

Subsurface Structure Near Charleston, South Carolina—Results of COCORP Reflection Profiling in the Atlantic Coastal Plain

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SUBSURFACE STRUCTURE NEAR CHARLESTON, SOUTH CAROLINA—RESULTS OF COCORP REFLECTION PROFILING IN THE ATLANTIC COASTAL PLAIN

By F. STEVE SCHILT,¹ LARRY D. BROWN,¹ JACK E. OLIVER,¹ and SIDNEY KAUFMAN¹

ABSTRACT

In May and June of 1978, the Consortium for Continental Reflection Profiling (COCORP) surveyed four lines totalling 72 km in length in the Charleston-Summerville area of South Carolina. The objective was to map the structure of the entire crust in that area. Some particularly interesting near-surface structures were detected in addition to deeper features. A strong event at 0.7 s (seconds) is present on all profiles and corresponds to the lower Mesozoic basalt layer penetrated at about 750 m in U.S. Geological Survey drill holes. The top of an older basement having as much as 1 km of relief can be seen at about 1.0 s (~1600 m). The Coastal Plain sediments, basalt layer, and basement can all be traced with good continuity over much of the lines; they are cut by a reverse fault and possibly by a small fault-bounded graben, each having an offset of a few tens of meters. A line that crosses a zone of recent seismicity shows noticeable differences in shallow structures on either side, although the shallow section across part of the seismic zone itself was not observed on this line, owing to a gap in the data on either side of the Ashley River. Beneath the Mesozoic and younger strata, the upper crust appears generally transparent to seismic energy down to 6.0 s (~18 km). From about 6.0 to 11.0 s, many short scattered reflections having a laminated appearance suggest a transition from relatively homogeneous igneous rocks to a more anisotropic and metamorphosed lower crust. The crust-mantle transition appears to be represented by a distinct band of short reflection segments at 10.5–11.0 s, whose depth (~32–34 km) agrees with data from a refraction study in the central Appalachian Piedmont. If the gently dipping Appalachian overthrust discovered in Georgia by a COCORP survey extends beneath the Charleston area, it is conceivable (but speculative) that some of the reflections below 6.0 s are metasedimentary layers beneath imbricate thrusts.

INTRODUCTION

As part of the effort to determine the structural setting of the Charleston seismic zone and to investigate proposed extensional structures of a rifted continental margin, the Consortium for Continental Reflection Profiling (COCORP) surveyed four lines near Summerville, S. C. The project was jointly funded by the National

Science Foundation, the U.S. Geological Survey (USGS), and the Nuclear Regulatory Commission. A recording time of 20 seconds (s) was used to collect data down to the crust-mantle boundary and deeper if possible. The VIBROSEIS² technique was used, and the various seismic parameters (see table 1) were similar to those used in previous COCORP surveys (Oliver and others, 1976; Brown and others, 1979; Schilt and others, 1979; Brewer and Oliver, 1980).

The reflection survey was designed primarily for penetration and resolution of deep crustal features (down to several tens of kilometers). Consequently, reflections shallower than about 0.4 s (~400 m) are not discernible. However, shallow reflections and structures in the range 0.4–1.5 s (~400–2,600 m) are clearly seen, and deep reflections are observed on some records as late as 12.0 s (~36 km). The reflection data are discussed in two parts: the shallow sedimentary section and deep reflections (greater than 1.5 s).

Cretaceous shelf sediments, a lower Mesozoic basalt, and an older basement have been traced over most of the survey area. The older basement has a relief of at least 1 km over the area surveyed. Although no exposed faults have been mapped at the surface, some shallow faults (two apparently normal and one possibly reverse) have been interpreted on the basis of the reflection data. The reverse fault is near the greatest concentration of earthquake epicenters, and another inferred zone of faulting beneath the Ashley River is near the southeastern end of the epicentral pattern. These faults are not necessarily those along which the current seismicity occurs, as most of the hypocenters appear to be deeper than 5 km. However, the spatial correlation of the faults and the epicenters suggests a possible causal relationship.

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²Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

TABLE 1.—Seismic survey parameters

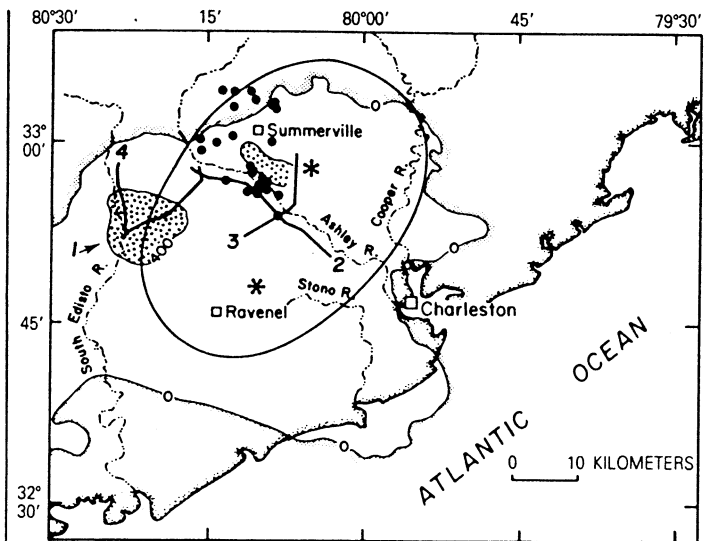
Source	5 VIBROSEIS vibrators, 23 m apart		
Sweep frequencies	8–32 Hz (upsweep)		
Recording system	96 channels (MDS-10)		
Record length	20 s		
Sampling interval	8 ms		
Distance to nearest station	469 m (1,540 ft)		
Station spacing	67 m (220 ft)		
Length of receiver array	6,370 m (20,900 ft)		
Nominal fold:			
Line 1 (sta. 41–199), line 2, and line 3	24		
Line 1 (sta. 948–41) and line 4	16		
Nominal fold after muting:	Time (s)	Fold (16 max.)	Fold (24 max.)
	0.0	0	0
	.5	1	1
	1.0	2	3
	1.5	4	6
	2.0	5	8
	3.0	11	16
	4.0–20.0	16	24

Deep reflections were recorded; they were especially concentrated in the depth range of 18–33 km. Reflections near 11.0 s (~33 km) are interpreted as representing the Moho (Mohorovicic discontinuity) on the basis of their depth, which is consistent with depths to the Moho derived from a refraction survey in the Piedmont and from offshore multichannel recordings of similar deep reflections.

Acknowledgments.—We thank I. Zietz, P. Popenoe, B. Houser, A. Tarr, H. Ackermann, and B. Morgan for proposing this area to COCORP for reflection profiling. We gratefully acknowledge discussions with many USGS Charleston Project scientists, especially H. Ackermann, J. Behrendt, D. Campbell, G. Gohn, and D. Rankin. Discussions with graduate students and staff of Cornell University influenced parts of this paper. The seismic data were acquired and processed by Petty Ray Geophysical Company. Support for this research came from National Science Foundation grants EAR-7713653 and EAR-7714674, the U.S. Geological Survey, and the Nuclear Regulatory Commission.

SITE OF REFLECTION PROFILES

The regional location of the four reflection profiles, which total 72 km in length, is shown in figure 1. A more detailed map showing the location of the lines and selected station numbers is shown in figure 2. Line 1 begins near the center of the largest magnetic high [>600 nT (nanoteslas)] and proceeds northeast toward Summerville, passing three USGS drill holes (maximum depths of 800–1,150 m). Line 2 crosses line 1 near the northeastern end of the latter; it heads southeast, parallel to the Ashley River, obliquely crossing a north-west-trending group of epicenters south of Summerville. Line 3 also crosses the southern end of the



EXPLANATION

- 0 nT magnetic contour. Pattern on side of decreasing intensity
- 400 nT magnetic contour. Pattern area greater than 400 nT
- Earthquake epicenter, 1973–1978 (Tarr and Rhea, 1983)
- Approximate meizoseismal area of 1886 earthquake (Bollinger, 1977)
- * Epicenter of 1886 earthquake (Dutton, 1889)
- 3— Seismic reflection line

FIGURE 1.—Index map showing location of COCORP lines. Four lines totalling 72 km in length overlap to form a net about 30 km north-west of Charleston.

epicenter trend near the Ashley River; it crosses line 2 and the river at approximately right angles, heading from southwest to northeast, then bends north toward Summerville and passes over a large elliptical magnetic high (>500 nT). The last and shortest line, line 4, starts at the southwestern end of line 1 and heads due north.

PREVIOUSLY KNOWN STRATIGRAPHY

Line 1 passes three deep test holes drilled by the USGS near Clubhouse Crossroads, S. C. All three of the wells (henceforth referred to as CC#1, CC#2, and CC#3) penetrated 750–776 m of Upper Cretaceous and younger sediments and then encountered amygdaloidal basalt, which occurs as multiple subaerial flows. An $^{40}\text{Ar}/^{39}\text{Ar}$ age of 184 ± 3.3 m.y. for a sample from CC#2 indicates an Early Jurassic age (Lanphere, 1983). Chemical analyses indicate that these basalts are mostly quartz-normative tholeiites, which closely resemble the lower Mesozoic high-Ti quartz-normative diabases of eastern North America (Gottfried and others, 1977, 1983). A seismic-refraction study by Ackermann (1977,

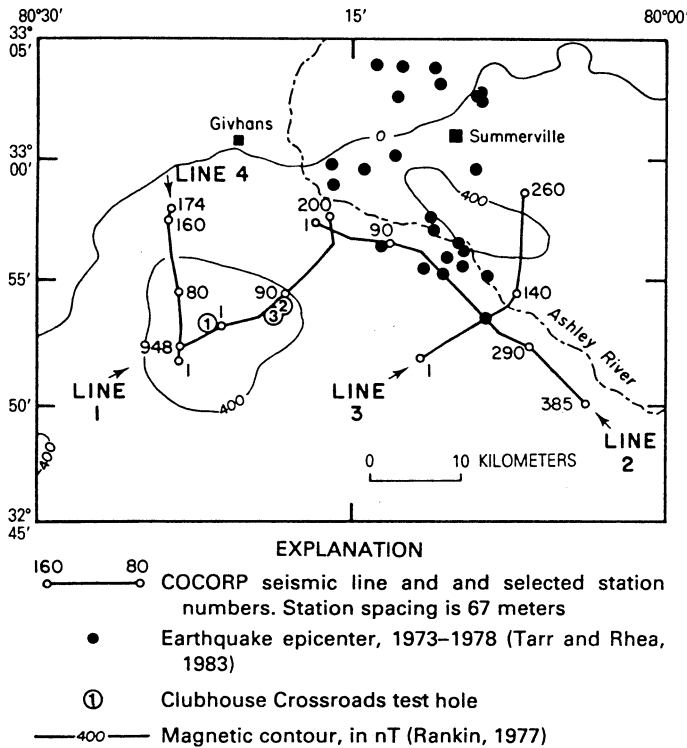


FIGURE 2. — Location of COCORP seismic lines and station numbers.

1983) traced the basalt (or pre-Cretaceous unconformity) as a refracting horizon about 30 km eastward from CC#1. Contours of the depth and velocity of the refractor show a general trend of decreasing velocity and increasing depth to the east.

Although CC#1 and CC#2 (total depths 792 m and 907 m, respectively) bottomed within the basalt, CC#3 (total depth 1,152 m) penetrated over 250 m of basalt and then passed through about 120 m of unfossiliferous sedimentary red beds before stopping. These red beds bear a lithologic similarity to Upper Triassic and Lower Jurassic continent-derived sediments in exposed grabens along eastern North America. An immature conglomerate unit in the red beds contains quartz-feldspar lithic fragments and some basalt clasts, which implies a local erosional source of plutonic granitic rocks as well as an older basalt (Gohn, 1983). None of the three holes penetrated beyond the red beds, but seismic-refraction surveys in the area (Ackermann, 1983) indicate a high-velocity basement (~ 6 km/s) beneath the red-bed sequence at a depth of about 1,200–1,300 m near CC#1.

The sediments above the basalt are all interpreted to be of marine origin, with the exception of the partly continental Cape Fear Formation (Upper Cretaceous), which immediately overlies the basalt, and the mostly continental Middendorf Formation (Upper Cretaceous), which in turn overlies the Cape Fear (Gohn and others,

1977). The top of the Middendorf represents the last pre-Pleistocene fluvial deposition in the area and is an unconformity marked by an abrupt decrease in the sand/clay ratio.

The subsequent marine sediments are Late Cretaceous through Oligocene in age; an unconformity near the surface separates a thin Pleistocene(?) cover from underlying Eocene or Oligocene limestone. The post-Middendorf strata are interpreted as predominately inner-shelf sediments.

STACKING AND INTERVAL VELOCITY DETERMINATION

The velocity functions used to stack the reflection data were determined primarily by comparison of stacked sections produced by using different constant stacking velocities. The velocities obtained in this way were subsequently checked against selected velocity spectra and constant-velocity common-depth-point (CDP) gathers; they generally agree fairly well with only minor differences.

Although there is some variation in the stacking velocities as a function of position along the profiles, these changes are not major. A representative stacking velocity function obtained by analysis of constant velocity stacks (from line 2) is shown in table 2. Also listed are the corresponding interval velocities and depth estimates. At this point on line 2, an event near 0.94 s is the deepest reflection that is reasonably coherent and continuous over large distances; it probably represents the boundary between lower Mesozoic sediments and crystalline basement or an older basalt. The depth to this boundary at this point is approximately 1,400 m. Velocities below about 3.0 s are not well constrained by normal moveout patterns and were to some extent arbitrarily specified on the basis of probable rock types.

An abrupt increase in the stacking velocity occurs at about 0.7 s, as shown in table 2. Two velocity spectra that clearly illustrate the steep change in velocity past 0.7 s are shown in figure 3. The strong peak at 0.7–0.8 s and the subsequent increase in the stacking velocity were also reported by Yantis and others (1983). Drilling, reflection, and refraction data indicate that this velocity jump is caused by an extensive subsurface basalt layer, as discussed below.

The rapid velocity increase from sediments to basalt or other high-velocity rocks could be expected to cause multiple reflections. Strong multiples were observed on constant-velocity stacks for velocities corresponding to the sediments, but the multiples were strongly attenuated when realistic stacking-velocity functions were used. The rapid velocity increase from sediments to crystalline rocks tends to discriminate against these

TABLE 2.—*Representative stacking velocities, interval velocities, and implied depths*

[Data from station 23, line 2]

Time (s)	Stacking velocity (km/s)	Interval velocity (km/s)	Depth below surface (km)
0.00	1.98	1.98	0.
.48	1.98	2.80	.475
.72	2.29	5.23	.811
.84	2.90	5.08	1.13
.94	3.20	5.87	1.38
3.00	5.18	6.51	7.42
9.00	6.10	7.24	26.9
12.00	6.40	8.17	37.8
20.00	7.16		70.5

sedimentary multiples during stacking. The multiples are undercorrected by the normal moveout for primary reflections and are stacked out of phase; thus they tend to be cancelled. Faint remnants of multiples are sometimes visible in the 1- to 3-s range.

GENERALIZED SEISMIC STRATIGRAPHY

Three conspicuous reflections or groups of reflections can generally be seen throughout the area surveyed. All three are clearest on line 3 (figs. 8, 9) but are present to a varying degree on almost all the profiles. An especially notable and coherent reflection occurs at about 0.7 s (two-way traveltimes) on line 1 (fig. 4) and can be easily traced onto the other three lines. The velocities derived from the reflection data imply a depth of approximately 800 m at 0.7 s. Interval velocities increase from about 2.0–3.0 km/s above this horizon to 4.5 km/s or greater below it (see table 2 and fig. 3). Refraction velocities measured from common-source recordings (an individual source recorded by a linear array of recording stations) show a corresponding jump from 1.9–2.3 km/s to 4.5–5.5 km/s at about the same depth. We interpret this event to represent the top of the Jurassic basalt found at 750–770 m depth in the USGS test holes. (The 0.7-s horizon is referred to hereafter as "J," for brevity.) It is generally consistent with a refractor mapped at similar depths by Ackermann (1977, 1983).

This surface may not necessarily be basalt everywhere. The reflection amplitude and character vary considerably, especially along line 2. An interface of upper Cretaceous sediments over Triassic red beds could be present in some areas and could be expected to produce a good reflection. On the other hand, the 250-m thickness of the basalt observed in CC#3 suggests an area that could easily be as large as or larger than the area covered by the COCORP survey. The Watchung Basalt flows of the Newark basin are of comparable thickness (individual flow units 50–100 m thick) and are estimated to have covered an area of 5,000 km² (Faust, 1975), corresponding to a radial dimension of the order

of 40 km. The Charleston basalts could have a similar or greater extent.

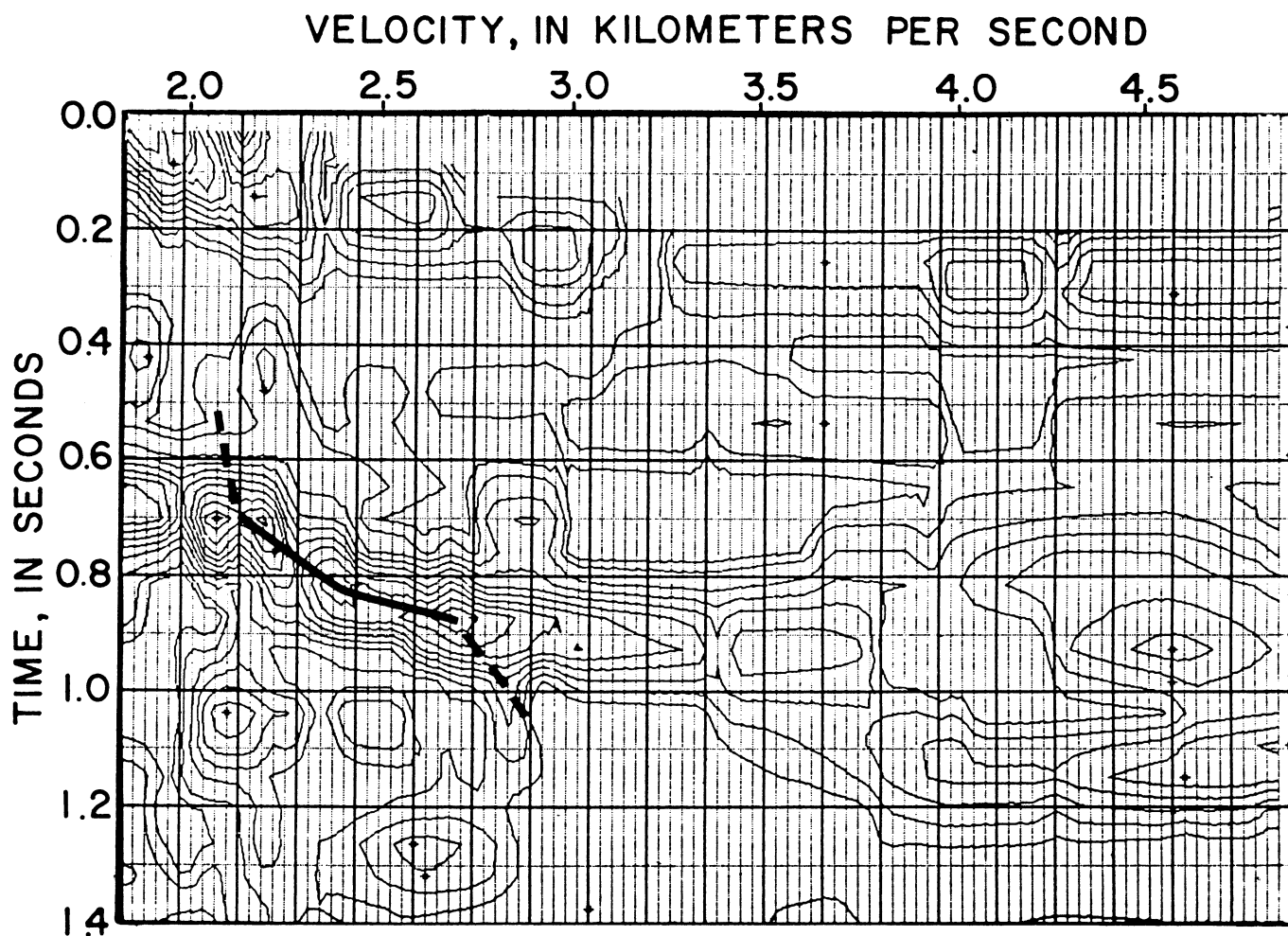
A high-velocity basalt layer between lower velocity sediments could be expected to produce some seismic resonance (constructive interference between reflections from top and bottom). For a thickness of 250 m and a velocity of 5.0 km/s, the first three resonant frequencies are 5, 15, and 25 Hz. Although the first is below the 8–32 Hz sweep, the second and third fall near the center of this range. The effective pulse duration of an 8–32 Hz Klauder wavelet is about 65 milliseconds (ms) (width of central peak plus one side lobe), and the reflection spacing is about 100 ms; thus even a small resonance effect would tend to mask the bottom of the basalt. This may explain the ringing character along some portions of the survey.

Dillon and others (1979, 1983) have reported a very strong reflection beneath the inner Blake Plateau and Continental Shelf offshore from South Carolina. On the basis of its amplitude, high refraction velocity, and proximity to the Clubhouse Crossroads basalt (~80 km), they interpret this event to represent the seaward portion of a regional volcanic layer and estimate its areal extent offshore to be of the order of 100,000 km². Dillon and McGinnis (1983) have observed a corresponding strong refractor (5.8–6.3 km/s) on offshore refraction profiles.

At about 0.45–0.55 s, well above the pre-Cretaceous unconformity, a pair of reflections within the Cretaceous section can be clearly traced across all four lines (see figs. 6, 7). The top of the Black Creek Formation (410 m in CC#1) and the unconformity between the Black Creek and Middendorf (560 m in CC#1) are probably the major contributors to this signature. (This reflection pair will be referred to hereafter as "K.")

The third group of conspicuous reflections shows the greatest variation in time (and depth); arrival times range from about 0.85 to 1.05 s (~1,200–1,700 m). Refracted arrivals on common-source playouts show a refraction crossover corresponding to this reflection boundary. The refraction velocities (unreversed) at this crossover increase from around 4.5–5.5 km/s (a refraction along the top of the basalt layer) to 6.0–7.0 km/s (a refraction along the top of an older high-velocity unit beneath the red beds).

This band of reflections is inferred to correspond to a pre-Late Triassic unconformity on crystalline basement, which probably developed considerably prior to the rifting that generated the modern Atlantic Ocean basin. The basement event is referred to hereafter as "B" in the text and figures. There are no drill holes in the immediate vicinity of the reflection profiles deep enough to sample this pre-Mesozoic basement. Numerous wells west and southwest of Savannah, Ga., have penetrated a variety of basement rock types (rhyolite, volcanic ash,



A

FIGURE 3. — Examples of velocity spectra (stacking velocity against time). *A*, From station 60, line 1. Note rapid increase in velocity below 0.7 s, when basalt layer is encountered. *B*, From station 32, line 3. Reflection peaks occur slightly later, and deeper, than those in *A*.

arkose, granite, diabase, and others) at 1,200–1,400 m depth (Chowns and Williams, 1983). To the north, near the border between North and South Carolina, samples of chlorite schist have been recovered from approximately 400 m depth (Popenoe and Zietz, 1977).

The existence of basalt clasts in the red beds drilled in CC#3 (Gohn and others, 1983) raises the possibility that some of these reflections in the 0.9- to 1.1-s range are from basalt, older than the red beds, which may locally cover still older red beds and (or) a predominantly granitic basement.

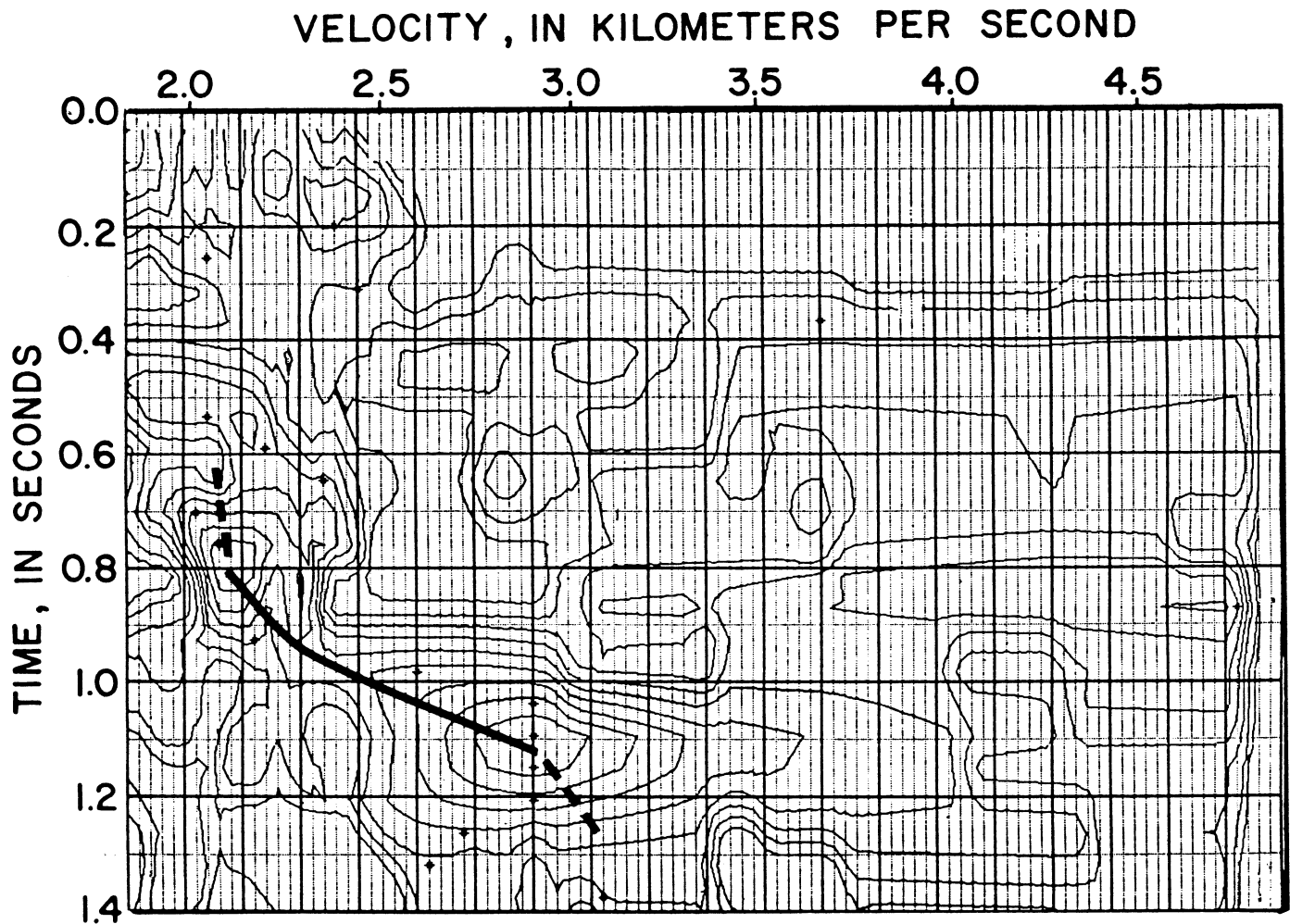
SHALLOW FAULTS AND STRATIGRAPHIC VARIATION

Line 1

A line drawing of the seismic section obtained along line 1 and the locations of the adjacent USGS test holes

are shown in figure 4. Reflections K and J appear to be offset by about 30 ms between stations 74 and 75, just beyond drill hole CC#2. However, no such feature was observed on USGS reflection profile SC10 (Behrendt and others, 1981), which overlaps COCORP line 1 here. Special reprocessing of this portion of line 1 will be necessary to resolve this question.

The deepest of the three holes (CC#3) ended in red beds at 1,152 m. The drill probably came within 100 m of basement if a reflection segment at 0.89 s near station 50 is interpreted to be basement. If the average velocity of the basalt and red beds is assumed to be 5 km/s, the basement is estimated to occur about 400 m beneath the top of the basalt, or at about 1,170 m total depth. This estimate, of course, depends upon the selected 0.89-s peak in the waveform coinciding with the actual lithologic interface, which interpretation is subject to



B

FIGURE 3.—Continued.

uncertainty. However, the estimated depth is consistent with a refraction depth estimate of approximately 1,200 m here (Ackermann, 1983).

All three reflectors, K, J, and B, appear to have very little regional dip along the direction of line 1.

Line 4

Line 4, a north-south line, intersects station 948 of line 1 at station 16 (see fig. 5). Although reflections J and K are still evident, reflection B is not clearly developed, and its discontinuous identification in figure 4 is tentative. Minor irregularities which could be small offsets can be seen along the J horizon but cannot be correlated with breaks in K or B, and thus no faults have been interpreted. As on line 1, the regional dip of these shallow reflectors is very small.

Line 2

Line 2, the longest of the profiles, runs from northwest to southeast and intersects station 177 on line 1 at station 29 (see fig. 6). Much more structural and stratigraphic variation is apparent along lines 2 and 3 than along lines 1 and 4. Lines 2 and 3 do, in fact, cross the northwest-trending seismic zone identified by the South Carolina seismograph net since its installation in 1973 (Tarr, 1977; Tarr and Rhea, 1983).

From stations 5 to 100 on line 2, the three shallow sets of reflections are very similar to the shallow reflections from line 1. Near station 130, however, reflections K and J bow upward slightly into a moderately dipping reverse fault that offsets both horizons (see fig. 7). The basement reflection B cannot be clearly traced through this fault. The offset is approximately 20 ms, which

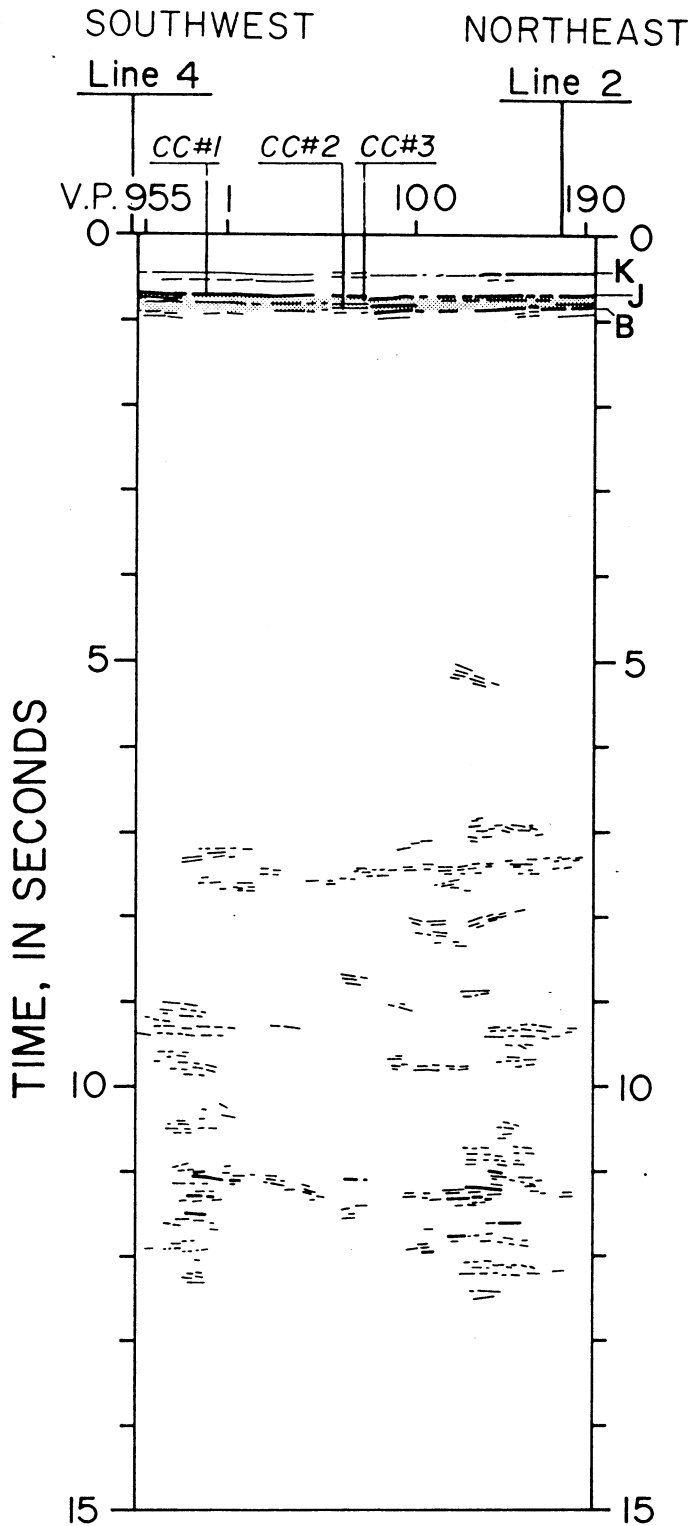


FIGURE 4.—Line drawing of seismic section for line 1, showing the upper 15 s of a 20-s record. Clubhouse Crossroads test holes are projected to line 1. K = reflections near 0.5 s, interpreted to represent reflectors within the Upper Cretaceous Coastal Plain sediments at about 500 m depth. J = reflections near 0.7 s (especially prominent), interpreted to be the top of a Jurassic basalt layer at about 800 m depth, which overlies at least 120 m of red beds (according to USGS drilling results). B = reflections near 1.0 s, inferred to be pre-Mesozoic crystalline basement at 1,200–1,300 m depth. Stippled interval shows inferred basalt layer and underlying Triassic or Jurassic sedimentary rocks.

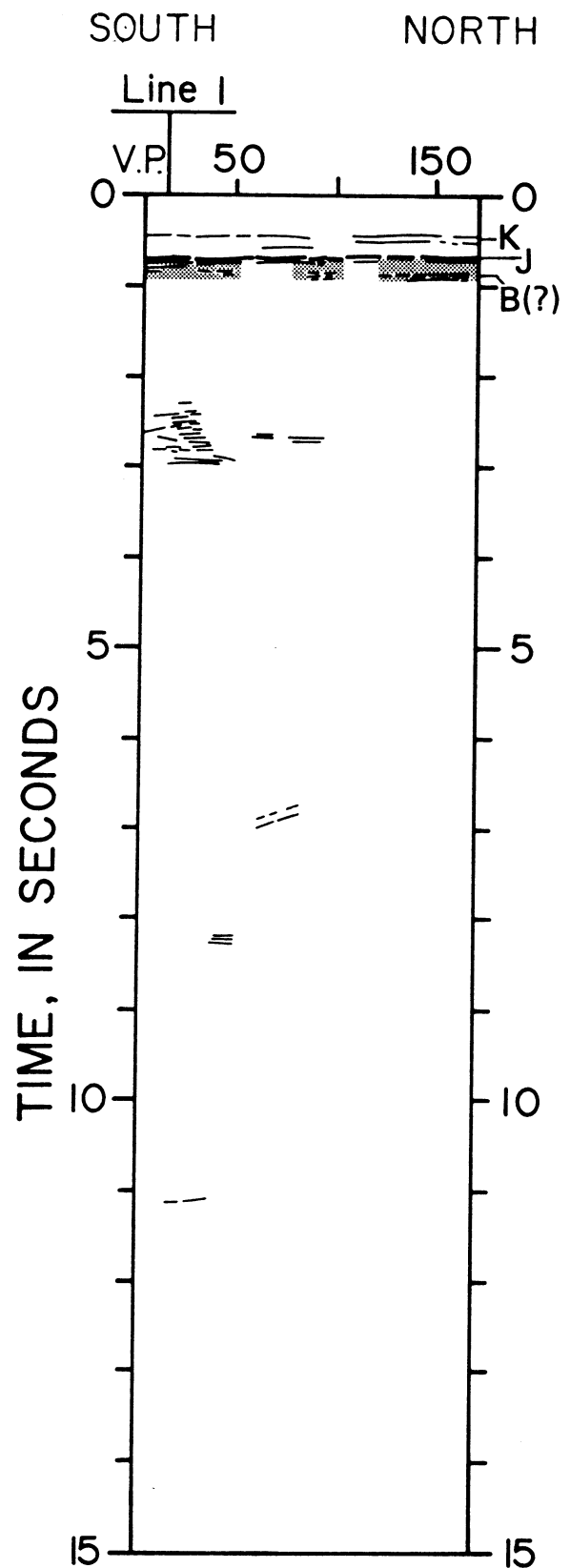


FIGURE 5.—Line drawing of seismic section for line 4. See explanation of figure 4.

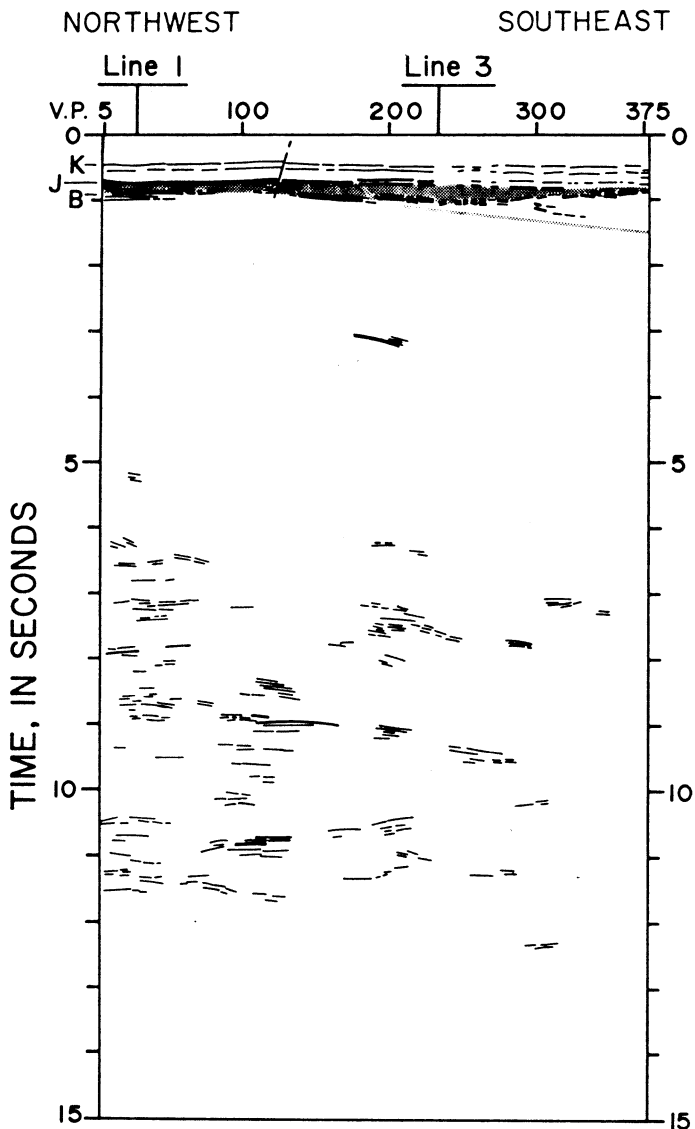


FIGURE 6. — Line drawing of seismic section for line 2. See explanation of figure 4.

implies a displacement of 20–30 m. The angle of dip calculated from the profile (an apparent dip, since the strike of the fault cannot be specified) is 50–60°. Behrendt and others (1981) have correlated this offset with a similar feature on USGS reflection line SC10 and have suggested a northeast strike for the fault, which they have named the Cooke fault. From about station 130 to station 180, all three reflections deepen and dip slightly toward the southeast. The dip is greatest on the basement event B (about 3°), as the estimated depth increases from about 1,200 to 1,400 m.

Continuing southeast beyond this moderate-angle thrust, line 2 passes Middleton Place, located at station 234 and near the center of the 1886 meizoseismal region. Numerous shallow V-shaped gaps from here to

the end of line 2 are the result of editing necessitated by noisier data. The shallow reflections from the Upper Cretaceous and younger units may be just as continuous beyond station 230 as before it, but the reflections past station 230 are somewhat weaker and less coherent.

Beyond station 230, the basement reflections appear to become shallower (less than 1.0 s) to the southeast and show an overall dip back toward the northwest. However, refraction studies by Ackermann (1977, 1983) suggest that the basement here is at a depth of approximately 2,000 m, which implies a reflection time of 1.2–1.3 s. This is supported by refraction analysis of first arrivals from a common-source reflection record near the end of line 2. On the basis of these refraction results, the shallower reflections near 1.0 s here probably represent a stratigraphic unit that does not occur in the Clubhouse Crossroads test holes. The velocity of this unidentified unit is not sufficiently great to produce a distinct refracted first arrival on the common-source records. This does not rule out the possibility, however, that these reflections are from a second basalt layer. The presence of such a layer would tend to be masked on refraction records by the uppermost basalt (at 0.7 s two-way traveltime).

A long, gently dipping event is weak but visible below 1.0 s, extending from station 200 (1.0 s) to the end of line 2 (1.5 s); it is shown on the far right of figure 6. It is very planar and might represent the top of the basement here; however, it is much weaker than the basement reflection along the first half of the line. An alternative interpretation is that it is a feature within the basement. This could be a Paleozoic thrust plane developed during the collisional orogenies of the Paleozoic (see discussion below of COCORP Appalachian survey results).

Line 3

Line 3 was designed to cross the seismic zone from southwest to northeast in a more or less orthogonal sense, subject to the constraints of roads and population density. It intersects station 234 on line 2 at station 89 (see fig. 8). Middleton Place is nearly coincident with the intersection of lines 2 and 3. A large gap in the data exists between stations 90 and 135, caused by the Ashley River and its lowlands. The gap is about 3 km wide and divides the line into two segments of different azimuth; south of the Ashley River the line trends southwest-northeast, whereas north of the river it trends north-south.

Reflections K, J, and B are all clearly identifiable over almost all of line 3. There is a noticeable contrast in the apparent structure of the basement reflection B on either side of the gap (figs. 8, 9). To the southwest, the reflections are flat and fairly continuous, showing only minor variations in the reflection waveforms. To the

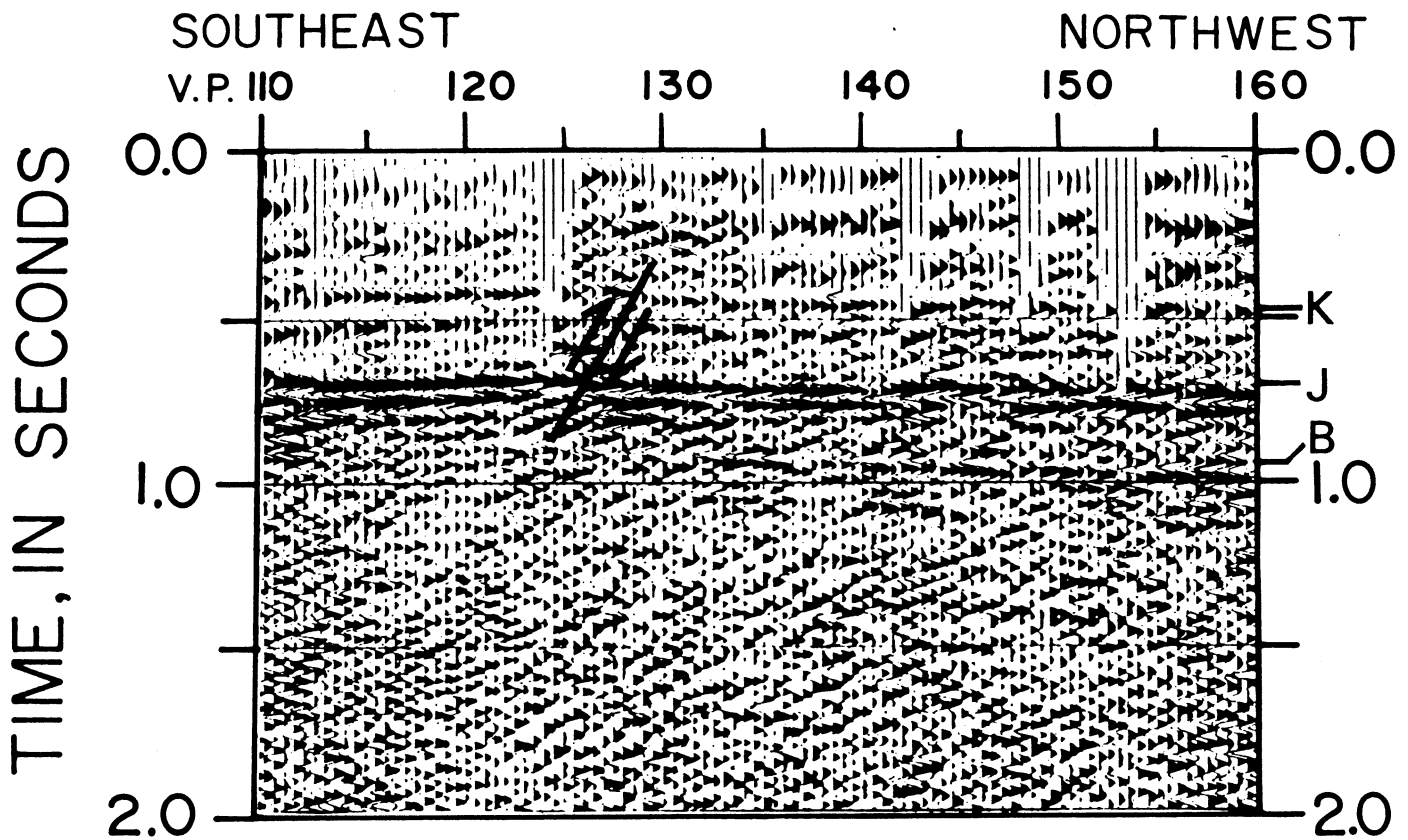


FIGURE 7.—Detail of part of seismic section for line 2, showing reverse fault near station 130. The offset is approximately 20 ms on reflection K, which implies a displacement of 20–30 m.

north, the B horizon is quite variable and discontinuous, showing apparent regional dip to the south of about 3–4°.

The reflections K and J dip downwards near station 160 as they approach the gap and have an apparent dip to the south of about 1°; along the rest of the line they are nearly flat. Thus, although the arrival times of these reflections match across the gap, their apparent dip does not. The difference in dip could result from the two profile segments having slightly different azimuths above southeast-dipping reflectors; however, these events on line 2 show no significant dip as they cross line 3. Alternatively, the dip could be an artifact of a velocity decrease in the overlying sediments, but no such velocity decrease is evident from velocity analyses. (However, velocities above 0.5 s are poorly resolved, as the smallest source-receiver offset is 469 m.)

The arrival time of the basement reflection mismatches by about 0.1 s across the gap. Furthermore, it has a more complex character on the north edge of the gap (fig. 9), and there is an event curving downward away from the gap whose curvature suggests it is a diffraction coming from a discontinuity within the gap.

The mismatch in the local apparent dip of events J and K, the mismatch in arrival time and regional dip of event

B, and the possible diffraction suggest structural complexity (perhaps faulting) within the gap. The southeastern cluster of epicenters (Tarr and Rhea, 1983) is locally subparallel to the Ashley River, which is a major drainage system for the region. Perhaps crustal movements associated with the Charleston seismic zone have influenced the drainage pattern.

Another interesting feature of this line is a graben-like offset of the reflection groups between stations 200 and 211. The graben offsets can be traced to the shallowest reflection resolved; that is, the K reflection. This offset pattern is shown in enlargements of a portion of the seismic section for line 3 (figs. 10A, 10B).

In the graben, reflections J and K are shifted by about 30 ms (~30 m, assuming a velocity of 2.1 km/s). Reflection B shows an asymmetrical offset of about 30 ms near station 200 and about 100 ms near station 209. The asymmetry could be a result of development of the graben along a preexisting basement fault. An abrupt decrease in the velocity of the sediments (possibly due to a buried river channel, for example) overlying reflection K could create the appearance of a graben. Close examination of stacking velocities revealed no such anomaly. However, as stated previously, velocities above 0.5 s are not well constrained, because the angles

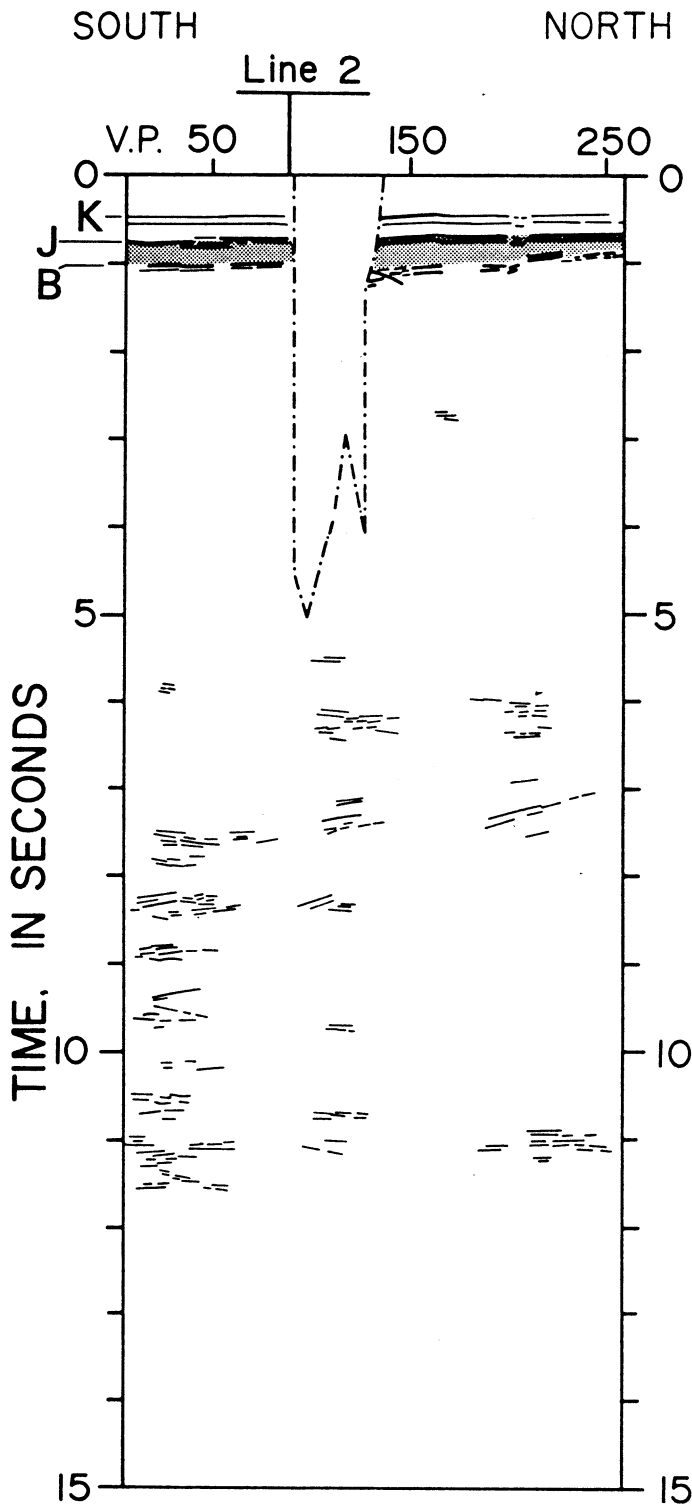


FIGURE 8. — Line drawing of seismic section for line 3. See explanation of figure 4. The large notch between stations 90 and 130 is a data gap caused by the Ashley River, which flows to the Atlantic Ocean through Charleston.

of incidence of these rays become large. If the faults are real, and not the result of a shallow low-velocity region,

these suggested normal faults would be at least as young as middle Late Cretaceous.

If the graben feature is an actual structure, it may be genetically related to the 1886 shock; it occurs very near one of the two epicenters designated by Dutton (1889) in his study of intensity patterns (see fig. 1).

Fence Diagram

The reflections and faults discussed above are represented in the fence diagram in figure 11. All faults shown in the fences appear to be distinct from each other; that is, each fault is observed on only one line.

The fences illustrate the relatively smooth and minor variation of the depth to the K and J interfaces. The basement horizon B shows greater variation in its depth, deepening toward the southern half of line 3 (1,500 m) and southeastern end of line 2 (2,300 m) and shallowing towards the northern end of line 3 (1,200 m).

RELATIONSHIP OF FAULTS TO SEISMICITY

No faults have been mapped at the surface within 100 km of the Charleston meizoseismal area (Rankin, 1977). However, three cases of post-Jurassic faults (possibly post-Cretaceous, but the resolution is marginal for strata this shallow) are suggested by the COCORP reflection data: (a) an east-directed reverse (?) fault near station 130 on line 2; (b) two normal faults forming a graben between stations 200 and 211 on line 3; and (c) possible faulting of unknown type near the Ashley River, inferred on the basis of structural differences observed on either side of the river.

All these faults show offsets of a few tens of meters, except (c), which is not directly observed. The offset along (c) could be as much as 200 m. Features (a) and (c) are located within or very near the currently active epicentral zone at Middleton Place (instrumentally located events since 1973), as shown in figure 2. The graben (b) is approximately 5 km northeast of the zone. Items (b) and (c) cannot be unambiguously traced through two different lines, and thus their trends have not been accurately determined.

Tarr (1977) has discussed the recent seismicity near Charleston; he associates instrumentally located events since 1973 with the source volume of the 1886 Charleston earthquake. Tarr and Rhea (1983) identify three clusters of epicenters within this zone. Their hypocenter cross sections and focal mechanisms suggest that most of the current activity is taking place along two near-vertical planes that trend northwest. The sense of motion along the preferred nodal planes is reverse; the fault planes dip nearly vertically or very steeply to the southwest. Hypocentral depths range from about 3 to 13 km for 25 events; six of the best-

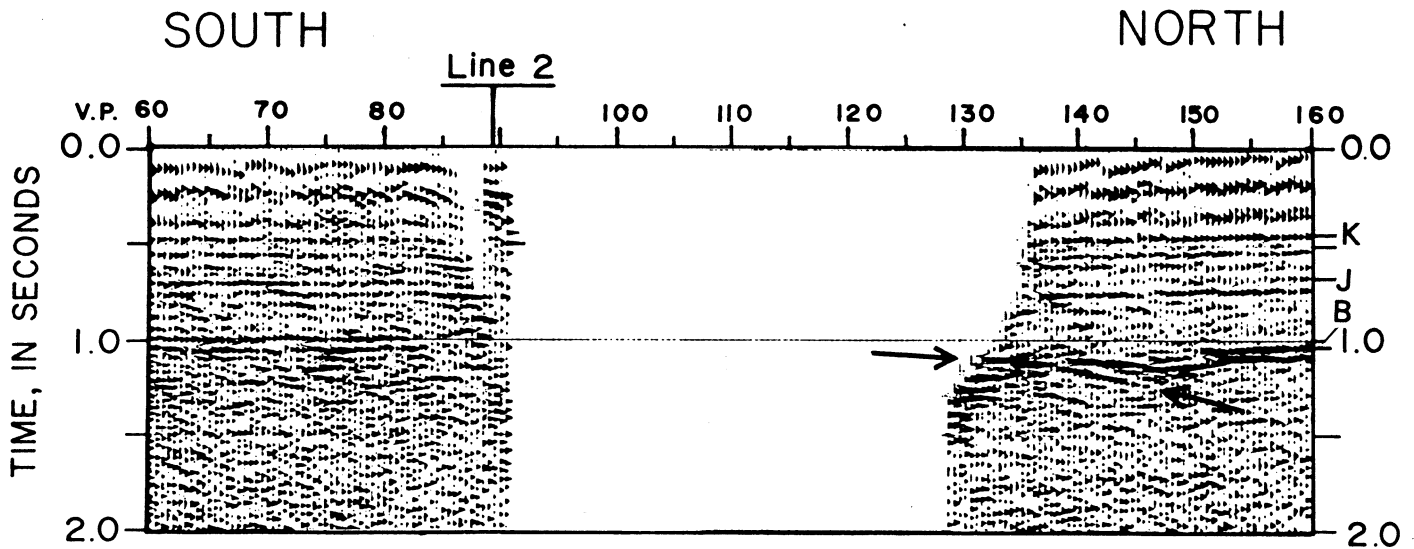


FIGURE 9.—Detail of part of seismic section for line 3 between stations 60 and 160, the region of the data gap caused by the Ashley River. Reflections are more complex near 1.0 s (labelled B) at the north end of the gap than they are at the south end. Arrows indicate diffraction coming from within the gap.

located events in the Middleton Place cluster fall between 4 and 8 km.

Other investigations (Amick and Talwani, 1979; Amick, 1979) that use a refined crustal model have suggested a northwest-trending seismic zone. Their composite focal plane solution suggests a northwest-trending thrust fault (N. 58° W.), with a southwesterly dip (50° SW.). Hypocentral depths, constrained by a seismograph station in operation since 1977 at Middleton Place, are greater than 5 km.

The reverse fault near station 130 on line 2 of the COCORP profiles apparently trends northeast (Behrendt and others, 1981) and thus cannot be readily associated with the main pattern of current seismicity. In addition, seismic slip confined to the upper few kilometers would not be consistent with hypocentral depths below 4 km, although the fault on line 2 could extend deeper than is evident from the reflection data.

Alternatively, the inferred faulting beneath the Ashley River may be the primary zone in which seismicity is occurring. The sense of basement relief there (higher on the southwest side of the gap; see figs. 8, 9) is also consistent with a northwest-trending, southwest-dipping thrust fault. The depth to which such faulting could extend is not well determined by line 3, owing to the depth of the gap. The gap (fig. 8) extends to below 3 s, which corresponds to a depth greater than 7 km.

If the major earthquake fault zone is not a low-angle thrust, some simple speculations on earthquake frequency are possible. Because near-surface faulting is relatively minor (~ 10 – 100 m, this study; Behrendt and others, 1981), earthquakes of the size of the 1886 event

(magnitude ~ 7 , slip ~ 1 m; Bollinger, 1983) may have been infrequent in the past. If the seismic zone has been active along a dip-slip fault of moderate to steep dip for the last million years or more, the recurrence interval for major events is of the order of 10,000 years or more. If such events occurred more often during that length of time, they would have resulted in vertical fault movements greater than any presently observed. On the other hand, if seismic slip began as recently as 20,000 years ago, such earthquakes could be as frequent as every 200 years.

If a major fault associated with the large 1886 event is of the order of 10 km deep, then the degree of surface faulting is indirect and less conclusive evidence for constraining earthquake frequency. However, it is difficult to postulate large accumulated displacement on a dip-slip fault at mid-crustal depth that does not have major effects near the surface, which are not observed along these profiles.

Behrendt and others (1983) interpret a major horizontal surface offshore at considerable depth (~ 10 – 13 km), on the basis of multichannel reflection profiles near Charleston. They postulate a regional horizontal fault along a décollement as a possible source zone of the seismicity near Charleston. The pattern of recent seismicity does not strongly support this hypothesis, although it does not completely disallow it, as discussed by Behrendt and others (1983). Whether or not the discontinuity is seismically active, it might be an extension of the large-scale Appalachian overthrusts reported by Cook and others (1979), but the connection must be regarded as uncertain. The possibility that the

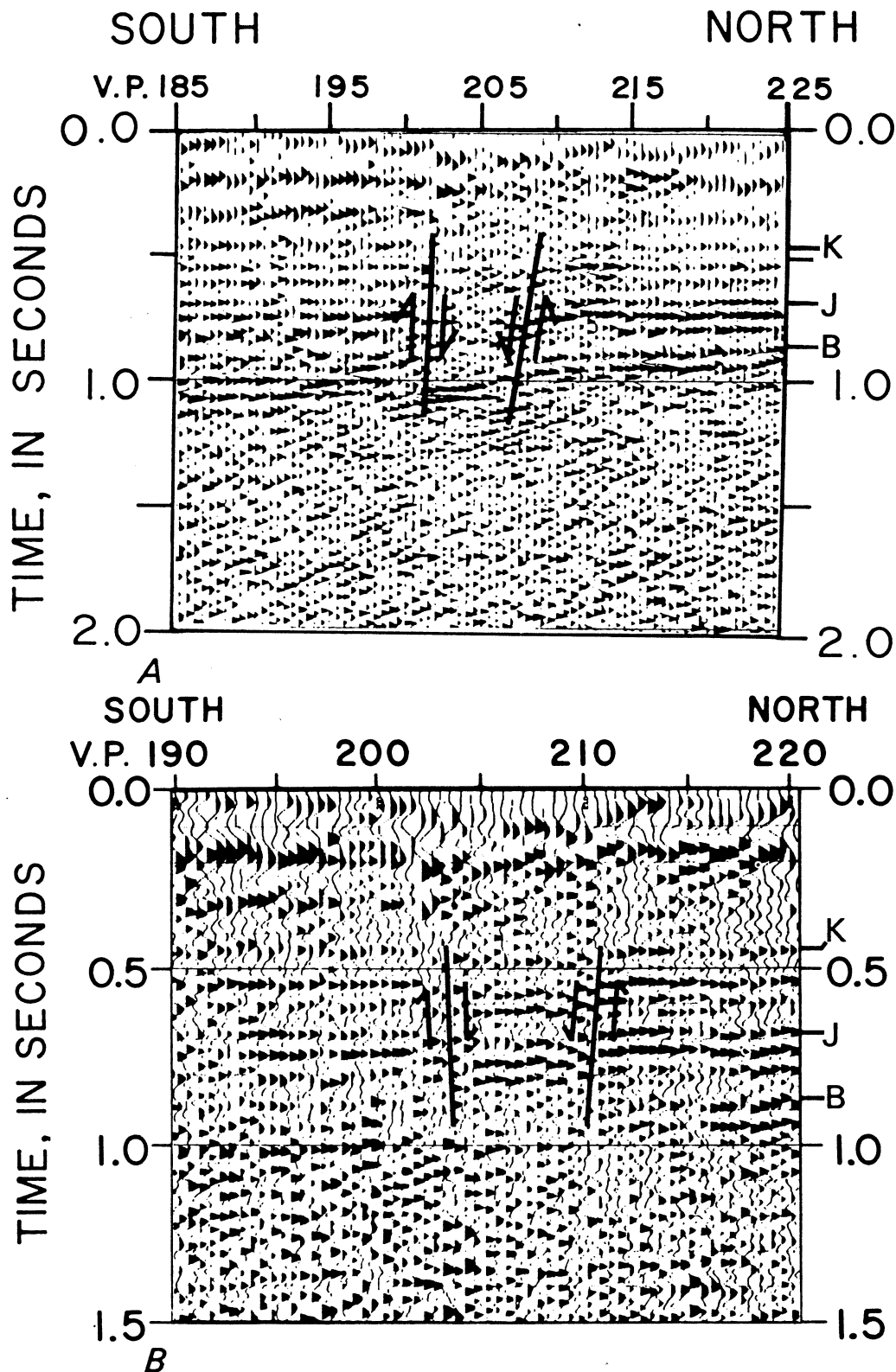


FIGURE 10.—Detail of parts of seismic section for line 3. *A*, Shows possible fault-bounded graben between stations 200 and 210. Normal stack shows paired offsets of basement reflection *B*. The overlying reflections *K* and *J* are also affected but cannot be clearly followed. *B*, Shows possible fault-bounded graben between stations 200 and 210. Reduced stack shows the same area as *A* at a larger scale.

Unlike *A*, which shows a fully stacked section (as many seismic traces as possible are used), *B* shows a stack in which only the four traces nearest to each source have been included in the stack. This restricted stack allows the reflections *K* and *J* to be traced across the offsets. It does not show reflection *B* as clearly as does the complete stack, however.

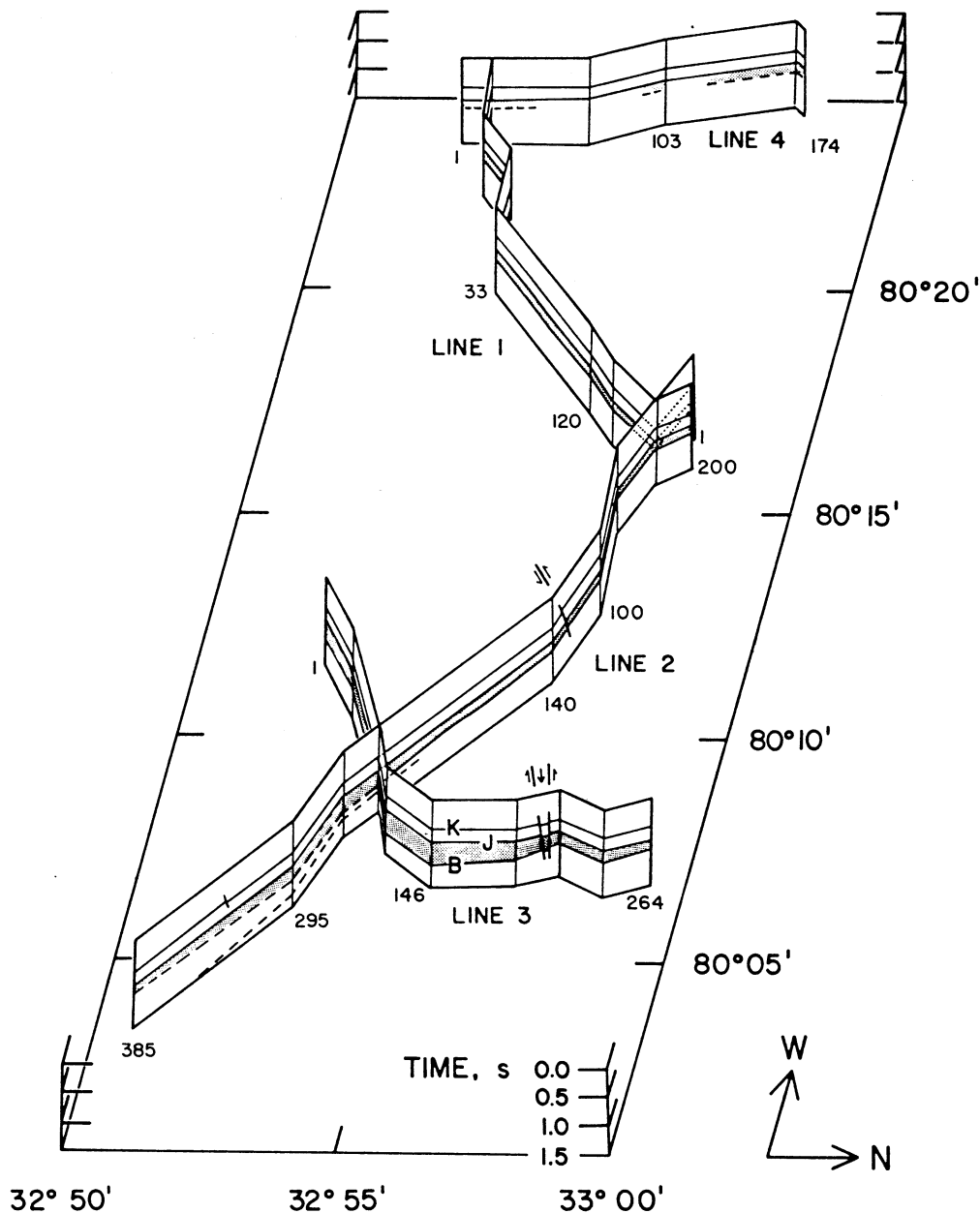


FIGURE 11.—Fence diagram representing reflections and faults from 0.0 to 1.5 s (two-way traveltime). The letters K, J, and B are defined in figure 4. Reflections are dashed where continuity is uncertain.

Appalachian overthrust extends beneath South Carolina is discussed below.

Wentworth and Mergner-Keefe (1983) argue that the 1886 event occurred along a high-angle, northeast-trending reverse fault like the Cooke fault. They emphasize the regional geological evidence for such faulting along the Eastern United States and suggest that the seismicity since the 1886 earthquake has occurred mostly along subsidiary northwest-trending structures. Seeber and Armbruster (1980) hypothesize that the 1886 Charleston earthquake occurred on a shallow-dipping detachment.

Until specific earthquakes can be pinned to specific faults, none of the alternative models are compelling. Additional high-resolution reflection data that cover the epicentral area more completely and uniformly might help to discriminate these hypotheses but, for logistical reasons, may be very difficult to obtain.

STRESS MEASUREMENTS

Stress measurements have been made by means of the hydrofracture technique in sediments at 200–400 m depth in CC#2 and CC#3 (Zoback and others, 1978).

Values for the least principal stress were found to be considerably sublithostatic, perhaps sufficient to activate normal-type fault motion on favorably oriented faults. The azimuth of the hydrofractures suggests relative horizontal extension in a northeast-southwest direction, favoring normal displacement on faults striking northwest. Unfortunately, the trend of the normal faults on line 3 has not been determined. Nothing in the reflection data is inconsistent with a northwest trend for these faults, however.

The existence of normal (b) and reverse (a, c?) faulting in the same region suggests that not all of these faults were formed as a direct result of contemporaneous tectonic stress and that at least some of these reflect adjustments on preexisting faults or zones of weakness. The importance of preexisting zones of weakness for the origin of the Charleston seismic zone has been emphasized by many workers (Bollinger, 1972; Fletcher and others, 1978; Sykes, 1978; Nishenko and Sykes, 1979; Behrendt and others, 1981; Tarr and Rhea, 1983). Amick (1979) points out that the lack of agreement between the stress measurements and the composite focal mechanism may be reconciled by the >5-km depth of the earthquake. If this is the case, the small faults seen at the surface in the reflection data may be minor surficial adjustments to a more deep-seated and intense compressional stress regime in the upper middle crust.

Turcotte and others (1977) suggest that stresses associated with the cooling and subsidence of the oceanic lithosphere and subsequent sedimentary loading may be responsible for the seismicity along the eastern continental margin of the United States. From such a model, one would expect high-angle displacements along faults trending parallel to the margin, rather than the northwest trend suggested by either the stress measurements (normal) or the hypocentral pattern (reverse; Tarr and Rhea, 1983; Amick, 1979). Behrendt and others (1981) identify fault (a) as trending northeast, but the reflector offsets indicate reverse motion, which implies possible reactivation of a Triassic normal fault by a later stress field. Obviously, further work is necessary to resolve better the patterns of shallow faulting and to determine their relationship to stress and seismicity.

RELATIONSHIP OF PROFILES TO GRAVITY AND MAGNETIC DATA

Detailed gravity and aeromagnetic surveys have been made of the Coastal Plain of South Carolina and Georgia, and these indicate that the crust beneath Charleston is considerably different in structure and composition from that exposed in the nearby Piedmont to the northwest (Popenoe and Zietz, 1977; Daniels and others, 1983). In the vicinity of Charleston, both gravity and magnetic data show a broad-wavelength, east-west-

trending low between 33° and 33°15' N., flanked on both sides by complementary regional highs (fig. 2). Superimposed on these regional magnetic and gravity highs are numerous shorter wavelength magnetic highs having magnitudes as high as 650 nT. This pattern of narrow highs on broad ones has been attributed to mafic plutons beneath extensive basalt flows in a rift setting; the broad central low may indicate a down-dropped crustal block flanked by uplifted horsts.

The COCORP profiles and USGS test holes are situated over the regional high just south of the prominent east-west low near 33° N. The strongest gravity and magnetic high in the region occurs at the site of CC#1 (see figs. 2, 4).

The southwestern end of line 1 and the southern end of line 4 converge over this most prominent magnetic high but show few reflections that can be clearly interpreted as the source region for the anomaly. Southwest of station 50 on line 1 are some dipping events whose relatively constant dip, occurrence in successive trains, and sense of dip (away from the source) suggest they are source-generated noise (for example, surface waves, guided waves, and reflected refractions). Similar wave trains having the same dip occur north of station 100 on line 4, dipping towards the south (again, dipping away from the source).

On line 4, there is a cluster of reflections from 2.3 to 3.0 s near station 30. Depths of 4.7–6.5 km are implied by these times, which are probably too deep for these reflections to represent the source of the observed magnetic high (Phillips, 1977). They could, however, be reflections caused by cumulate-type layering near the base of a mafic intrusive body. Few reflections can be seen on line 1 (the cross line in that area), but this might be due to structural asymmetry.

Other magnetic highs occur near the junction of lines 1 and 2 (~300 nT), near stations 300–350 on line 2 (~300 nT), and near stations 200–220 on line 3 (~500 nT). These have no clear seismic expression. Some possible explanations which come to mind are

- (1) The primary magnetic sources are shallow basalt flows.
- (2) The mafic plutons are difficult to detect seismically because the impedance contrast between the crystalline host rock and the intruded rock is small.
- (3) The top of the pluton is coplanar with the top of the crystalline basement, and its sides are too steep to reflect energy.

The first explanation is not consistent with a study of the depth to magnetic sources made by Phillips (1977). His study suggests that most of the power in the anomalies is produced by strongly magnetized sources (interpreted to be mafic intrusive bodies) at depths of

2–4.5 km. Furthermore, thin, extensive basalt flows do not explain the strong gravity peak near CC#1. Thus, some combination of explanations (2) and (3) is more reasonable.

DEEP STRUCTURE

From about 1.5 to 6.0 s, little coherent energy is present on the reflection profiles. Exceptions are the clusters of events at the southern end of line 4 near 3.0 s, discussed previously, and an isolated event at 3.0 s near station 200 on line 2. This zone is apparently a relatively transparent one; many scattered short reflections are present on lines 1–3 from about 6.0–12.0 s. (Line 4 shows a few reflections below 3.0 s, but it seems to have a significantly lower signal-to-noise ratio than the other lines, as suggested by its poorer definition of shallow events.)

The strongest deep reflection occurs at 9.0 s from stations 105 to 165 along line 2 (see fig. 12). Assuming a mean crustal velocity of 6 km/s, the depth is approximately 27 km. The event consists of only two cycles, which implies a rather sharp impedance contrast very deep within the crust. There is no cross line here, so if the reflection were outside the plane of the profile, it might be somewhat shallower. The apparent depth is probably too shallow for this event to represent the Moho discontinuity, since a refraction survey in the central Piedmont of Georgia and South Carolina obtained a crustal thickness of 33 km (Kean and Long, 1978). Furthermore, there is a deeper group of reflections near 11.0–11.5 s (~33–35 km) (fig. 11), which we interpret as the base of the crust on the basis of the agreement with this refraction estimate. The short, discontinuous reflections disappear rather quickly past 11.5–12.0 s. Similar observations of reflections in this time range have been made from USGS multichannel reflection profiles along the eastern Continental Shelf and margin (Hutchinson and Grow, 1979). They interpreted reflections between 9 and 12 s (many in the 10–11 s range) in the area of the Long Island Platform as representing the Moho at depths of 30 to 35 km.

Zones of no reflections in the shallow crust overlying deeper zones having numerous short, discontinuous reflection segments have also been observed on COCORP profiles in the Rio Grande Rift (Brown and others, 1979) and along the northwestern portion of COCORP profiles in the Wind River Basin (Brewer and others, 1980). Brown and others (1979) have suggested that the transparent zones observed on the Rio Grande Rift profiles may indicate homogeneous plutons (granitic) emplaced in the upper crust, and a similar interpretation may apply here.

POSSIBLE RELATIONSHIP TO COCORP SOUTHERN APPALACHIAN TRAVERSE

COCORP surveys across parts of Tennessee, North Carolina, and Georgia have shown that the crystalline rocks of the southern Appalachians constitute an allochthonous thrust sheet 6 to 15 km thick, which thickens to the southeast (Cook and others, 1979). The thrust wedge is interpreted to have moved at least 260 km westward over relatively undisturbed lower Paleozoic sedimentary rocks of the proto-Atlantic continental margin. The thrust plane has been traced as far eastward as the Carolina slate belt near the Coastal Plain overlap in Georgia. Harris and Bayer (1979) have made a palinspastic reconstruction of a cross section across Virginia and North Carolina that is consistent with the crustal shortening proposed by Cook and others (1979). Harris and Bayer (1979) further interpret deep reflections present on USGS marine seismic-reflection profiles near Cape Lookout and Cape Fear as a continuation of the thrust observed on the COCORP Appalachian traverse beneath the Continental Shelf; they postulate a detachment zone consisting of imbricate thrusts at two-way traveltimes of 8.0–11.0 s.

The extension of the fault surface beneath the present continental margin would imply a minimum displacement much greater than that which Cook and others (1979) have interpreted on the basis of the present reflection data. In any case, one might expect to observe similar features in the COCORP lines near Charleston.

In the absence of continuous deep seismic-reflection data from the southeastern end of the Appalachian lines to Charleston, this extrapolation of the southern Appalachian thrust system must be regarded as speculative at this time. However, it is conceivable that some of the events below 6 s (for example, the event near 9 s on Charleston line 2) could occur along such a regional shear zone, and the overall seismic character can be construed as being consistent with the southern Appalachian structure as described by Cook and others (1979).

As discussed earlier, Behrendt and others (1983) have observed a marked seismic discontinuity at 3–4 s (10–13 km) just offshore from Charleston. This surface, which is defined by the tops of several diffractions, is interpreted as a décollement extending landward and projecting into the Charleston seismic zone. No clearly similar group of events in this depth range is evident in the Charleston COCORP data, although there are a few widely scattered returns.

The strength of the reflections defining the Appalachian overthrust (Cook and others, 1979) varies considerably, so it is possible that the reflection strength of

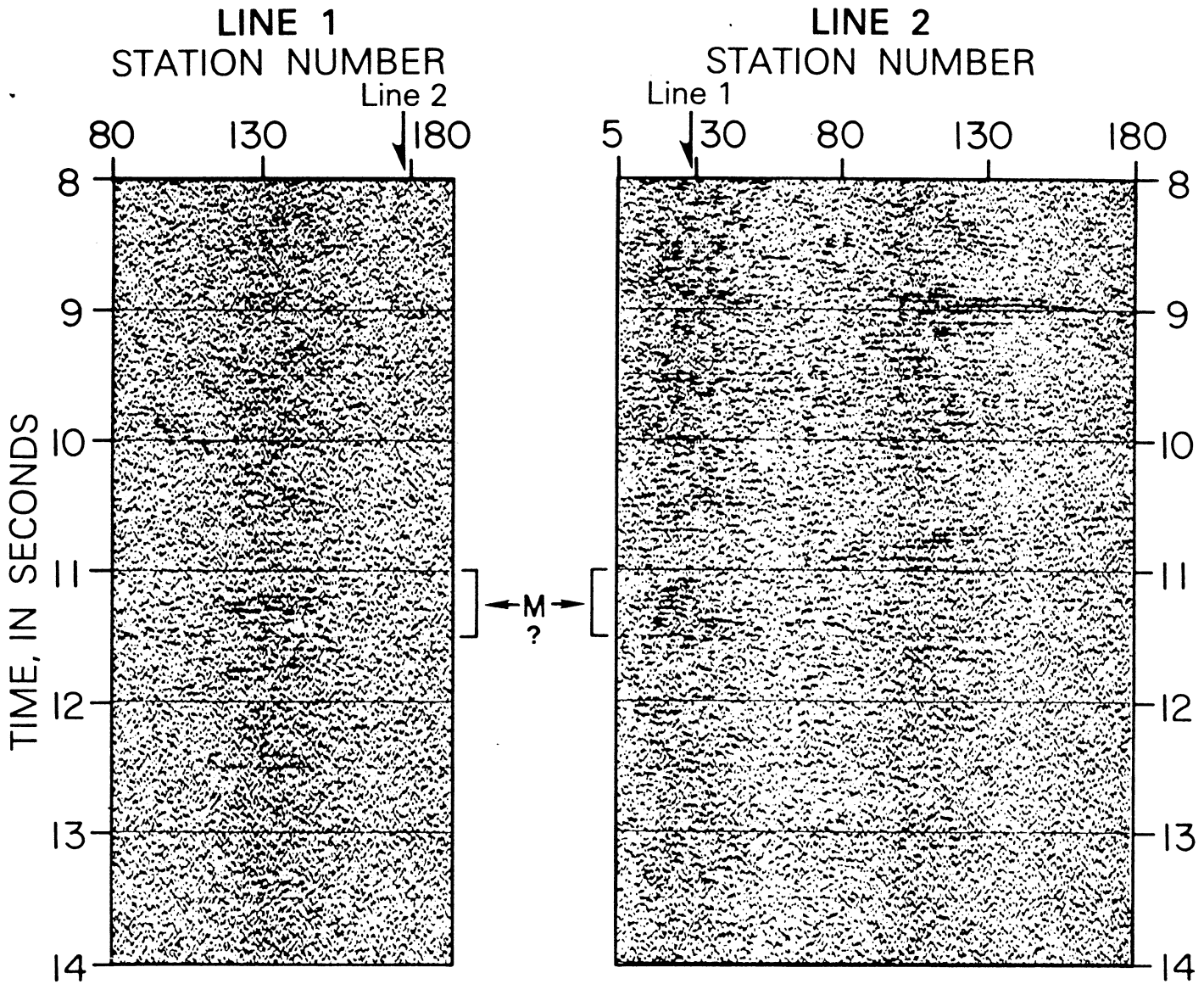


FIGURE 12.—Detail of seismic sections for lines 1 and 2, showing strong reflection at 9.0 s. The reflections near 11.0 s are interpreted as the Moho (M) or crust-mantle transition zone.

this boundary is less beneath the Charleston lines. It is also possible that the marine data are of somewhat better quality than are the land data. A third possibility is that the reflections near 6 s on the Charleston COCORP lines correlate with the 3- to 4-s events offshore, although this would require major relief on the surface over the relatively short distance between the two surveys.

New COCORP Appalachian data in central and southeastern Georgia indicate that the overthrust tectonic pattern is also present there (Cook and others, 1981). The depth to the top of the sediments in southeastern Georgia is variable but is of the order of 10-15 km.

POSSIBLE RELATIONSHIP OF CHARLESTON COCORP DATA TO CONDUCTIVITY STRUCTURE

Edwards and Greenhouse (1975) studied temporal variations in the geomagnetic field along an Appalachian profile extending from the Chesapeake Bay into northern West Virginia. Their data show a surprisingly small geomagnetic "coast effect" and appear to require anomalously low conductivity in the lower crust, especially under the eastern half of their profile. Although the modeling results are nonunique, Edwards and Greenhouse (1975) point out that their results might be explained by the presence of water at considerable depths within the crust.

If the upper crust beneath Charleston is in fact allochthonous with respect to the lower crust, some or most of the numerous reflections from 6–10 s (~18–30 km) might be from water-rich metasedimentary layers pushed tens of kilometers downward as an allochthonous wedge was driven over them. More extensive and detailed conductivity surveys would be of considerable interest to see if these results can be verified at other sites along the Eastern United States.

CONCLUSIONS

Seismic-reflection profiling in the Coastal Plain near Charleston, S. C., has delineated the regional Mesozoic and younger stratigraphy there and has identified faults in these units. Both normal and reverse faults appear to have been active late in the Cretaceous or Tertiary(?), causing displacements of a few tens of meters. Although it cannot be conclusively stated whether any of these faults is responsible for the 1886 Charleston earthquake or the seismicity currently being monitored, at least some of the post-Jurassic faults may be related to the seismicity. The relatively small offsets on these faults suggest either that events the size of the 1886 earthquake have been infrequent, unless the Charleston seismicity developed just a few tens of thousands of years ago, or that the earthquakes are not related to these faults. Additional shallow, higher resolution seismic profiling was undertaken by the USGS and Nuclear Regulatory Commission in light of the COCORP results (Behrendt and others, 1981).

Many deep reflections were recorded by COCORP, most of which occurred in the lower crust (~18–36 km). There appears to be a pronounced difference in the reflectivities of the upper and lower crust. The upper crust is rather featureless at these frequencies (8–32 Hz), whereas the lower crust shows a complex pattern of short, discontinuous reflections not unlike portions of seismic records from other COCORP sites. Some of the reflections from the lower crust may be from metasedimentary rocks deeply buried by Appalachian thrusting (Cook and others, 1979, 1981), a hypothesis that might also help to explain anomalously high conductivity in the lower crust along the Atlantic margin.

A group of deep reflections was observed at 10.5–11.5 s (~33 km); they appear to be more coherent than surrounding events and are postulated to represent reflected energy from the crust-mantle boundary or transition zone. This interpretation is based on compatibility with a nearby refraction profile and supplemented by observations of reflections at similar times on USGS offshore multichannel seismic profiles.

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