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A seismic refraction interpretation of the eastern margin of the Red Sea depression, southwest Saudi Arabia

by

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1/ USGS Menlo Park, CA
2/ USGS Reston, VA

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A SEISMIC REFRACTION INTERPRETATION OF THE EASTERN MARGIN OF THE RED SEA DEPRESSION, SOUTHWEST SAUDI ARABIA

by

H. R. Blank[1/], W. D. Mooney[2/], J. H. Healy[1/], M. E. Gettings[1/], and R. J. Lamson

ABSTRACT

A seismic deep-refraction profile across the Arabian Shield provides new constraints for crustal models of the southwestern Shield and the structural transition from the Shield to Red Sea axial trough. The crust thins abruptly from 40 to 16 km at the eastern edge of the coastal plain, and further thins without any detected lateral disconformity to about 8 km (of which about half is composed of a Miocene evaporite sequence) beneath the Red Sea shelf. The upper crustal layer has a mean velocity of about 6.2 ± 0.2 kms/s on either side of the exposed Shield margin, and may be composed predominantly of diabase (analogous to the oceanic layer 2).

The 16-km crustal thickness beneath the coastal plain and 6.2 km/s crustal velocity indicate that the crust is not typical oceanic crust, but the required total crustal thinning from 40 km on the Shield to 4 km (of non-evaporite crust) beneath the Red Sea shelf would seem to rule out a continental composition west of the Shield margin. This transitional crust, with an intermediate velocity, high density, and a thickness decreasing from that of attenuated crust (16 km) of an initial rift valley floor to that of a typical oceanic environment (4km), may be representative of crust produced during early stages of seafloor spreading. In general, such transitional crust is also a magnetic quiet zone, but, in the region traversed by the seismic refraction profile, magnetism was sufficiently localized with respect to a fixed axis of spreading to produce the distinct stripe anomalies.

The seismic interpretation supports the hypotheses of (1) essentially shore-to-shore opening of the Red Sea between Aqaba and the Tihamat Asir; (2) two-stage extension; and (3) Miocene and younger crust beneath most of the Afar.

INTRODUCTION

A 1,000-km-long, deep-refraction seismic profile was recorded in early 1978 by the U.S. Geological Survey (USGS) and the Saudi Arabian Directorate General for Mineral Resources (DGMR) across southwestern Saudi Arabia. Its purpose was to provide estimates of crustal thickness and the bulk properties of the crust and upper mantle beneath the principal tectonic provinces of the Arabian Shield and its margins.

The profile transects the Shield in a south and southwesterly direction, extending from Phanerozoic "cover rock" terrain of the Arabian platform, near Riyadh, to the

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outer edge of the Farasan Islands, in the southern Red Sea, less than 40 km from the edge of the Red Sea axial trough. Six shots were employed, and more than 500 recording stations were occupied. One hundred specially developed, portable, programmable instruments recorded the shots using 2-Hz vertical-component seismometers. A description of equipment, field procedures, and initial results are contained in Blank and others (1979), and a general account of the results and their interpretation are given in Healy and others (1982). The present report is concerned specifically with the interpretation of the southwesternmost 480 km of the recorded profile. The report focuses on the structural transition from Arabian Shield to oceanic crust of the central Red Sea and on the problem of the composition of the crust beneath the southern Red Sea shelf and coastal plain.

ACKNOWLEDGMENT

This project is part of a continuing program of cooperative geological investigations being carried out under the terms of a work agreement between the USGS and the Saudi Arabian Ministry of Petroleum and Mineral Resources.

TECTONIC SETTING

One of the world's youngest oceanic basins, the Red Sea, separates the Arabian Shield from the Nubian Shield. The narrow, axial trough of the Red Sea is generally accepted as a divergent plate margin, the locus of seafloor spreading associated with the separation of Arabia from Africa (McKenzie and others, 1970; Lowell and Genik, 1972; Girdler and Styles, 1974; LePichon and Francheteau, 1978). Analysis of high amplitude, axially symmetrical magnetic anomalies in the central region indicates that new oceanic crust has been forming in the axial trough for approximately the last 4 to 8 Ma (Vine, 1966; Phillips, 1970; Roesser, 1975; Noy, 1978; Hall, 1980). This activity is concommitant with extension in Afar and the Gulf of Aden, and with sinistral shear on the Dead Sea rift system. The pole rotation for the Arabian Plate as a whole is generally considered to lie in the eastern Mediterranean Sea.

The width of the entire Red Sea depression is several times that of its axial trough. In southwest Saudi Arabia the depression can be considered to consist of both the Red Sea with its axial trough and the "Tihamat Asir", a region that includes the coastal plain and the foothills of the flanking Asir escarpment. The boundaries of the two Red Sea troughs do not have everywhere a sharp morphological expression, but between lat 16° N. and 17° N., in the region traversed by the USGS/DGMR refraction profile, the eastern margin of the trough is a steep submarine escarpment. The deeper part of the main trough has been referred to as its "axial zone", and the shallower part as its "marginal zones" (Tramontini and Davies, 1969), or shelves. Most of the main trough is above the 200 m isobath (Laughton, 1970).

Reconnaissance geologic mapping of southern Saudi Arabia at a scale of 1:100,000 has recently been completed and the data have been compiled at 1:250,000 scale (Blank and others, in press; Fairer, 1983). Precambrian rocks at the eastern edge of the coastal plain are overlain by a veneer of Paleozoic and Mesozoic sedimentary rocks that are displaced from elevated positions on the escarpment along a 10-km-wide tectonic belt that trends parallel to the Red Sea, only a few hundred meters above sea level. Together with Tertiary sedimentary and igneous rocks in the tectonic belt, they form a rift-valley-floor assemblage that provides important clues to development of the region.

The Precambrian and cover rocks, after an early stage of listric faulting and detachment, were invaded by closely-spaced diabase dikes, broken into narrow northwest-trending tectonic slices, and further rotated seawards. Rotation of the Paleozoic-Mesozoic strata is as much as 90°, but averages about 60°, and increases westward; that of the diabase dikes is about 20-30° (Kellogg and Blank, 1982). The number of dikes and the dike/host volume ratio increases from east to west across the Shield margin; westernmost exposures consist almost entirely of sheeted dikes, flows and pillow lavas, and volcaniclastic rocks. Masses of gabbro and granophyric rocks transect the dike complex, and are rotated seaward along with it. The Tertiary igneous assemblage has close petrochemical affinities with oceanic tholeiite (Ghent and others, 1980). Blank (1977), on the basis of studies of the dike system, and Gettings (1977), from gravity interpretation of a regional survey, believed that the exposed western edge of the Shield marks a Tertiary oceanic-continental crustal boundary. Other workers (e.g. Cochran, 1981) regard the greater part of the Red Sea depression as a zone of extreme continental extension, with oceanic crust confined to the axial trough and axial portion of the main trough.

Bedrock on the coastal plain is concealed beneath a cover of late-Cenozoic alluvial deposits, and geologic interpretations must rely heavily on data from deep drilling and geophysical surveys.

This report adds the results of the USGS/DGMR 1978 seismic deep-refraction profile to existing gravity, aeromagnetic, and heatflow data for this region.

PREVIOUS SEISMIC WORK

Early seismic work in the Red Sea has been reviewed by Girdler (1969). The pioneering surveys were carried out by "VEMA" and "ATLANTIS" in 1958, with 15 refraction profiles in the northern, central, and southern sections (Drake and Girdler, 1964). Profiles 170 through 176 of this set, in the southern sector, show a sedimentary cover 0.5 to 4.5 km thick (velocity 3.49 to 4.48 km/s) that consists largely of Miocene evaporite and clastic deposits. A profile near the center of the axial trough southwest of the Farasan Islands shows basement velocities ranging of 7.16 to 7.31 km/s, whereas two profiles on the southern shelves (at lat 16.5° N. and west of the axial trough, and lat 15° N. and east of the axial trough) show basement velocities ranging from 5.53 to 5.91 km/s. Similar results were obtained elsewhere in the Red Sea in this survey; velocities for profiles over the axial trough ranged mainly from 6.8 to 7.3 km/s, and for profiles over the shelves from 5.8 to 6.1 km/s. Locally, the velocities on the shelves were as high as 6.97 km/s (between lat 23° N. and 23.5° N. Girdler (1969) interpreted the high-velocity basement in the axial trough as oceanic crust, and the typically, much lower velocity basement on the shelves as continental crust.

Other early seismic work in the Red Sea includes continuous "sparker" reflection profiles by "CHAIN" over the axial trough in 1964 (Knott and others, 1966; Phillips and Ross, 1970), and refraction profiles by "DISCOVERY" on the shelf of the northern sector in 1967, and by "ASSAB" in the center sector in 1967-68 (Tramontini and Davies, 1969). On the "ASSAB" survey, which covered in detail a limited area mainly over the axial trough between lat 22° N. and 23° N., an average basement velocity of 6.6 km/s, and an average depth to basement of 4.6 km were found for the portion of the main trough adjacent to the axial trough. "DISCOVERY"'s refraction results were similar to those of the 1958 surveys.

Two seismic deep-refraction profiles along and across the northern Red Sea margin of Saudi Arabia have recently been recorded by a joint team from the University of Hamburg and King Abdulaziz University, Jeddah. These data indicate a crustal thickness of about 30 km beneath the Shield, 20 km beneath the coastal plain, and 16 to 18 km offshore; the upper-mantle velocity decreases from 8.0 km/s to 7.6-7.7 km/s between the Shield and the Red Sea (Makris and others, 1982).

In summary, seismic refraction data available from previous surveys of the Red Sea indicate clearly that the material with oceanic crustal velocities is present in the axial trough, and that the basement of the main trough is composed at least in part of material with similar velocities. Very little information has been obtained for velocities beneath the marginal (landward) portion of the main trough, because of the difficulty of navigation in the shallow waters. No estimates of crustal thickness in the southern and central sectors were obtained on any refraction surveys.

A seismic reflection survey of the seaward portion of the coastal plain in southwest Saudi Arabia was made by Auxirap during 1963 (Gillman, 1968). The surface of the "Jurassic and basement" was shown to dip toward the Red Sea at an angle of about 10^{o}, its depth increasing from about 2 km to some 20 km inland to nearly 5 km in the vicinity of the Mansiyah No. 1 drill hole and the Jizan salt dome on the coast. Unfortunately, the Mansiyah drill hole had to be abandoned at 3.9 km depth, short of the seismic basement. The profiles did not extend northeastward on to the Precambrian terrane, and therefore its seismic properties could not be compared with those of basement beneath the coastal plain.

An important series of geophysical investigations in the Saudi Arabia-Sudanese common sector has been carried out by the Saudi-Sudanese Red Sea Joint Commission, sponsored by the two nations. Some data and interpretations of the surveys have been reported by Yousif (1982). The work included seismic reflection, magnetic, gravimetric, and bathymetric surveys. South of the latitude of Jeddah, the accoustical basement dips landward from the axial trough for an average distance of 70 to 75 km on either side of the axis, and is identified as oceanic crust on the basis of its near-continuity with accoustical basement that is known to be basalt exposed in the trough.

No seismic deep-refraction data have previously been obtained for southwestern Saudi Arabia. Studies of waves on the path Addis Ababa-Shiraz, which passes through the Afar depression, have yielded an average crustal thickness of about 35 km (Niazi, 1968; Knopoff and Fonda, 1975).

USGS/DGMR EXPERIMENT

Figure 1 shows locations of the shot points and selected recording sites for the USGS/DGMR seismic refraction experiment. Shot points 4 through 6 provided energy for the southwestern end of the recorded profile that includes the transition zone from the Arabian Shield to the Red Sea rift. The distance between shot points 4 and 5 is 240 km, and that between shot points 5 and 6 is 160 km. Shot point 4 was well inland on the Shield, near the town of Bishah. Shot point 5 was within 10 km of the exposed margin of the Shield, near Ad Darb; the profile crosses the margin a few kilometers south of a 25-km left-lateral offset of the Tertiary-Precambrian contact. Shot point 6 was located in the Red Sea, the charges having been set off near Dumsuq Island, an uplifted-coral islet of the Farasan group, at a depth of about 50 m. A total of 10 shots was fired at these shot points. The size of charge ranged from 1,300 to 4,000 kg.

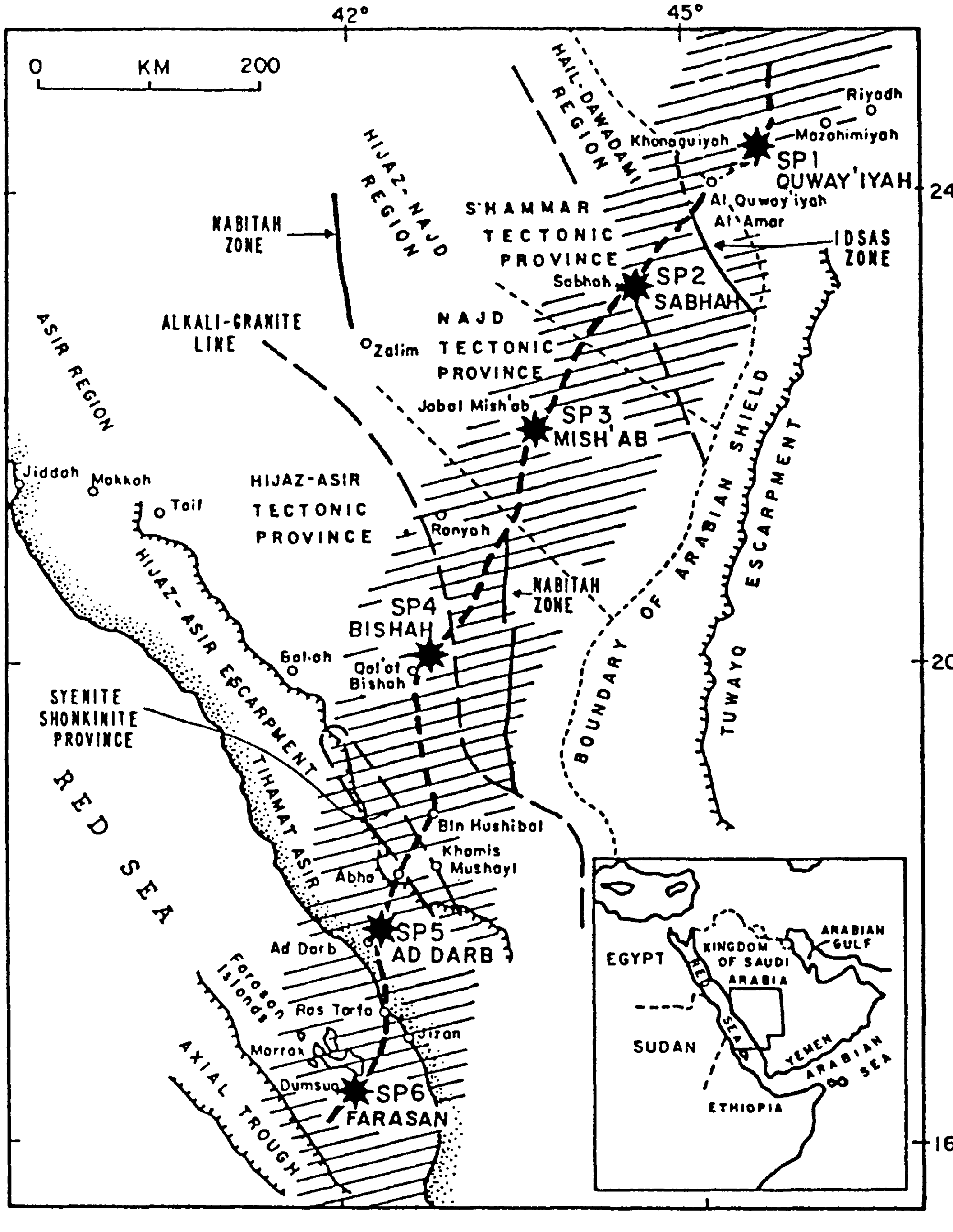

Figure 1.--*Generalized map of a portion of southwest Saudi Arabia, showing principal tectonic provinces of the Arabian Shield and the location of the USGS/DGMR seismic refraction profile*

Receivers were stationed at 2-km intervals, where feasible. No bottom recorders were used, and the station spacing at sea depended on the separation of islands. The most western recording station was on the island of Marrak, 24 km southwest of shot point 6, and about 30 km northeast of the steep slopes at the edge of the axial trough. The Marrak-Dumsuq segment of the profile was the only segment in the southwest region not "reversed" during the course of the experiment.

DATA INTERPRETATION

Figure 2 shows the reversing profiles from the escarpment (shot point 5) to the Red Sea (shot point 6). On the profile from the escarpment to the Red sea (fig. 2A), basement first-arrivals have been fitted by straight lines; offsets are near the 30 and 65 km range where abrupt changes in sedimentary thickness occur. Second-arrivals between 70 and 85 km have been interpreted to be those of a reflection (PmP) from the crust-mantle boundary beneath the coastal plain. The apparent velocity of the mantle refraction (Pn) phase is 8.6 km/s (fig. 3). These arrivals indicate a crustal thickness of 18 km southwest of shot point 5. The reversed profile (fig. 2B) indicates a quite different structure at the marine shot point. Gaps in the record correspond to gaps between the islands. The first arrivals indicate velocities of 4.2 and 6.9 km/s for layers in the uppermost crust: the high-amplitude second-arrivals at a range of about 20 km are interpreted to be mantle reflections (PmP). The mantle refraction is generally weak, and the apparent velocity of 7.8 km/s is obtained by correlating the PmP reflection with clear first-arrivals at a range of about 130 km. Based on this interpretation, a crustal thickness of 8 km has been derived for the vicinity of the Red Sea shot point, and the complete reversed profile has been calculated as shown in figure 4. A thin layer with a velocity of 6.8 km/s has been included above the crust- mantle boundary in conformance with the Red Sea refraction observation reported by Drake and Girdley (1964) and Davies and Tramontini (1970), but no head wave that travelled along the upper boundary of such a layer was identified in the records. The continuous reflection data for the shelf (Phillips and Ross, 1970) indicate that the basement is highly faulted and may have considerable surface relief, which agrees with aeromagnetic depth interpretations by Blank and others (1980) and Yousif (1982). The major features of the proposed seismic model are the crustal and upper mantle velocities, and the 5° landward dip of the crust mantle boundary. It is significant that the average crustal velocity, 6.2 $\pm$ 0.2 km/s, found beneath the coastal plain and the Red Sea shelf is close to typical sialic crustal velocities and to typical diabase velocities (Birch, 1962; Birch, 1982), but not to velocities typical of any oceanic crustal layer. The mantle velocity of 8.05 $\pm$ 0.2 km/s indicates a normal rather than an anomalous mantle in the region. The authors recognize that the data do not provide a detailed picture of the true velocities nor of the degree of lateral velocity variations along the profile; supplementary cross-profiles are needed to reduce the ambiguities.

Synthetic seismograms were calculated for the model between shot points 5 and 6 with the method described by McMechan and Mooney (1980) as a check on the traveltime interpretation. The results for shot point 5 SW (fig. 4) show high amplitudes on the PmP branch between 50 and 100 km in good agreement with the data as plotted in true amplitude format. The Pg phase is somewhat higher in amplitude than the Pm phase in both the observed and synthetic sections.

The comparison of observed and synthetic data for shot point 6 NE shows several interesting features (fig. 5). The highest amplitude phase in the synthetic profiles is the direct wave through the sediments which propagates to 50 km. This phase is not as

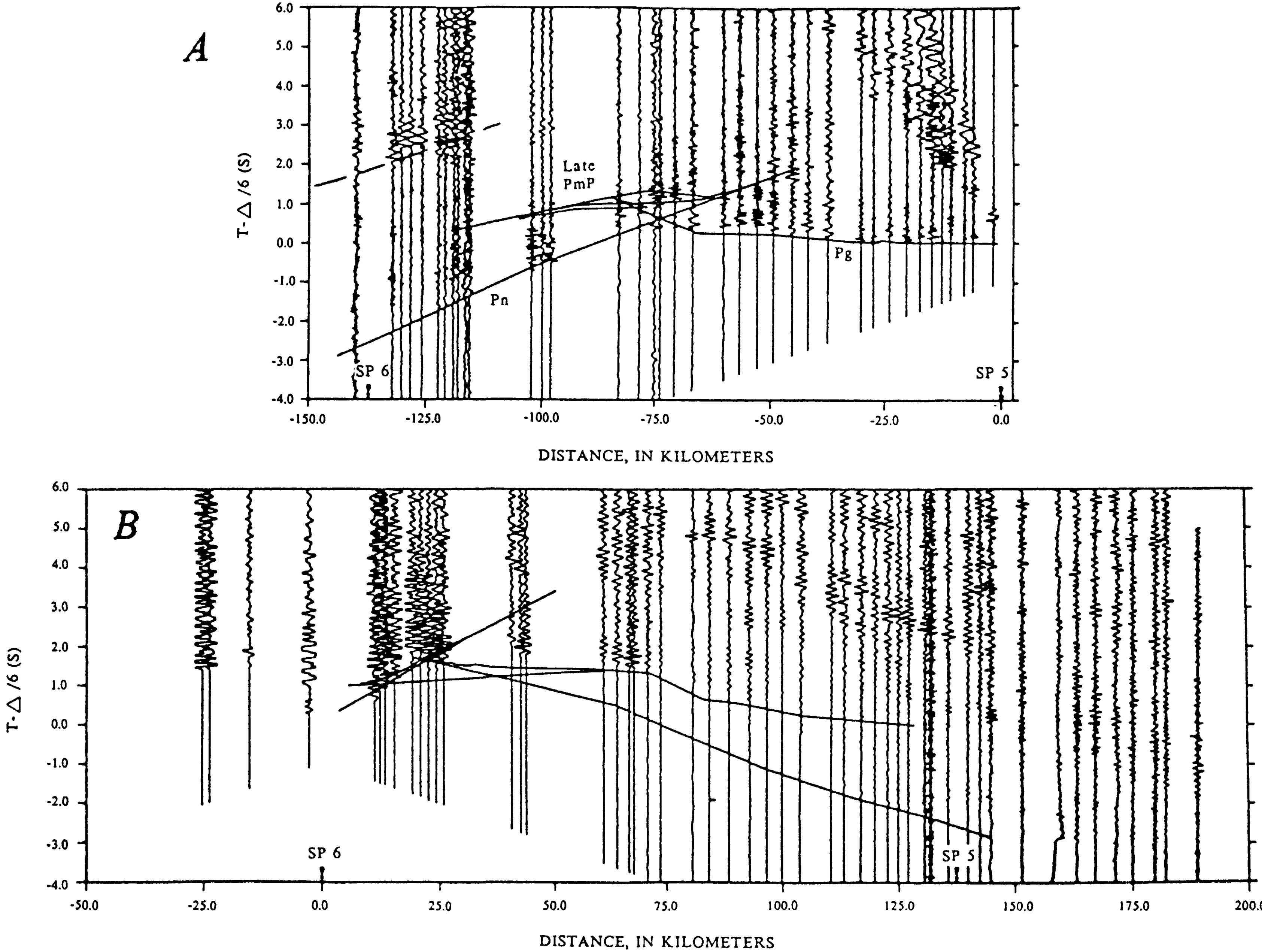

Figure 2.--*Seismic record section with 6.0 km/s reduction velocity for shot point 5 SW* (A) *and shot point 6 NE* (B)

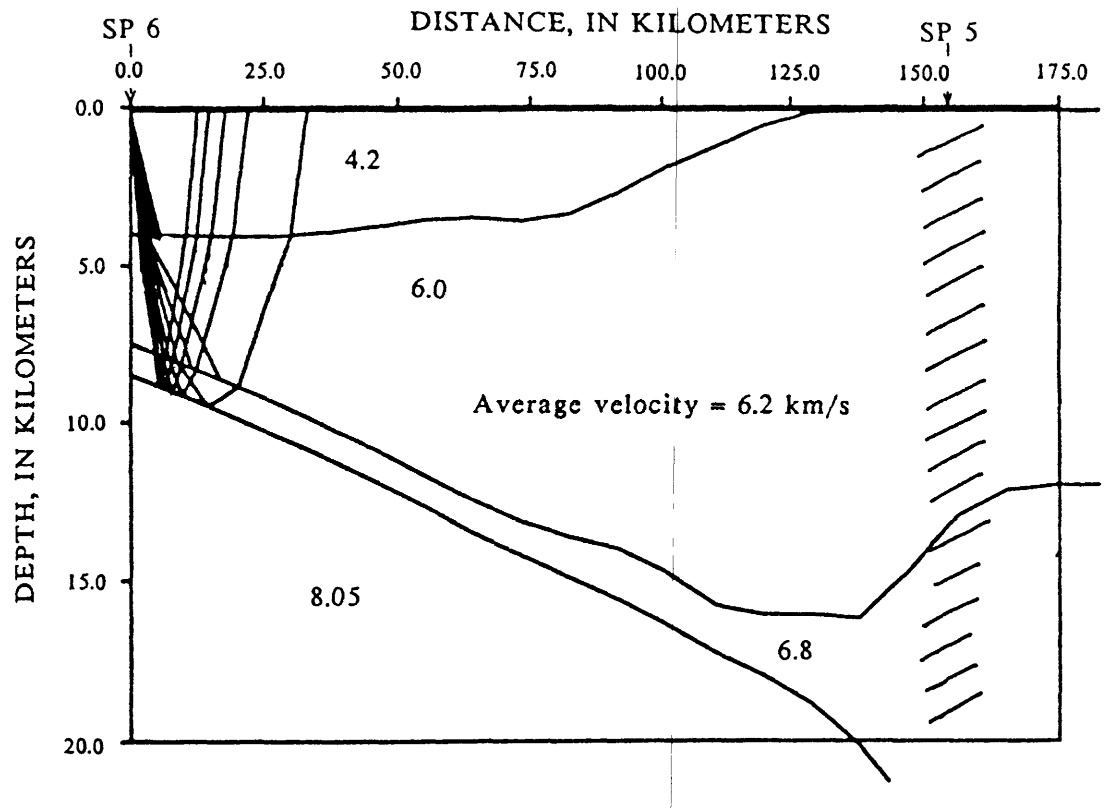

Figure 3.--*Interpreted crustal velocity structure, shot point 6 to shot point 5, showing PmP reflections*

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prominent in the observed data. The PmP phase is prominent in both the observed and synthetic sections, while the Pn phase is undiscernible between 40 and 70 km on both sections (fig. 5). Beyond 70 km the Pm phase increases in amplitude with distance on both the observed and synthetic sections. The low amplitude of the Pn phase in the near-distance range appears to be an effect of the low velocity gradient in the mantle and a scaling effect. The PmP reflection is of very high amplitude in this crust. Overall, the synthetic seismograms support the proposed interpretations of the crustal structure between the shot points 5 and 6.

A very different velocity structure has been derived from the data obtained northeast of the escarpment between shot points 5 and 4 (fig. 1). Intracrustal refracted and reflected phases (Pi and PiP) are clearly evident in the data (fig. 6). A thick crust is indicated by the large distance (200 km) at which the mantle arrivals cross over the crustal arrivals (fig. 6); a somewhat thicker crust is indicated by the data near shot point 4 than those near shot point 5. Considered as a reversed profile, these data have been used to obtain the velocity-depth model of figure 7. The model indicates an average crustal thickness of 40 km between the two shot points, and 2.2^{o} eastward dip on the crust-mantle boundary. A rather high average crustal velocity of 6.6 km/s is indicated near shot point 5 by the time and distance of the Pmp critical point.

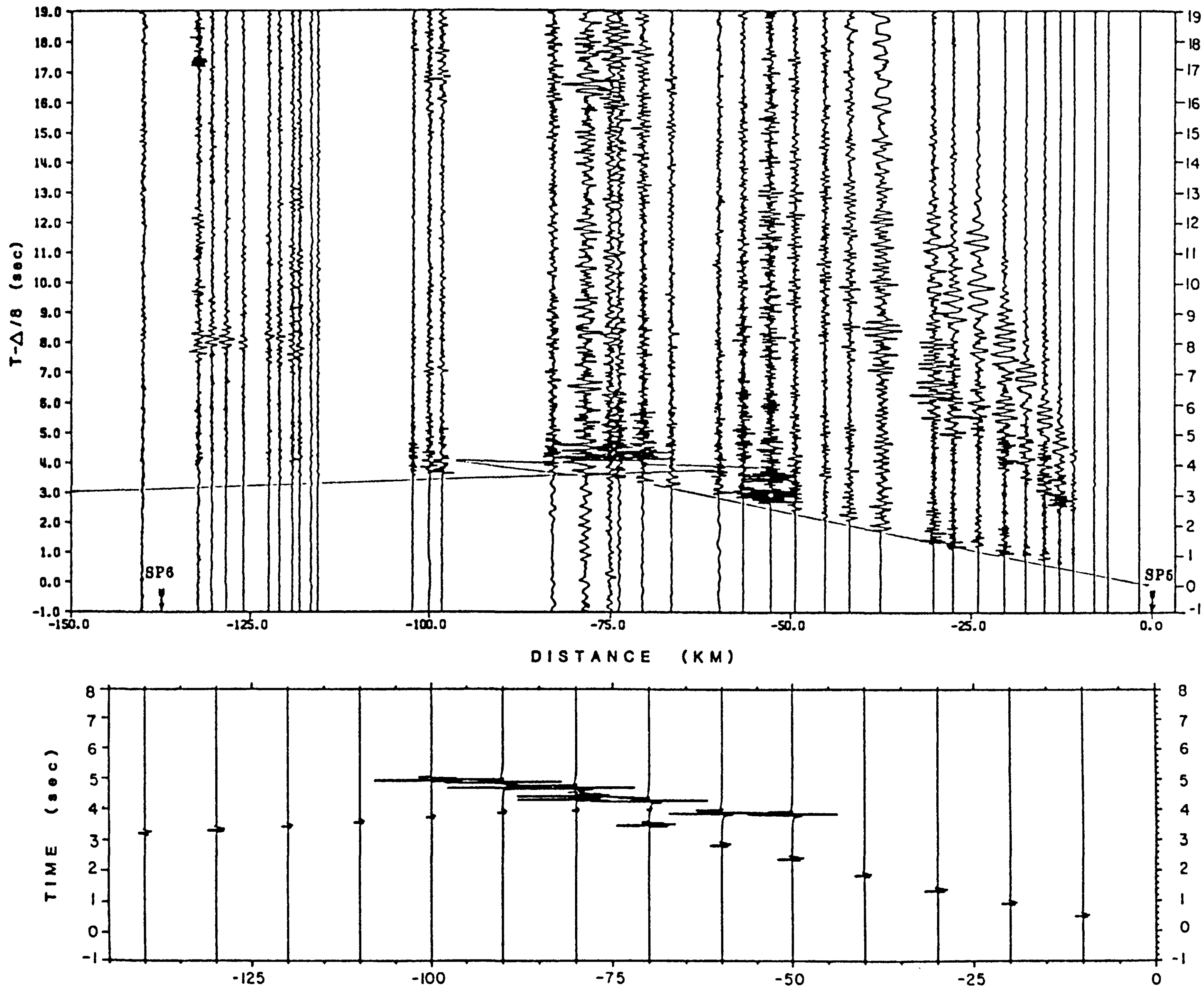


Figure 4.--*Synthetic record section with 8.0 km/s reduction velocity for crustal model of figure 3 (shot point 5 SW)*

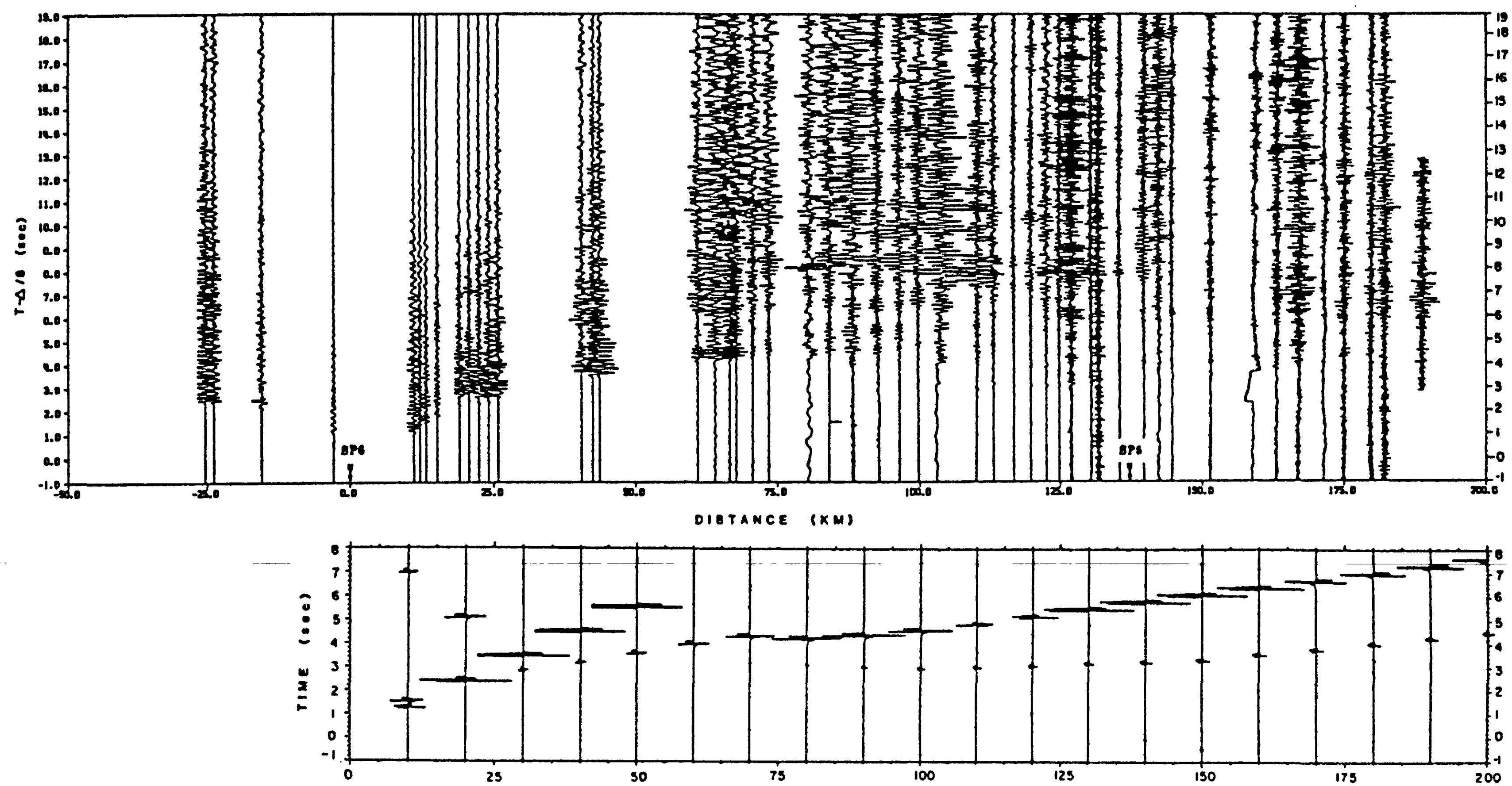


Figure 5.--*Synthetic record section with 8.0 km/s reduction velocity for crustal model of figure 3 (shot point 6 NE)*

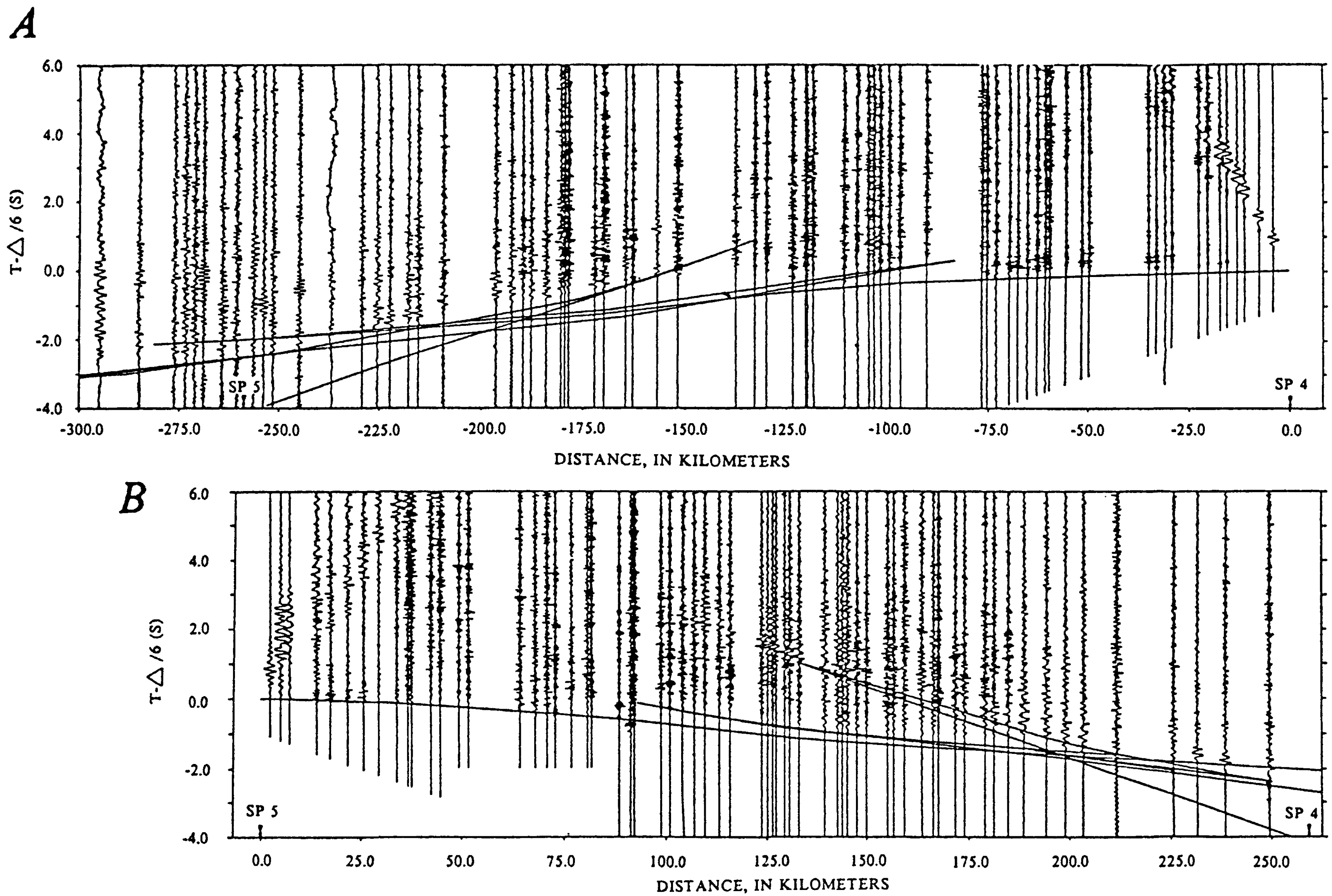


Figure 6.--*Seismic record section with 6.0 km/s reduction velocity for shot point 4 SW* (A) *and shot point 5 NE* (B)

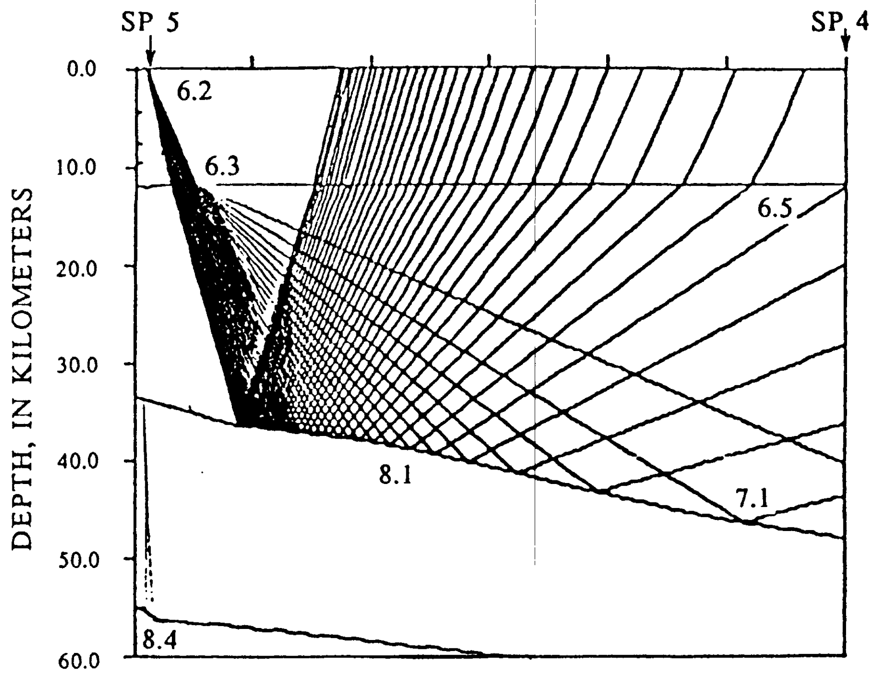


Figure 7.--*Interpreted crustal velocity structure, shot point 5 to shot point 4, showing PmP reflections*

COMBINED MODEL

The two models described above must in some way be joined together near shot point 5. The data of the true-amplitude record section from shot point 6 (fig. 8) to a distance of 300 km provide some of the restraints on this union (the data to a range of 140 km have been already discussed (fig. 2). Between 160 and 210 km, the data show a remarkable lack of coherency; the seismic energy appearing only diffusely in the records. This region of highly emergent energy corresponds with those stations for which the seismic ray paths must have traversed the region directly beneath shot point 5. The record character can be explained as the result of scattering of seismic energy at the Shield-Red Sea boundary that is characterized by a highly irregular velocity structure. At 225 km, there is a sudden change in the character of the seismographs that marks the onset of a coherent, high-amplitude arrival with an apparent velocity of 8.5 km/s. This arrival is delayed by 2.5 s from the mantle arrival observed along the coastal plain between 20 and 150 km, and differs from those arrivals by its higher amplitude and apparent velocity. These factors and detailed travel-time modelling suggest that the 8.5 km/s arrivals do not represent head waves from the crust-mantle boundary (at a depth of 40 km), but rather are reflected and/or refracted arrivals from a submantle discontinuity at approximately 50 km depth. The regional distribution and nature of such sub-Moho discontinuities have been discussed extensively in the literature (Fuchs and others, 1977; Meissner and Fluh, 1979). The union between the two models has been accomplished by connecting the layer boundaries with smooth curves and comparing the observed travel-times and apparent velocities for the 8.5 km/s arrivals with those obtained for the model (fig. 9).

This combined crustal model for the transition zone is far from unique. Ambiguities in the interpretation arise as a result of sharp lateral structural and compositional inhomogeneities; the relative sparsity of recording sites (particularly between the Farasan Islands and the mainland); the difficulty of trace-to-trace phase correlation; and the association of phase arrivals with specific travel paths.

The Saudi Arabian deep-refraction data-set was supplied to members of the Commission on Controlled Source Seismology of the IASPEI (the International Association of Seismology and Physics of the Earth's Interior) as a common data set for discussion at the Third Triennial Meeting of the Commission, held in Park City, Utah, in 1980 (Mooney, 1981). The various interpreters arrived at a range of velocity structures for both crust and upper mantle in the transition zone. The depth of M between shot points 5 and 6, for example, ranged from about 9 to 21 km, the mean being 15-16 km.

DISCUSSION

Lithologic and tectonic explanations are required of the interpreted seismic velocity structure between shot points 4 and 6, and in particular for the apparent crustal thickness and velocity southwest of shot point 5, beneath the coastal plain and the shelf of the Red Sea. It is evident that the crust has thinned by about half (this report's model) or at least by one third (from interpretations of the other participants at the Park City Symposium; Mooney, 1981) passing from shot point 4 across the Asir Mountains to shot point 5 at the edge of the coastal plain. The crust has even more drastically thinned passing from shot point 5 to shot point 6, across approximately the full width of the Red Sea shelf. The total thinning ratio between shot points 4 and 6 is about 1:10. The uppermost layer west of shot point 5 has been excluded from these estimates.

The top layer west of shot point 5 has a mean velocity of 4.2 km/s and certainly represents the thickest blanket of Miocene evaporites and clastic sediments that overlies the basement throughout the main trough of the Red Sea. This layer varies from 4 to 7 km in thickness, and up to 4 km have been penetrated in exploratory drill holes on either side of the southern Red Sea (for example, Mansiyah No. 1 drillhole). Both the top and the bottom of the layer apparently have considerable relief, and seismic reflection data provide clear evidence of internal structural deformation, including piercement structures and high-angle normal faults (Yousif, 1982). The Farasan Bank (shoal waters) and the Farasan Islands are laced with salt domes. A broad shallowing of the second crustal layer, velocity 6.2 km/s, is present beneath the islands, and approximately coincides with a shallowing of the magnetic basement.

About all of the second crustal layer seaward of the Shield margin at shot point 5 has a velocity less than 6.4 km/s, and the average velocity is 6.2 km/s in this interpretation; the proposed model allows a thin layer (2 to 3 km thick) of 6.8 km/s velocity just above the mantle; but, as previously noted, no such layer was detected, and this report's upper mantle velocity, 8.0, is only slightly lower than the velocity under the interior Shield. Other interpreters found that a 6.7-km/s layer could be as much as 10 km thick beneath the Red Sea shelves, but in that case, a thick LVZ (7.5 km/s) wedge was required in the upper mantle; this wedge might extend beneath the Shield at shot point 5 at between 35 and 40 km depth.

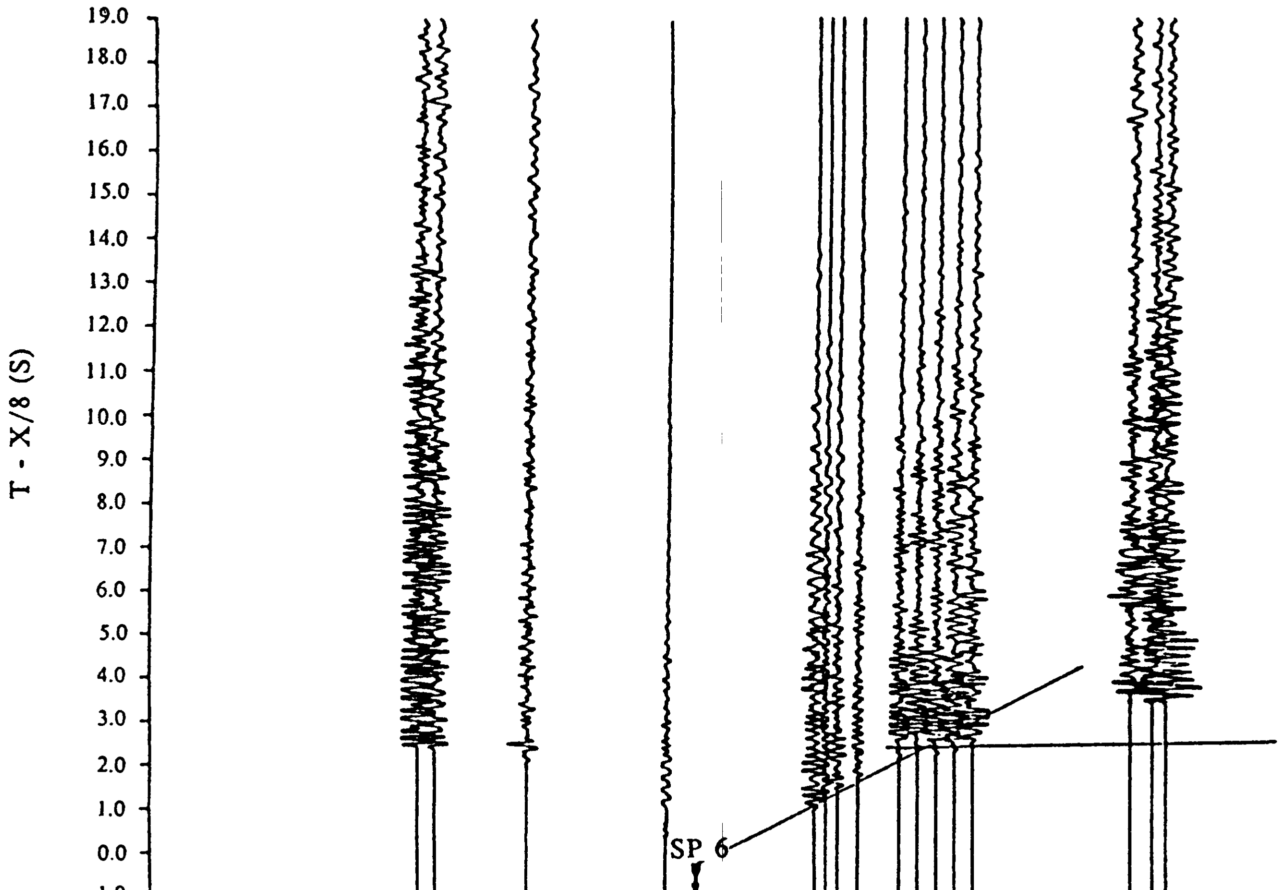
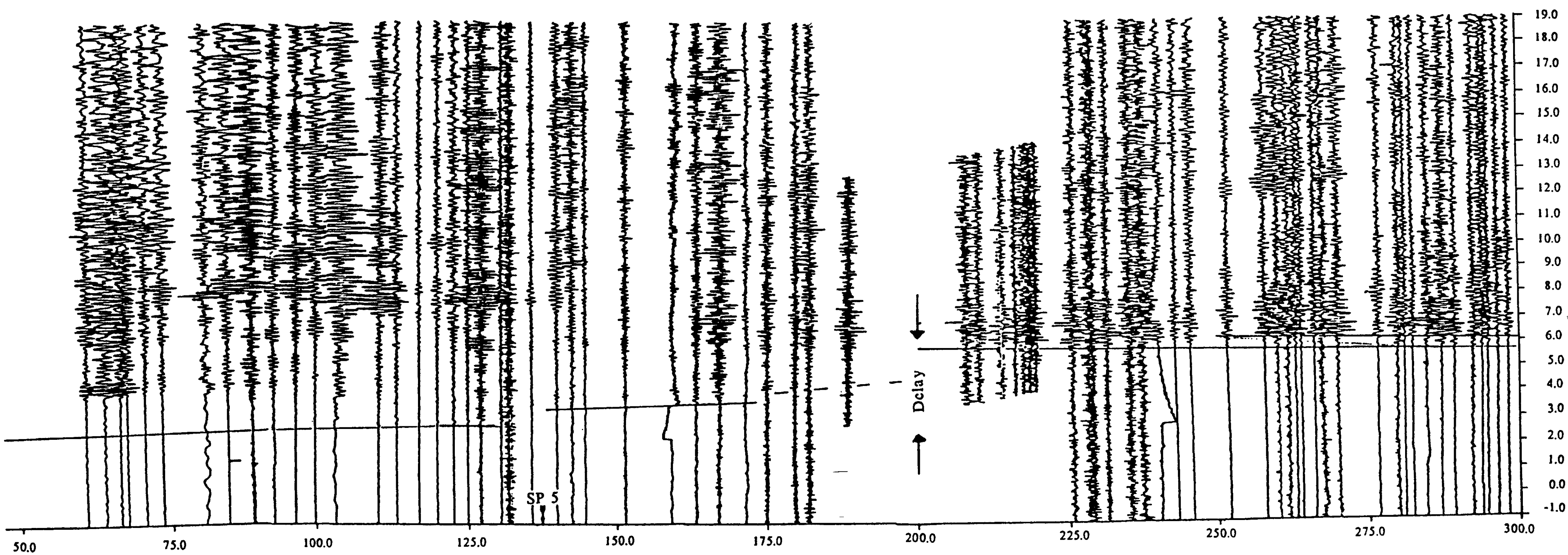


Figure 8.--*True-amplitude seismic-record section with 8.0 km/s, shot point 6 NE to a distance of 300 km*



DISTANCE, IN KILOMETERS

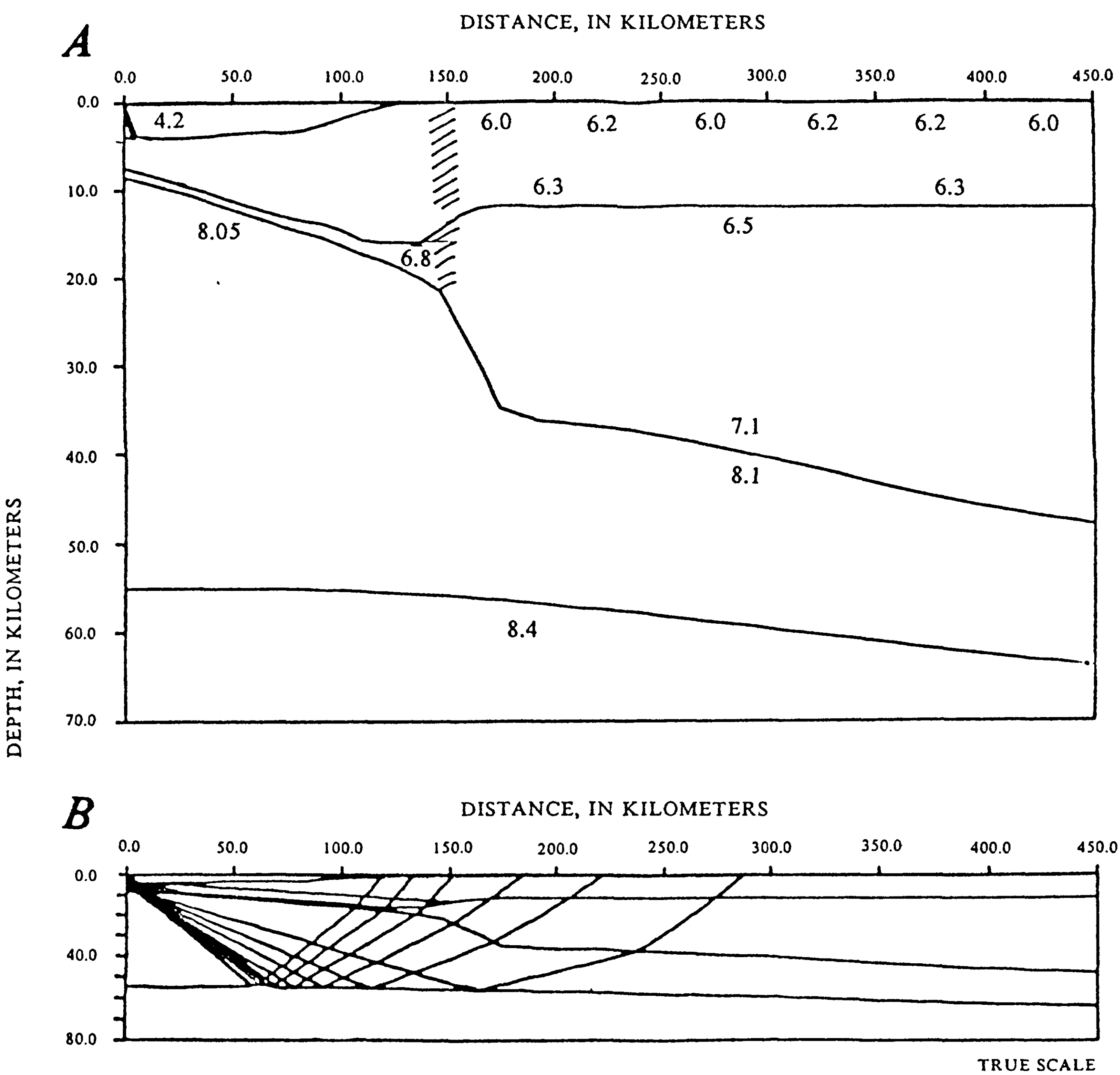


Figure 9.--*Interpreted crustal velocity structure, shot point 6 to shot point 4:* A, *exaggerated;* B, *true scale; showing PmP reflections*

The crustal composition of the 6.2-km/s layer cannot be determined separately; the seismic velocity does not discriminate between granitic and mafic crust, so that other evidence must be examined in order to interpret this layer. The lateral velocity discontinuity at shot point 5 occurs within a zone having a maximum width of 30 km, and coincides exactly (within the tolerance of the accuracy of the location uncertainty) with a gravity step of 140 mgals (Gettings, 1977) and with the eastern limit of magnetic "stripe" anomalies (Blank and others, 1981). The gravity and magnetic expressions of the layer are essentially continuous between shot points 5 and 6, and seem to require that it be dense (mafic) and strongly magnetized. We interpret the seismic properties as most likely those of diabase. Our interpretation satisfies all three parameters, density, magnetism, and compressional wave velocity, and agrees with the facts that a diabase swarm exists at the Shield margin and that diabase is the principal constituent of the pre-upper Miocene basement exposed to seaward.

Our interpretation is shown on the crustal model of figure 10, on which are projected the mean reflector locations and the crustal interpretation of Yousif (1982) for seismic traverses in latitudes between Jeddah and Al Qunfudhah (mean lat 19°45' N.). The model also is annotated with the seismic refraction velocities of Tramontini and Davies (1969). The entire layer to the west of shot point 5 is regarded as "transitional" crust because neither its thickness nor its mean velocity are typically oceanic, yet it is not thought that it is stretched crust of the Arabian Shield. The required stretching factor for an attenuated continental crust interpretation is extreme, and such a model is not in accord with the inferred density and magnetization. The layer seems to be more likely a complex consisting essentially of shorter diabase dikes emplaced at the onset of paar development; that is, complete continental separation in the lower to middle Miocene. The dikes were initially emplaced in the vicinity of the axis of a rift valley floor, and formed new crust that progressively thinned as the paar widened.

The implications of this report's interpretations are significant for the tectonic synthesis of the Red Sea region as a whole. The interpretations support the hypothesis of (1) essentially shore-to-shore opening of the Red Sea between Aqaba and the Tihamat Asir; (2) a two-stage extension to effect this opening, whether tectonic or magnetic, or both; and (3) Miocene and younger crust beneath most of the Afar.

DATA STORAGE

Data and work materials used in preparation of this report include record sections, travel-time curves and other geophysical profiles and are archived as data-file USGS-DF-06-2 which is stored at the office of the U.S. Geological Survey Mission in Jeddah, Saudi Arabia. No Mineral Occurrence Documentation System (MODS) localities were established in connection with work on this report.

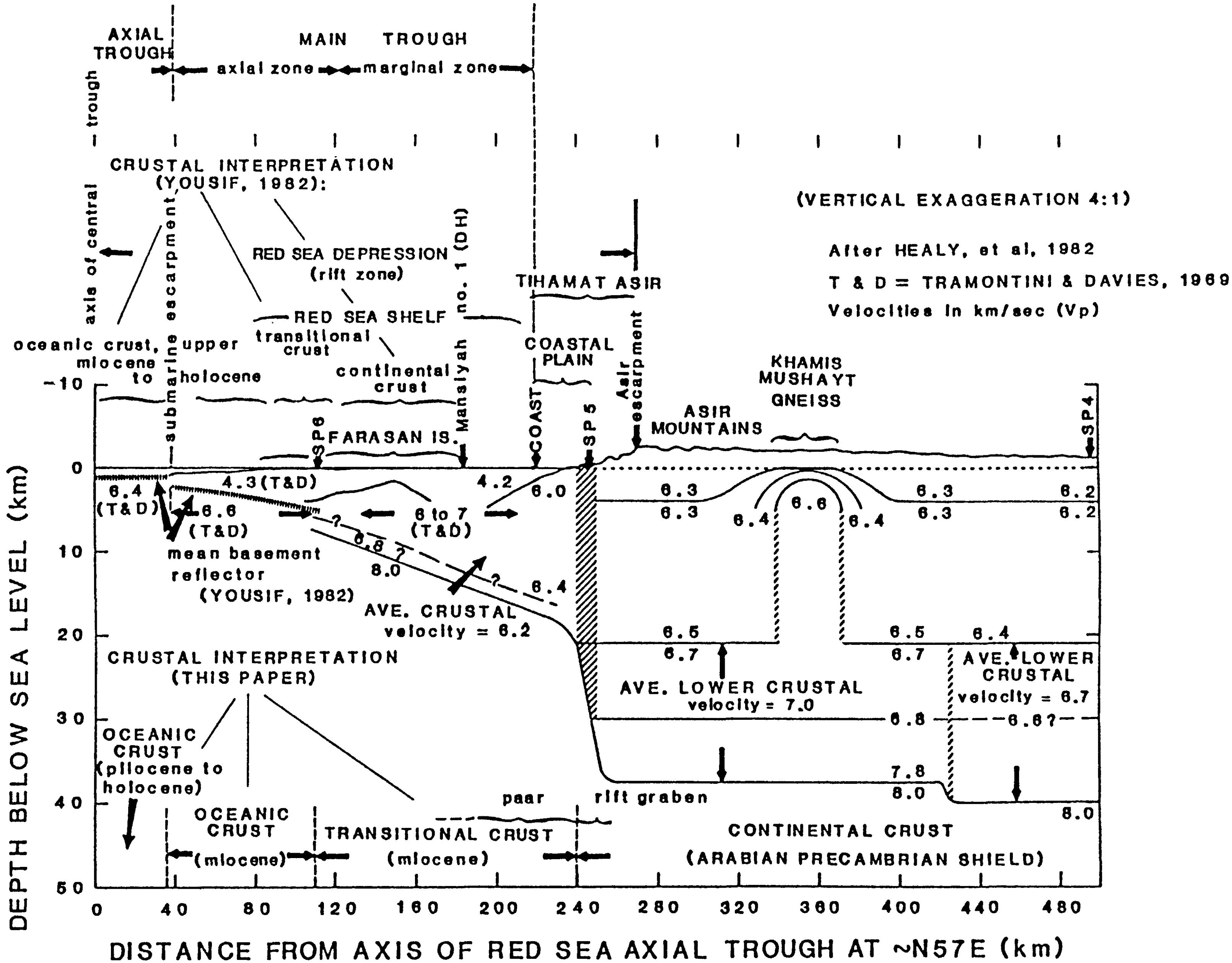


Figure 10.--*Seismic velocities and crustal structure, shot points 4 to 6*

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