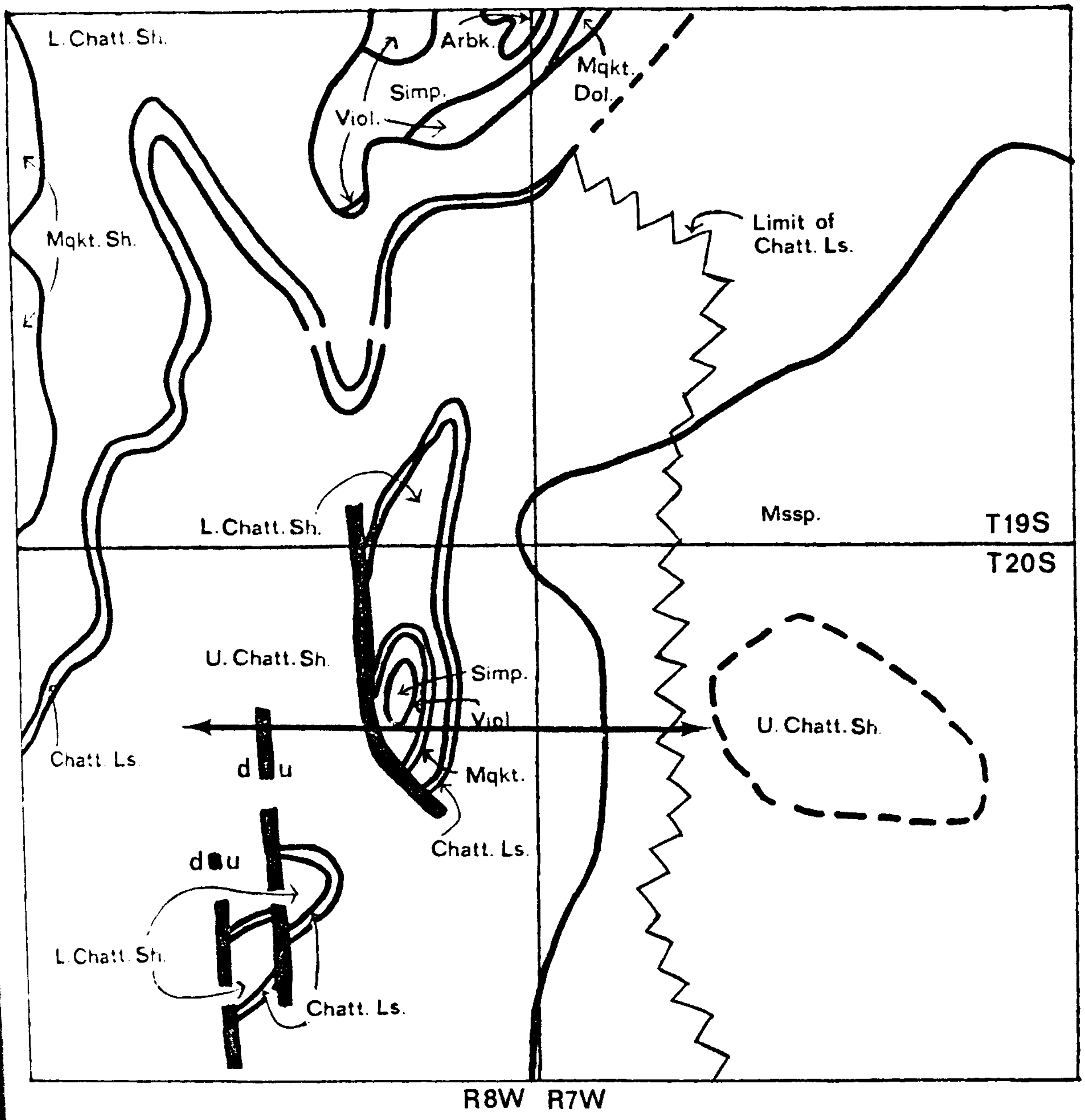


Figure 26 - Subcrop map of pre-Pennsylvanian unconformity (after Newell, 1984). Same as Figure 25 with addition of zigzag line to indicate possible eastward extent of Chattanooga limestone unit.

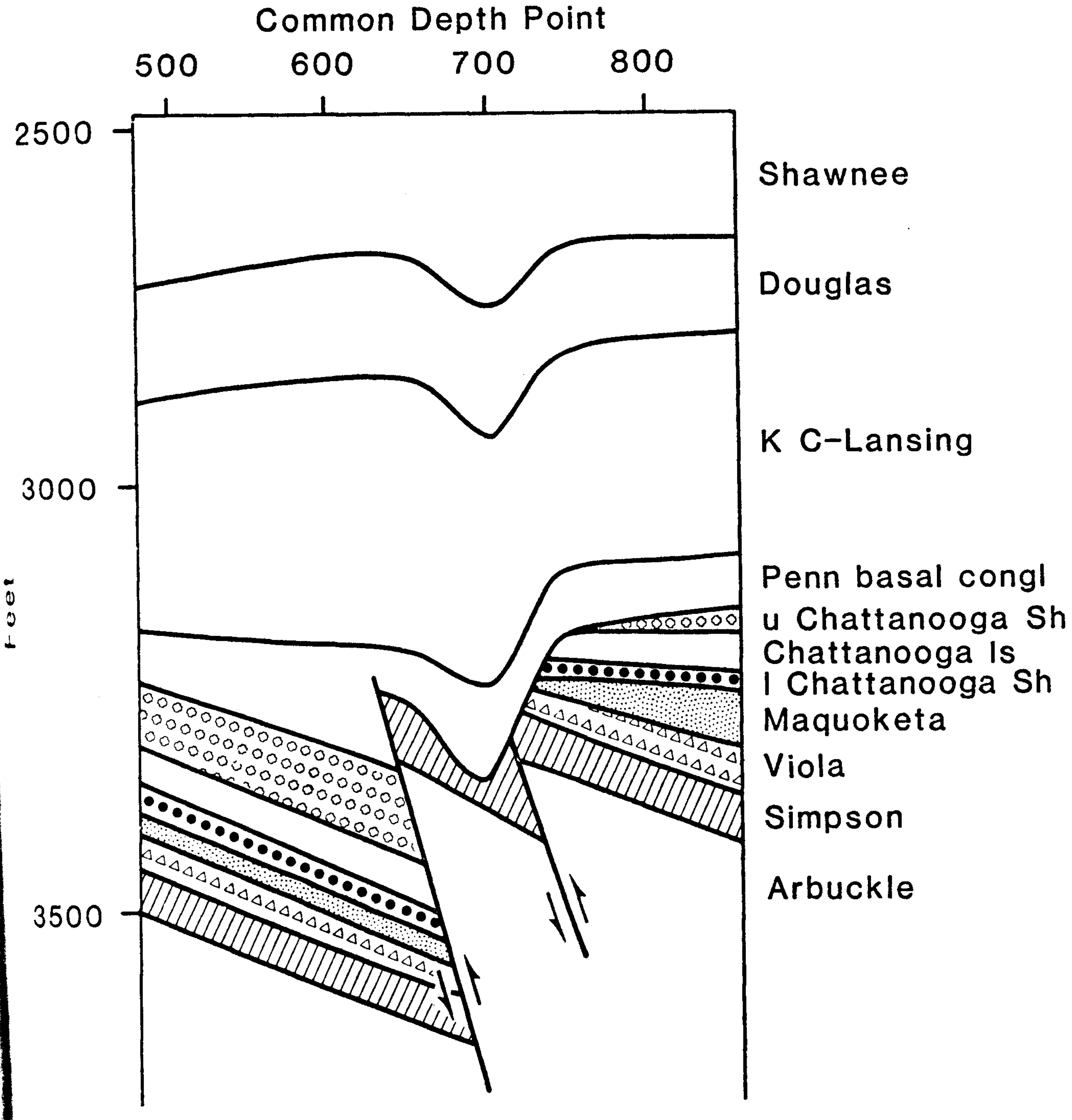


Figure 27 - Geologic cross-section along part of Rice County seismic section showing detail of unnamed anticline. Five times vertical exaggeration.

this limestone is not known, but it is considered to have been eroded both to the west as it crops out against the Central Kansas Uplift, and to the east where it was replaced by siltstones during deposition of the Upper Chattanooga Shale (K.D. Newell, pers. comm., 1984).

From Upper Pennsylvanian through the Quaternary local structural activity is absent. Cyclic deposition dominates local as well as statewide geology during the Pennsylvanian and Permian. Regional tilting, first to the south in response to a combination of southeastward and southwestward subsidence during Pennsylvanian and Lower Permian time, and then to the west and north toward the Hugoton and Denver Basins during Permian through Cretaceous time, is indicated by thickening of beds. Regional and local sedimentary deposition are most evident as cyclothems of transgressive marine limestone and shale deposits followed by regressive limestone, lagoonal shale and channel sand deposits. Facies are generally consistent throughout the area.

# RICE COUNTY REFLECTION SEISMIC PROFILE

## PROCESSING

Initial processing consisted of the following sequence of steps. All processing of the data was conducted on the Kansas Geological Survey's Data General MV8000 computer. The software used was predominantly Seismic Processing Executive (SPEX) from Sytech, Inc., Houston, TX, supplemented by programs of the author (Appendix B), T. Ready (1984), and R. Knapp of the Kansas Geological Survey. Although seismic data is unique to the area of acquisition, all profiles follow the same initial processing sequence, and therefore brevity in its description is justified.

1) Reformat of raw, demultiplexed data to standard reel and trace header format.

2) Initial edit of bad field records and traces.

3) Data entry of line geometries and sorting from shot-gathered to CDP-gathered (common depth point) traces.

4) Secondary edit of CDP gathers.

5) Initial elevation statics corrections to "flatten" surface topography to 504 meters (1654 feet) above sea level.

6) Initial velocity analysis using CDP traces stacked at constant velocity to determine stacking velocities.

After applying the initial velocity functions of step 6, a brute stack (Figure 28) is produced, and the seismic processor and interpreter can evaluate for the first time the potentials and problems of the seismic section. The brute stack and other similar figures are scaled to one hundred CDP traces per inch, producing a "squash plot". The ratio of horizontal to vertical distance gives an approximate vertical exaggeration of five. This type of plot is most useful for structural interpretation, and is, for this particular line, also convenient for page-size reduction. The traditional "wiggle traces" have been removed and variable area shading alone has been used with white indicating a negative trough.

At this point the Rice County line shows great potential with numerous continuous and discontinuous reflectors throughout. Most importantly the unnamed anticline is easily seen as a gradual dipping and thinning of reflectors over a wide expanse to the left of center between .6 and .8 seconds.

Many problems are also evident. The velocity of the weathered layer used to correct for elevation statics has produced an undulation in all reflections east

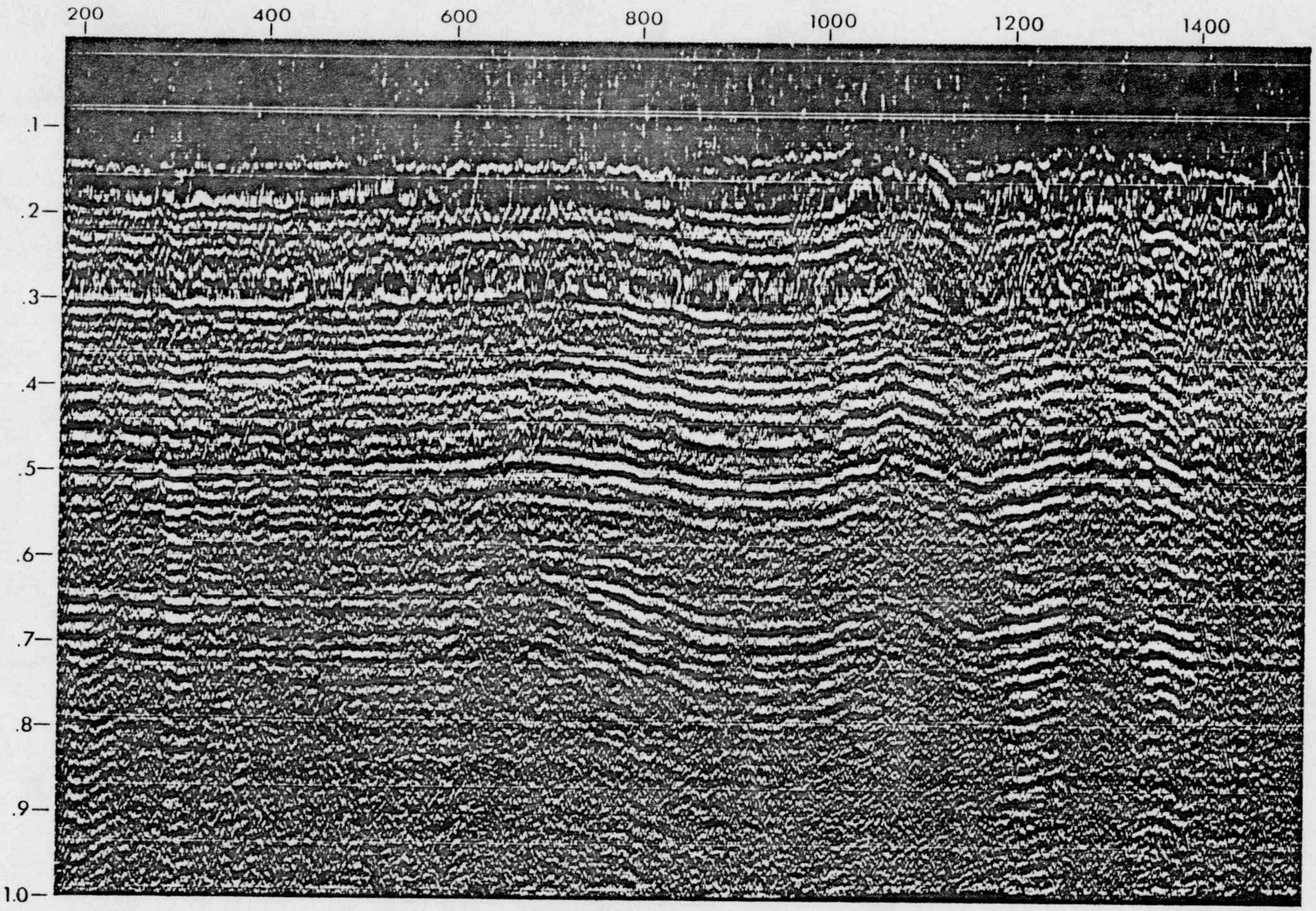
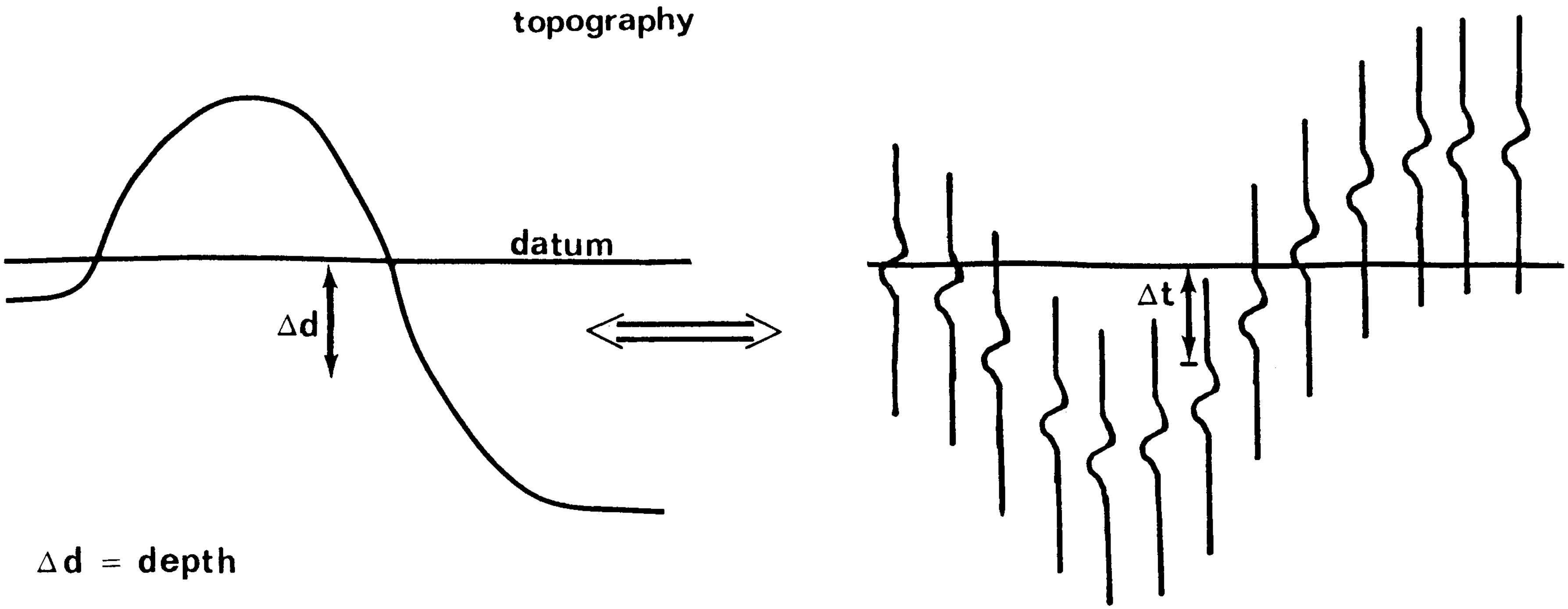


Figure 28 - Brute stack of Rice County seismic section using one stacking velocity function and elevation statics corrections at 2000 ft/sec. One mile = 192 CDP.

of center. The velocity used (2,743 m/sec, 9,000 ft/sec) is much too fast and is not producing a large enough correction, however determination of the correct value is difficult. Because of the large distance between the shot point and the closest geophone, the direct arrival of energy through the weathered layer is masked in the field records by faster-arriving refracted and reflected waves, and its velocity cannot be calculated. Instead a rough estimate of 610 m/sec (2,000 ft/sec) is obtained by dividing the time shift needed at several points in the data into the depth reduction determined from the elevation survey (Figure 29).

Another obvious problem is the fading out and replacement by noise of reflectors in large blocks of CDP traces. Lateral changes in velocity, problems with statics and the weathered layer, diffractions, or random and coherent noise may be held accountable. Improvements in stacking velocity functions (Appendix A), trace editing, and further statics corrections helped to resolve many areas. However, it is the opinion of the author that although great care was taken in all acquisition components to obtain the optimum resu,ts, overheating of the field computer system resulted in dileterious system noise that secondary and tertiary trace editing could not remove from CDP's 1130-1200 and 1400-1517. Part of the noise could be attributed to



$\Delta d$ = depth

$\Delta t$ = two-way travel time

$$\text{Weathered zone velocity} = \frac{2 \times \Delta d}{\Delta t}$$

Figure 29 - Method used for determining velocity of weathered zone. Velocity is calculated from the elevation measurements used to flatten the topography and the corresponding amount of time needed to flatten the reflection (i.e., distance divided by time equals velocity).

weathered layer problems from the small hill that can be seen in the statics shifts (Figure 30). However, the hill consists of massive red and grey shales of the Nippewalla Group, and reflections over portions of the hill are noise-free for acquisition conducted when the system was apparently functioning properly.

With the secondary processing applied, the reflection profile reveals several new and interesting features (Figure 30). The unnamed anticline displays asymmetry with beds dipping and pinching out on the east flank (CDP's 700 to 750, .620 to .650 ms). The beds abruptly terminate on the crest (CDP 675 to 680, .620 ms); caused possibly by a series of interfering, fault-related diffractions. To the the west the expression of a large fault with sharply dipping beds is evident (CDP's 580 to 625, .620 to .700 ms). Directly above the anticline a single discontinuous flat layer under several domed layers yields an interesting interpretation (CDP's 655 to 800, .540 ms) of a possible carbonate mound and subsequent draping of sediments. Further to the east many of the reflectors are uplifted, dipping west in an apparent recent thrust fault (CDP's 1005 to 1075, .250 to .800 ms).

Up to this point all processing and interpretation had been conducted without reference to detailed geological data from well logs and cores. The cross-section

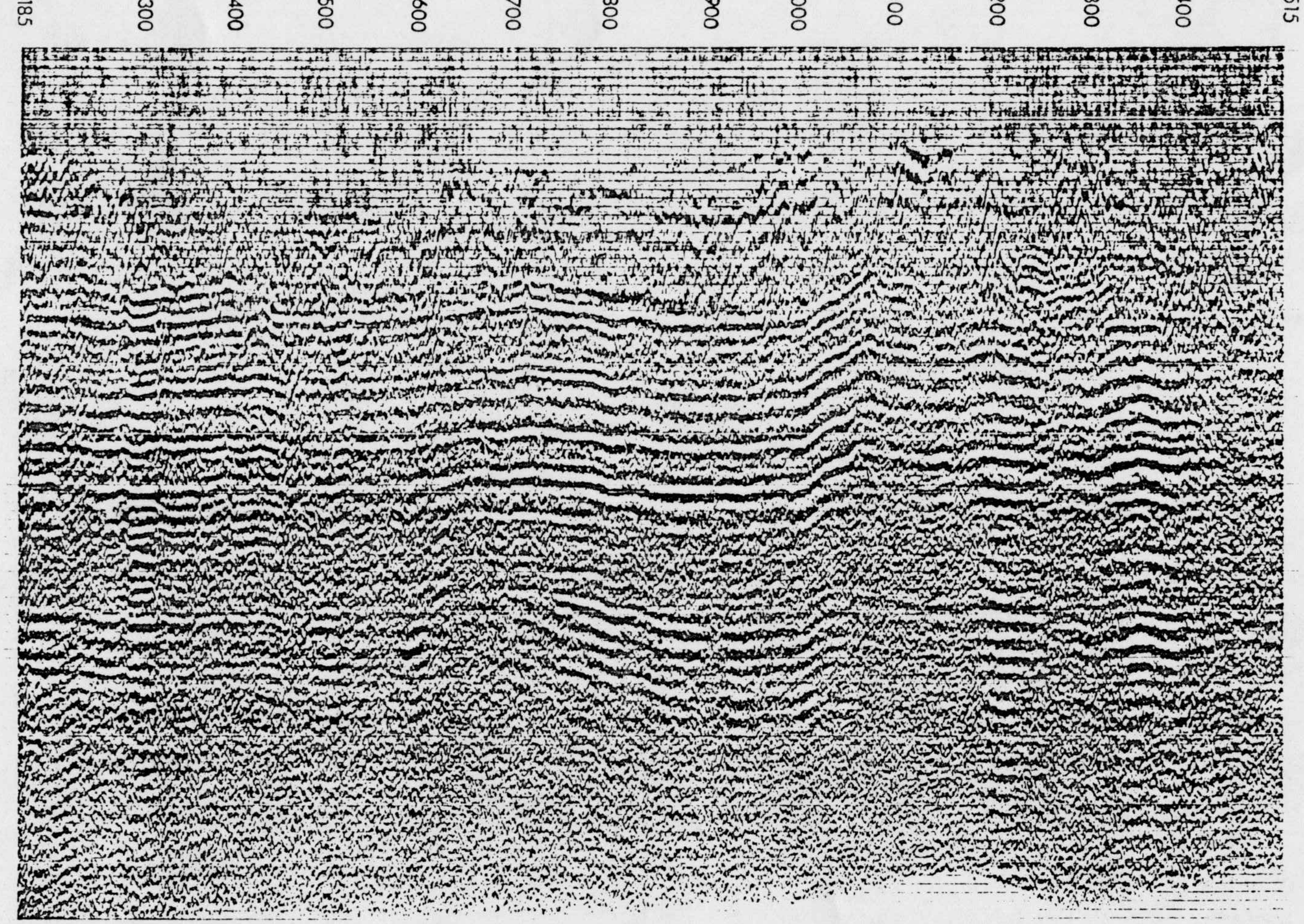


Figure 30 - Processed stack of Rice County seismic section after extensive velocity analysis and elevation statics corrections at 2,000 ft/sec. Undulating area of no trace information below .9 sec indicates topography across the seismic line. One mile = 192 CDP.

of Figure 23 was subsequently made from sonic, gamma ray, and neutron logs close to the seismic line (see Figure 4 for locations), and the author was properly startled by the realization that the dome above the unnamed anticline was actually a basin, and that seismic evidence for a recent west-dipping thrust fault was misleading. Pennsylvanian and Permian beds show minimal deviation from horizontal (Figure 23). The source of error was still in the statics; this time apparently caused by lateral velocity changes within the Permian redbeds. Lateral variations within a few hundred meters are typical for the Permian shales and siltstones, and are primarily due to zones of oxidation (Berendsen and Lambert, 1981). To correct the statics problem, shifts of individual CDP traces were measured and applied to several Upper Pennsylvanian strata to reflect bed attitude as determined in well log data (Figures 31 and 32). Each trace was shifted to correctly align the Upper Pennsylvanian reflectors according to the geologic cross-section of Figure 23.

Although several attempts and subsequent failures at further data enhancement were made, this series of static shifts represents the final stage of processing and best possible data resolution for seismic interpretation.

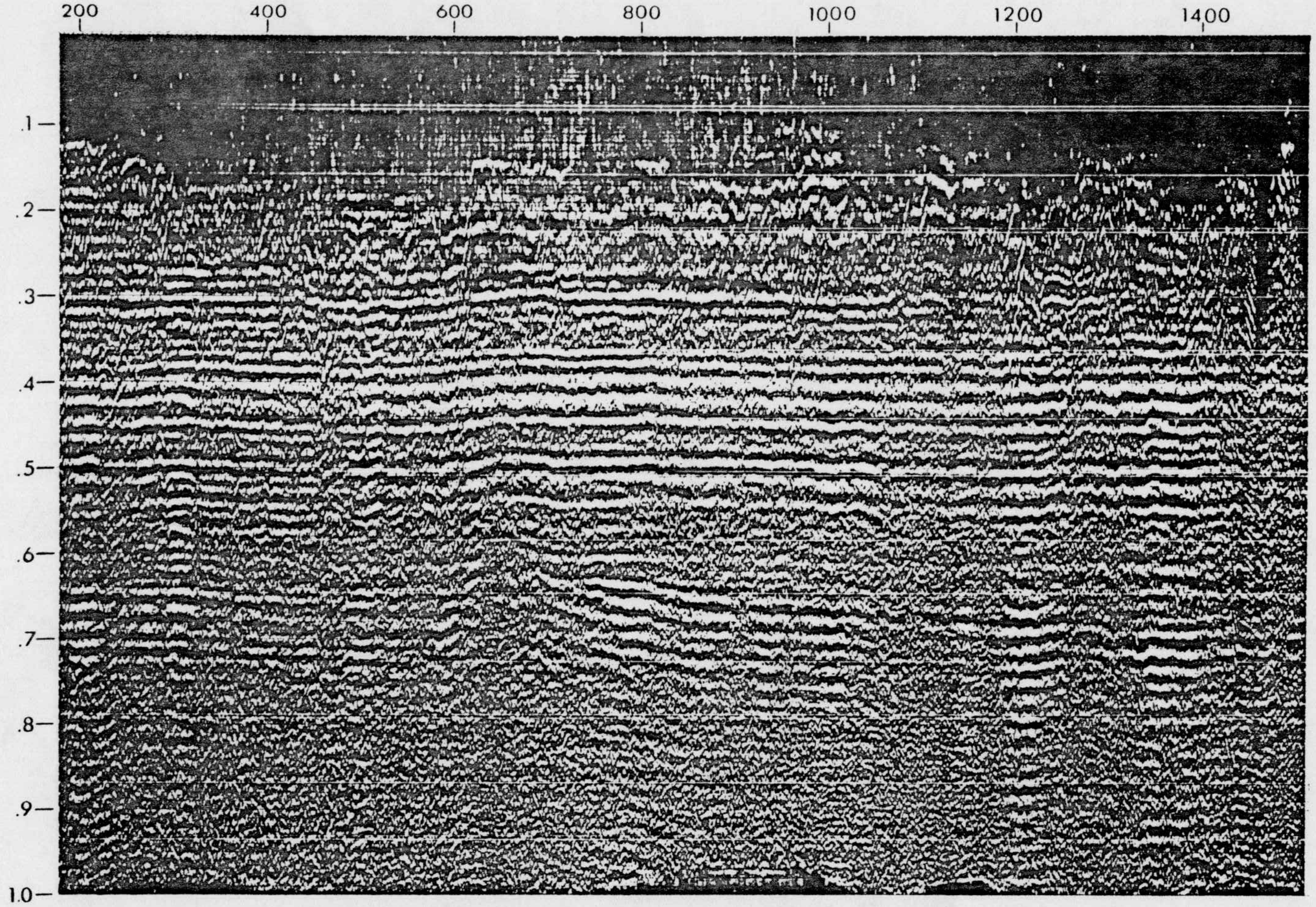


Figure 31 - Processed stack of Rice County seismic section with same processing as Figure 30 and additional "flattening" to correspond to attitude of Upper Pennsylvanian strata. One mile = 192 CDP.

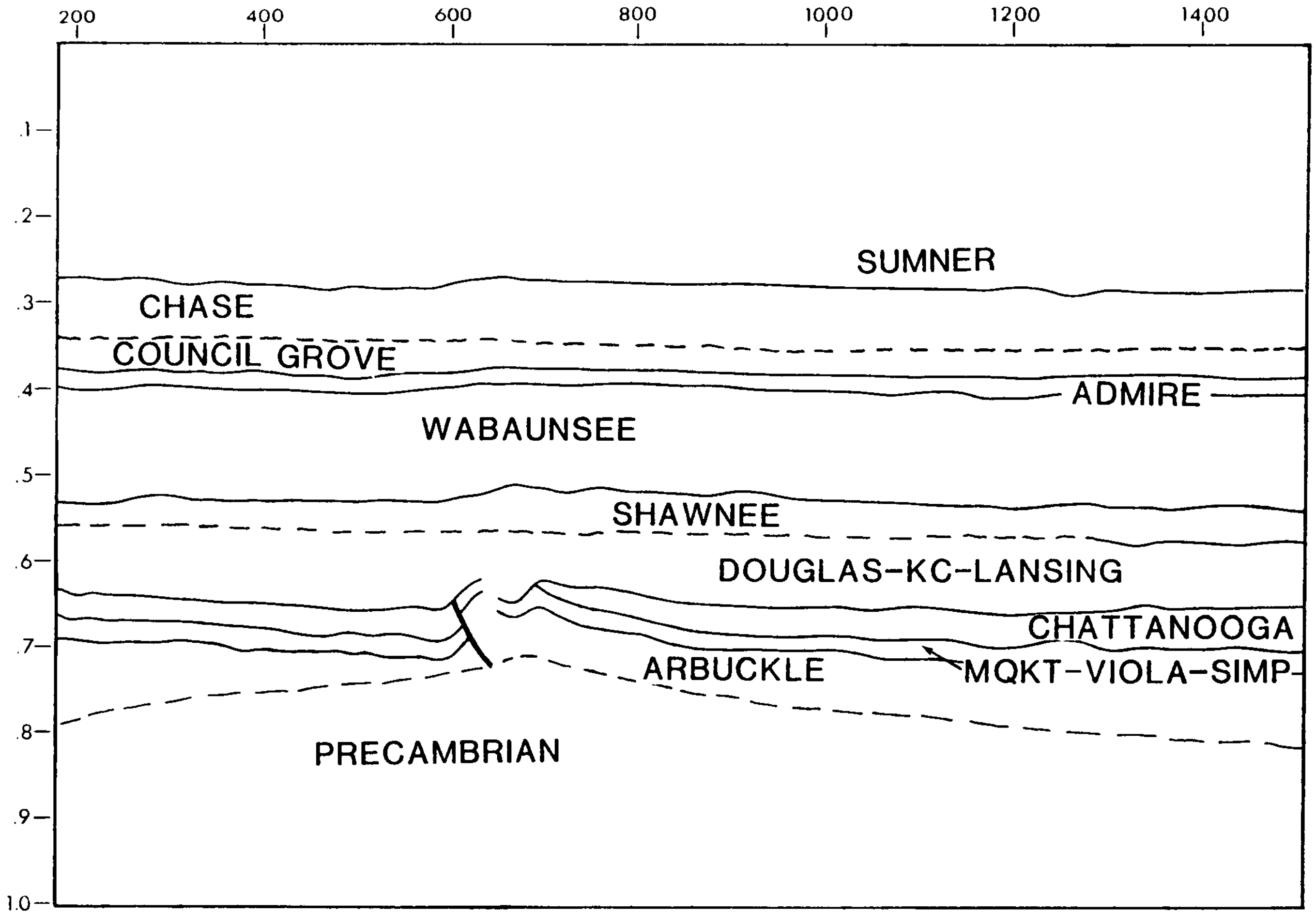


Figure 32 - Interpreted Rice County seismic section. Processing same as Figure 31. Note depth scale is not linear. One mile = 192 CDP.

# SEISMIC STRATIGRAPHY

Seismic stratigraphy is the study and analysis of lithologic changes that are seismically expressed. Seismic stratigraphic analysis of a seismic sequence, a subset of reflections within a seismic section, and analysis of seismic facies reveal unique patterns yielding information on bed attitude, sedimentary structure, direction of sediment transport, facies, depositional environment, and sequence of geologic events. Seismic stratigraphic analysis of reflection character examines the effect of changes in rock and interstitial fluid type, porosity and pressure on density and seismic velocity, which in turn alter the reflection character or reflectivity at lithologic boundaries. Forward seismic modeling, the construction of synthetic seismic traces, implements well log data under the constraints of seismic resolution to determine, through models, the range of acceptable geologic interpretations. Together seismic sequence and facies analysis, reflection character analysis, and seismic modeling constitute the basis for seismic stratigraphic interpretation. These analytical methods in conjunction with previous geophysical and geological studies are used to interpret the Rice County reflection seismic section.

All seismic stratigraphic methods rely on the principle that seismic reflections represent time-stratigraphic, or constant time boundaries (Mitchum, et al., 1977a). It is not geologically possible to have a continuous boundary exist between one lithology and the next correlatable lithology strictly on the basis of time-transgressive rock-stratigraphic boundaries. As an example, a lateral facies change cannot be correlated by lithology but does represent synchronous deposition. The later facies change will be represented as a change in acoustic impedance, reflection amplitude, polarity, and wavelet character. The reflection cannot skip up or down to the next similar lithologic boundary as does a rock-stratigraphic correlation. Of special interest, an unconformable surface represents the depositional hiatus during which the depositional environment will change, often creating an abrupt change in lithology and a larger than normal reflection amplitude. The seismic section consequently represents the rock configuration and depositional sequence in time, and through well log, core, geochemical, or paleontological control can be dated and displayed as the continuous geologic cross-section.

## Seismic Sequence Analysis

Seismic sequence analysis examines the geometrical relationships of depositional sequences through reflection terminations (Vail, et al., 1977). Sequence boundaries are either concordant (no termination of reflector) or discordant, and will indicate sequence conformity, erosion or nondeposition (Figure 33). Concordant reflections within a sequence can most easily be traced from the point of discordance into the depositional sequence. Concordance indicates uninterrupted deposition or, if the boundary is continuous into discordance, nondeposition. Three types of terminations, the discordant boundaries, toplap, onlap, and downlap, indicate nondeposition. Onlap and downlap indicate basin fill and one component of the direction of sediment source. Toplap suggests deltaic or submarine fan complexes. Erosional truncation, in which older beds show termination instead of onlap of younger beds, obviously displays an erosional hiatus.

Usually the seismic sequence consists of units deposited in a similar geologic environment, and the sequence boundaries represent changes in the environment and will therefore be discordant and often erosional. In Kansas major unconformities separate the Phanerozoic section into seismic sequences. The pre-Chattanooga unconformity serves as the top boundary of the lower Paleozoic sequence, predominantly of dolomites and lesser amounts of sands and shales. The pre-Pennsylvanian unconformity demarkates the base of the thick sequence of Upper Pennsylvanian and Lower Permian cyclothems.

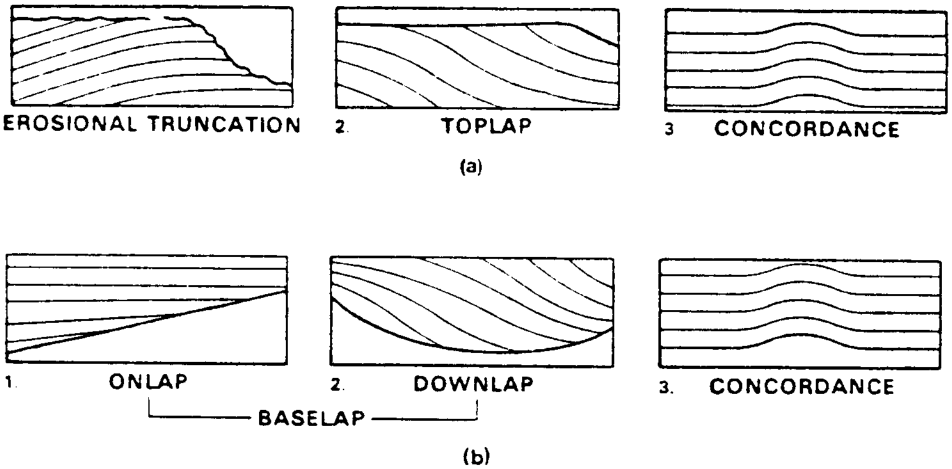


Figure 33 - Types of boundary terminations (from Mitchum, et al., 1977a). (A) Terminations at top of sequence may be either discordant, showing erosional truncation (1) or deltaic toplap deposition (2), or concordant (3), suggesting continuous deposition or paraconformity. (B) Terminations at bottom of sequence may be either discordant, showing low energy onlap (1) or angular high energy downlap (2), or concordant (3), suggesting continuous deposition or paraconformity.

## Seismic Facies Analysis

Seismic facies analysis examines the reflection configuration, continuity, amplitude, frequency, and interval velocity within each seismic sequence to determine depositional environment and lithology (Mitchum, et al., 1977b). Within a seismic sequence the reflection configuration type may be parallel, divergent, wavy, lenticular, chaotic, reflection-free, etc. Reflections that diverge indicate gradual subsidence or uplift during deposition. Other patterns, such as contorted, chaotic, and oblique or missing toplap in progradational sequences, represent high wave or flow regime energy. Within the Rice County seismic section reflection configurations are highly to moderately continuous, and either parallel or divergent. Using the classification scheme of Brown and Fisher (1979) this indicates a geologic environment supporting interbedded high and low energy shelf deposits of alternating fluvial to marine sandstones, shales and limestones. All parameters except true reflection amplitude, which is not recoverable from the MiniSOSIE recording system, are considered together to obtain an interpretation of environmental setting, depositional processes, and lithofacies estimates (Sheriff, 1980).

## Reflection Character Analysis

Reflection character analysis is the study of changes in the waveshape, such as amplitude, polarity, frequency, and timing, which are produced by lithologic and interstitial fluid changes. Modeling using synthetic seismograms is essential in this analysis to determine the seismic waveshape expressions of boundaries and facies as they change laterally. All seismic stratigraphic analyses, and, in particular, reflection character analysis and modeling, must work within the constraints of seismic resolution (Anstey, 1977; Sheriff, 1980; Neidell, 1981).

Resolution limits--Horizontal or spatial resolution limits are defined by the first Fresnel zone (Figure 34). Assuming a point source of energy and, therefore, spherical divergence, most coherent, in-phase information is reflected from an area, the first Fresnel zone, which increases in proportion to velocity, and the square root of wavelength and distance to the reflecting boundary (Anstey, 1977; Sheriff, 1980; Neidell, 1981; Knapp and Steeples, in press, b). Using the dominant MiniSOSIE impulse response frequency of 80 Hz, an average velocity of 3,650 m/sec, and a distance of 1,000 meters to the top of the Chattanooga limestone, the Fresnel zone radius is 151 meters, creating an area

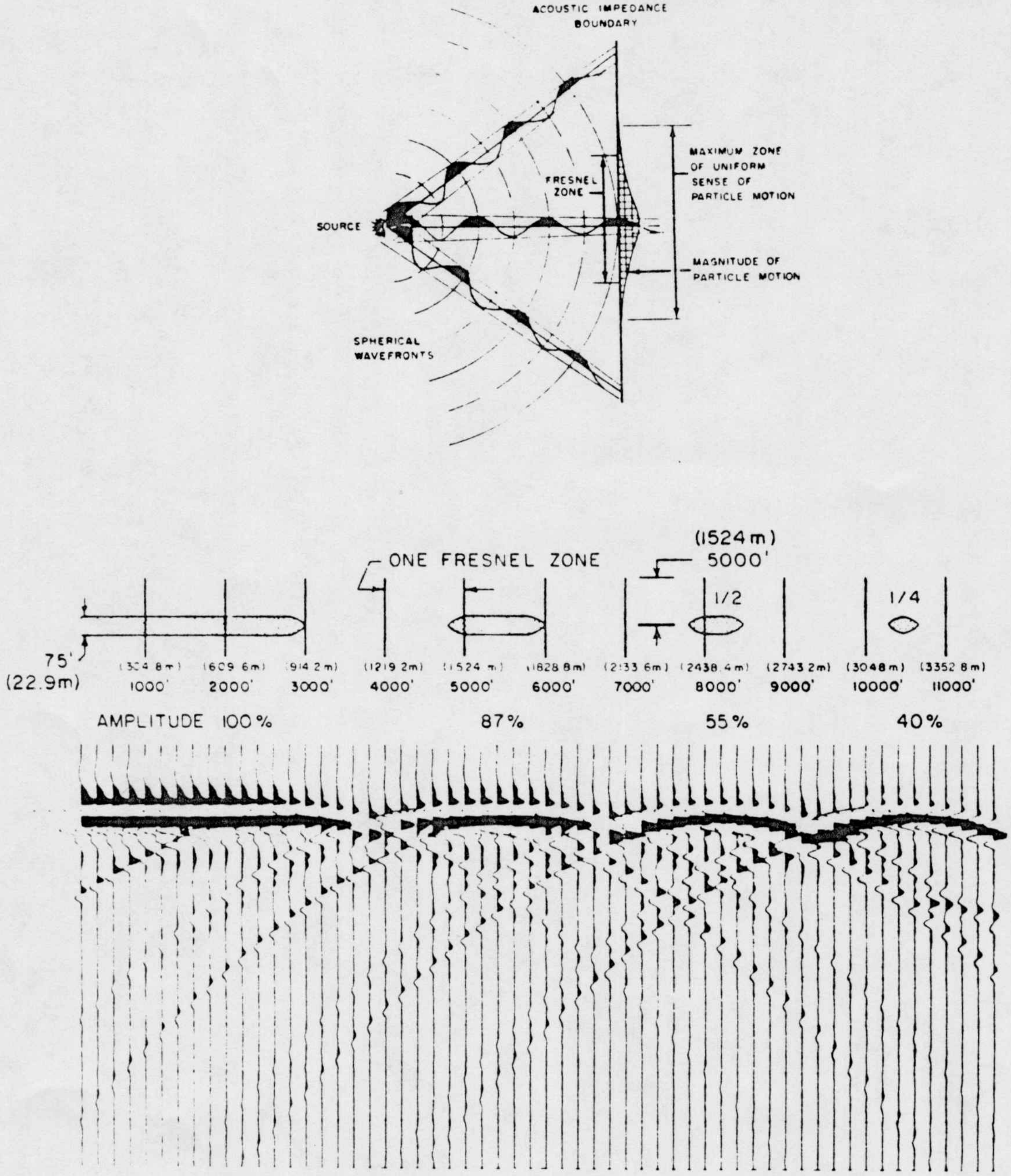


Figure 34 - Fresnel zone theory (after Neidell, 1981). Spherical wavefront of point source. Area of reinforced amplitude is dependent on velocity and the square-root of wavelength and distance to the reflector.

easily detected by surface sensors spaced at 16-meter intervals, but with the undesirable potential to "average out" boundary irregularities smaller than the Fresnel zone.

Vertical resolution is limited by the shape and length in time of the impulse wavelet, determined by the wavelet's frequency bandwidth and phase spectra (Knapp and Steeples, in press, b). Frequency filtering, predictive deconvolution and dephasing will sharpen or contract the wavelet by broadening its frequency bandpath and zeroing its phase to better separate a reflection from the ones above and below it. The result is greater accuracy in picking correct times, determining polarity, and understanding the interference patterns of closely spaced reflectors and multiples. Although wavelet extraction was not attempted, the wavelet of the MiniSOSIE data shows an acceptable agreement with a 90-degree phase delay, mixed-delay character wavelet that was used in the modeling. The dominant frequency of the MiniSOSIE bandpass is 80 Hz, which provides much greater resolution than lower dominant frequency sources such as Vibroseis, dynamite, and airgun (Knapp and Steeples, in press, a and b). Both frequency filtering and predictive deconvolution were attempted on the data. Both added noise and camouflaged the reflections. The frequency filtering did so because of unresolved software problems. The predictive deconvolution failed due to the non-causal characteristics of the MiniSOSIE wavelet (R. Knapp, pers. comm., 1984).

Both horizontal and vertical resolution are set by field parameters, source energy, recording geometries, instrument limitations, and the earth filter. Through processing, these original parameters can be only finitely enhanced, and resolution is confined by these limitations.

Interference patterns--In general all reflections seen on a seismic section are the combination or interference of two and generally more wavelets plus noise. The wavelets can interfere destructively to cancel their combined character or they may interfere constructively to boost their combined wavelet amplitude. The simplest example describes the interference pattern of reflections from the top and bottom of a wedge (Widess, 1973; Neidell, 1981), which models the thinning of a stratum (Figures 35 and 36). As the wedge thins the reflections from both the top and bottom can be observed until they are separated by one-quarter of a wavelength or less. One-fourth of the wavelength is defined as the resolvable limit. If the reflections are opposite in polarity at a separation of one-quarter of the wavelength, the combined character is "tuned" to constructively interfere as a single, larger-than-normal reflection (Figure

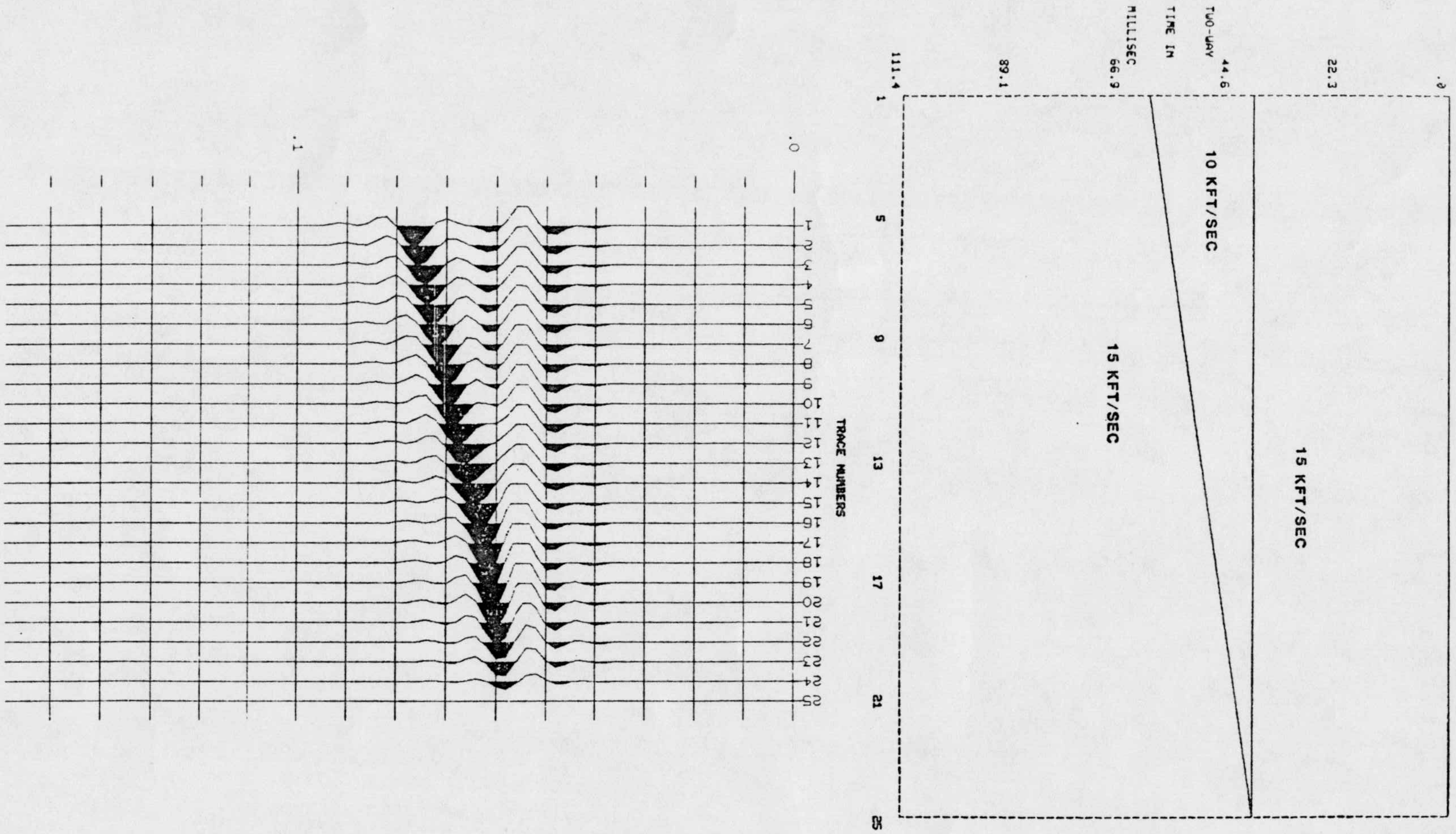


Figure 35 - Interference of opposite polarity wedge showing area of tuning at a wedge width of one-fourth wavelength.

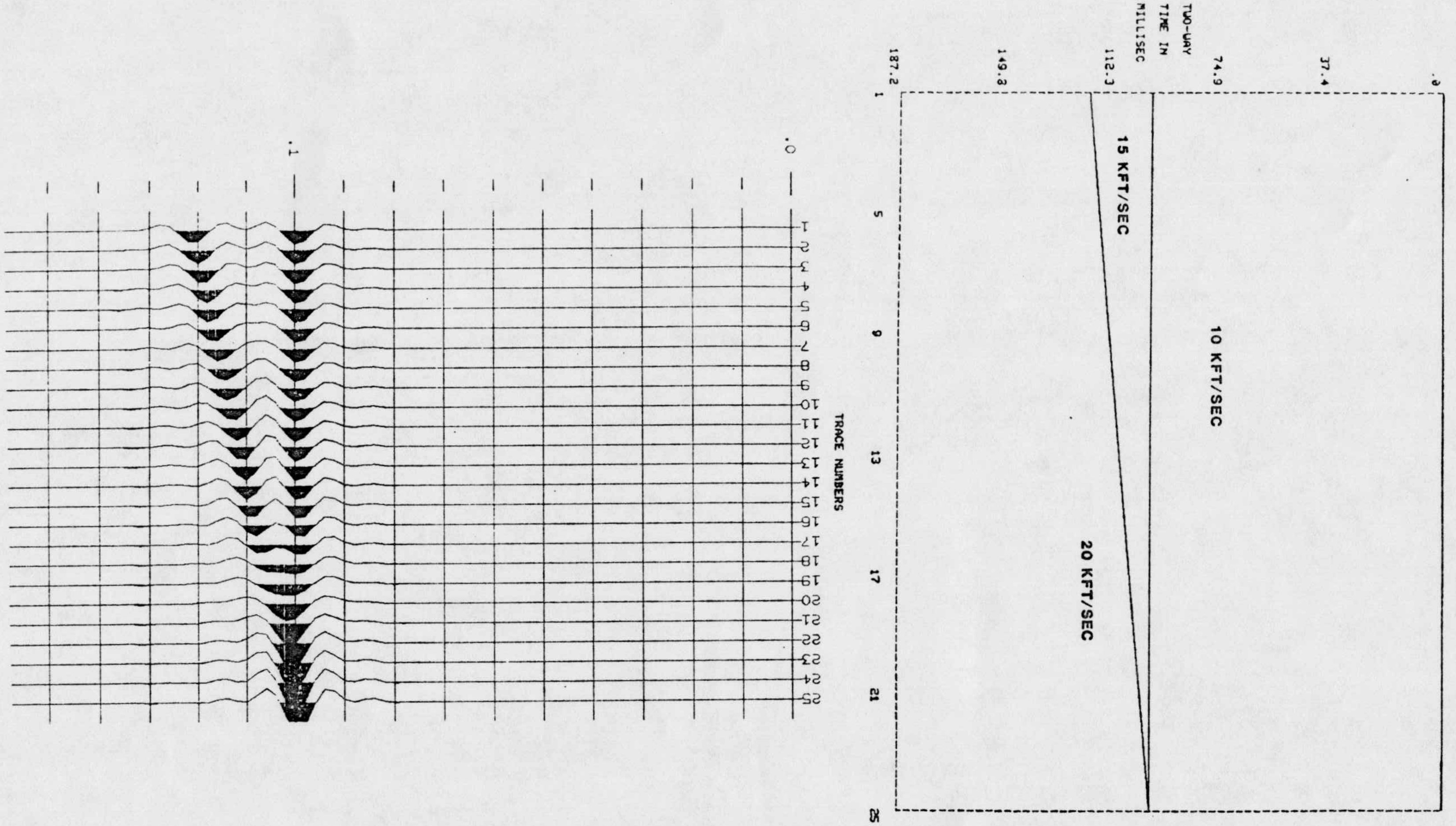


Figure 36 - Interference of similar polarity wedge showing area of cancellation at a wedge width of one-fourth wavelength.

35). The single-wavelet reflection then fades until the detectable limit is reached at about 1/30th of the wavelength, after which the wedge does not give a reflection discernible from noise. For wedge reflections of the same polarity, resolvable and detectable limits are still one-fourth and 1/30th of the wavelength, respectively, although cancellation instead of tuning occurs near the resolvable limit (Figure 36) (Anstey, 1977).

## Forward Modeling - the Synthetic Seismogram

Forward modeling involves construction of synthetic seismograms from well log data, correlation of the synthetic seismogram to the data, and ultimately modeling with the synthetic seismogram to create seismic expressions of geologic possibilities.

Synthetic seismogram manufacture consists of several steps before a correlation can be attempted. Initially a sonic log, which records P-wave transit time through the rock unit adjacent to the borehole, is digitized in one-foot (.3-meter) intervals. The digitizing program of Ready (1984) was used which employs slope calculations by the trapezoidal rule to determine the average transit time value over each one-foot interval. Once digitized the transit times are converted to velocities for each foot. Density logs were available but not used for several reasons: 1) density logs are noisy and sometimes give unreliable values, introducing and compounding errors; 2) density only affects wavelet amplitude and polarity and then not to the degree that velocity does; and 3) density plays no part in the depth-to-time conversion (Thomas, 1977; Durschner, 1958). Seismic data is sampled in equal time intervals rather than equal depth intervals, and thus the next step involves conversion and resampling of the sonic log to one-half millisecond, two-way time intervals. This is an average depth sampling of 1.4 meters (4.5 feet). Interval velocities are averaged over each half-millisecond step and reflection coefficients calculated. The result is a reflection coefficient series (Figure 37A) which grossly represents the impedance contrast of the earth's layers. Next, transmission losses and all multiples except surface multiples are calculated (subroutine initially written by Vargas, 1983) and added to the reflection coefficient series. Transmission losses are counteracted by short-path multiples, which add to the downgoing energy but with a response slightly delayed in time. This results in stretching of the wavelet to lower frequencies, and causes either constructive or destructive interference, depending on bed thickness (Widess, 1973; Neidell, 1981). A bandpass filter is next convolved with the reflection coefficient

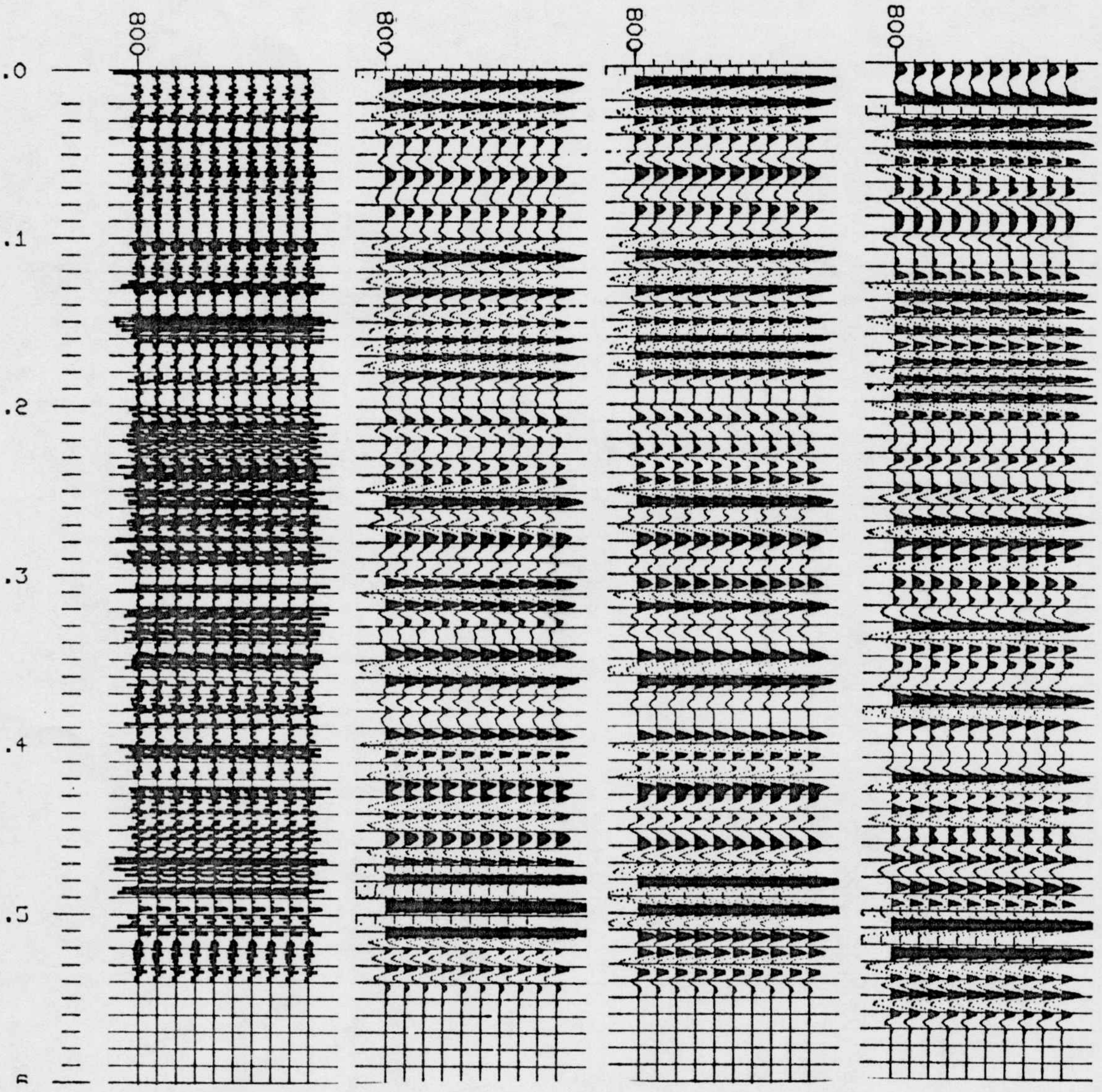


Figure 37 - Development of synthetic seismogram for CDP 800. Steps are: A) reflection coefficient series, B) zero-phase band-pass filtered synthetic seismogram, C) addition of multiples, D) additional 90-degree phase filter.

series to produce a zero-phase synthetic seismogram. The synthetic seismogram is then resampled to 2 millisecond intervals, the sample rate of the actual data. The bandpass is representative of the dominant frequencies of the MiniSOSIE source. Further attempts at various bandpass and phase filters (Knapp, 1981, 1983) result in obtaining the best correlation when a 90-degree phase delay filter is applied.

Correlation of actual and synthetic data (Figure 38) shows areas of good matching, areas of good matching if the synthetic is slightly shifted, and areas which show no matching. The correlation is centered for an exact match at the reflector at .5 seconds, which is the Pennsylvanian Howard Limestone. The synthetic seismogram appears shortened, and if slightly stretched would make a better correlation (Figure 39). Although theoretically the correlation should be perfect unless seismic processing has been inadequate, several reasons have been proposed for the discrepancies (Thomas, 1977; Sheriff, 1980; Stewart, et al., 1984).

1) Dispersion, the variance of velocity with frequency, will cause higher frequencies to travel faster than lower frequencies. This may cause the higher sonic frequencies (10 kHz to 30 kHz) to travel faster than the lower seismic frequencies (10 to 100 Hz).

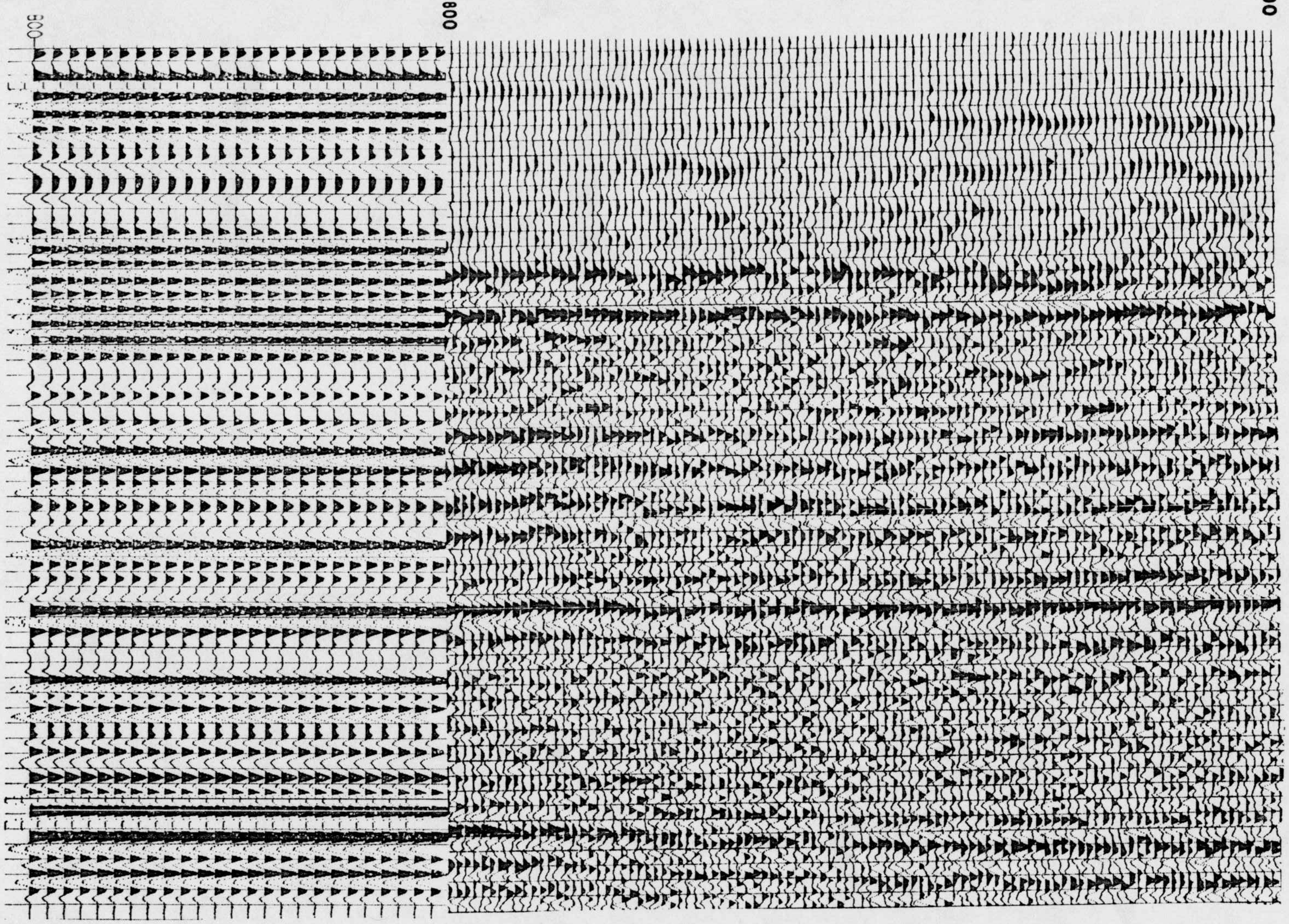


Figure 38 - Correlation of synthetic seismogram of CDP 800 with real data at CDP 800 and beyond. Short-path multiples and negative 90-degree phase shift filter are applied to the synthetic data.

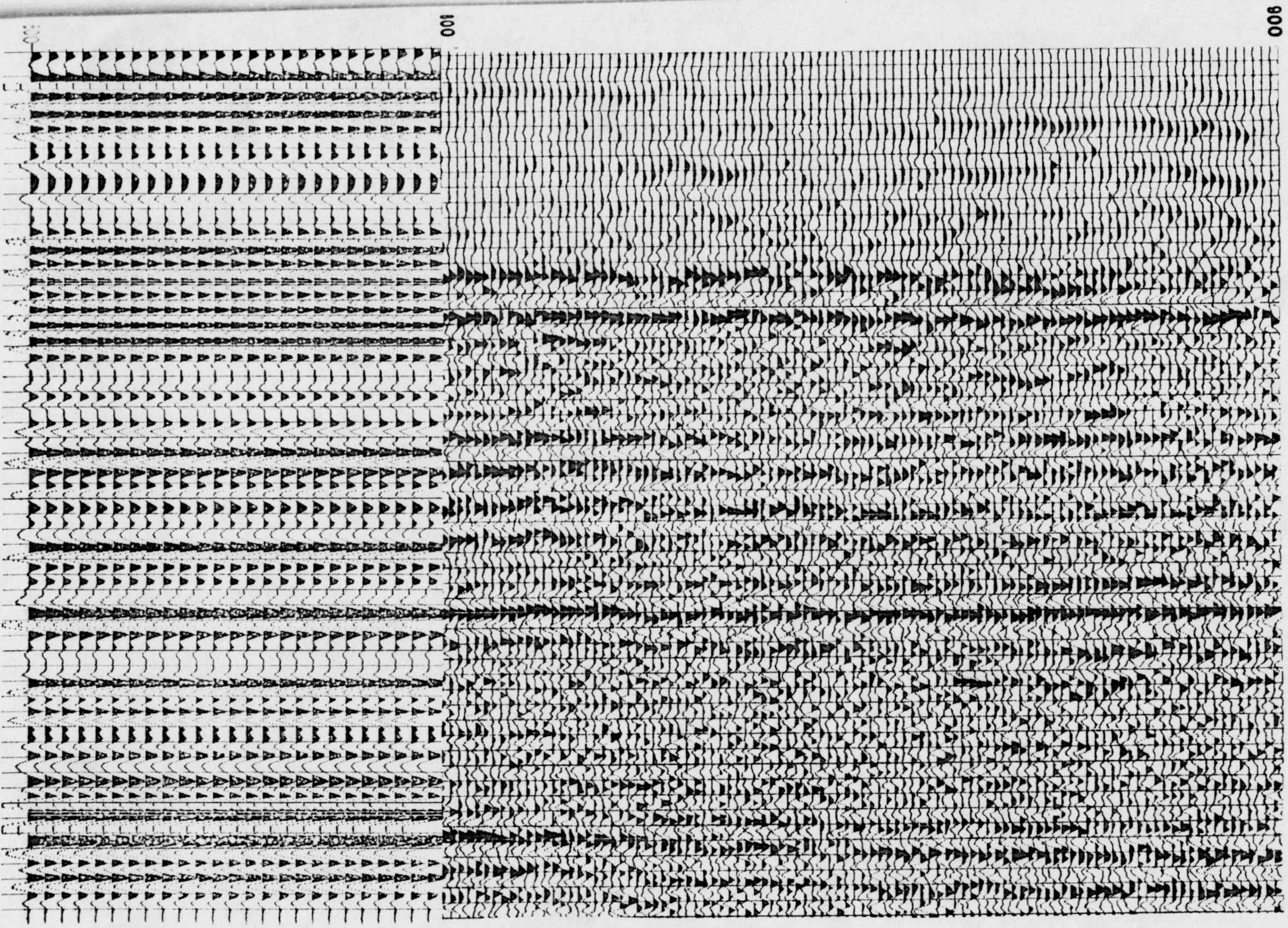


Figure 39 - Correlation of synthetic seismogram of CDP 800 with real data at CDP 800. Same as Figure 38 with addition of 5% stretching of synthetic for better correlation.

2) The rock volume sampled by the sonic log is only the few cubic meters adjacent to the well and is often altered by drilling and invasion of mud. In contrast, the rock volume sampled by seismic waves is much greater and lateral variations in rock properties may occur between the downgoing and upgoing waves.

3) Often the sonic log is not complete and will not have recorded the velocity of the near surface rocks. This will lead to incomplete calculation of short-path multiples. As an example, with all short-path multiples calculated, a reflector at a depth of 10,000 feet can be delayed 24.5 ms from its two-way time with no multiples calculated (Schoenberger and Levin, 1979). Also, inaccurate correlation with the seismic section may occur with no sonic logging of the shallow geology.

4) The logging tool may record a short transit time (i.e., high velocity) by triggering on noise before the sonic waves arrive. Another logging tool problem, having the opposite effect, is cycle skipping. In this case the sonic wave produces a lower than normal amplitude that is not sensed. The logging sonde instead triggers on the second or third cycle of the sonic wave. Cycle skips, and at times noise triggers, can often be detected by comparing the sonic log with either gamma ray or resistivity logs.

Regardless of the inaccuracies involved in the forward modeling, synthetic seismograms remain a most important tool in seismic stratigraphy. With the synthetic seismogram the seismic section can be correlated to the stratigraphy and reflections can be given unique chrono-stratigraphic meaning (Figure 40).

## SEISMIC INTERPRETATION

Based on the principles of seismic stratigraphy and contrained by previous geological and geophysical studies, the following interpretation is the most accurate picture of Rice County, Kansas geology produced within the limits of seismic resolution.

### Seismic Expressions of the Precambrian

The Precambrian underlies an average of 183 meters (600 feet) of Arbuckle Group dolomites. The contact between the Precambrian granites and the Arbuckle dolomites cannot be seen seismically. Using an average velocity of 4,267 m/sec (18,000 ft/sec), this places the Precambrian greater than 90 milliseconds (two-way time) below the top Arbuckle reflector (Figure 41). Consequently, the seismic record extends about 610 meters (2,000 feet) into the Precambrian. Several parallel reflections, fading in and out with the data quality, are seen within the Precambrian. The reflections generally follow the Paleozoic sequence and may be

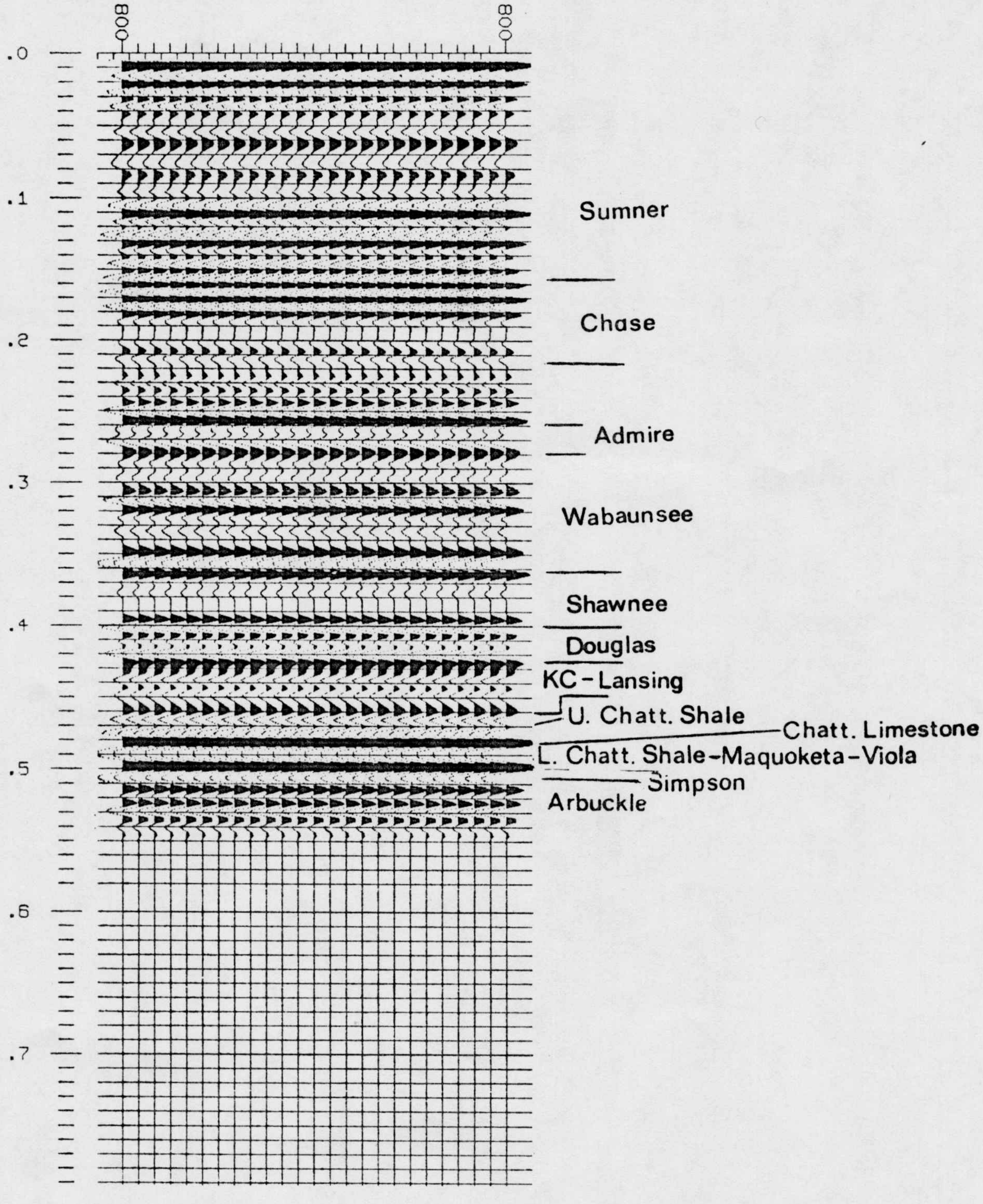


Figure 40 - Repeated synthetic seismogram from sonic log near CDP 800. Correlation with sonic log determines location in two-way time of labelled reflectors. Zero-phase bandpass filter has been applied.

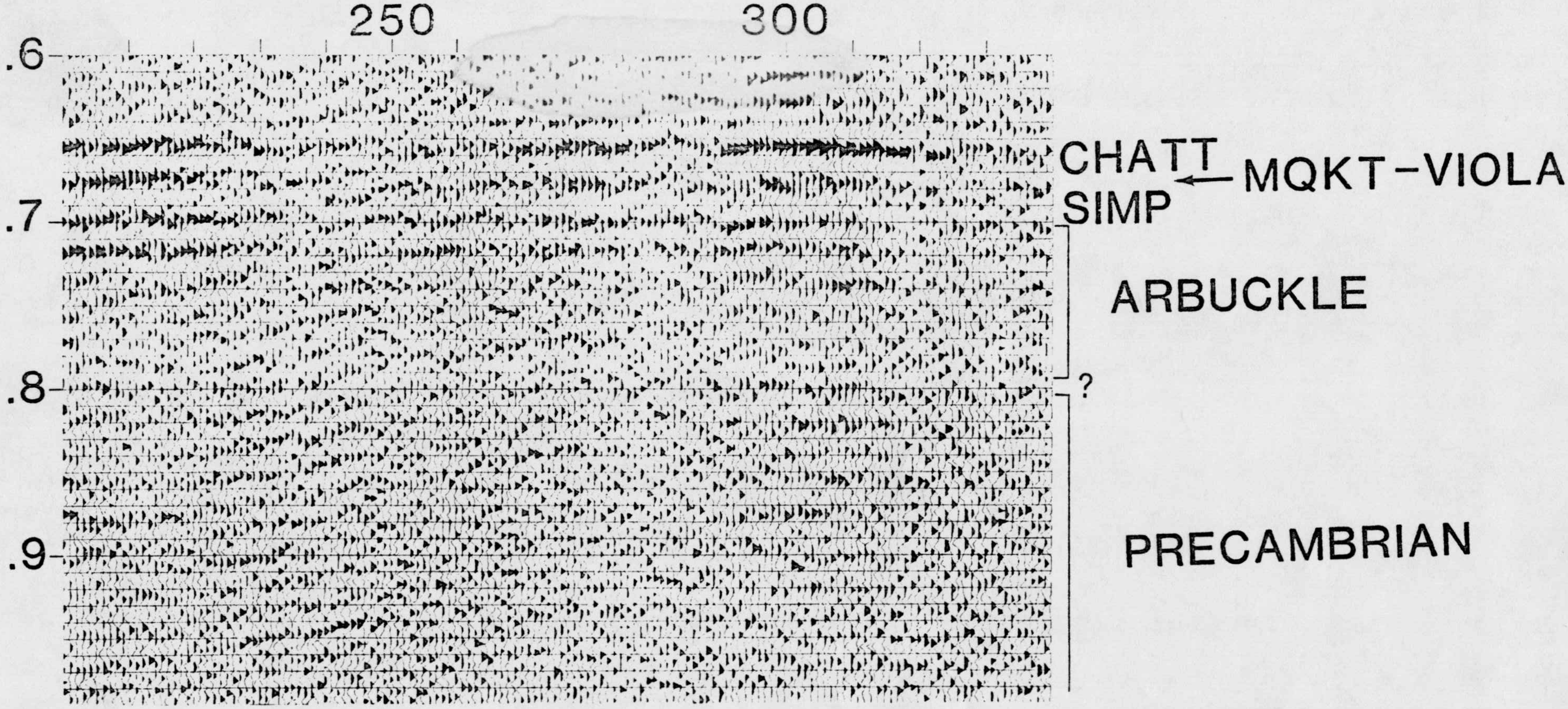
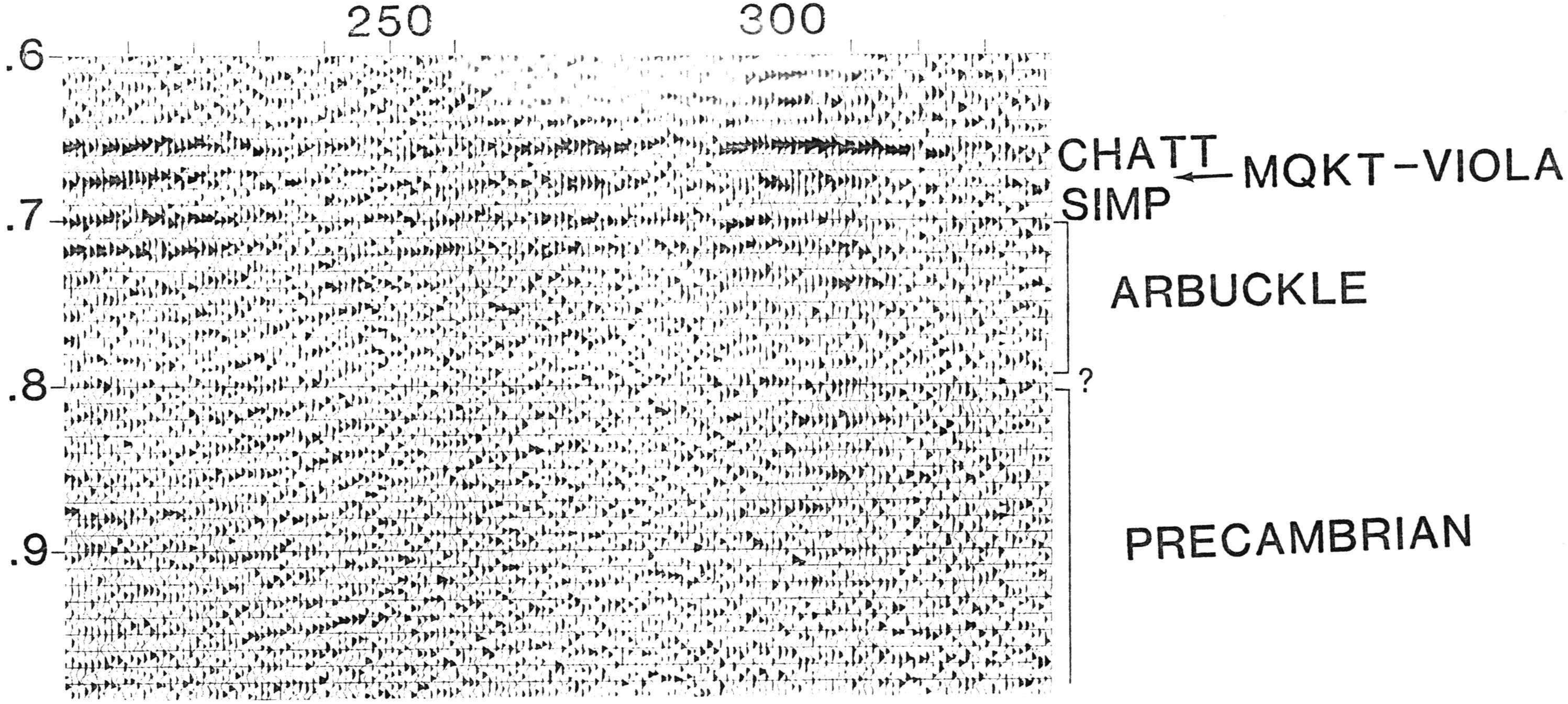

250
300
.6
.7
.8
.9
CHATT
MQKT-VIOLA
SIMP
ARBUCKLE
?
PRECAMBRIAN

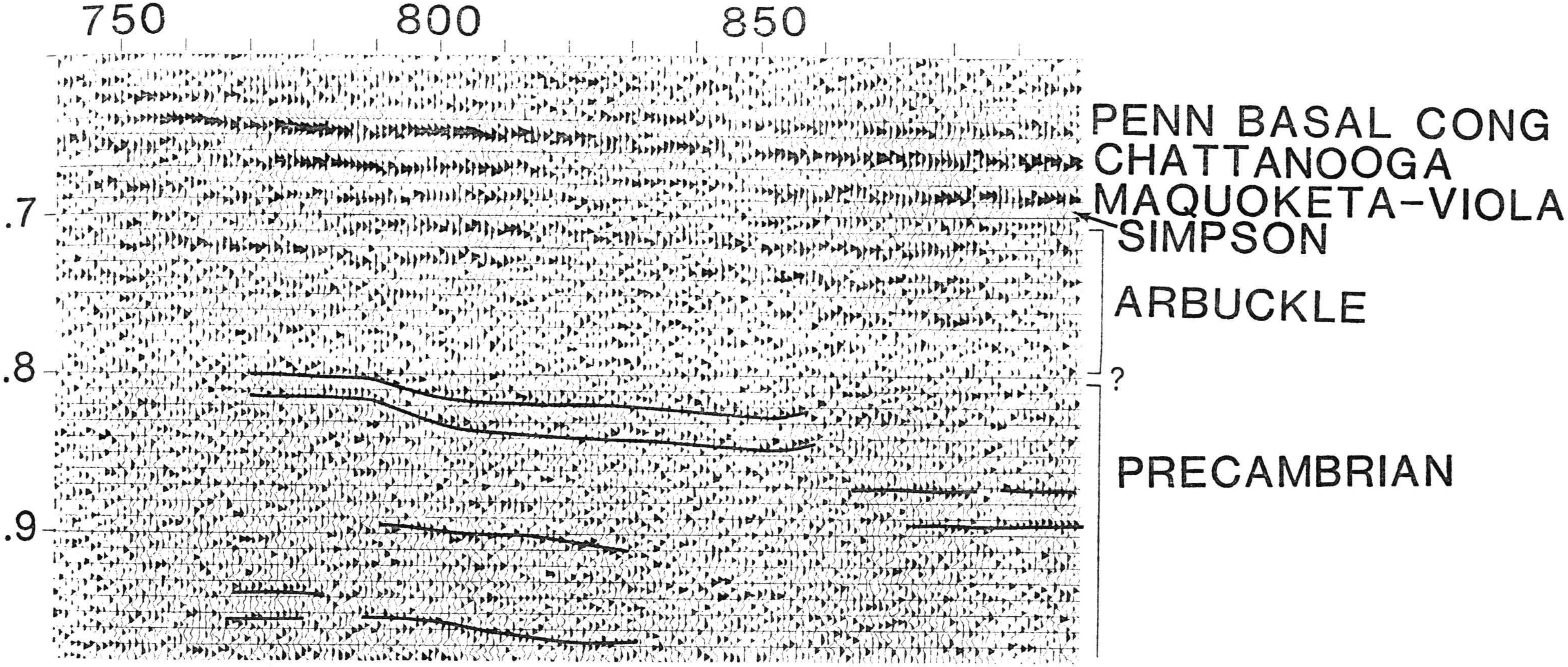
Figure 41 - Large scale detail of Rice County seismic section with interpretation showing parallel configuration of Chatttanooga through Simpson Groups. Discordance of west-dipping Arbuckle and Precambrian reflectors indicate west flank of unnamed anticline during the Proterozoic through Ordovician. Pennsylvanian basal conglomerate is shown to thin to the west as its reflection fades.


250
300
.6
.7
.8
.9
CHATT
SIMP
MQKT-VIOLA
ARBUCKLE
?
PRECAMBRIAN

multiples, however, the high stacking velocities necessary for these events refutes this interpretation (Appendix A). The top of the Precambrian is expected to be arkosic sandstones of the Upper Keweenawan Rice Formation which, according to the COCORP data, should contain very few good reflectors (Brown, et al., 1983; Serpa, et al., 1984). Gravity and aeromagnetic data suggest this sequence thins in Rice County to expose igneous rocks of a transition zone between the northern and southern terranes (Yarger, 1983; Yarger and Lam, 1982). The transition zone should be expressed seismically as reflectionless (Serpa, et al., 1984; Brown, et al., 1983), although, the discontinuous layering shown in Figure 31 implies a consistent stratified rock type throughout the study area. However, layering of the Precambrian in the central part of the seismic section does not appear to extend as deep (CDP's 340 to 1180, .750 to 1.0 sec) (Figure 31 and 42), and instead upwarping of a different rock type into the unnamed anticline is evidenced by thinning and onlapping of the Arbuckle onto a raised Precambrian surface.

Assuming two different Precambrian rock types exist, Figure 42 shows thinning of a Precambrian Rice Formation layer due to upwarping and erosion (CDP's 770 to 885, .800 to .840 sec). This implies existence of the unnamed anticline during the Late Proterozoic, and

Figure 42 - Large scale detail of the Rice County seismic section with interpretation. Uplift of the unnamed anticline is indicated by dipping and thinning of reflections in the Precambrian Rice Formation.


750
800
850
.7
.8
.9
PENN BASAL CONG
CHATTANOOGA
MAQUOKETA-VIOLA
SIMPSON
ARBUCKLE
?
PRECAMBRIAN

that the uplift is possibly related to Keweenawan rifting.

## Seismic Expressions of the Cambrian and Ordovician

Except for reflections from CDP's 185 to 290, the character of the Arbuckle sequence appears as continuous high-amplitude parallel reflections. To the west, (CDP's 185 to 290, .700 to .800 sec) (Figure 41) and to the east (CDP's 730 to 1450, .680 to .800 sec) (Figure 43), reflections diverge indicating uplift of the unnamed anticline during the time the Arbuckle was deposited. The westward dip and divergence of reflectors between CDP's 185 and 290 contrasts with westerly thinning and eastward dip of the Simpson through Shawnee Groups. This suggests an earlier opposing deformation, of subsidence to the west into the Southwest Kansas Basin. Discordance in the form of erosional truncation under a series of horizontal reflections occurs within the Arbuckle Group (CDP's 200 to 250, .680 to .740 sec) to indicate a period of no uplift along the unnamed anticline prior to renewed activity during the Ordovician to Early Pennsylvanian.

Above the Arbuckle Group, the Simpson Group maintains a constant time thickness and has a noisy, negative-polarity reflection character. The noise is a result of the interbedding of shales, sandstones and dolomites within the group. It is easily identified by the strong positive peaks of the Viola above and Arbuckle below, and is distinguished from the lower Chattanooga shale by the clean, relatively noise-free, negative amplitude character of the lower Chattanooga. Well log data indicate that the Simpson crops out on the crest of the unnamed anticline (Figure 43) (CDP's 595 to 620, .620 to .650 sec, and CDP's 685 to 710, .620 to .660 sec) and that it thins just east of the major reverse fault (CDP's 595 to 620, .620 to .650 sec), possibly to expose Arbuckle in the area of multiple diffractions (CDP's 620 to 650, .610 to 1.0 sec). The diffractions are caused by either tight folding or a series of faults and mask all reflections below the Pennsylvanian sequence. Unlike the straight-line geologic interpolation of Figure 23, the Simpson is folded down into a river valley between CDP's 650 and 700 (.640 to .660 sec) and underlies weathered deposits of the Viola in the valley center. The abrupt termination of Arbuckle, Simpson, and Pennsylvanian basal conglomerate reflections on the west side of the valley suggests a fault scarp on the west valley slope.

The velocities of the Maquoketa Group are intermediate between those of the lower Chattanooga shale and Misener Sandstone above and the Viola below. This results in a transitional, stretched, positive reflection combining the Maquoketa and the Viola, and

Figure 43 - Large scale detail of Rice County seismic section with interpretation. Structure related to Late Mississippian - Early Pennsylvanian deformation of unnamed anticline is shown. Tuning and cancellation due to interference of thinning beds indicates an erosional flank outcrop pattern.

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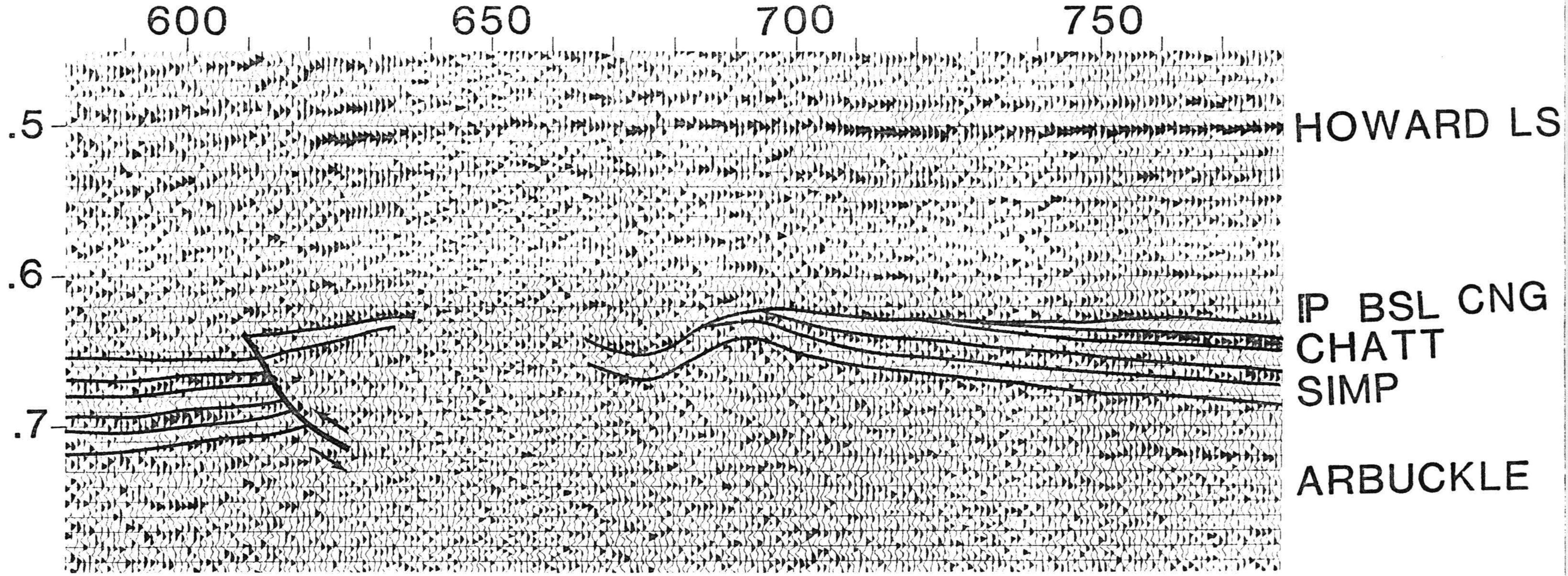


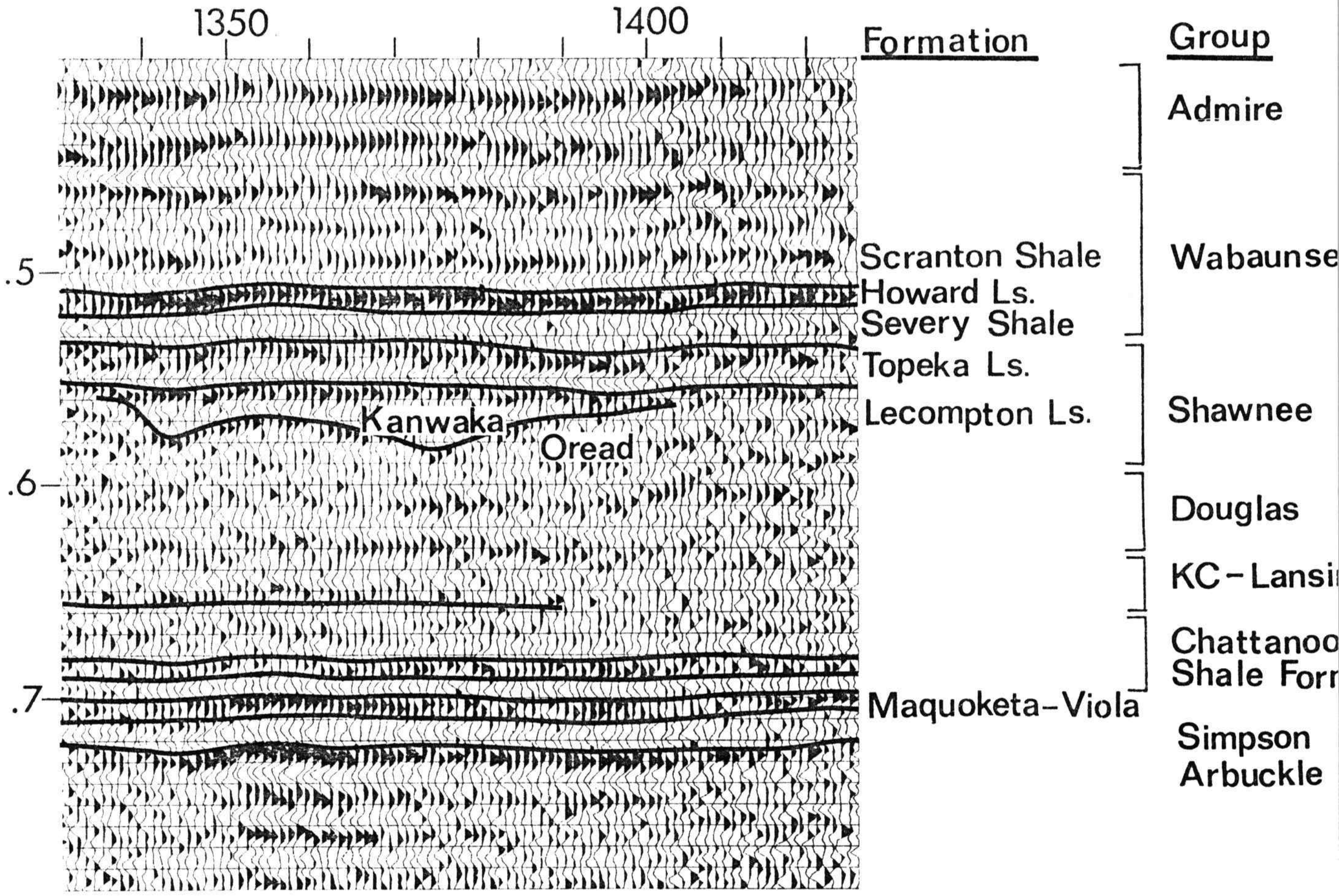
seismically the groups must be considered together. The groups' reflection character is one of the strongest positive peaks on the section and is easily identified as the first peak below the even stronger positive peak of the Chattanooga limestone. The general trend from west to east shows thinning or dimming of both the Chattanooga limestone and Viola-Maquoketa reflectors in contrast to a brightening of the underlying Arbuckle reflectors. As the layers move into the McPherson Valley (Figure 44) much of the Maquoketa has been eroded. The Viola-Maquoketa thins over the unnamed anticline and the reflection is lost, possibly the result of one-quarter wavelength cancellation of similar polarity thinning beds as previously discussed.

## Seismic Expressions of the Devonian and Mississippian

The major unconformity that exists above the Maquoketa (Figure 44) does not produce either the angular terminations or the high-amplitude reflections necessary for seismic detection. It is doubtful that thinning of the Maquoketa would have been noticed without geologic control.

The lower Chattanooga shale contains the basal Misener Sandstone as it approaches both the Central Kansas Uplift and the unnamed anticline. The reflection character is consistently a broad negative polarity

Figure 44 - Large scale detail of Rice County seismic section with interpretation. Stratigraphic relationships of Arbuckle through Wabaunsee Groups are shown. Fading out of Chattanooga limestone reflector indicates a short interval in which it is replaced by siltstones or shales (CDP's 1350 to 1360). Channel sand of Kanwaka Shale Formation shows erosion through several units down to the Oread Limestone Formation.


1350
1400
Formation
Group
Admire
Scranton Shale
Howard Ls.
Severy Shale
Wabaunse
Topeka Ls.
Lecompton Ls.
Shawnee
Kanwaka
Oread
Douglas
KC-Lansi
Chattanoo
Shale Forr
Maquoketa-Viola
Simpson
Arbuckle
.5
.6
.7

which does not change to indicate when the basal Misener is present. Throughout the section the lower Chattanooga shale remains a constant time thickness except where it is thinned by erosion beneath the pre-Pennsylvanian unconformity and crops out against the unnamed anticline. There it shows an excellent example of tuning in an opposite polarity wedge interference pattern.

Well log data show that the Chattanooga limestone unit thins to the east and passes into siltstones by the east edge of the seismic section. In many parts of the seismic section the Chattanooga limestone is by far the brightest positive amplitude reflector. To the east of the unnamed anticline, the width of the peak thins but does not terminate within the areas of good data quality (Figure 43). One zone of apparent partial siltstone replacement can be seen between CDP's 1350 and 1360. In this area data are of good quality, and all reflectors except the limestone have a bright, noise-free character, which suggests the limestone has either thinned or has been replaced by a lower velocity material to produce only a nominal positive kick. As the limestone thins over the unnamed anticline, cancellation is observed (CDP's 715 to 735, .630 sec) and the limestone is not detectable to the west until it merges with the pre-Pennsylvanian unconformity to strengthen its amplitude at CDP's 724 and 725.

The upper Chattanooga shale is expressed as a broad negative-polarity reflection above the bright positive-polarity Chattanooga limestone reflection. Eastward the shale thickens dramatically by CDP 1330 (Figure 44). This is the major diverging layer in the seismic section and indicates subsidence of the McPherson Valley. As it thins over the anticline, tuning is observed between CDP's 750 and 760 (Figure 43). Note the similarities in thickness between the upper and lower Chattanooga shales where tuning occurs.

## Seismic Expressions of Early Paleozoic Structure

The general eastward dip of the Early Paleozoic sediments reflects the location of the seismic section to be on the flank of the Central Kansas Uplift. Parallel reflectors in the Pennsylvanian indicate that deformation along the Central Kansas Uplift had ceased. The more predominant local structure of the unnamed anticline can be described in greater detail. Continuity of the Chattanooga limestone and other layers between Simpson and the upper Chattanooga shale indicate that the unnamed anticline was not active during the time of their deposition, and that not until Late Mississippian did it again become active. Abrupt termination of all strata from the Arbuckle through the Pennsylvanian basal conglomerate easily defines the fault plane and suggests a reverse sense of displacement along the fault between CDP's 610 and 620. Relative dating of the fault is Late Mississippian due to preservation of the Upper Chattanooga Shale on the downthrown block. Evidence that the Pennsylvanian basal conglomerate is cut by the fault suggests renewed fault movement after the Late Mississippian to Early Pennsylvanian deformation. Structure in the area of diffractions (CDP's 634 to 664, .600 to 1.0 sec) is undecipherable, although the diffractions are caused by structural deformation in the form of tight folding or faulting contemporaneous with the Late Mississippian to Early Pennsylvanian deformation.

## Seismic Expressions of the Pennsylvanian

The unconformity at the base of the Pennsylvanian produces a low-amplitude, discontinuous reflection, which is most easily identified by the angular erosional truncations underneath. Except for the river valley in the small downfold of the anticline, the land surface in the Middle Pennsylvanian had been flattened and the reflection of the unconformity can be somewhat easily traced across the seismic section at approximately 650 milliseconds. The Pennsylvanian basal conglomerate reflector fades between CDP's 185 and 250, probably due to thinning. General thickening from west to east of the Chattanooga below this horizontal reflector and absence of Silurian and Devonian rocks are evidence of flank structure between the Central Kansas Uplift and the Salina Basin.

Cyclothems of the Kansas City, Lansing, and Douglas Groups display a similar reflection configuration of low continuity and amplitude, parallel to folded bedding. According to Brown and Fisher (1979) this indicates dominantly non-marine clastics deposited by river currents and associated marginal marine transport processes, which is in agreement with the known stratigraphy. Channel sands and shelf-margin limestone lenses and oolite shoals frequently occur within these lower cyclothem units. Synthetic seismograms suggest moderate amplitude reflections should occur from Middle to Late Pennsylvanian cyclothems, although when placed next to each other for correlation, the synthetics from different parts of the study area show little consistency (Figure 45). Well log data indicate the Kansas City and Lansing Groups are composed predominantly of limestones with shales thin enough to be less than the detectable limit. In contrast, the Douglas Group is made up almost entirely of shales and channel sands. Marine limestone mounding, undetectable shales, and extensive erosional hiatuses combine to produce, in general, only nominal reflections for interpretation of the Kansas City,

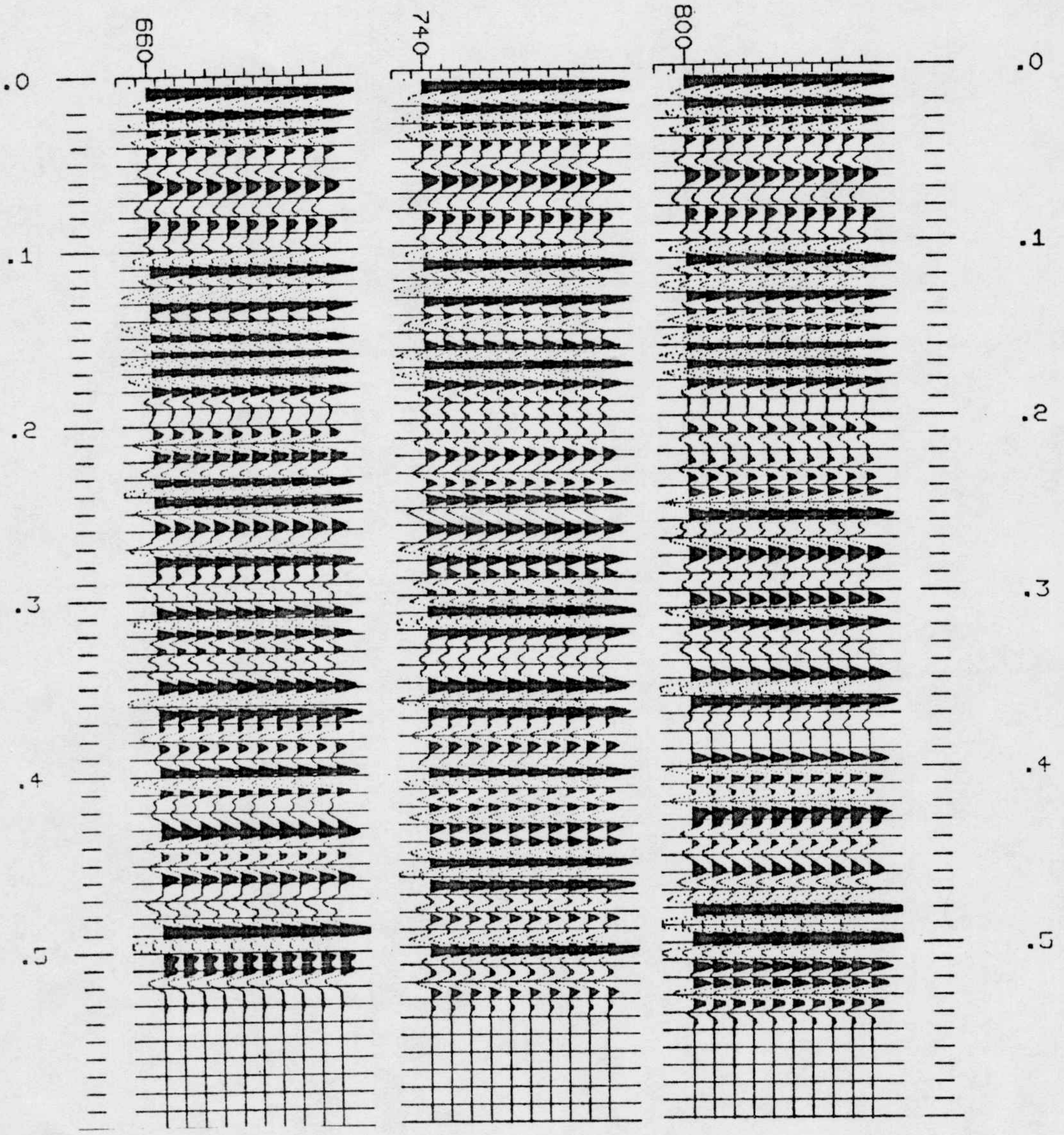


Figure 45 - Comparison of synthetic seismograms at CDP's 660, 740 and 800 to display noncorrelation of reflectors in Kansas City, Lansing, and Douglas Group. Arbuckle through Chattanooga reflectors do not show correlation due to erosion over the unnamed anticline. Note changes in interference patterns of Lower Permian reflectors.

Lansing, and Douglas Groups.

The Shawnee Group displays seismic expressions of two limestone formations, the Topeka at the top of the group, and the Lecompton near the center (Figure 44). The thickness of the intervening Calhoun Shale varies across the section, indicating moderate erosion and fluvial channeling during the hiatus before its deposition. One area of interest and high data quality within the Shawnee Group between CDP's 1330 and 1410 exhibits a potential hydrocarbon prospect in a stream channel fill of Kanwaka Shale (Figure 44). Although the Heebner Shale Member at the base of the Shawnee is highly visible in well logs and cores, its six-foot thickness is only 3/100th's of a wavelength, making its seismic expression virtually invisible.

Within the Wabaunsee, two limestone formations exhibit high amplitude continuous reflections. The Howard near the base and the Stotler near the top both possess abrupt lithologic boundaries that produce high reflection coefficients (Figure 46). These reflections are the most continuous of the cyclothem sequence and were used as a guide for much of the statics correction "flattening". The Severy Shale Formation immediately below the Howard shows the greatest thickness variation of all units, suggesting an undulating erosional surface on top of the Topeka Limestone Formation (Figure 44).

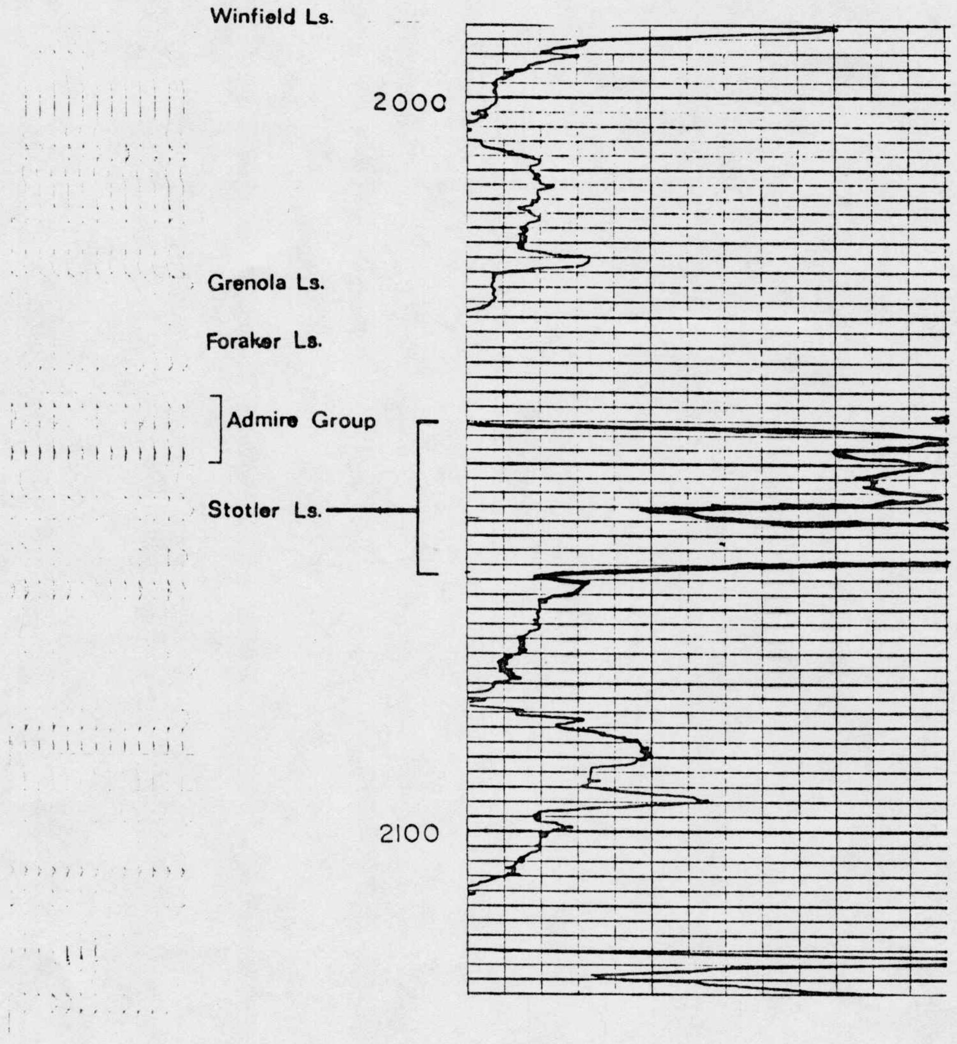


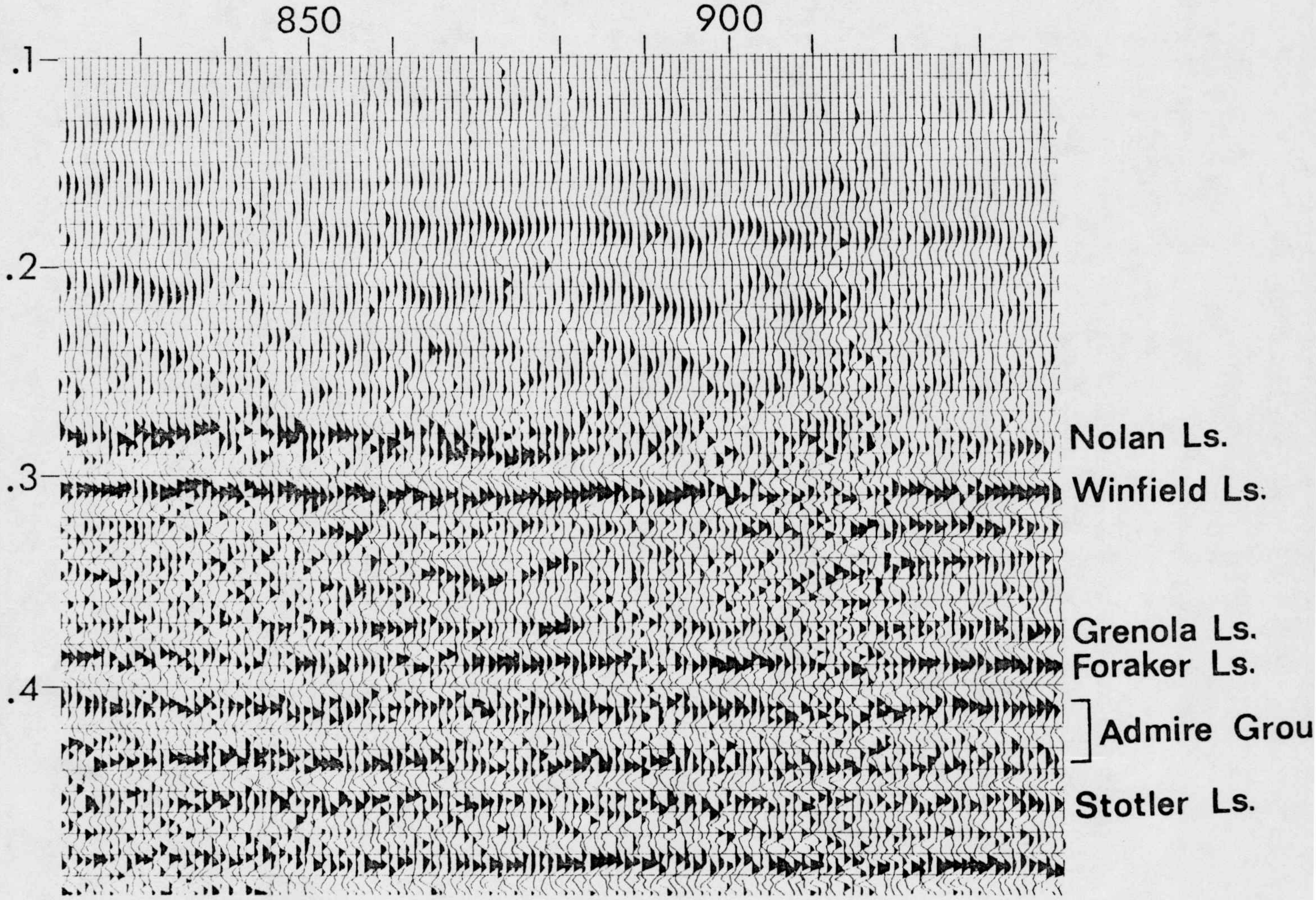
Figure 46 - Correlation of synthetic seismogram with sonic log near CDP 800. High positive amplitude with transitional negative amplitude tail of Stotler Limestone Formation creates a contstant-amplitude reflector across the Rice County seismic section.

Between the Stotler and the Howard appear several reflections of laterally varying character and amplitude. The sonic log shows these reflections to be composed of several thin limestone and shale units which have interfered constructively to appear as a single unresolvable reflection. From the stratigraphy, these beds are often discontinuous, resulting in variable reflection character. In other areas, such as the Shawnee Group in the area of the Heebner, interference is destructive and produces cancellation of unresolvable beds.

## Seismic Expressions of the Permian

The Admire, Council Grove and Chase Groups of the Lower Permian produce reflection configurations that are similar to the high-amplitude, continuous reflections of the Wabaunsee (Figure 47). Reflections are often the result of interference of unresolvable thin beds, which are laterally constant enough in thickness and reflectivity to maintain a continuous reflection across the seismic section. The Admire Group, Foraker, Grenola and Winfield Formations are good examples (Figure 48). Within the Chase Group thickening shale units between the Grenola and Foraker change laterally to show at times minimal velocity variations and give a reflection-free character associated with a more or less homogeneous unit. The Nolans Formation also varies laterally

Figure 47 - Large scale detail of Rice County seismic section with interpretation. Stratigraphic relationships of Wabaunsee through Council Grove Groups are shown. Interference patterns of thin shales and limestones create variable amplitude and character reflectors of the Admire Group and Foraker Limestone Formation. The Nolans Limestone illustrates a stretched amplitude due to a transitional boundary.


850
900
.1
.2
.3
.4
Nolan Ls.
Winfield Ls.
Grenola Ls.
Foraker Ls.
Admire Grou
Stotler Ls.

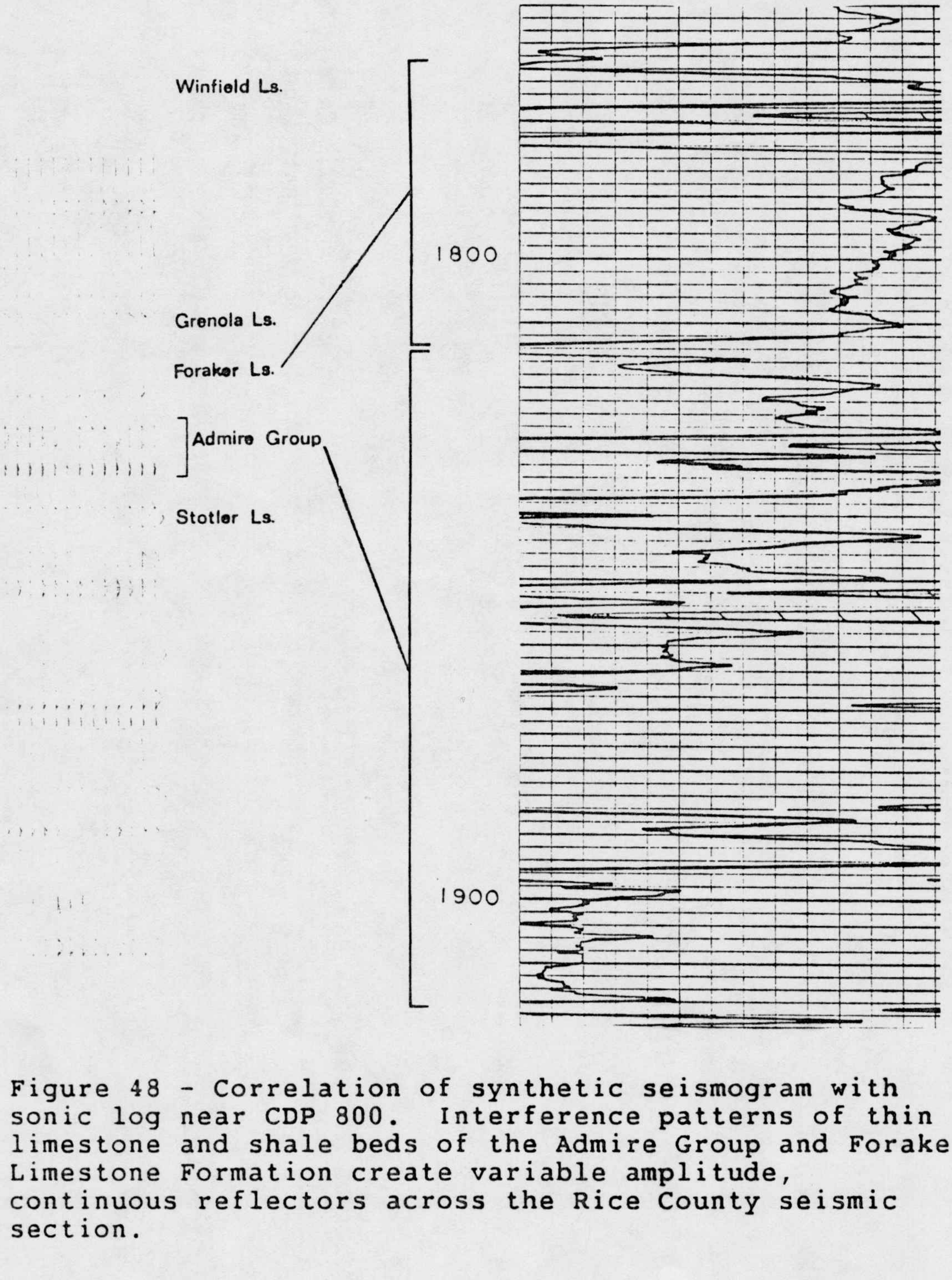


Figure 48 - Correlation of synthetic seismogram with sonic log near CDP 800. Interference patterns of thin limestone and shale beds of the Admire Group and Foraker Limestone Formation create variable amplitude, continuous reflectors across the Rice County seismic section.

and is at times a gradational transition from limestone to shale which results in a stretched-out pulse.

The Sumner and Nippewalla Groups are not seen in this particular reflection seismic section, although other Kansas Geological Survey seismic studies in nearby locations describe these upper units in detail (Miller, et al., 1984, a and b)

## CONCLUSIONS

Although the Rice County reflection seismic profile generally confirms the straight-line interpolations of well geology, by seeing beyond and below the first dimension of the borehole, reflection seismology has added the following contributions to greatly improve area stratigraphy and structural history.

1) Layered reflections of the Precambrian Rice Formation are present and thin onto the unnamed anticline. The reflection character of the Precambrian beneath the unnamed anticline differs from the layered reflections in the Rice Formation, implying a different rock type, possibly granite of the terrane transition zone.

2) Unlike reflectors of the Lower Paleozoic (Simpson through Shawnee Groups), which diverge from the Central Kansas Uplift, Arbuckle reflectors show divergence from the east and west flanks of the unnamed anticline. This indicates uplift of the unnamed anti-

cline and subsidence in the area of the Central Kansas Uplift during Proterozoic, Cambrian, and Early Ordovician. The unnamed anticline during this time was a much larger feature, possessing a west-dipping flank rather than a terminating fault as in the Early Pennsylvanian.

3) The unnamed anticline, known to exist from well data, is accurately defined through reflection seismology. The valley in the "nose" of the anticline, is a deformational rather than erosional feature, caused by a small synclinal fold, and terminated on the west by a fault scarp. Diffractions to the west of the river valley imply tight folding or faulting, and culminate in a reverse fault with over 200 meters of vertical displacement. Terminations of pre-Pennsylvanian strata on the east flank can be precisely located. The unnamed anticline is now redefined as a larger, symmetrically folded, Proterozoic, positive feature. It was eroded during the Ordovician, and reactivated during the Late Mississippian to Early Pennsylvanian as a smaller, asymmetrical, highly folded and faulted, positive feature.

4) Within the areas of good data quality, the Chattanooga limestone unit is continuous across the seismic profile. Gradual thinning develops from west to east, and partial replacement by lower velocity lithologies (siltstone or shale) occurs between CDP's 1350

and 1360. Further seismic studies extending east of the present seismic section would determine where complete replacement occurs.

5) Most resolvable Pennsylvanian and Permian cyclothems display constant seismic facies throughout the seismic section, although bed thickness can be highly variable due to intercyclic erosion. In particular, the Lecompton Limestone - Calhoun Shale and Topeka Limestone - Severy Shale boundaries continuously change thickness over distances far outside well log resolution.

6) The potential stratigraphic play observed in the Kanwaka Shale Formation would have only been seen through tight well spacing of expensive Arbuckle dry holes.

In addition, the following contribution to Kansas reflection seismology is of great importance to industrial as well as academic applications:

A) In detail correlation of area geology with reflection seismology has been determined, and reflection character of all prominent strata are described and correlated in time from the Precambrian into the Lower Permian.

## FURTHER RESEARCH

Additional seismic studies using a deeper-penetrating source, and executed parallel and 1.6 to 3.2 km (1 to 2 miles) north of the present line would provide a more three-dimensional structural picture and should probe deeper into the crustal configuration of Kansas. An eastward extension of the present seismic study, including reacquisition of CDP's 1400 to 1517, would greatly enhance the present interpretation, and would determine configuration of the McPherson Valley and Chattanooga limestone unit.

# LIST OF REFERENCES

Anstey, Nigel A., 1977, Seismic Interpretation: The Physical Aspects: Internat. Human Resource Development Corp., Boston, pp. 40-123.

Barbier, M.G., P. Bondon, R. Mellinger, J.R. Viallix, 1976, Mini-SOSIE for land seismology: Geophysical Prospecting, Vol. 24, pp. 518-527.

Bayne, C.K., and J.R. Ward, 1974, Geology and hydrology of Rice County, Central Kansas: Kansas Geol. Survey Bulletin 206, Pt. 3.

Berendsen, P., and K.P. Blair, 1984, Structural development of basement and overlying rocks across the Central North American Rift System, Central Kansas: Kansas Geol. Survey Map Series, in press.

Berendsen, P., and M.W. Lambert, 1981, Copper sulfides in the Lower Pennsylvanian redbeds of south-central Kansas, stratigraphy and host rock lithology: Kans. Geol. Survey Bull. 223, Part 1, 86 pgs.

Bickford, M.E., K.L. Harrower, W.J. Hoppe, B.K. Nelson, R.L. Nusbaum, J.J. Thomas, 1981, Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas: Geol. Soc. Amer. Bull., Part 1, Vol. 92, pp. 323-341.

Brewer, J.A., R. Good, J.E. Oliver, L.D. Brown, S. Kaufman, 1983, COCORP profiling across the Southern Oklahoma aulacogen: overthrusting of the Wichita Mountains and compressions of the Anadarko Basin: Geology, Vol. 11, pp. 109-114.

Brookins, D.G., and H.O.A. Meyer, 1974, Crustal and upper mantle stratigraphy beneath eastern Kansas: Geophy. Res. Let., Vol. 1, pp. 269-272.

Brown L.F., and W.L. Fisher, 1979, Principles of seismic stratigraphic interpretation: notes for Amer. Assoc. Pet. Geol. petroleum exploration school. Table is in Sheriff, 1980.

Brown, L., L. Serpa, T. Setzer, J. Oliver, S. Kaufman, R. Lillie, D. Steiner, D.W. Steeples, 1983, Intracrustal complexity in the United States midcontinent: preliminary results from COCORP surveys in northeastern Kansas: Geology, Vol. 11, pp. 25-30.

Brown, L., L. Jensen, J. Oliver, S. Kaufman, D. Steiner, 1982, Rift structure beneath the Michigan Basin from COCORP profiling: Geology, Vol. 10, pp. 645-649.

Cole, V., 1976, Configuration of the top of the Precambrian rocks in Kansas: Kansas Geol. Survey M Series maps, M-7. Scale 1:500,000.

Durschner, H., 1958, Synthetic seismograms from continuous velocity logs: Geoph. Prosp., Vol. 6, pp. 272-284.

Ehm, A.E., 1965, Lyons west field, Kansas Oil and Gas Fields, Vol. IV: Kansas Geological Society, pp. 146-156.

Ervin, C.P., 1981, Rift patterns in the North American craton inferred from regional gravitational anomalies, unpub. Master's thesis: N. Illinois Univ.

Harriss, R.L., J.J. Stone, C.R. King, A. James III, E.D. Goebel, 1966, Type Logs of Kansas, Logs for Rice County, Sec. 20, T19S, R8W: Kansas Geological Society, drafted by H.R. Trapp.

Jewett, J.M., 1951, Geologic structures in Kansas: Kansas Geol. Survey Bull. 90, Part 6, pp. 105-172.

King, E.R., and I. Zeitz, 1971, Aeromagnetic study of the midcontinent gravity high, central United States: Geol. Soc. Amer. Bull., Vol. 82, pp. 2187-2208.

Kluth, C.F., and P.J. Coney, 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, Vol. 9, pp. 10-15.

Knapp, R.W., 1981, Simple filters: unpub. paper.

Knapp, R.W., 1983, 90-degree phase shift filters: unpub. paper.

Knapp, R.W., and D.W. Steeples, in press, a, High resolution common depth point seismic reflection profiling, instrumentation.

Knapp, R.W., and D.W. Steeples, in press, b, High resolution common depth point reflection profiling: field acquisition parameter design: Soc. Explor. Geophysicists special monograph on Engineering Geophysics.

Lee, W., 1939, Relation of thickness of Mississippian limestones in central and eastern Kansas to oil and gas deposits: Kansas Geol. Survey Bull. 26, 42 pgs.

Lee, W., 1956, Stratigraphy and Structure of the Salina Basin: Kansas Geol. Survey Bull. 121, pp. 1-151.

Merriam, D.F., 1963, The geological history of Kansas: Kansas Geol. Survey Bull. 162, 317 pgs.

Miller, R., D.W. Steeples, C.D. McElwee, 1984, a, Seismic reflection survey of salt dissolution sinkholes in Reno County, Kansas: Kansas Geol. Survey report to Reno County Commission, to be submitted to Journ. Geoph. Res..

Miller, R., D.W. Steeples, J.A. Treadway, 1984, b, Seismic reflection survey of a salt dissolution sinkhole in Ellsworth County, Kansas: Kansas Geol. Survey report, unpub.

Mitchum, R.M. Jr., P.R. Vail, S. Thompson III, 1977, a, Seismic Stratigraphy and Global Changes in Sea Level Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis, in Seismic Stratigraphy--Applications to Hydrocarbon Exploration, C.E. Payton, ed.: Amer. Assoc. Pet. Geol. Memoir 26, pp. 53-62.

Mitchum, R.M. Jr., P.R. Vail, J.B. Sangree, 1977, b, Seismic Stratigraphy and Global Changes in Sea Level Part 6: Stratigraphic Interpretation of Seismic Reflection Patterns in Depositional Sequences, in Seismic Stratigraphy--Applications to Hydrocarbon Exploration, C.E. Payton, ed.: Amer. Assoc. Pet. Geol. Memoir 26, pp. 117-133.

Neidell, N.S., 1981, Stratigraphic Modeling and Interpretation: Geophysical Principles and Techniques, Educational Course Series 13: Amer. Assoc. Pet. Geol., 141 pg.

Newell, K.D., in prep., Salina Basin Project, study in progress at the Kansas Geol. Survey, to be published.

Ocola, L.C., and R.R. Meyer, 1973, Central North American Rift System, 1, structure of the axial zone from seismic and gravimetric data: Journ. Geoph. Res., Vol. 78, pp. 5173-5194.

Paul, S.E., J.T. Fish, J.S. Wells, R. Peters, J.Gilmore, J.H. Mosler, 1979, Oil and gas developments in north mid-continent in 1978, Amer. Assoc. Pet. Geol. Bull., Vol. 63, No. 8, p. 1307.

Rascoe, B. Jr., and F.J. Adler, 1983, Permo-Carboniferous hydrocarbon accumulations, mid-continent, U.S.A.: Amer. Assoc. Pet. Geol. Bull., Vol. 67, No. 6, pp. 979-1001.

Ready, T., 1984, Identification and interpretation of seismic data in Miami County, Kansas, unpub. Master's thesis: Univ. of Kansas.

Schoenberger, M. and F.K. Levin, 1979, The effect of subsurface sampling on one-dimensional synthetic seismograms: Geophysics, Vol. 44, No. 11, pp. 1813-1829.

Serpa, L., T. Setzer, H. Farmer, L. Brown, J. Oliver, S.Kaufman, J. Sharp, D.W. Steeples, 1984, Structure of the southern Keweenawan rift from COCORP surveys across the Midcontinent Geophysical Anomaly in northeastern Kansas: Tectonics, Vol. 3, No. 3, pp. 367-384.

Sheriff, R.E., 1977, Limitations on resolution of seismic reflections and geological detail derivable from them, in Seismic Stratigraphy--Applications to Hydrocarbon Exploration, C.E. Payton, ed.: Amer. Assoc. Pet. Geol. Memoir 26, pp. 3-14.

Sheriff, R.E., 1980, Seismic Stratigraphy, Internat. Human Resource Development Corp., Boston, Mass., 227 pgs.

Sleep, N.H., and L.L. Sloss, 1978, A deep borehole in the Michigan Basin: Journ. Geoph. Res., Vol. 83, pp. 5815-5819.

Sloss, L.L., 1980, The midcontinent province: United States: Northwestern University, preprint to Decade of North American Geology.

Somanas, C., 1984, A comprehensive geophysicsal interpretation of the Midcontinent Geophysical Anomaly in northeastern Kansas, unpub. Masters thesis: Univ. of Kansas.

Steeples, D.W., and M.E. Bickford, 1981, Piggyback drilling in Kansas: an example for the Continental Scientific Drilling Program: EOS Trans., Am. Geoph. Union, Vol. 62, No. 18, pp. 473-476.

Stewart R.R., P.D. Huddleston, T.K. Kan, 1984, Seismic vs. sonic velocities: a vertical seismic profile study: Geophysics, Vol. 49, No. 8, pp. 1153-1168.

Thomas, D.H., 1978, Seismic applications of sonic logs: The Log Analyst, Jan.-Feb., 1978, pp. 23-32.

Vail, P.R., R.G. Todd, J.B. Sangree, 1977, Seismic Stratigraphy and Global Changes in Sea Level Part 5: Chronostratigraphic Significance of Seismic Reflections, in Seismic Stratigraphy--Applications to Hydrocarbon Exploration, C.E. Payton, ed.: Amer. Assoc. Pet. Geol. Memoir 26, pp. 99-116.

Van Schmus, W.R., and M.E. Bickford, 1981, Proterozoic chronology and evolution of the midcontinent region, North America, Chap. 11, Precambrian Plate Tectonics, A. Kroner, ed.: Elsevier Scientific Pub.

Vargas, J.F., 1983, Deterministic deconvolution model for high resolution seismic data in Kansas, unpub. Masters thesis: Univ. of Kansas.

Widess, M.B., 1973, How thin is a thin bed?: Geophysics, Vol. 38, No. 6, pp. 1176-1180.

Yarger, H.L., 1983, Regional Interpretation of Kansas Aeromagnetic Data: Kansas Geol. Survey Geophysics Series 1.

Yarger, H.L., and C. Lam, 1982, Gravity measurements in Kansas, Assessment of the geothermal resources of Kansas: Department of Energy Report, pp. 220-232.

Yarger, H.L., C. Lam, R. Sooby, A. Martin, K. Ng, R. Robertson, R. Woods, G. Rothe, D. Steeples, 1983, Bouguer gravity map of eastern Kansas: Kansas Geol. Survey open file. Scale 1:500,000.

Zeller, D.E., 1968, The stratigraphic succession in Kansas: Kansas Geol. Survey Bull., No. 189, 81 pgs.

# APPENDIX A

## FINAL STACKING VELOCITIES AND RELATED PROCESSING PARAMETERS FOR RICE COUNTY REFLECTION SEISMIC SECTION

First arrival mutes:

| | | Offset distance | |
|---|---|---|---|
| All CDP's | time (ms) | (ft) | (m) |
| | 120 | 745 | 227 |
| | 280 | 2010 | 613 |

Stacking velocities:

| | | Velocities | |
|---|---|---|---|
| CDP | time (ms) | (ft/s) | (m/s) |
| 220 | 220 | 7740 | 2359 |
| | 310 | 9070 | 2765 |
| | 410 | 9700 | 2957 |
| | 500 | 10070 | 3069 |
| | 660 | 10940 | 3335 |
| | 890 | 13660 | 4164 |
| 265 | 170 | 6300 | 1920 |
| | 180 | 6577 | 2005 |
| | 190 | 7240 | 2207 |
| | 200 | 8103 | 2470 |
| | 260 | 8310 | 2533 |
| | 310 | 8945 | 2726 |
| | 320 | 10083 | 3073 |
| | 465 | 11205 | 3415 |
| | 510 | 12080 | 3682 |
| | 660 | 12800 | 3901 |
| 290 | 170 | 7370 | 2246 |
| | 240 | 8425 | 2568 |
| | 310 | 10070 | 3069 |
| | 510 | 10940 | 3335 |
| | 660 | 14710 | 4484 |
| | 920 | 16050 | 4892 |
| 310 | 140 | 6680 | 2036 |
| | 210 | 8440 | 2573 |
| | 290 | 9535 | 2906 |
| | 400 | 10070 | 3069 |
| | 590 | 10710 | 3264 |
| | 670 | 12117 | 3693 |
| | 885 | 14200 | 4328 |

Appendix A (continued)

Stacking Velocities (continued)

| CDP | Time (ms) | Velocities (ft/s) | Velocities (m/s) |
|---|---|---|---|
| 360 | 140 | 6940 | 2115 |
| | 230 | 8100 | 2469 |
| | 290 | 9370 | 2856 |
| | 400 | 10070 | 3069 |
| | 510 | 10940 | 3335 |
| | 670 | 12800 | 3901 |
| 435 | 150 | 6450 | 1966 |
| | 290 | 7710 | 2350 |
| | 380 | 9700 | 2957 |
| | 570 | 10480 | 3194 |
| | 645 | 11470 | 3496 |
| 450 | 120 | 6680 | 2036 |
| | 230 | 8800 | 2682 |
| | 310 | 10070 | 3069 |
| | 400 | 10940 | 3335 |
| | 510 | 12080 | 3682 |
| | 730 | 14710 | 4484 |
| 555 | 140 | 6680 | 2036 |
| | 200 | 8310 | 2533 |
| | 290 | 9700 | 2957 |
| | 380 | 10480 | 3194 |
| | 450 | 11470 | 3496 |
| | 700 | 16050 | 4892 |
| 635 | 170 | 6350 | 1935 |
| | 240 | 6940 | 2115 |
| | 310 | 9335 | 2845 |
| | 390 | 9700 | 2957 |
| | 510 | 11470 | 3496 |
| | 630 | 12080 | 3682 |
| | 885 | 14200 | 4328 |
| 655 | 170 | 6450 | 1966 |
| | 225 | 6940 | 2115 |
| | 300 | 9178 | 2797 |
| | 410 | 9700 | 2957 |
| | 500 | 10070 | 3069 |
| | 610 | 11470 | 3496 |

Appendix A (continued)

Stacking Velocities (continued)

|  | Time |  | Velocities |
|---|---|---|---|
| CDP | (ms) | (ft/s) | (m/s) |
| 690 | 150 | 6940 | 2115 |
|  | 220 | 7900 | 2408 |
|  | 260 | 8310 | 2532 |
|  | 370 | 10480 | 3194 |
|  | 500 | 12080 | 3682 |
|  | 730 | 14710 | 4484 |
| 720 | 170 | 6940 | 2115 |
|  | 210 | 7710 | 2350 |
|  | 300 | 9070 | 2765 |
|  | 400 | 9370 | 2856 |
|  | 490 | 10070 | 3069 |
|  | 620 | 12080 | 3682 |
| 750 | 130 | 6680 | 2036 |
|  | 180 | 7900 | 2408 |
|  | 300 | 9370 | 2856 |
|  | 400 | 9700 | 2957 |
|  | 500 | 10070 | 3069 |
|  | 680 | 12080 | 3682 |
|  | 890 | 12800 | 3901 |
| 810 | 150 | 6940 | 2115 |
|  | 220 | 7740 | 2359 |
|  | 290 | 9700 | 2957 |
|  | 400 | 10070 | 3069 |
|  | 510 | 10940 | 3335 |
|  | 660 | 12080 | 3682 |
| 950 | 130 | 6810 | 2076 |
|  | 220 | 7710 | 2350 |
|  | 310 | 9370 | 2856 |
|  | 420 | 10700 | 3261 |
|  | 510 | 10840 | 3304 |
|  | 670 | 12800 | 3901 |
| 990 | 210 | 6680 | 2036 |
|  | 300 | 10070 | 3069 |
|  | 460 | 10840 | 3304 |
|  | 510 | 11470 | 3496 |
|  | 690 | 13860 | 4225 |

Appendix A (continued)

Stacking Velocities (continued)

| CDP | Time (ms) | (ft/s) | Velocities (m/s) |
|---|---|---|---|
| 1010 | 170 | 6570 | 2003 |
| | 220 | 8310 | 2533 |
| | 310 | 10480 | 3194 |
| | 410 | 12080 | 3682 |
| | 510 | 14710 | 4484 |
| | 690 | 17820 | 5432 |
| 1040 | 120 | 6680 | 2036 |
| | 190 | 7710 | 2350 |
| | 290 | 9370 | 2856 |
| | 480 | 10070 | 3069 |
| | 650 | 12080 | 3682 |
| 1060 | 120 | 6810 | 2076 |
| | 230 | 8310 | 2533 |
| | 380 | 9070 | 2765 |
| | 480 | 10070 | 3069 |
| | 750 | 14710 | 4484 |
| 1140 | 180 | 7220 | 2201 |
| | 260 | 8670 | 2643 |
| | 410 | 12080 | 3682 |
| | 485 | 13660 | 4164 |
| | 650 | 16050 | 4892 |
| 1210 | 110 | 6840 | 2085 |
| | 180 | 8100 | 2469 |
| | 315 | 8800 | 2682 |
| | 400 | 9700 | 2957 |
| | 475 | 10480 | 3194 |
| | 640 | 12080 | 3682 |
| | 760 | 13660 | 4164 |
| 1290 | 140 | 7220 | 2201 |
| | 190 | 8540 | 2603 |
| | 300 | 11470 | 3496 |
| | 390 | 12800 | 3901 |
| | 460 | 14710 | 4484 |
| | 760 | 17820 | 5432 |

Appendix A (continued)

Stacking Velocities (continued)

| CDP | Time (ms) | Velocities (ft/s) | Velocities (m/s) |
|---|---|---|---|
| 1325 | 170 | 6570 | 2003 |
| | 315 | 8310 | 2533 |
| | 365 | 9730 | 2966 |
| | 485 | 10940 | 3335 |
| | 700 | 13660 | 4164 |
| 1360 | 110 | 6450 | 1966 |
| | 190 | 6940 | 2115 |
| | 250 | 7340 | 2237 |
| | 355 | 9070 | 2765 |
| | 470 | 9700 | 2957 |
| | 685 | 10480 | 3194 |
| | 800 | 14710 | 4484 |
| 1400 | 120 | 6450 | 1966 |
| | 180 | 7710 | 2350 |
| | 310 | 9700 | 2957 |
| | 360 | 10070 | 3069 |
| | 490 | 11470 | 3496 |
| | 670 | 14710 | 4484 |
| 1435 | 150 | 6450 | 1966 |
| | 310 | 9070 | 2765 |
| | 380 | 9700 | 2957 |
| | 565 | 10480 | 3194 |
| | 645 | 11470 | 3496 |

Normal moveout -- eliminating stretched amplitudes greater than four/thirds of the original.

Automatic gain control scaling -- 50 ms window, based on absolute value of largest amplitude in window.

Common depth point stacking.

# APPENDIX B

# COMPUTER PROGRAMS

# SOURCE CODE

```
C
C     PROGRAM TO CONSTRUCT A SEISMIC MODEL FROM USER-SUPPLIED DEPTH-VELOCITY PAIRS.
C     OUTPUT IS IN THE FORM OF SEGY-READY REFLECTION COEFFECIENT SERIES.
C     THE OUTPUT SERIES SHOULD THEN BE CONVOLVED USING THE SPEX *FILT
C     ROUTINE TO PRODUCE THE ACTUAL "WIGGLE TRACE" MODEL.
C
C     DEPTH-VELOCITY PAIRS MUST BE IN F12.5 FORMAT.
C     THE USER IS EXPECTED TO SUPPLY ENOUGH INFORMATION ABOUT THE
C     GEOLOGICAL CONFIGURATION SO THAT ONLY A SIMPLE, STRAIGHT LINE
C     INTERPOLATION IS NEEDED.  ALL LAYERS USED MUST BE SPECIFIED IN
C     EACH USER-SUPPLIED DEPTH-VELOCITY SERIES.
C     IF A LAYER IS PINCHED-OUT OR DOES NOT EXIST FOR PORTIONS OF THE
C     MODEL, THE LAYER MUST BE CARRIED THROUGH THE NON-EXISTING PARTS
C     BY INDICATING THE LAYER'S DEPTH AS THE DEPTH OF THE BOUNDARY AT
C     WHICH IT PINCHES-OUT.
C     IN OTHER WORDS, IF TWO LAYERS ARE GIVEN THE SAME DEPTH VALUE, THIS
C     INDICATES TO THE PROGRAM ZERO THICKNESS OF THE SECOND LAYER.
C
C     ****************************************************************
C
C     LIST OF VARIABLES
C     ****************************************************************
C

      CHARACTER*50  FILNAM
      REAL  DEPTH(25,100), RC(25,100), DEP, VEL1, VEL2, VEL(25,100)
      REAL  COEF, MAXDEP, MINDEP, TTMAX, TTMIN, TRACE(25,4000)
      REAL  VELIN(5,100), DEPIN(5,100), TTIN(5,100), TAPE2(4000)
      INTEGER  CDP1, CDP2, INTVL, CDP(25), CDPMIN, CDPMAX, J, P, C(5)
      INTEGER  SAMPLNUM, Q, NUM
      INTEGER*2  IIFC/21/,IOFC/20/,ISIZ/4/,IHFC/22/,IHPFC/23/
      CHARACTER*1  ANS
      COMMON/MODEL/TT(25,100)
C
C     INITIALIZE GRFMAN PLOTTING ROUTINE
C     ****************************************************************
C

      OPEN (IIFC, FILE="@INPUT", FORM="UNFORMATTED", RECFM="DYNAMIC")
      OPEN (IOFC, FILE="@OUTPUT", FORM="UNFORMATTED",
      &          RECFM="DYNAMIC", MAXRECL=8000)
      OPEN (IHFC, FILE=":KGSVS2:GIMMAP:HERSHEY4", ACCESS="DIRECT",
      &          MODE="BINARY", RECL=162)
      OPEN (IHPFC, FILE=":KGSVS2:GIMMAP:ALPTRS4", ACCESS="DIRECT",
      &          MODE="BINARY", RECL=380)
      CALL GMCINI (ISIZ,IIFC,IOFC)
      CALL GMBINI
C
```

```
C      ASK FOR METHOD OF USER INPUT.
C      ***************************************************************
C
 20    WRITE (*,*) "DO YOU HAVE DEPTH-VELOCITY FILES ALREADY CREATED"
       WRITE (*,*) "                                     IN F12.5 FORMAT? --- "
       READ (*,371) ANS
C
C      CHANGE CHARACTER RESPONSE TO UPPER CASE LETTERS.
C      ***************************************************************
C
       CALL ZAPUP (ANS)
       IF (ANS .EQ. "N") CALL INPUT
C
C      ZERO ALL THE ARRAYS.
C      ***************************************************************
C
       CALL INIT (CDP, DEPTH, FC, VEL, VELIN, DEPIN, C, TAPE2, TRACE)
C
C      SET UP ARRAYS FOR DEPTH AND VELOCITIES
C      FROM EXTERNAL FILES SUPPLIED BY THE USER.
C      ***************************************************************
C
C      INPUT IS FROM FILES OF DEPTH-VELOCITY PAIRS, WITH DEPTH
C      CORRESPONDING TO THE TOP OF THE LAYER.  VELOCITY IS DEFINED
C      BETWEEN THE PAIRED DEPTH AND THE NEXT LOWER DEPTH.
C      ***************************************************************
C
       SAMPLNUM = 0
       MAXDEP = 0.0
       TTMIN = 0.0
       TTMAX = 0.0
       P = 1
       WRITE(*,*)"WHAT IS THE FIRST DEPTH VS. VELOCITY SERIES FILENAME? --- "
       READ (*,40) FILNAM
 40    FORMAT (A50)
       J = 1                            !J IS THE TOTAL NUMBER OF TRACES USED.
       WRITE(*,*)"WHAT IS THE TRACE NUMBER FOR THIS FILE? --- "
       READ *, CDP1
       CDPMIN = CDP1
       C(P) = CDP1                      !ARRAY C HOLDS USER-SUPPLIED TRACE NUMBERS.
 90    OPEN(1, FILE=FILNAM, RECFM="DS", ERR=500)
       READ(1,95, END=200, ERR=901) DEP, VEL1
 95    FORMAT (F12.5, 2X, F12.5)
       TIME = 0.0
       I = 1
       DEPIN(P,I) = DEP
```

```
      MINDEP = DEP
      VELIN(P,I) = VEL1
 100  I = I + 1
      READ(1,55,END=200, ERR=902) DEP, VEL2
      VELIN(P,I) = VEL2
      DEPIN(P,I) = DEP
      TIME = TIME + (2000*(DEP-DEPIN(P,I-1))/VELIN(P,I-1))
      TTIN (P,I) = TIME
      IF (TIME .GT. TTMAX) TTMAX = TIME
      IF (DEP .GE. MAXDEP) MAXDEP = DEP               !SET MAXIMUM
      IF (DEP .LE. MINDEP) MINDEP = DEP               !AND MINIMUM DEPTHS.
      GO TO 100
 200  CLOSE (1)
C
C     SAMPLNUM CONTAINS THE TOTAL NUMBER OF LAYERS.
C     ****************************************************************
C
      IF (I .GT. SAMPLNUM) SAMPLNUM = I - 1
C
C     ASK FOR NEXT USER-SUPPLIED DEPTH-VELOCITY SERIES AND PUT IT INTO
C     THE NEXT ARRAY COLUMN.
C     ****************************************************************
C
      WRITE(*,*)"WHAT IS THE FILE NAME FOR THE NEXT DEPTH VS. VELOCITY SERIES?"
      WRITE(*,*)"IF THERE ARE NO MORE, TYPE 'N'. --- "
      READ (*,40) FILNAM
      CALL ZAPUP (FILNAM)
      IF(FILNAM .EQ. "N") GO TO 300
      WRITE(*,*)"WHAT IS THE TRACE NUMBER FOR THIS FILE? --- "
      READ *,CDP2
      CDPMAX = CDP2
C
C     P IS THE NUMBER OF TRACES SUPPLIES BY THE USER.
C     ****************************************************************
C
      P = P + 1
      C(P) = CDP2
C
      J = J + ABS(CDP1-CDP2)!INCREMENT J TO REFLECT THE TOTAL NUMBER OF
      CDP1 = CDP2              !TRACES IN THE MODEL.
      GO TO 50
C
C     END OF USER-SUPPLIED DEPTH-VELOCITY INPUT.  NEXT PLOT GIVEN
C     MODEL OR CHANGE IT AS THE USER REQUESTS.
C     ****************************************************************
C
```

```
 300  WRITE (*,*) "END OF MODEL INPUT."
      WRITE (*,*) "DO YOU WANT A PLOT OF THE MODEL? --- "
      READ (*,371) ANS
 371  FORMAT (A1)
      CALL ZAPUF (ANS)
      IF (ANS .EQ. "Y") CALL PLOT(CDPMIN,CDPMAX,MAXDEP,MINDEP,P,C,
     &                     DEPIN,J,SAMPLNUM,TTIN,TTMAX,TTMIN,IHFC,IHPFC)
C
      WRITE (*,*) "DO YOU WANT TO CHANGE THE MODEL? --- "
      READ (*,371) ANS
      CALL ZAPUF (ANS)
        DO WHILE (ANS.EQ."Y")
 373  CALL CHANGE(VELIN,DEPIN,TTIN,TTMAX,C,P,SAMPLNUM,
     &                              J,TTMIN,MAXDEP,CDPMIN,CDPMAX,MINDEP,IHPFC,IHFC)
      WRITE (*,*) "DO YOU WANT A PLOT OF THE NEW MODEL?. . . "
        READ (*,371) ANS
      CALL ZAPUF (ANS)
      IF (ANS .EQ. "Y") CALL PLOT(CDPMIN,CDPMAX,MAXDEP,MINDEP,P,C,
     &  DEPIN,J,SAMPLNUM,TTIN,TTMAX,TTMIN,IHFC,IHPFC)
      WRITE (*,*) "DO YOU WANT TO CHANGE THE MODEL? --- "
      READ (*,371) ANS
      CALL ZAPUF (ANS)
        END DO
C
C     AFTER MODEL HAS BEEN PLOTTED AND CHANGED AND IS ACCEPTABLE TO
C     THE USER, THE NEXT STEP IS TO INTERPOLATE BETWEEN THE USER
C     INPUT FILES AND FORMAT THE DATA INTO A SPEX COMPATIBLE FILE.
C     ***************************************************************
C
      WRITE (*,*) "DO YOU WANT THE REFLECTION COEFFICIENTS WRITTEN IN SEGY"
      WRITE (*,*) "FORMAT -- I.E. GENERATE A SPEX DATAFILE? --- "
      READ (*,371) ANS
      CALL ZAPUF (ANS)
C
C     INTERPOLATION SUBROUTINE WILL FILL IN THE INTERVAL OF THE RC,
C     DEPTH, AND VEL ARRAYS BETWEEN THE
C     DEPTH-VELOCITY SERIES SUPPLIED BY THE USER.
C     ***************************************************************
C
C     TWOWAY WILL CALCULATE TWO-WAY TIME FOR ALL REFLECTION COEFFICIENTS.
C     ******************************************************************
C
C     TAPEGEN CREATES A SEGY DATA FILE FOR SPEX AND ASSUMES A TWO-
C     MILLISECOND SAMPLE INTERVAL AND TWELVE-FOLD STACKED CDP TRACES.
C     ***************************************************************
C
```

```
C
C     SUBROUTINE TO CHANGE THE TRACE LENGTH AND NUMBER OF SAMPLES
C     TO THAT SPECIFIED BY THE USER.  MAXIMUM NUMBER OF SAMPLES PER
C     TRACE IS 4000.
C
C     *****************************************************************
C
      SUBROUTINE OUT (TRHOUT, TAPE2, R, L)
      INTEGER*2  TRHOUT(120), L
      INTEGER*4  R
      REAL TAPE2(R)
      WRITE (1) L, TRHOUT, TAPE2
      RETURN
      END
```

```
C
C     PLOT ROUTINE WILL PLOT BOTH DEPTH AND TWO-WAY TIME LINE DRAWINGS
C     OF THE SEISMIC MODEL.
C
C     *****************************************************************
C
      SUBROUTINE PLOT(CDPMIN,CDPMAX,MAXDEP,MINDEP.P,C.DEPIN,J,
     &                   SAMPLNUM, TTIN, TTMAX, TTMIN, IHFC, IHPFC)
      INTEGER  CDPMIN, CDPMAX, P, C(5), J, SAMPLNUM, V
      REAL  MAXDEP,MINDEP,DEPIN(5,100),POINT.CCDPMIN,CCDPMAX.NEGTIM(5,100)
      REAL  CC(5), TTIN(5,100), TTMAX, TTMIN,NEGDEP(5,100),TOP,BOT
      INTEGER*2  NNN1/0/, NNN2/900/, NNN3/700/, NNN4/100/, NNN5/75/
      INTEGER*2  NNN6/1000/, NNN7/750/, NWAIT, IHFC, IHPFC, X/3/
      INTEGER*2  ICSET/9/, IJ/0/, IDEV/1/
      INTEGER*4  IPOINT
      CHARACTER*1  ANS
      CHARACTER*1  ITERM, STRARR(100)
      CHARACTER*50  STRING
      CHARACTER*75  DSTRING, TSTRING
C
      WRITE (*,*) "WHAT IS THE TITLE FOR THIS MODEL?"
      READ (*,500) STRING
 500  FORMAT (A)
C
C     READ TITLE STRING INTO CHARACTER ARRAY.
C     *****************************************************************
C
      DSTRING = "DEPTH MODEL - "//STRING//"/"
      DO 505 I = 1,100
         STRARR(I) = DSTRING(I:I)
 505  CONTINUE
C
C     PLOT DEPTH MODEL
C     *****************************************************************
C
      ITERM = "/ "
      NWAIT = 0
      TOP = -MINDEP
      BOT = -MAXDEP - 50.0
      CALL GMCERA
      CALL GMCGMD
      CCDPMIN = CDPMIN
      CCDPMAX = CDPMAX
C
C     SET UP SCREEN WINDOW AND VIRTUAL WINDOW.
C     *****************************************************************
```

```
C
      CALL GMSWND (NNN4, NNN5, NNN2, NNN3)
      CALL GMVWND (CCDPMIN, BOT, CCDPMAX, TOP)
      CALL GMCEMD
      CALL GMCCSZ (X)
      CALL GMCZMD (X)
      CALL GMVFRM (X)
      DO 509 I = 1,P
         CC(I) = C(I)                  !CONVERT FROM INTEGER TO REAL.
C
C     CHANGE DEPTH VALUES TO NEGATIVE VALUES SO THAT Y-AXIS STARTS AT
C     LOWER VALUES AND GOES TO HIGHER VALUES (DEPTH AXIS).
C     **************************************************************
C
         DO 510 M = 1,SAMPLNUM
            NEGDEP(I,M) = -DEPIN(I,M)
            NEGTIM(I,M) = -TTIN(I,M)
 510     CONTINUE
 509  CONTINUE
C
C     PUT PLOTTING LINES FOR DEPTH MODEL INTO BUFFER.
C     **************************************************************
C
      DO 511 I = 1,SAMPLNUM
         CALL GMBGMD
         CALL GMBVCR (CC(1), NEGDEP(1,I))
         DO 521 K = 2,P
            CALL GMBVCR (CC(K), NEGDEP(K,I))
 521     CONTINUE
 511  CONTINUE
C
C     PLOT DEPTH MODEL LINES.
C     **************************************************************
C
      CALL GMBPLT (NWAIT)
C
C     PLOT TITLE FOR DEPTH MODEL
C     **************************************************************
C
      CALL GMCEMD
      CALL GMSWND (NNN1, NNN1, NNN6, NNN7)
      CALL GMVWND (0.0, 0.0, 1000.0, 750.0)
      CALL GMTITL(0.,725.,-1.,-1.,STRARR,ITERM,10.,0.,ICSET,IJ,IDEV,IHFC,IHPFC)
C
C     PLOT UNIT VALUES FOR AXES - DEPTH MODE
C     **************************************************************
```

```
      CALL GMCSMD
      CALL GMSWND (NNN1, NNN5, NNN5, NNN3)
      CALL GMVWND(0.0, BOT, 1000.0, TOP)
      CALL GMVMOV (0.0, BOT/2)
      WRITE (*,*) "DEPTH"
      RNUM = (BOT/2) - 8
      CALL GMVMOV (0.0, RNUM)
      WRITE (*,*) "IN FT"
      SCAL = (BOT - TOP)/5
      DO 531 I = 0,5
         POINT = TOP + (SCAL*I)
         CALL GMVMOV (20.0, POINT)
         WRITE (*, 533) ABS(POINT)
 533     FORMAT (F12.1)
         CALL GMVMOV (0.0,POINT)
         WRITE (*, 534) ABS(POINT)
 534     FORMAT(103X,F12.1)
 531  CONTINUE
C
C     PLOT HORIZONTAL AXIS - CDP (TRACE) NUMBERS
C     ******************************************************************
C
      CALL GMCSMD
      CALL GMSWND (NNN4, NNN1, NNN2, NNN7)
      CALL GMVWND (CCDPMIN, 0.0, CCDPMAX, 750.0)
      CALL GMVMOV (0.0, 10.0)
      WRITE(*,537)
 537  FORMAT (55X,"TRACE NUMBERS")
      CALL GMVMOV (0.0, 15.0)
C
C     DETERMINE HOW OFTEN CDP'S SHOULD BE LABELLED ON X-AXIS.
C     ******************************************************************
C
      IF ((CDPMAX-CDPMIN) .LE. 20) V = 1
      IF (((CDPMAX-CDPMIN) .GT. 20).AND.((CDPMAX-CDPMIN) .LE. 60)) V=4
      IF (((CDPMAX-CDPMIN).GT.60).AND.((CDPMAX-CDPMIN) .LE. 200)) V=10
      IF ((CDPMAX-CDPMIN) .GT. 200) V = 100
      DO 539 I = 0, (CDPMAX-CDPMIN), V
         IPOINT = CDPMIN + I
         POINT = IPOINT
         CALL GMVNUM (POINT,45.0,IPOINT)
 539  CONTINUE
      NWAIT = 1
      CALL GMBPLT(NWAIT)
C
```

```
C      HAVE HARD COPY MADE OF SCREEN IMAGE.
C      ******************************************************************
C
       CALL GMCHCP
C
       CALL GMSWND (NNN1, NNN1, NNN5, NNN7)
       CALL GMVWND (0.0, 0.0, 1000.0, 750.0)
       CALL GMVMOV (0.0,20.0)
       WRITE (*,*) "DO YOU WANT THIS MODEL PLOTTED IN TWO-WAY TIME? --- "
       READ (*,500) ANS
       CALL ZAPUP (ANS)
C
C      ERASE SCREEN.
C      ******************************************************************
C
       CALL GMCERA
       IF (ANS .EQ. "N") RETURN
C
C      PLOT TWO-WAY TIME MODEL
C      ******************************************************************
C
C
       TOP = -TTMIN
       BOT = -TTMAX - 50.0
       CALL GMCGMD
       CALL GMSWND (NNN4,NNN5,NNN2,NNN3)
       CALL GMVWND (CCDPMIN, BOT, CCDPMAX, TOP)
       CALL GMCGMD
       CALL GMVFRM (X)
C
C      PUT TIME MODEL PLOTTING LINES INTO BUFFER.
C      ******************************************************************
C
       DO 541 I = 1, SAMPLNUM
          CALL GMBGMD
          CALL GMBVDR (CC(1),NEGTIM(1,I))
          DO 543 K = 2, P
             CALL GMBVDR (CC(K),NEGTIM(K,I))
 543      CONTINUE
 541   CONTINUE
       NWAIT = 0
C
C      PLOT BUFFER CONTENTS TO SCREEN.
C      ******************************************************************
C
       CALL GMBPLT (NWAIT)
```

```
C
C     PLOT TITLE FOR TWO-WAY TIME MODEL.
C     ********************************************************
C
      CALL GMCGMD
      CALL GMSWND (NNN1, NNN1, NNN6, NNN7)
      CALL GMVWND (0.0, 0.0, 1000.0, 750.0)
      TSTRING = "TWO-WAY TIME MODEL - "//STRING//"/"
      DO 555 I = 1,100
         STRARR (I) = TSTRING (I:I)
 555  CONTINUE
      CALL GMTITL(0.,725.,-1.,-1.,STRARR,ITERM,10.,0.,ICSET,IJ,IDEV,IHFC,IHFFC)
C
C     PLOT UNIT VALUES FOR AXES - TWO-WAY TIME MODE
C     ********************************************************
C
      CALL GMCGMD
      CALL GMSWND (NNN1, NNN5, NNN6, NNN3)
      CALL GMVWND (0.0, BOT, 1000.0, TOP)
      CALL GMVMOV (0.0, (BOT/2)+8)
      WRITE (*,*) "TWO-WAY"
      CALL GMVMOV (0.0, BOT/2)
      WRITE (*,*) "TIME IN"
      CALL GMVMOV (0.0, (BOT/2)-8)
      WRITE (*,*) "MILLISEC"
      SCAL = (BOT - TOP)/5
      DO 581 I = 0, 5
         POINT = TOP + (SCAL*I)
         CALL GMVMOV (20.0, POINT)
         WRITE (*,574) ABS(POINT)
 574     FORMAT (F12.1)
         CALL GMVMOV (0.0, POINT)
         WRITE (*,575) ABS(POINT)
 575     FORMAT (103X,F12.1)
 581  CONTINUE
C
C     PLOT HORIZONTAL AXIS - TWO-WAY TIME MODEL
C     ********************************************************
C
      CALL GMCGMD
      CALL GMSWND (NNN4, NNN1, NNN2, NNN7)
      CALL GMVWND (CCDPMIN, 0.0, CCDPMAX, 750.0)
      CALL GMVMOV (0.0, 15.0)
      WRITE (*,537)
      DO 587 I = 0,(CDPMAX-CDPMIN), V
         IPOINT = CDPMIN + I
```

```
          POINT = IPOINT
          CALL GMVNUM (POINT,40.0,IPOINT)
  587   CONTINUE
          NWAIT = 1
        CALL GMBPLT (NWAIT)
C
C       HAVE HARD COPY MADE OF SCREEN IMAGE.
C       ***************************************************************
C
        CALL GMCHCP
        PAUSE
C
C       ERASE SCREEN AND RETURN TO MAIN PROGRAM.
C       ***************************************************************
C
        CALL GMCERA
        RETURN
        END
C
```

```
C
C       THIS SUBROUTINE CREATES THE REEL HEADER  AND TRACE HEADERS
C       FOR STACKED CDP TRACES - TWELVE FOLD. THE TRACES CONSIST OF
C       THE REFLECTION COEFFICIENTS.  WRITTEN BY READY, 1984.  MODIFIED
C       BY ROEHL, 1984.
C
C***********************************************************************
C
        SUBROUTINE TAPEGEN(TRACE,CDP,P,J,SAMPLNUM,Q,NUM)
        REAL  TRACE(25,4000), TAPE2(4000)
        INTEGER  CDP(25), P, J, SAMPLNUM, N, M, D, G, R, NUM
        INTEGER*2  L,K,REEL1(1600),REEL2(200),TRHOUT(120)
        CHARACTER*1 ANS
        CHARACTER*20  FILNAM
        COMMON/MODEL/TT(25,100)
C
        WRITE (*,*) "WHAT DO YOU WANT YOUR SPEX DATA FILE NAMED? --- "
        READ (*,810) FILNAM
 810    FORMAT(A20)
        OPEN (1,STATUS="NEW",RECFM="DYNAMIC",FILE=FILNAM,FORM="UNFORMATTED",MODE="BINARY")
C
C       D IS THE TRACE LENGTH IN MILLISECONDS (IF LENGTH IS GREATER THAN
C       OR EQUAL TO 1000 MILLISECONDS) OR MICROSECONDS (IF LENGTH IS
C       LESS THAN 1000 MILLISECONDS).
C       *****************************************************************
C
        D = Q
        IF (Q .GE. 1000) D = Q/1000
        WRITE (*,*) "YOU HAVE ", NUM, " SAMPLES IN EACH TRACE."
        WRITE (*,*) "HOW MANY SAMPLES DO YOU WANT PER TRACE? --- "
        READ (*,*) R
C
C       WRITE THE REEL HEADER DATA INTO ARRAY REEL2 FROM USER-SPECIFIED
C       SAMPLE INTERVAL (D) AND NUMBER OF TRACES(R).
C       *****************************************************************
C
        REEL2(7)=1
        REEL2(9)=D
        REEL2(10)=D
        REEL2(11)=R
        REEL2(12)=R
        REEL2(13)=1
        REEL2(15)=1
        L=1600
        K=200
C
```

```
C     WRITE REEL HEADERS TO THE SPEX FILE.
C     ****************************************************************
C
      WRITE(1)L,REEL1,K,REEL2
C
C     CALCULATE THE NUMBER OF BYTES NEEDED FOR EACH TRACE (INCLUDES
C     THE TRACE HEADER).
C     ****************************************************************
C
      L= 120 + (R*2)
      I = 1
      DO WHILE (I.LE.J)
C
C     INITIALIZE ARRAY TAPE2.
C     ****************************************************************
C
         DO N = 1, 4000
            TAPE2(N) = 0.0
         END DO
C
C     WRITE TRACE DATA FROM 2-D TRACE ARRAY INTO 1-D TAPE2 ARRAY.
C     ****************************************************************
C
         DO N = 1,R
                TAPE2(N) = TRACE(I,N)
         END DO
C
C     WRITE TRACE HEADERS INTO 1-D ARRAY TRHOUT.
C     ****************************************************************
C
         TRHOUT(2)=I
         TRHOUT(4)=I
         TRHOUT(6)=I
         TRHOUT(8 )=1
         TRHOUT(12)=CDP(I)
         TRHOUT(14)=1
         TRHOUT(15)=1
         TRHOUT(17)=12
         TRHOUT(18)=1
         TRHOUT(58)=R
         TRHOUT(59)=D
         TRHOUT(88)=1
         TRHOUT(92)=I
         TAPE2(1) = .000001
         TAPE2(R) = .000001
C
```

```
C       CALL SUBROUTINE OUT TO CHANGE TO SIZE OF ARRAY TAPE2 TO THE USER
C       SPECIFIED SIZE, AND WRITE SAMPLED DATA IN SPEX FORMAT.
C       ***************************************************************
C
           CALL OUT (TRHOUT, TAPE2, R, L)
                I = I + 1
        END DO
        CLOSE (1)
        RETURN
        END
```

```
C
C      CALCULATION OF TWO-WAY TIME USING DEPTH AND VELOCITY
C      FOR ENTIRE SYNTHETIC MODEL
C      REFLECTION COEFFICIENTS ARE ALSO WRITTEN TO THE TIME
C      SERIES ARRAY TRACE.  THIS ARRAY WILL CONTAIN ZEROES
C      EXCEPT DURING THE TIME INTERVALS THAT REFLECTION
C      COEFFICIENTS ARE ENCOUNTERED.
C
C      **************************************************************
C
      SUBROUTINE TWOWAY (DEPTH,VEL,J,SAMPLNUM,RC,Q,TRACE,NUM)
      REAL   DEPTH(25,100),VEL(25,100),TIME,RC(25,100),TRACE(25,4000)
      INTEGER  M,N,J,SAMPLNUM,NUM,S,Q,FLAG,INT
      COMMON/MODEL/TT(25,100)
C
      FLAG = -1
 101    M = 1
      DO WHILE (M .LE. J)
         N = 2
         NUM = 1
         INT = 0
         TIME = 0.0
         DO WHILE (N .LE. SAMPLNUM)
C
C      CALCULATE THE TWO-WAY TIME IN MICROSECONDS DOWN AND BACK FROM
C      THE TOP OF THE NTH LAYER.
C      **************************************************************
C
            TIME = TIME + ((2000*(DEPTH(M,N)-DEPTH(M,N-1))/VEL(M,N-1)) * 1000)
            TT(M,N) = TIME
C
C      INCREMENT THE SAMPLING INTERVAL (INT) AND THE COUNTER NUM TO
C      THE PROPER TIME (ARRAY POSITION) THAT CORRESPONDS TO THE
C      TWO-WAY TIME JUST CALCULATED.
C      **************************************************************
C
            DO WHILE (TIME .GT. INT+(Q/2))
               INT = INT + Q
               NUM = NUM + 1
            END DO
            IF ((TIME .LE. INT+Q/2) .AND. (TIME .GT. INT-Q/2)) THEN
C
C      CHECK TO SEE IF INT HAS BEEN INCREMENTED BEFORE ASSIGNING THE
C      NEW TIME VALUE.  IF IT HAS NOT BEEN INCREMENTED, THEN THE SAMPLE
C      INTERVAL IS NOT FINE ENOUGH, AND USER IS ASKED FOR A SMALLER
C      SAMPLE INTERVAL.
```

```
C     ****************************************************************
C
               IF (FLAG .EQ. INT) THEN
                  IF (TT(M,N) .NE. TT(M,N-1)) THEN
                     WRITE (*,*)"SAMPLE INTERVAL IS TOO LARGE FOR YOUR DATA SET."
                     WRITE (*,*)"PLEASE TYPE IN A SMALLER SAMPLE  INTERVAL."
                     WRITE (*,*)"REMEMBER, IT MUST BE IN MICROSECONDS. --- "
                     READ (*,*) Q
                     GO TO 101
                  END IF
               END IF
                                FLAG = INT
               IF (RC(M,N) .NE. 0.0) TRACE(M,NUM)=RC(M,N)
            END IF
C
C     INCREMENT THE DEPTH AND VELOCITY ARRAYS TO THE NEXT DEEPER LAYER
C     ****************************************************************
C
            N = N + 1
         END DO
C
C     INCREMENT THE TRACE NUMBER.
C     ****************************************************************
         M = M + 1
      END DO
      M = 1
C
C     REDIMENSION TIME ARRAY FROM MICROSECONDS TO MILLISECONDS FOR
C     EASIER DISPLAY AND FASTER COMPREHENSION.
C     ****************************************************************
C
      DO WHILE (M .LE. J)
         L = 1
         DO WHILE (L .LE. SAMPLNUM)
            TT(M,L) = TT(M,L)/1000.0
            L = L + 1
         END DO
         M = M + 1
      END DO
      RETURN
      END
```

```
!
!     subroutine ZAPUP
!
!     Last update:  3/24/84
!
!     Force the alphabetic characters in a string to be upper case.
!
!     A KANSAS GEOLOGICAL SURVEY LIBRARY ROUTINE
!

      subroutine ZAPUP (S)

      implicit none

      integer N
      character*(*) S

      intrinsic char
      intrinsic ichar
      intrinsic len


      do N = 1, len(S)
         if (S(N:N).ge."a" .and. S(N:N).le."z") S(N:N) = char(ichar(S(N:N))-32)
      end do
      return

      end
```

```
C
C     INTERACTIVE ROUTINE TO ALLOW THE USER TO CHANGE DEPTH,
C     TWO-WAY TIME, AND VELOCITY VALUES OF THE SYNTHETIC SEISMIC MODEL.
C     SUBROUTINE DOES NOT ALLOW FOR INSERTION OR DELETION OF LAYERS.
C
C     *****************************************************************
C
      SUBROUTINE CHANGE (VELIN, DEPIN, TTIN, TTMAX, C, P, SAMPLNUM,
     &                   J,TTMIN,MAXDEP,MINDEP,CDPMIN,CDPMAX,IHFC,IHPFC)
      REAL  VELIN(5,100), DEPIN(5,100), TTIN(5,100), TTMAX
      REAL  TTMIN, MAXDEP, MINDEP, VALUE
      INTEGER  C(5), P, SAMPLNUM,J,CDPMIN,CDPMAX,L,I,NUCDP,NULAYER
      INTEGER*2  IHFC, IHPFC
      CHARACTER*1  ANS
C
C     DISPLAY ALL VALUES SUPPLIED BY THE USER (DEPTH-VELOCITY PAIRS)
C     *****************************************************************
C
 101  DO 103 I = 1, P
         WRITE (*, 109) " CDP NUMBER =  ",C(I)
 109     FORMAT (A,I3,34X)
         WRITE (*,*)" LAYER       DEPTH         VELOCITY    2-WAY TIME"
         DO 112 L = 1, SAMPLNUM
            WRITE(*,113)L,DEPIN(I,L),VELIN(I,L),TTIN(I,L)
 113        FORMAT(I3,6X,3(F12.5))
 112     CONTINUE
 103  CONTINUE
C
C     ASK FOR WHICH CDP AND LAYER ARE TO BE CHANGED.
C     *****************************************************************
C
      WRITE(*,*) "TYPE 'CDP,LAYER' FOR POINT TO BE CHANGED"
      WRITE(*,*) "IF NO MORE CHANGES ARE NEEDED, TYPE '0,0'. . . "
      READ (*,*) NUCDP, NULAYER
      IF (NUCDP .NE. 0) THEN
         I = 1
 121     IF (C(I) .NE. NUCDP) THEN        !SET I SUBSCRIPT TO BE CHANGED.
            I = I + 1
            GO TO 121
         END IF
C
C     ASK USER WHETHER DEPTH OR VELOCITY IS TO BE CHANGED.
C     *****************************************************************
C
         WRITE(*,*) "TYPE 'D' FOR NEW DEPTH OR TYPE 'V' FOR NEW VELOCITY . . . "
         READ (*,130) ANS
```

```
 130     FORMAT (A1)
         CALL ZAPUP (ANS)
         WRITE (*,*) "WHAT IS THE NEW VALUE? . . . "
         READ (*,*) VALUE
C
C     CALCULATE NEW DEPTH AND TWO-WAY TIMES IF DEPTH IS TO BE CHANGED.
C     *****************************************************************
C
         IF (ANS .EQ. "D") THEN
            DEPIN(I,NULAYER) = VALUE
            TIME = TTIN(I,NULAYER-1)
            IF (NULAYER .EQ. 1) NULAYER = 2
            DO 141 K = NULAYER,SAMPLNUM
               TIME = TIME + (2000*(DEPIN(I,K)-DEPIN(I,K-1))/VELIN(I,K-1))
               TTIN (I,K) = TIME
 141        CONTINUE
C
C     CALCULATE NEW VELOCITY AND TWO-WAY TIME IF VELOCITY IS TO BE CHANGED.
C     **********************************************************************
C
         ELSE
            VELIN(I,NULAYER) = VALUE
            TIME = TTIN(I,NULAYER)
            DO 151 K = (NULAYER+1), SAMPLNUM
               TIME = TIME + (2000*(DEPIN(I,K)-DEPIN(I,K-1))/VELIN(I,K-1))
               TTIN (I,K) = TIME
 151        CONTINUE
         END IF
C
C     CHANGE MAXIMUM TWO-WAY TIME FOR TRACES IF IT IS INCREASED.
C     *****************************************************************
C
         IF (TIME .GT. TTMAX) TTMAX = TIME
C
C     LOOP BACK UP TO ASK USER FOR THE NEXT CHANGE.
C     *****************************************************************
C
         GO TO 101
      END IF
      RETURN
      END
C
```

```
C
C     DISPLAY WILL PRINT TO THE TERMINAL INFORMATION CALCULATED
C     FOR ANY TRACE (DEPTHS, VELOCITIES, TWO-WAY TIMES, AND
C     REFLECTION COEFFICIENTS).
C
C     *****************************************************************
C
      SUBROUTINE DISPLAY (DEPTH,VEL,RC,CDP,J,SAMPLNUM)
      REAL  DEPTH(25,100), VEL(25,100), RC(25,100)
      INTEGER  CDP(25), J, T(25), SAMPLNUM
      CHARACTER*1  ANS
      CHARACTER*50 FILNAM
      COMMON/MODEL/TT(25,100)
C
      WRITE(*,*)"DO YOU WANT TO SEE ANY OF THE INTERPOLATED TRACE DATA? --- "
      READ (*,700) ANS
 700  FORMAT (A)
      CALL ZAFUF (ANS)
      IF (ANS .NE. "Y") GO TO 800          !AND WRITE OUTPUT TO FILE
C
C     ASK USER FOR THE TRACES TO BE DISPLAYED.
C     *****************************************************************
C
      WRITE (*,*) "HOW MANY TRACES? --- "
      READ (*,'(I3)') NUMBER
      DO 701 I = 1,NUMBER
         WRITE (*,*) "TRACE NUMBER = ?  "
         READ *, T(I)
 701  CONTINUE
C
C     WRITE THE TRACE DATA REQUESTED TO THE TERMINAL.
C     *****************************************************************
C
      DO 711 I = 1,NUMBER
         K = 1
 715     IF (K .GT. J) THEN
            WRITE(*,*) "<BEL>TRACE NUMBER ", T(I), " NOT FOUND."
            GO TO 711
         ELSE IF (T(I) .EQ. CDP(K)) THEN
C
C     WRITE TABLE HEADINGS TO THE SCREEN.
C     *****************************************************************
C
           M = 1
           WRITE(*,*)"COUNT DEPTH      VELOCITY    2-WAY TIME  REF. COEF."
           WRITE(*,*)"                 FT/SEC      MILLESEC"
```

```
          WRITE(*,*) CDP(K)
C
C     WRITE INTERPOLATED DEPTH, VELOCITY, TWO-WAY TIME, AND REFLECTION
C     COEFFICIENTS TO THE SCREEN.
C     ******************************************************************
C
             DO WHILE (M .LE. SAMPLNUM)
             WRITE(*,722) DEPTH(K,M),VEL(K,M),TT(K,M),RC(K,M)
 722         FORMAT (6X,F12.5,F12.5,F12.5,F12.5)
             M = M + 1
           END DO
        ELSE
           K = K + 1
           GO TO 715
        END IF
      PAUSE
 711  CONTINUE
C
C     ASK USER IF NEW FILES OF ANY OF THE INTERPOLATED DATA SHOULD BE
C     CREATED.
C     ******************************************************************
C
 800  WRITE(*,*)"DO YOU WANT ANY OF THE INTERPOLATED TRACES MADE INTO"
      WRITE(*,*)"DEPTH-VELOCITY FILES?"
      READ (*,700) ANS
      CALL ZAPUP ( ANS )
      IF (ANS .EQ. "N") RETURN
      WRITE (*,*) "ENTER TRACE NUMBER."
      WRITE (*,*) "IF NO MORE FILES ARE WANTED, TYPE '9999'. --- "
      READ (*,*) NUMBER
      IF (NUMBER .EQ. 9999) RETURN
      WRITE (*,*) "WHAT DO YOU WANT THE DEPTH-VELOCITY FILE NAMED? --- "
      READ (*,700) FILNAM
C
C     CREATE FILE AND WRITE TO IT DEPTH AND VELOCITY VALUES FROM
C     THE INTERPOLATED SEISMIC DATA.
C     ******************************************************************
C
      OPEN (1, FILE=FILNAM, STATUS="NEW", RECFM="DS")
      DO I = 1,J
        IF (CDP(I) .EQ. NUMBER) THEN
           DO K = 1, SAMPLNUM
             WRITE (*,*)I,K,DEPTH(I,K),VEL(I,K)
             WRITE (1,803) DEPTH (I,K), VEL(I,K)
 803         FORMAT (F12.5, 2X, F12.5)
           END DO
```

```
C
C     DO LOOP TO PERFORM SIMPLE, STRAIGHT-LINE INTERPOLATION.
C     CALLED BY SUBROUTINE INTERP TO DO THE ACTUAL INTERPOLATION.
C
C     *****************************************************************
C
      SUBROUTINE DOINTERP (DIFF, DEPTH, K, M, L, INTVL, VEL, RC)
      REAL  DIFF, DEPTH(25,100), VEL(25,100), RC(25,100)
      INTEGER  K, M, L, INTVL
C
C     SUBROUTINE CALCULATES VALUES BETWEEN USER INPUT VALUES, AND DOES
C     NOT ALTER USER INPUT VALUES.
C     *****************************************************************
C
            DIFF = (DEPTH(L,M) - DEPTH(K,M))/INTVL
            DO 341 N = 1, INTVL-1
               DEPTH(K+N,M) = DEPTH(K,M)+(DIFF*N)
               VEL(K+N,M) = VEL(K,M)
               RC(K+N,M) = RC(K,M)
 341        CONTINUE
            M = M + 1
      RETURN
      END
C
```

```
C
C     SUBROUTINE INIT WILL INITIALIZE ALL ARRAYS TO ZERO VALUES
C
C     *****************************************************************
C
      SUBROUTINE INIT (CDP,DEPTH,RC,VEL,VELIN,DEPIN,C,TAPE2,TRACE)
      REAL  DEPTH(25,100), RC(25,100), VEL(25.100)
      REAL  VELIN(5,100), DEPIN(5,100), TAPE2(4000), TRACE(25,4000)
      INTEGER  CDP(25), C(5)
      COMMON/MODEL/TT(25,100)
C
      DO 11 I = 1, 25
         CDP(I) = 0
         DO 12 J = 1, 100
            DEPTH (J,I) = 0.0
            RC(J,I) = 0.0
            VEL(J,I) = 0.0
            TT(J,I) = 0.0
 12      CONTINUE
 11    CONTINUE
      DO 13 I = 1, 5
         C(I) = 0
         DO 14 J = 1, 100
            VELIN (I,J) = 0.0
            DEPIN (I,J) = 0.0
 14      CONTINUE
 13   CONTINUE
      DO 15 I = 1, 4000
         TAPE2(I) = 0.0
         DO 16 J = 1,25
            TRACE (J,I) = 0.0
 16      CONTINUE
 15   CONTINUE
      RETURN
      END
```

```
C
C      SUBROUTINE TO TAKE USER DEPTH-VELOCITY PAIRS FROM THE TERMINAL
C      AND INPUT THE VALUES INTO F12.5 FORMATTED FILES.
C
C      ***************************************************************
C
       SUBROUTINE INPUT
       REAL  DEP, VEL
       INTEGER  I
       CHARACTER*1  ANS
       CHARACTER*50 FILNAM
C
 100   WRITE (*,*) "WHAT DO YOU WANT YOUR FILE NAMED?"
       READ (*,101) FILNAM
 101   FORMAT (A)
       OPEN (1, FILE=FILNAM, STATUS="NEW", RECFM="DS", ERR=202)
C
C      SUBROUTINE PROMPTS USER TO INPUT ONE DEPTH, VELOCITY PAIR PER LINE
C      *****************************************************************
C
       WRITE(*,*) "TYPE IN DEPTH,VELOCITY PAIRS; ONE PAIR OF VALUES PER LINE."
       WRITE(*,*) "TO END INPUT, TYPE '1,1'"
       I = 1
 102   WRITE (*,103) I
 103   FORMAT(" DEPTH, VELOCITY # ",I2," ---")
       READ (*,*) DEP,VEL
       IF ((DEP .EQ. 1.0) .AND. (VEL .EQ. 1.0)) GO TO 150
       WRITE (1,104) DEP,VEL
 104   FORMAT (F12.5, 2X, F12.5)
       I = I + 1
       GO TO 102
 150   WRITE (*,*) "DO YOU WANT TO CREATE ANOTHER FILE OF DEPTH, VELOCITY PAIRS? ---"
       READ (*, 101) ANS
       CALL ZAPUF (ANS)
       CLOSE (1)
       IF (ANS .EQ. "Y") GO TO 100
       RETURN
 202   WRITE (*,*) "PROBLEMS WITH TRYING TO OPEN FILE FOR USER INPUT"
       END
```

```
C
C     SUBROUTINE TO INTERPOLATE DEPTH VALUES ALONG STRAIGHT LINES
C     USING INFORMATION FROM USER SUPPLIED DEPTH, VELOCITY FILES.
C     REFLECTION COEFFICIENTS ARE THEN ASSIGNED FOR LAYER BOUNDARIES.
C       VELOCITIES ARE NOT INTERPOLATED.
C     REFLECTION COEFFICIENTS MUST BE RECALCULATED FOR THE DIFFERENT
C     TYPES OF GEOLOGIC GEOMETRIES WHICH MAY BE ENCOUNTERED (EG. PINCH
C     OUTS, DISCORDANT BOUNDARIES).
C     INTERPOLATION IS CALCULATED FROM TOP TO BOTTOM FOR A SINGLE
C     INTERVAL.  THE INTERPOLATION THEN PROGRESSES TO THE NEXT CDP
C     INTERVAL.
C
C     ****************************************************************
C
      SUBROUTINE INTERPOLATION (J,DEPTH,VEL,RC,C,P,CDPMIN,VELIN,DEPIN,SAMPLNUM,CDP)
      INTEGER  J, C(5), P, CDPMIN, L, M, INTVL, K, SAMPLNUM
      INTEGER  CDP(25), STARTK
      REAL  DEPTH(25,100), VEL(25,100), RC(25,100), DIFF
      REAL  VELIN(5,100), DEPIN(5,100)
C
C     FILL IN ONE-DIMENSIONAL CDP ARRAY.
C
      COUNT = CDPMIN
      DO 301 L = 1, J
         CDP(L) = COUNT
         COUNT = COUNT + 1
 301  CONTINUE
C
C     FILL IN DEPTH, VELOCITY AND RC ARRAYS WITH INITIAL USER-SUPPLIED DATA.
C       ****************************************************************** *****
C
      H = 1
      DO 305 I = 1,P
         DO WHILE (CDP(H) .NE. C(I))
            H = H + 1
         END DO
         VEL(H,1) = VELIN(I,1)
         DEPTH(H,1) = DEPIN(I,1)
         RC(H,1) = 0.0
         VEL1 = VEL(H,1)
         DO 309 K = 2, SAMPLNUM
            DEPTH(H,K) = DEPIN(I,K)
            VEL(H,K) = VELIN(I,K)
            VEL2 = VEL(H,K)
            COEF = (VEL2 - VEL1)/(VEL2 + VEL1)
            RC(H,K) = COEF
```

```
            VEL1 = VEL2
 309     CONTINUE
 305  CONTINUE
C
C     FILL IN REST OF DEPTH, VELOCITY, AND RC ARRAYS WITH INTERPOLATED VALUES.
C     ************************************************************************
C
      K = 1
      L = 1
      DO 311 I = 1, (P-1)
C
C     ESTABLISH CDP INTERVAL BETWEEN USER-SUPPLIED DEPTH-VELOCITY
C     FILES (INTVL) AND INCREMENT K AND L COUNTERS TO THESE CDP
C     BOUNDARIES.
C     ****************************************************************
C
 313     IF (CDP(K) .NE. C(I)) THEN
            K = K + 1
            GO TO 313
         END IF
 314     IF (CDP(L) .NE. C(I+1)) THEN
            L = L + 1
            GO TO 314
         END IF
C
C     M IS THE LAYER COUNTER WHICH IS SET TO ZERO HERE AND IS
C     INCREMENTED AFTER EACH INTERPOLATION IN THE DOINTERP
C     SUBROUTINE.
C     ****************************************************************
C
         M = 1
         INTVL = L - K
         IF (INTVL .EQ. 1) GO TO 311
 321     IF (M .GT. SAMPLNUM) GO TO 311
C
C     COMPARE TWO ADJACENT DEPTH VALUES (REFERRED TO AS TOP AND
C     BOTTOM) ACROSS THE CDP INTERVAL.
C     ****************************************************************
C
C     DETERMINE WHICH RC VALUES SHOULD BE ZEROED IF BOTH PAIRS OF TOP AND
C     BOTTOM DEPTH VALUES ARE THE SAME.
C     *******************************************************************
C
         IF((DEPTH(K,M).EQ.DEPTH(K,M+1)).AND.(DEPTH(L,M).EQ.DEPTH(L,M+1)))THEN
            NOLAY = M
            STARTK = K
```

```
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            IF (K .NE. 1) THEN
               IF (RC(K-1,M-2) .EQ. 0.0) THEN
                  WRITE(*,*)"BOTH PAIRS EQUAL, FIRST IF STATEMENT"
                  GO TO 335
               END IF
               IF (RC(K-1,M-1) .EQ. 0.0) THEN
                  GO TO 331
               END IF
C              IF (RC(K+1,M-2) .EQ. 0.0) THEN
C                 RC(L,M-2) = 0.0
C                 M = M + 1
C              END IF
               IF (RC(K+1,M-2) .EQ. 0.0) THEN
                  RC(L,M-2) = 0.0
               END IF
               IF (RC(K+1,M-1) .EQ. 0.0) THEN
                  RC(L,M-1) = 0.0
                  M = M + 1
               END IF
            END IF
            M = M - 1
            GO TO 321
 331        DO 332 N = STARTK, K
               RC(N,M-1) = 0.0
 332        CONTINUE
            NOLAY = 0
            M = M - 1
            GO TO 321
 335        DO 336 N = STARTK, K
               RC(N,M-2) = 0.0
 336        CONTINUE
            NOLAY = 0
            M = M - 1
            GO TO 321
C
C     DETERMINE WHICH RC VALUES SHOULD BE ZEROED IF THE FIRST PAIR
C     OF TOP AND BOTTOM DEPTH VALUES ARE DIFFERENT, AND THE SECOND PAIR
C     ARE THE SAME.
C     ******************************************************************
C
         ELSE IF (DEPTH(K,M) .EQ. DEPTH(K,M+1)) THEN
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            DIFF1 = ABS(DIFF)
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
```

```
            DIFF2 = ABS(DIFF)
C
C     IF THE SLOPE OVER THE INTERVAL IS GREATER ACROSS THE BOTTOM
C     LAYER, THEN ZERO THE FIRST PAIR BOTTOM RC VALUE.
C     SET THE REST OF THE BOTTOM LAYER RC VALUES EQUAL TO THE
C     SECOND PAIR BOTTOM RC VALUE.
C     *****************************************************************
C
            IF (DIFF2 .GT. DIFF1) THEN
               RC(K,M-1) = 0.0
               DO 342 N = 1, INTVL-1
                  RC(K+N,M-1) = RC(L,M-1)
 342           CONTINUE
               IF (DEPTH(K,M-3).EQ.DEPTH(K,M-2))RC(K,M-2)=0.0
               IF ((M-2) .EQ. NOLAY) THEN
                  DO N = STARTK,K
                     RC(N,M-1) = 0.0
                  END DO
               END IF
               IF (M .NE. SAMPLNUM) M = M + 1
            ELSE
C
C     ZERO TOP RC VALUE OF FIRST PAIR, AND SET REST OF TOP RC
C     VALUES TO THE SECOND PAIR TOP RC VALUE.
C     *****************************************************************
C
               RC(K,M-2) = 0.0
               DO 346 N = 1, INTVL-1
                  RC(K+N,M-2) = RC(L,M-2)
 346           CONTINUE
               IF (DEPTH(K,M).EQ.DEPTH(K,M-1))RC(K,M-1)=0.0
               IF ((M-2) .EQ. NOLAY) GO TO 335
            END IF
            M = M - 1
            GO TO 321
C
C     DETERMINE WHICH RC VALUES SHOULD BE ZEROED IF THE TOP AND
C     BOTTOM DEPTH VALUES OF THE SECOND PAIR ARE THE SAME.
C     *****************************************************************
C
         ELSE IF (DEPTH(L,M) .EQ. DEPTH(L,M+1)) THEN
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            DIFF1 = ABS(DIFF)
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            DIFF2 = ABS(DIFF)
C
```

```
C     IF THE SLOPE OVER THE INTERVAL FOR THE TOP LAYER  IS GREATER
C     THAN THE SLOPE OVER THE BOTTOM LAYER, ZERO THE TOP RC VALUE OF
C     THE SECOND PAIR.
C     ***************************************************************
C
            IF (DIFF1 .GT. DIFF2) THEN
               RC(L,M-2) = 0.0
               IF (DEPTH(L,M).EQ.DEPTH(L,M-1))RC(L,M-1)=0.0
            END IF
C
C     IF THE SLOPE OVER THE INTERVAL FOR THE BOTTOM LAYER IS LESS
C     THAN OR EQUAL TO THE SLOPE OVER THE TOP LAYER, ZERO THE BOTTOM
C     RC VALUE OF THE SECOND PAIR.
C     ***************************************************************
C
            IF (DIFF1 .LE. DIFF2) THEN
               RC(L,M-1) = 0.0
               IF (DEPTH(L,M).EQ.DEPTH(L,M-1))RC(L,M-2)=0.0
            END IF
C           M = M - 1
            GO TO 321
         ELSE
C
C     SIMPLY INTERPOLATE BETWEEN THE TWO TOP VALUES IF NEITHER OF THE
C     TOP AND BOTTOM DEPTH VALUES ARE EQUAL.
C     ***************************************************************
C
            CALL DOINTERP (DIFF,DEPTH,K,M,L,INTVL,VEL,RC)
            GO TO 321
         END IF
 311  CONTINUE
C
C     CHANGE REFLECTION COEFFICIENTS AT BOUNDARIES WHERE A LAYER HAS
C     BEEN DELETED.
C     ***************************************************************
C
      DO 351 Q = 1,J
         I = 2
         N = 0
 361     IF (RC(Q,I) .EQ. 0.0) THEN
           N = N + 1
           IF (RC(Q,I+1) .NE. 0.0) THEN
                  RC(Q,I+1)=(VEL(Q,I+1)-VEL(Q,I-N))/(VEL(Q,I+1)+VEL(Q,I-N))
             N = 0
           END IF
         END IF
```

```
          I = I + 1
          IF (I .EQ. SAMPLNUM) GO TO 351
          GO TO 361
351     CONTINUE
       RETURN
       END
```

```
C       SUBROUTINE TO CALCULATE EARTH RESPONSE TO REFLECTION COEFFICIENT
C       SERIES.  TRANSMISSION LOSSES AND ALL INTERBED MULTIPLES ARE
C       ACCOUNTED FOR.  ASSUMES EARTH TO BE HORIZONTALLY UNIFORM IN
C       ACOUSTIC IMPEDANCE.  SUBROUTINE WRITTEN BY VARGAS, 1983,
C       MODIFIED BY ROEHL, 1984.
C
C       ******************************************************************
C
        SUBROUTINE MULTIPLE (TRACE, NUM, J, Q)
C
        REAL  TRACE(25,4000), A(4000), B(4000), P, CX, CY, MULT(4000)
        INTEGER  J, NUM, I, L, LEN
        CHARACTER*1 ANS
C
        WRITE(*,*)"DO YOU WANT TRANSMISSIONS LOSSES AND MULTIPLES CALCULAT
        READ (*,6) ANS
  6     FORMAT(A)
        CALL ZAPUF (ANS)
        IF (ANS .EQ. "N") RETURN
        Q = Q/2
        DO 8 K = 1, J                          !DO CALCULATION FOR EACH TRACE
C
C       INITIALIZE VARIABLES
C       ******************************************************************
C
        LEN = 1
        DO 10 I = 1,2*NUM
           A(I) = 0
           B(I) = 0
           MULT(I) = 0
 10     CONTINUE
C
C       SET INITIAL POLYNOMIAL
C       ******************************************************************
C
        A(1) = 1/(1+TRACE(K,1))
        B(1) = TRACE(K,1)/(1+TRACE(K,1))
C
C       BEGIN MATRIX POLYNOMIAL CALCULATION
C       ******************************************************************
C
        DO 100 I = 2, NUM
           LEN = LEN + 2
C
C       CALCULATE ELEMENT 1,1 AND ELEMENT 2,1
```

```
C       ***************************************************************
C
           CX = A(1)*TRACE(K,I)/(1+TRACE(K,I))
           A(1) = A(1)/(1+TRACE(K,I))
           DO 200 L = 3,LEN,2
              CY = A(L)*TRACE(K,I)/(1+TRACE(K,I))+B(L-2)/(1+TRACE(K,I))
              A(L) = A(L)/(1+TRACE(K,I))+B(L-2)*TRACE(K,I)/(1+TRACE(K,I))
              B(L-2) = CX
              CX = CY
 200       CONTINUE
C
C       CALCULATE LAST COEFFICIENT FOR 2,1 ELEMENT
C       ***************************************************************
C
           B(LEN) = CX
 100    CONTINUE
C
C       END POLYNOMIAL CALCULATION
C       FIND IMPULSE RESPONSE FUNCTION BY FILTERING
C       ***************************************************************
C
        DO 270 I = 1,2*NUM
           TRACE(K,I) = 0.0
 270    CONTINUE
        DO 300 I = 1,2*NUM
           IF (LEN-I+1 .LT. 1) GO TO 400
           MULT(I) = B(LEN-I+1)/A(1)
 400       CONTINUE
           DO 300 L = 3,I,2
              IF (I-L+1 .LT. 1) GO TO 300
              IF (L .GT. LEN) GO TO 300
              MULT(I) = MULT(I) - A(L)*MULT(K,I-L+1)/A(1)
 300    CONTINUE
C
C       TRANSFER EARTH IMPULSE RESPONSE BACK TO RC ARRAY
C       ***************************************************************
C
        DO I = 1, NUM*2
           TRACE(K,I) = MULT(I)
        END DO
C
C       ZERO INITIAL REFLECTION AT TOP OF SURFACE
C       ***************************************************************
C
        TRACE(K,1) = 0.0
 8      CONTINUE
```

```
NUM = NUM * 2
RETURN
END
```

```
C
C      PROGRAM TO CREATE A SPEX DATA FILE FROM A SINGLE USER INPUT
C      FILE.  PROGRAM CONVERTS DEPTH-VELOCITY PAIRS INTO .5 MILLI-
C      SECOND TIME-VELOCITY PAIRS, AND HAS AN OPTION TO CALCULATE
C      MULTIPLES.
C      INPUT DATA FILE MUST BE IN F12.5,2X,F12.5 FORMAT.
C
C      ****************************************************************
C
       REAL  TIM1, TIM2, DEP1, DEP2, TT, RC(4000), VEL1, VEL2
       REAL  MINTVEL2, INTVEL1, INTVEL2, BOTDEP, TOPDEP, MSEC1, MSEC2
       REAL  DEPINTVL
       CHARACTER*50  FILNAM, OUTFILE
       INTEGER  SAMPLNUM, Q
C
       WRITE(*,*) "WHAT IS THE DEPTH VS. TRANSIT-TIME FILE NAME? --- "
       READ (*,99) FILNAM
 99    FORMAT(A)
       WRITE (*,*) "WHAT DO YOU WANT YOUR SPEX OUTPUT FILE NAMED? --- "
       READ (*,99) OUTFILE
       TIM2 = 0.0
       MSEC1 = 0.0
       MSEC2 = 0.5
C
C      OPEN DATA FILE AND READ FIRST DEPTH AND TRANSIT TIME VALUES.
C      ****************************************************************
C
       OPEN (1, FILE=FILNAM, RECFM="DS", ERR=298)
       OPEN (22, FILE=OUTFILE,STATUS="NEW",RECFM="DYNAMIC",
       &                 FORM="UNFORMATTED",MODE="BINARY",ERR=298)
       READ (1, 101, END=290, ERR=299) DEP2, TT
 101   FORMAT(F12.5,2X,F12.5)
C
C      CALCULATE VALUES FOR FIRST LAYER.
C      ****************************************************************
C
       I = 1
       INTVEL1 = 0.0
       TOPDEP = DEP2
       RC(1) = 0.0
       VEL2 = 1000000.0/TT
 105   VEL1 = VEL2
       DEP1 = DEP2
       TIM1 = TIM2
C
```

```
C       READ NEXT DEPTH, TRANSIT-TIME PAIR AND CALCULATE VALUES.
C       ******************************************************************
C
        READ (1,101,END=290,ERR=299) DEP2, TT
        VEL2 = 1000000.0/TT
        TIM2 = TIM1 + (2000 * (DEP2 - DEP1)/VEL1)
        IF ((TIM1 .LE. MSEC2) .AND. (TIM2 .GE. MSEC2)) THEN
           DIFF = (MSEC2 - TIM1)/(TIM2 - TIM1)
           BOTDEP = DEP2 + DIFF
           DEPINTVL = BOTDEP - TOPDEP
           INTVEL2 = (DEPINTVL * 2)/ .0005
           IF (INTVEL1 .NE. 0.0) RC(I)=(INTVEL2-INTVEL1)/(INTVEL2+INTVEL1)
C
C
           INTVEL1 = INTVEL2
           TOPDEP = BOTDEP
           MSEC1 = MSEC1 + .5
           MSEC2 = MSEC2 + .5
           I = I + 1
        END IF
        GO TO 105
        NUM = I
 290    SAMPLNUM = I
C
C       OPTIONAL CALCULATION OF MULTIPLES.
C       ******************************************************************
C
        CALL MULTIPLE (RC, NUM, Q)
C
C       REFORMAT DATA INTO SPEX-COMPATIBLE FILE.
C         SUBROUTINE SYNGEN IS SIMILAR TO SUBROUTINE TAPEGEN.
C       ******************************************************************
C
        CALL SYNGEN (RC, NUM, Q)
        GO TO 300
 298    WRITE(*,*) "TROUBLE IN OPENING FILE...CHECK ACCESSIBILITY"
        GO TO 300
 299    WRITE (*,*) "TROUBLE IN READING DATA...IS FORMAT IN F12.5,2X,F12.5?
        GO TO 300
 300    WRITE (*,301) OUTFILE
 301    FORMAT (" YOUR SPEX FILE IS  -- "A)
        CLOSE (22)
        CLOSE (1)
        STOP
        END
```