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Continental Crust Beneath the Agulhas Plateau, Southwest Indian Ocean

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The Agulhas Plateau lies 500 km off the Cape of Good Hope in the southwestern Indian Ocean. Acoustic basement beneath the northern one third of this large, aseismic structural high has rugged morphology, but basement in the south is anomalously smooth, excepting a 30- to 90-km-wide zone with irregular relief that trends south-southwest through the center of the plateau. Seismic refraction profiles across the southern plateau indicate that the zone of irregular acoustic basement overlies thickened oceanic crust and that continental crust, locally thinned and intruded by basalts, underlies several regions of smooth acoustic basement. Recovery of quartzo-feldspathic gneisses in dredge hauls confirms the presence of continental crust. The smoothness of acoustic basement probably results from erosion (perhaps initially subaerial) of topographic highs with redeposition and cementation of debris in ponds to form high-velocity beds. Basalt flows and sills also may contribute locally to form smooth basement. The rugged basement of the northern plateau appears to be of oceanic origin. A plate reconstruction to the time of initial opening of the South Atlantic places the continental part of the southern plateau adjacent to the southern edge of the Falkland Plateau, and both abut the western Mozambique Ridge. Both the Agulhas and Falkland plateaus were displaced westward during initial rifting in the Early Cretaceous. Formation of an RRR triple junction at the northern edge of the Agulhas continental fragment during middle Cretaceous time may explain the origin of the rugged, thickened oceanic crust beneath the northern plateau as well as the apparent extension of the continental crust and intrusion of basaltic magmas beneath the southern plateau.

INTRODUCTION

The Agulhas Plateau lies about 500 km southeast of the Cape of Good Hope in the southwesternmost Indian Ocean. This large (400 × 700 km) aseismic structural high is separated from the African continental margin by the Agulhas Fracture Zone and by the 4.5-km-deep Transkei Passage between the Transkei and West Agulhas Basins (Figure 1). Minimum depths on the plateau are slightly less than 2500 m, except for one large seamount near 39°S, 26°E that rises to a depth of less than 800 m. *Heezen and Tharp* [1964] recognized that gently undulating topography characterizes the southern two thirds of the plateau but that north of about 38°S the plateau is extremely irregular in profile. This contrast in seafloor topography is mirrored by similar, marked differences in the morphology of acoustic basement beneath a variable sediment cover [*Barrett*, 1977; *Tucholke and Carpenter*, 1977]. The southern plateau has unusually smooth acoustic basement that is locally interrupted by apparent normal faults of a few hundred meters offset, while the northern plateau has high-amplitude peak and trough topography with some scarps in excess of 1.5 km high.

Sediment thickness on the southern plateau ranges to slightly more than 1 km and consists predominantly of nannofossil oozes of Maestrichtian to Quaternary age. Abyssal currents have extensively reworked these sediments and have formed several major Cenozoic unconformities. The currents also have exposed elements of the smooth acoustic basement in an erosional zone that circumscribes the western and southern plateau between the 4500-m and 5000-m isobaths [*Tucholke and Carpenter*, 1977]. Both current-controlled sedimentation and slumping account for erratically distributed sediments ranging from zero to 1 km thick on the northern plateau.

The origin of the Agulhas Plateau has been enigmatic, and partly for this reason the plateau has been largely ignored in reconstructions of southern Gondwanaland, even though it occupies a key geographical position. Reconstructions of the South Atlantic [*LePichon and Hayes*, 1971; *Francheteau and LePichon*, 1972; *Rabinowitz and LaBrecque*, 1979] close South America and Africa along a small circle of opening that follows the Falkland-Agulhas Fracture Zone. In such reconstructions the Falkland Plateau overlaps the northern part of the Agulhas Plateau, indicating that at least that part of the Agulhas Plateau must be either of oceanic origin or else a continental fragment displaced to its present position during or following the westward movement of the Falkland Plateau.

Graham and Hales [1965] calculated a Moho depth of about 21 km beneath the Agulhas Plateau from a free-air-gravity model, but this crustal thickness could indicate either thinned continental or thickened oceanic crust. *Scrutton* [1973] used trends of seafloor morphology on the plateau to suggest that the feature was oceanic crust formed at a later abandoned spreading center. *Barrett* [1977] reported seismic refraction profiles over the rugged northern plateau that also suggested an oceanic origin, and he found that high-amplitude magnetic anomalies in that area can be explained simply by the topog-

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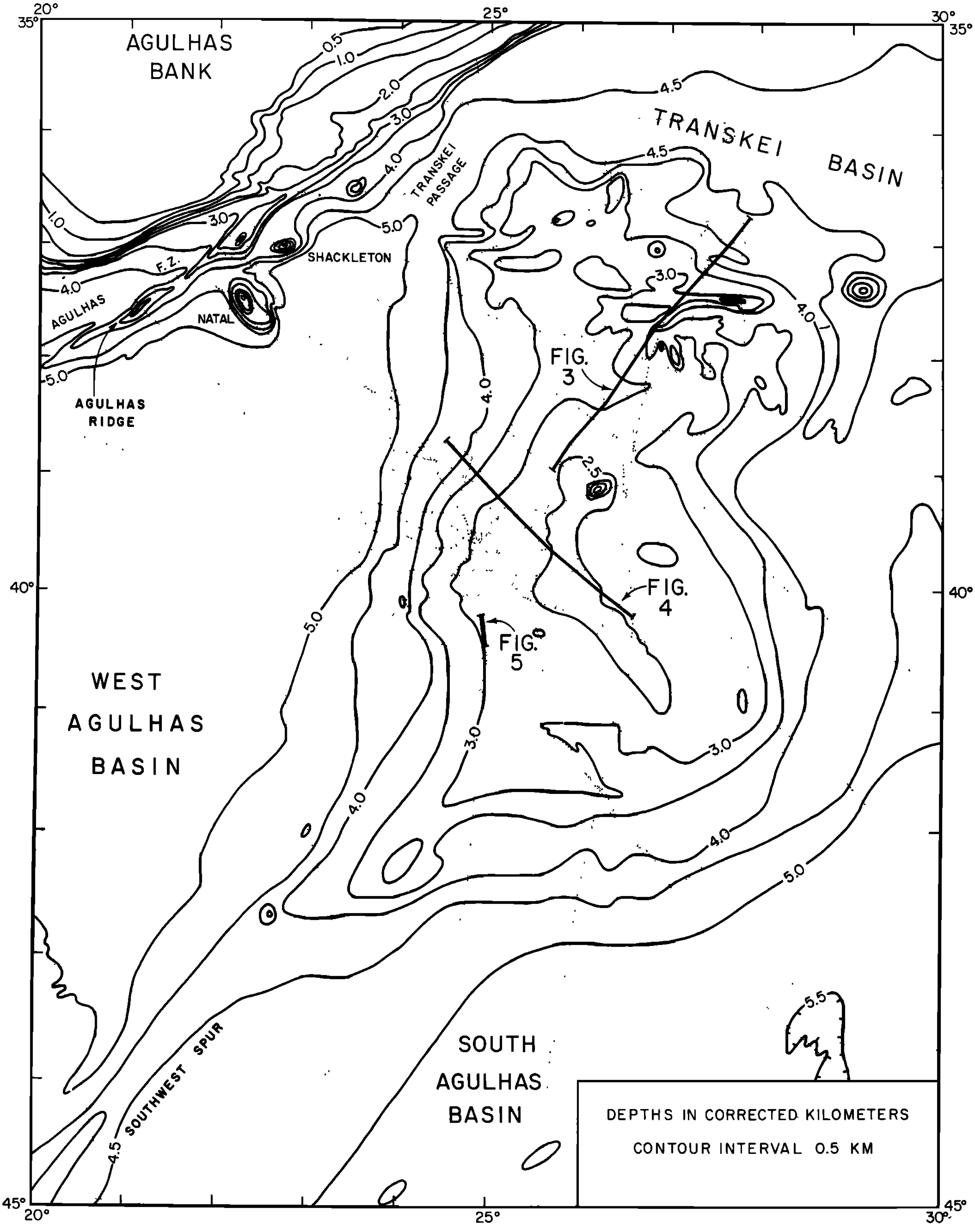

Fig. 1. Bathymetry of the Agulhas Plateau, modified from *Simpson* [1974]. Dotted lines show track control on acoustic basement mapped in Figure 2.

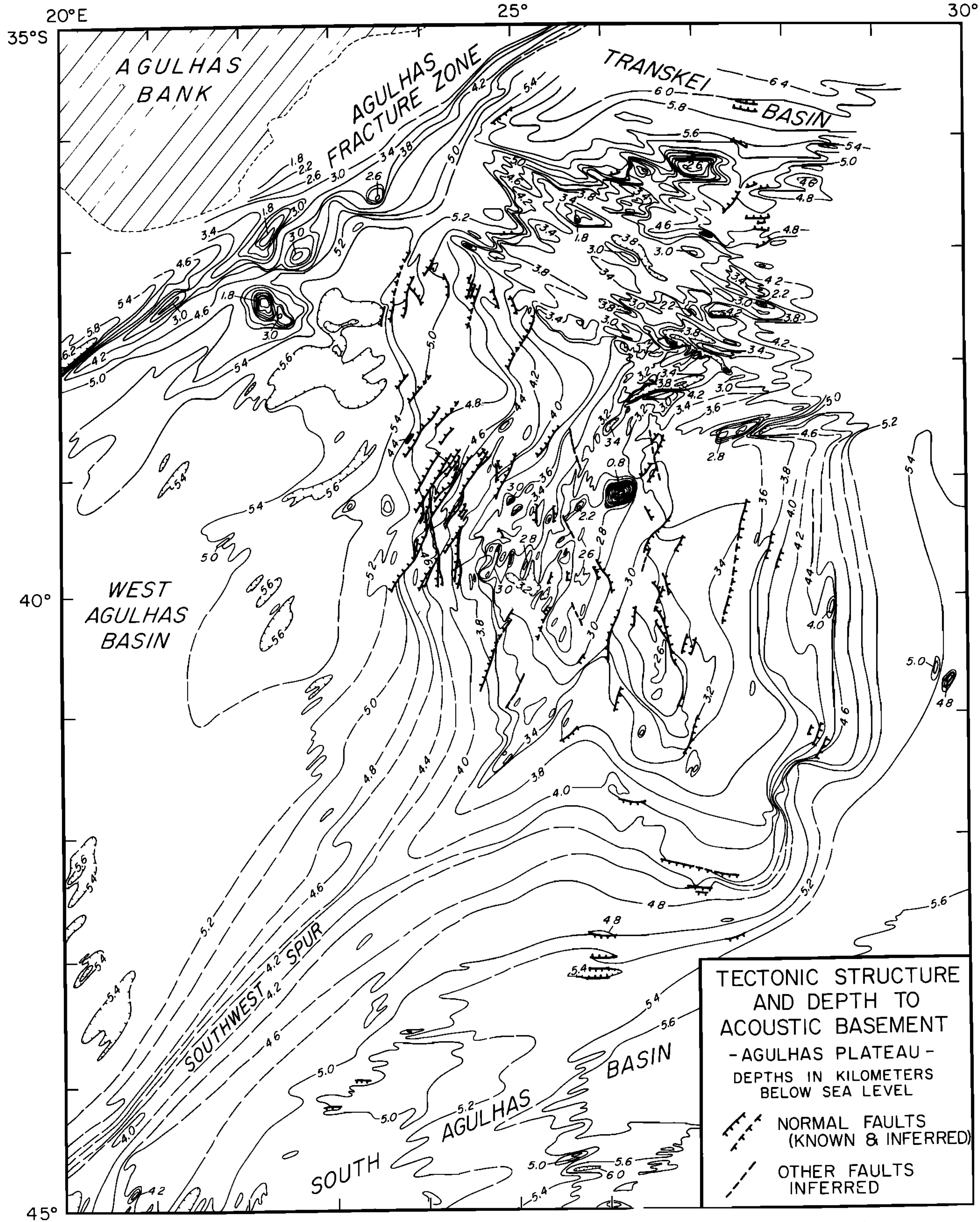

Fig. 2. Depth to acoustic basement in kilometers below sea level, assuming an average velocity of 2.0 km/s in sediments. Contour interval 0.2 km on southern plateau, 0.4 km on rugged northern plateau. Track control shown in Figure 1.

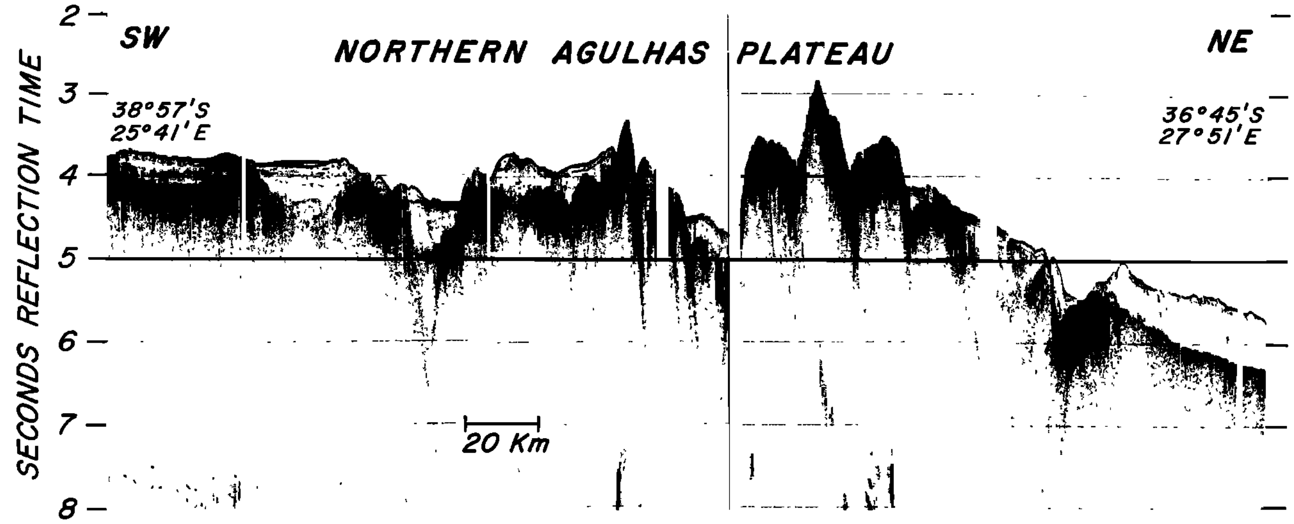

Fig. 3. Seismic profile across northern Agulhas Plateau illustrating rugged relief of basement; location in Figure 1. Note small patches of smooth basement at north and south.

raphy of uniformly magnetized basement rocks. *Barker* [1979] recently suggested that the northern plateau is of oceanic origin and that it could have formed at the position of a spreading-ridge jump about 98 Ma.

Because of the unusual structural makeup of the Agulhas Plateau and its potential importance in the Mesozoic evolution of the southern South Atlantic Ocean, we conducted detailed geological and geophysical surveys over the smooth southern part of the plateau on R/V *Vema* in January 1978. We report here the structural framework of the plateau and the results of a suite of refraction profiles which indicate that significant parts of the southern plateau are composed of continental crust. This conclusion is supported by petrographic studies of quartzo-feldspathic gneisses dredged from several outcrops during the *Vema* cruise (R. Allen and B. Tucholke, manuscript in preparation, 1981). In this paper we also discuss some constraints on placement of the plateau in plate reconstructions of southern Gondwanaland and on the possible plate-tectonic evolution of the surrounding basins. A separate report will describe the stratigraphy and depositional history of the Cenozoic sedimentary record in this region.

BASEMENT STRUCTURE

The map of tectonic structure and basement depth in Figure 2 clearly shows the marked difference in basement morphology on the northern and southern Agulhas Plateau. We use the term 'basement' as shorthand for 'acoustic basement,' which represents the deepest, continuously observed reflecting horizon in seismic profiles from the region; this horizon commonly corresponds to the surface of crystalline crustal rocks, although there are apparent exceptions, notably in areas of smooth acoustic basement. North of about 38°S the basement is highly irregular, with peak to trough amplitudes in excess of 1 km and slopes locally greater than 25° (Figure 3). Although

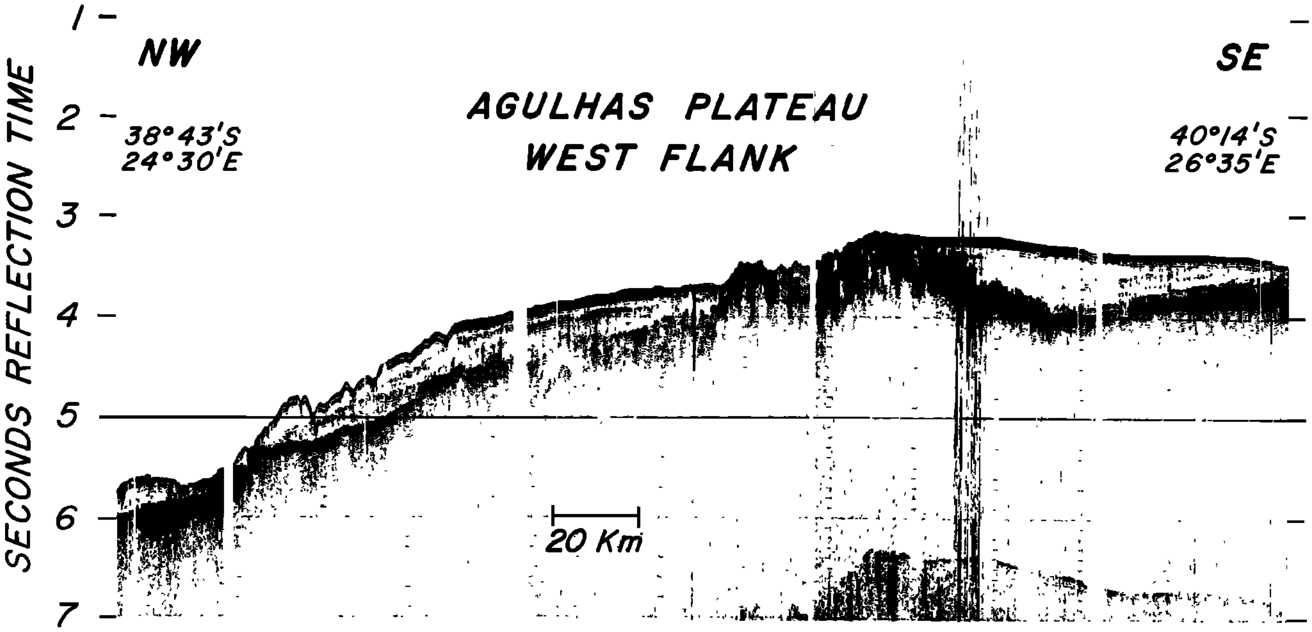

Fig. 4. Seismic profile across western and central Agulhas Plateau; location in Figure 1. Note zone of irregular basement at center and faulting of smooth basement at left.

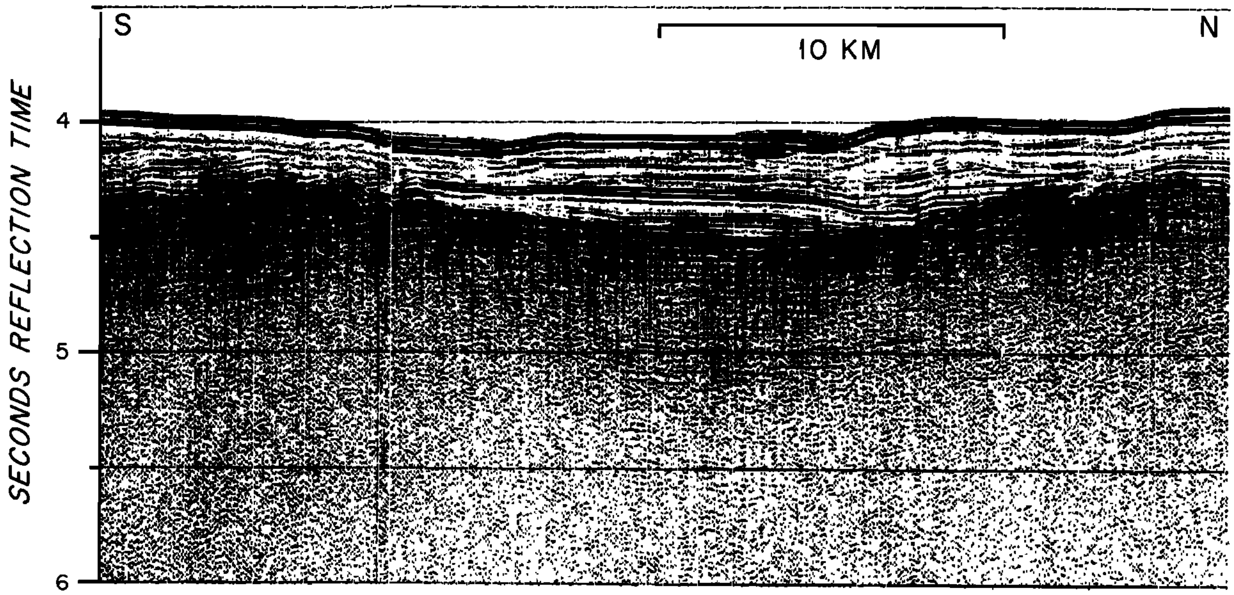

Fig. 5. Seismic profile (A II cruise 67) along western flank of Agulhas Plateau; location in Figure 1. Note apparent ponding of high-velocity material to form smooth acoustic basement at center.

the limited track control makes it somewhat difficult to define the structural fabric, basement topography north of 38°S and west of 27°30′E appears to be lineated along a west-northwest trend, whereas east of 27°30′E the trends are more nearly east-west. The eastward extent of this rugged basement is not well known. The trends that we have contoured on the northeastern part of the plateau agree with those suggested by *Barrett* [1977].

In marked contrast to the rugged basement of the northern plateau, basement south of 38°S is unusually smooth and gently sloping (Figure 4). The marked impedance contrast at the basement interface has precluded observation of subbasement reflections in most Lamont-Doherty seismic profiles obtained with a 328-cm^3 (20 in.^{3}) airgun, although *Tucholke and Carpenter* [1977] noted that very weak coherent reflectors could be observed in places beneath the basement surface. *Emery et al.* [1975] obtained a single seismic reflection line with a larger airgun sound source along the western plateau; these data more clearly suggest that ponded high-velocity sediments or basalt flows locally smooth the basement surface and mask underlying, somewhat more irregular basement topography (Figure 5). A piston core taken from the surface of smooth basement where it crops out in the erosional zone on the west flank of the plateau contains Cenomanian clays; higher on the plateau, sediments immediately overlying basement probably are Maestrichtian nannofossil chalks [*Tucholke and Carpenter,* 1977]. Thus the smooth basement is a surface of unconformity and at least 25 m.y. of the sedimentary record is missing.

The smooth basement of the southern plateau is interrupted by two kinds of features: (1) areas of irregular basement in sharp lateral contact with the smooth basement and (2) normal faults. Relief in the areas of irregular basement on the southern plateau is subdued compared to that of the rugged crust of the northern plateau (Figure 4), but it is similar to that of the basaltic crust in the adjacent West and South Agulhas basins. The irregular basement is restricted primarily to a well-defined zone about 30 to 90 km wide that extends south-southwest across the center of the plateau, but it also occurs in two small areas toward the southeast (Figure 6). The large seamount that rises to a depth of less than 800 m near the middle of the plateau occurs within the central zone of irregular basement. Isolated seamounts and small patches of irregular basement also are common to the west of this central zone. In all cases the irregular basement is shallower than the surrounding smooth acoustic basement (compare Figures 2 and 6), and in many locations the contact between the two is marked by steep slopes (and possibly by normal faults) at the perimeter of irregular basement (Figures 4 and 6).

Normal faults developed in the smooth basement typically have offsets of 200–300 m, although some offsets exceed 500 m. There is no indication that these faults continue into the overlying sedimentary column, and they therefore probably predate the Maestrichtian. Most of the faults occur around the perimeter of areas of irregular basement and the fault planes dip away from these areas (Figure 2). The faults are best defined in the numerous seismic profiles across the plateau's western flank where they trend north-northeast parallel to the local basement contours and subparallel to the Agulhas Fracture Zone. Similar trends are reasonably well defined on the central and eastern plateau. There is a suggestion that a second set of normal and possibly transcurrent faults trends northwest across the plateau. Unfortunately, none of these faults is sufficiently constrained by profiler tracks to confirm the trend completely. Possible east-west fault trends on the south flank of the plateau are poorly determined because the faults are observed mostly in single track lines.

SEISMIC REFRACTION RESULTS

Two reversed seismic refraction profiles and six unreversed profiles up to 72 km long were shot with explosives over both the smooth and the irregular basement areas on the southern Agulhas Plateau (Figure 6); an outline of recording techniques and data reduction is given in the appendix.

In addition, several short-range wide-angle-reflection and refraction profiles were recorded using a 328-cm^3 (20 in.^{3}) airgun and military sonobuoys. Refraction results are summarized in Table 1, Figure 7, and Figures 10–15.

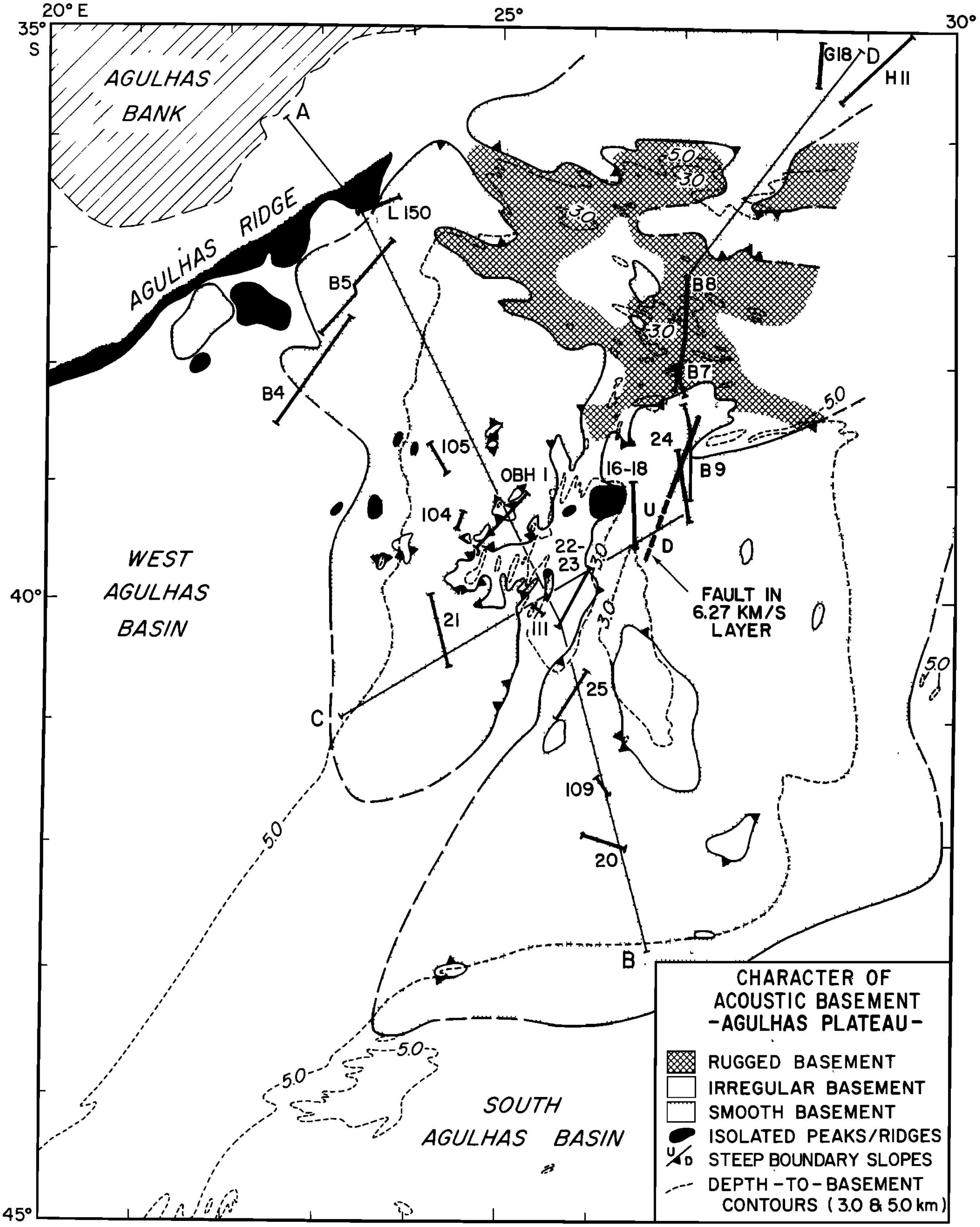

Fig. 6. Character of acoustic basement on the Agulhas Plateau. Locations of most refraction profiles are shown (sources of previously reported profiles B, G, H, L given in Figure 7). Cross sections A-B and C-D shown in Figure 7.

TABLE 1. Velocity, Layer Thickness, and Profile Locations, Agulhas Plateau and Vicinity

Profile	Water	H_2	V_2	H_3	V_3	H_4	V_4	H_5	V_5	H_6	V_6	H_7	V_7	Sound Source	Receiver Location	
															S. Lat.	E. Long.
1C14	2.94	0.72	2.49	-	-	-	-	-	-	-	-	-	-	Airgun	39°26'	24°56'
2C14	2.90	0.27	2.20	0.43	2.57	-	4.97	-	-	-	-	-	-	"	39°25'	24°59'
3C14	4.56	0.46	1.84	0.45	1.72	0.84	3.12	-	5.72	-	-	-	-	"	35°38'	28°50'
3V29	2.61	0.92	2.01	-	2.45	-	-	-	-	-	-	-	-	"	39°43'	26°29'
10V29	4.67	0.36	1.56	1.02	2.65	0.81	5.55	-	7.15	-	-	-	-	"	35°59'	25°34'
103V34	3.10	0.45	2.03	-	5.90	-	-	-	-	-	-	-	-	"	39°26'	24°48'
104V34	3.27	0.66	2.21	0.42	(3.9)	0.62	5.20	-	6.40	-	-	-	-	"	39°15'	24°36'
105V34	4.15	0.47	(2.2)	2.65	5.10	-	6.40	-	-	-	-	-	-	"	38°55'	24°25'
107V34	2.65	0.61	2.41	1.05	3.28	-	-	-	-	-	-	-	-	"	39°05'	26°28'
108V34	2.66	0.65	2.63	-	-	-	-	-	-	-	-	-	-	"	41°01'	25°24'
109V34	2.84	0.49	2.11	0.91	2.89	0.90	4.65	-	5.60	-	-	-	-	"	41°40'	26°15'
111V34	2.58	0.41	(2.2)	1.31	4.20	-	5.30	-	-	-	-	-	-	"	40°02'	25°22'
112V34	2.41	0.25	(2.2)	-	4.65	-	-	-	-	-	-	-	-	"	39°22'	25°35'
113V34	2.94	0.70	(2.2)	1.55	4.45	-	6.23	-	-	-	-	-	-	Airgun & Explosives	39°00'	25°23'
16N	2.78	0.57	(2.2)	1.27	4.00	2.62	4.75	5.52*	5.79	-	(7.20)	-	-	Explosives	38°57'	26°26'
18S	2.70	0.35	(2.2)	-	-	2.39	4.75	9.82*	5.79	-	(7.20)	-	-	"	39°33'	26°29'
17	2.68	0.16	(2.2)	1.17	3.45	-	4.58	-	-	-	-	-	-	"	39°36'	26°03'
19	3.98	0.26	(2.2)	-	5.03	-	-	-	-	-	-	-	-	"	42°07'	26°38'
20	3.80	0.67	(2.2)	2.20	5.05	4.33*	6.36		(7.2)	-	-	-	-	"	42°02'	26°24'
21	3.77	0.38	(2.2)	1.49	4.69	2.26	6.08	7.51*	7.13	-	(8.10)	-	-	"	40°34'	24°26'
22S	2.50	0.52	(2.2)	1.25	3.85	2.28	5.53	7.02*	6.86	-	(8.10)	-	-	"	40°13'	25°38'
23N	2.40	0.90	(2.2)	0.86	3.85	2.49	5.53	6.56*	6.86	-	(8.10)	-	-	"	39°41'	26°00'
24	3.23	0.45	(2.2)	3.74	5.14	6.38*	6.27	-	(7.2)	-	-	-	-	"	38°42'	26°57'
25	2.80	0.67	(2.2)	3.07	4.53	5.85*	6.38	-	(7.2)	-	-	-	-	"	40°35'	25°57'
26	3.00	0.88	(2.2)	1.64	4.50	-	6.00	-	-	-	-	-	-	"	39°13'	25°04'
OBH1	3.26	0.72	(2.2)	1.24	4.75	0.61	5.58	3.42	6.36	9.04*	7.10	-	(8.10)	"	39°33'	24°43'

Layer thicknesses in km and velocities in km/s.

* = minimum thickness.

N, S = reversed profiles.

() = assumed velocity.

Although the explosives profiles were shot to ranges as great as 72 km, mantle refractions were not observed. However, on three profiles (21, 22/23, OBH 1) minimum depths to mantle of 15.4, 13.4, and 18.3 km can be computed by assuming a mantle refraction line of 8.1 km/s that passes through the most distant observed refraction arrival.

Velocities of the deepest crustal layer beneath the southern plateau range from 6.86 to 7.13 km/s in these three profiles (21, 22/23, OBH 1). These velocities agree favorably with velocities of 6.6 to 7.0 km/s for the basal crustal layer previously determined in a velocity model of the rugged northern part of the plateau [*Barrett*, 1977] and in the adjacent Transkei Basin [*Green and Hales*, 1966; *Hales and Nation*, 1973; *Chetty and Green*, 1977]. The thickness of this 'oceanic layer' averages 4 km or less in the Transkei Basin and Transkei Passage, but it is at least 7 to 9 km thick beneath the Agulhas Plateau (Figure 7).

A layer of intermediate velocity (5.8 to 6.4 km/s) is well defined beneath most of the southern Agulhas Plateau, but it is thin or absent beneath the northern plateau (profile B8 of *Barrett* [1977]) and beneath the adjacent basins (Figure 7). In those profiles where the layer is thick (profiles 16/18, 20, 24, and 25), no refraction is observed from the underlying layer, and we have determined only minimum thickness by assuming a 7.2-km/s refraction line that intersects the most distant observed refraction arrival (see the appendix); these minimum thicknesses range from about 4.3 to 7.7 km. Beneath the west central plateau the 5.8- to 6.4-km/s layer is thinner, approximately 2.3 to 3.4 km in profiles 21 and OBH 1. Under the irregular basement at the center of the plateau, reversed profile 22/23 detected no layer of velocity 5.8–6.4 km/s.

Velocities in the range 5.8–6.4 km/s are characteristic of the 'granitic layer' in continental crust [e.g., *Smithson et al.* 1977; *Mueller*, 1977], but they are not uncommon in thickened oceanic crust and in crust beneath marginal basins [*Ludwig et al.*, 1970]. However, in oceanic crust this layer rarely is thicker than a few kilometers, in contrast to thicknesses of 5 to 20 km or more that are typical of continental crust (Figure 8). Thus the southeastern Agulhas Plateau, where the 5.8- to 6.4-km layer has minimum thicknesses of 4.3 to 7.7 km, has a close re-

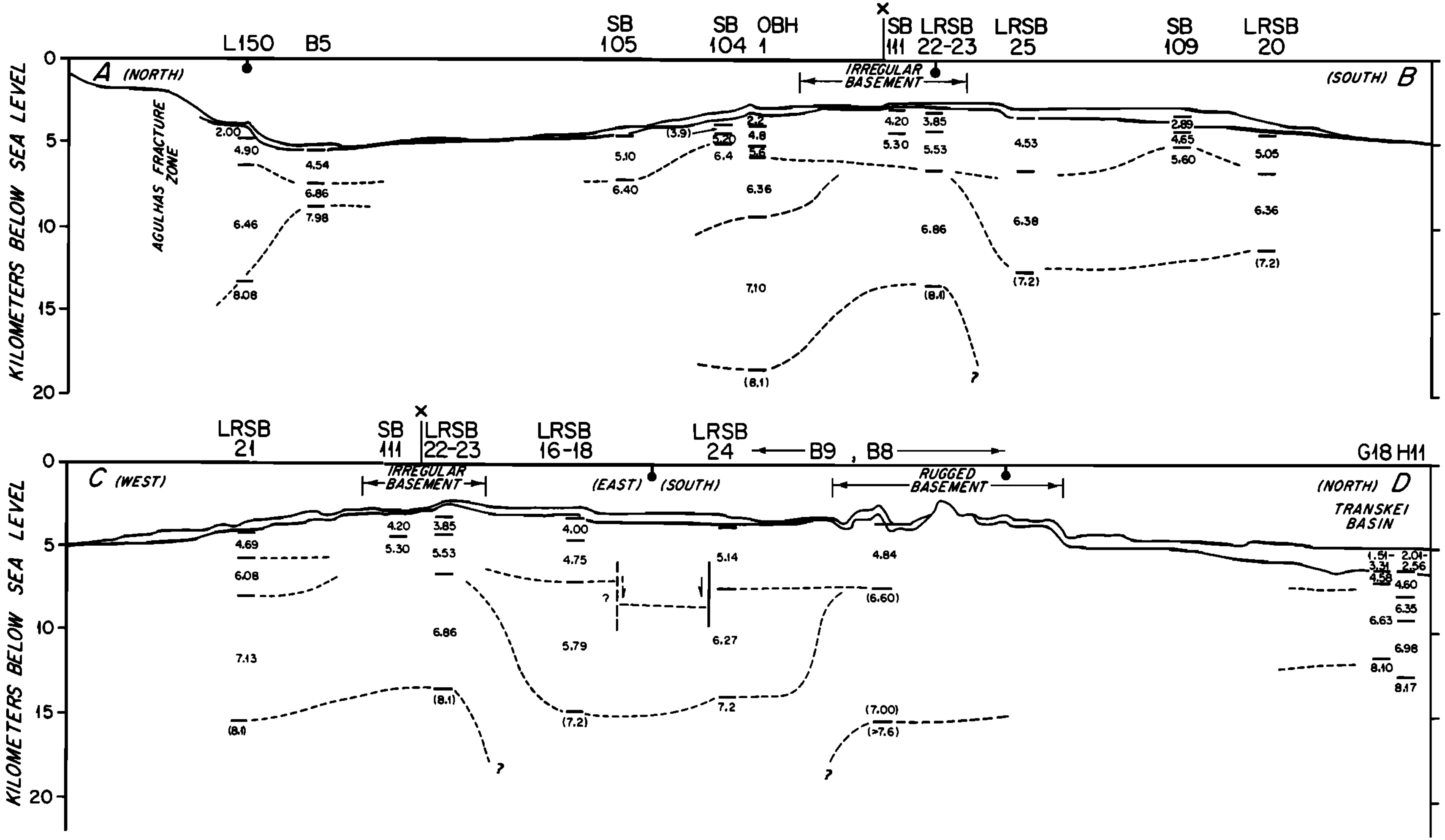

Fig. 7. Cross sections of crustal velocity structure across the Agulhas Plateau, located in Figure 6. Vertical exaggeration about ×10. Profile L150 from *Ludwig et al.* [1968], B5 and B8-9 from *Barrett* [1977], G18 from *Green and Hales* [1966], H11 from *Hales and Nation* [1973]. Long-range sonobuoy (LRSB), military sonobuoy (SB), and ocean-bottom hydrophone (OBH) profiles are as reported in this paper.

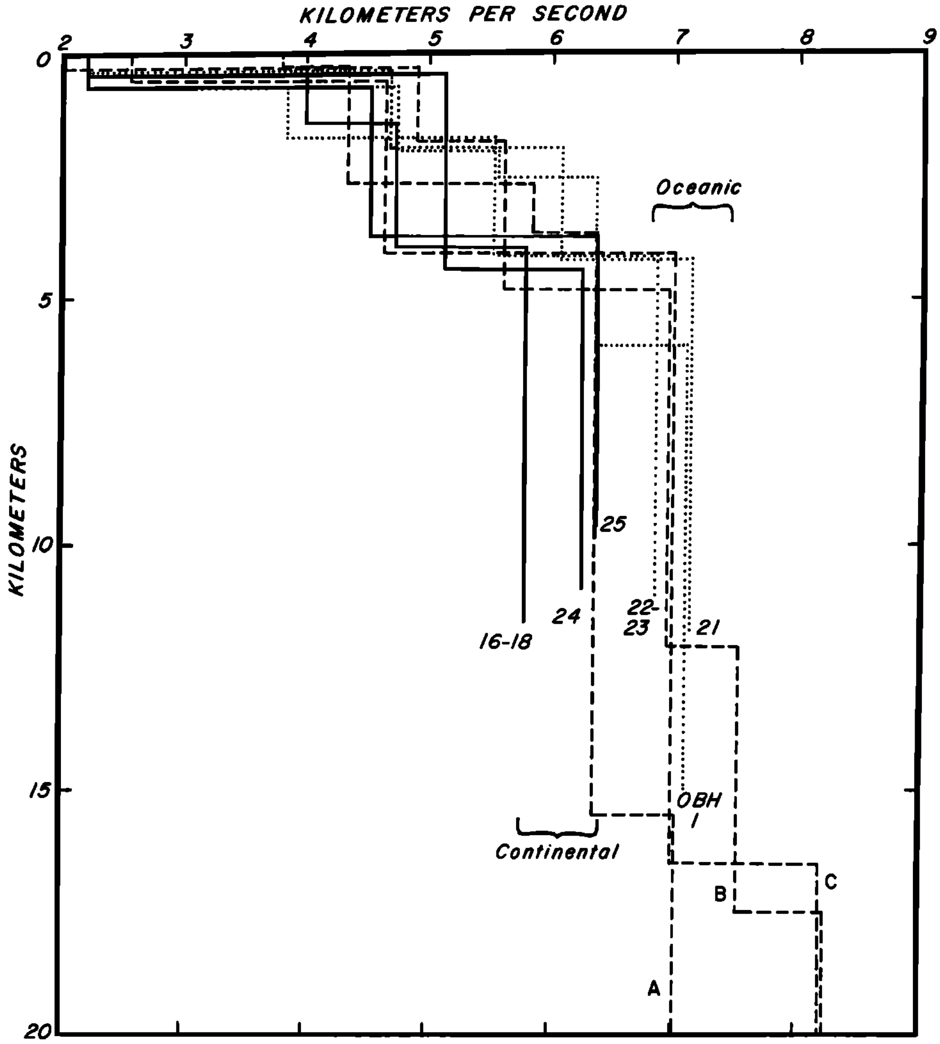

Fig. 8. Plot of velocity versus depth below seafloor for Agulhas profiles with continental-type velocity structure (solid lines) and with velocity structure typical of thickened oceanic crust (dotted lines). Dashed lines show for comparison: A, profile from Rockall Plateau microcontinent [*Scrutton,* 1972]; B, profile 6 from *Den et al.* [1969] obtained over smooth acoustic basement on the probably oceanic, Cretaceous-age Shatsky Rise; C, profile across the thickened oceanic crust of the western Hawaiian Ridge [*Shor,* 1960].

semblance to continental velocity structure, and we interpret this crust as being of continental origin. Velocities of 6.36 to 6.38 km/s measured in profiles 20 and 25 are at the high end of, but within, the range of velocities normally associated with the granitic layer. A comparable, well-determined velocity of 6.36 km/s was determined by *Scrutton* [1972] for a 12-km-thick crustal layer beneath the Rockall Plateau, which is generally accepted as being of continental origin [*Montadert et al.,* 1979].

Profile 24 on the central plateau shows a significant offset in the 6.27-km/s refraction line (Figure 14). Although we obtained only bathymetric data along this profile during the shooting run, seismic reflection profiles obtained at each end of the run and along earlier nearby tracks indicate a flat-lying basement surface. Thus we conclude that the break represents a fault with about 1.2 km vertical offset (down to east) that affects the 6.27-km/s surface but not the surface configuration of the overlying acoustic basement (5.14 km/s). A very similar offset appears in the travel time plot of *Barrett's* [1977] nearby profile 9 (B9 in Figure 6). Examination of profiles B9 and 24 shows that they are practically identical and have simply been interpreted differently. Hence an interpretation of our profile 24 that ignored the break in the 6.27-km/s line would yield a 6.7-km/s line as obtained by Barrett. Our identification of a fault within profile B9 is a crucial reinterpretation because it provides added confidence that continental rather than oceanic crust underlies the northernmost perimeter of the smooth basement. Connecting the offsets in profiles B9 and 24 results in a down-to-east normal fault that strikes north-northeast in the 6.27-km/s layer, parallel to the central zone of irregular basement and parallel to normal faults at the basement surface (Figures 6 and 7).

In contrast to the above continental-type velocity sections, reversed profile 22/23 on the central plateau lacks the 5.8- to 6.4-km/s layer, as does *Barrett's* [1977] velocity model for profile B8 on the northern plateau (Figures 7 and 8). Minimum depth to mantle in these profiles is 13 to 14 km. These results compare rather closely with the velocity structure of thickened oceanic crust beneath the Shatsky Rise and the western Hawaiian Ridge (Figure 8) [*Den et al.,* 1969; *Shor,* 1960].

Beneath the western part of the Agulhas Plateau (profiles 21, OBH 1), the layer of 6.1- to 6.4-km/s velocity has attenuated thickness, and minimum depth to mantle is 15 to 18 km. In terms of both crustal layer thicknesses and total depth to mantle, this crust appears to be intermediate between continental and thickened oceanic crust (Figure 7).

Across the entire plateau the shallowest crustal layer beneath acoustic basement has a wide range of velocities (3.85–5.6 km/s) that do not vary in any coherent pattern. Thickness of this layer varies between about 1 and 4 km, with the smaller values occurring beneath the west flank of the plateau. In the probably basaltic ocean crust of the adjacent Transkei Basin and Tranksei Passage the layer has similar but more constant values (4.5–4.6 km/s) and layer thickness is 1 to 2 km.

DISCUSSION

The presence of a thick (>4.3–7.7 km) crustal layer of velocity 5.8–6.4 km/s beneath smooth basement of the southeastern Agulhas Plateau provides strong evidence that at least this section of the plateau is of continental origin. This interpretation is substantiated by recovery of a suite of quartzo-feldspathic gneisses of lower amphibolite to granulite facies, along with quartzose metasedimentary rocks and a possible brecciated rhyolite, in four dredge hauls recovered from outcrops of smooth basement on the perimeter of the southern plateau (R. Allen and B. Tucholke, manuscript in preparation, 1981).

The strong lateral changes in crustal velocity structure beneath the southern plateau, particularly across the apparent thickened oceanic section of profile 22/23 on the south central plateau, suggest that the original continental crust was rifted and intruded by basaltic magmas. The correlation of the crustal velocity structure to the topographic irregularity of basement is significant. Refraction profiles over both the irregular zone of basement transecting the south central plateau and the rugged basement of the northern plateau indicate thickened oceanic crust (Figures 7 and 8), and it is reasonable to assume that most of the remaining irregular and rugged basement areas of the plateau also overlie thickened oceanic crust. Thus the zone of irregular basement extending south-southwest across the central plateau may define a principal axis of crustal extension, uplift, and basaltic intrusion (Figure 6). The distribution and orientation of normal faults in the smooth acoustic basement surrounding the areas of irregular basement support this interpretation (Figure 2). The apparent fault in the 6.27-km/s layer also parallels this trend, with the downthrown block toward the east, away from the irregular basement. The zone of irregular basement extends north and intersects the juncture of the west-northwest and east-west trends in the rugged basement of the northern plateau. The orientation of these three trends in thickened oceanic crust therefore suggests that a triple junction may have existed in the north central plateau (Figure 6). The southeastern part of the plateau, which has a reasonably thick and uniform 5.8- to 6.4-km/s granitic layer, appears to have been least affected by extension and intrusion, while crust beneath the western plateau may have been modified substantially in order to produce a velocity structure and thickness intermediate between that of continental and oceanic crust (Figure 7).

If the above interpretation is valid, it is possible that the crust-mantle interface and perhaps shallower, intracrustal interfaces are affected by small-scale irregularities. Such roughness could explain the absence of coherent refractions from the mantle and possibly from the base of the 5.8- to 6.4-km/s layer in many of our profiles. Unfortunately, in the latter instance the validity of our minimum-thickness calculations also could be affected; thus the dredge results provide especially important confirming evidence for the presence of continental crust.

In view of the evidence for extension of continental crust and intrusion of basalts beneath the southern plateau, it is likely that this crust was uplifted and peneplaned during initial rifting and during the early spreading of the South Atlantic [e.g., *Falvey,* 1974]. This erosional cycle, accompanied by ponding of erosional debris in topographic lows, is an attractive explanation for the origin of the smooth acoustic basement (Figure 5). It also is likely that basalt flows and later instrusion of sills contributed to formation of the smooth surface. The changing velocity and thickness of the shallowest crustal layer below acoustic basement (3.85–5.6 km/s) both could be explained by variable spatial distribution and diagenesis of beds containing clastic debris and basalt flows. Sedimentary rocks including arkosic sandstones, foliated argillites, and dense brown cherts, as well as intrusive and extrusive basalts have been dredged from smooth basement areas (R. Allen and B. Tucholke, manuscript in preparation, 1981). Formation of smooth basement by 'ponding' is especially likely along the northern and northwestern perimeter of the plateau because this basement surface overlies normal oceanic crust (Figures 6 and 7).

Although the regional geological and geophysical framework of the southwestern Indian Ocean still is rather poorly understood, it is useful at this stage to summarize the possible early evolution of the Agulhas Plateau based on known geophysical constraints. One such evolutionary sequence is illustrated in Figure 9. Although this model is not unique, it explains a variety of observations that must be considered in any reconstruction.

At the time of initial opening of the South Atlantic about 127 Ma, the eastern Falkland Plateau was adjacent to South Africa and occupied the present position of the Transkei Basin and the northern Agulhas Plateau (Figure 9*a*) [*Rabinowitz and LaBrecque,* 1979]; the eastern end of the Falkland Plateau probably abutted the northwestern edge of the Mozambique Ridge. In our reconstruction, the areas of continental crust are presumed to include the Mozambique Ridge, which has a crustal layer of velocity 5.8–6.2 km/s that is at least 5 to 7 km thick [*Chetty and Green,* 1977]; this velocity structure is very similar to that of the southern Agulhas Plateau. Refraction profiles across the eastern end of the Falkland Plateau also show a crustal layer of similar velocity (5.9–6.3 km/s) but of unknown thickness [*Ewing et al.,* 1971]. The crust on the eastern Falkland Plateau was confirmed as gneissose and granitic continental basement by drilling at DSDP site 330 [*Barker et al.,* 1977]. In South Africa, continental basement rocks typically have velocities of 5.8 km/s or greater [*Chetty and Green,* 1977], although velocities as low as 5.7 km/s may characterize basement beneath the Agulhas Bank [*Spence,* 1972].

The reconstruction to the time of initial opening includes only that part of the southern Agulhas Plateau which underlies smooth basement and which therefore may have a continental origin. Elimination of the apparently oceanic northern Agulhas Plateau allows closure of the Falkland Plateau to the Mozambique Ridge. The line of initial rifting is well constrained in the South Atlantic north of the Falkland-Agulhas

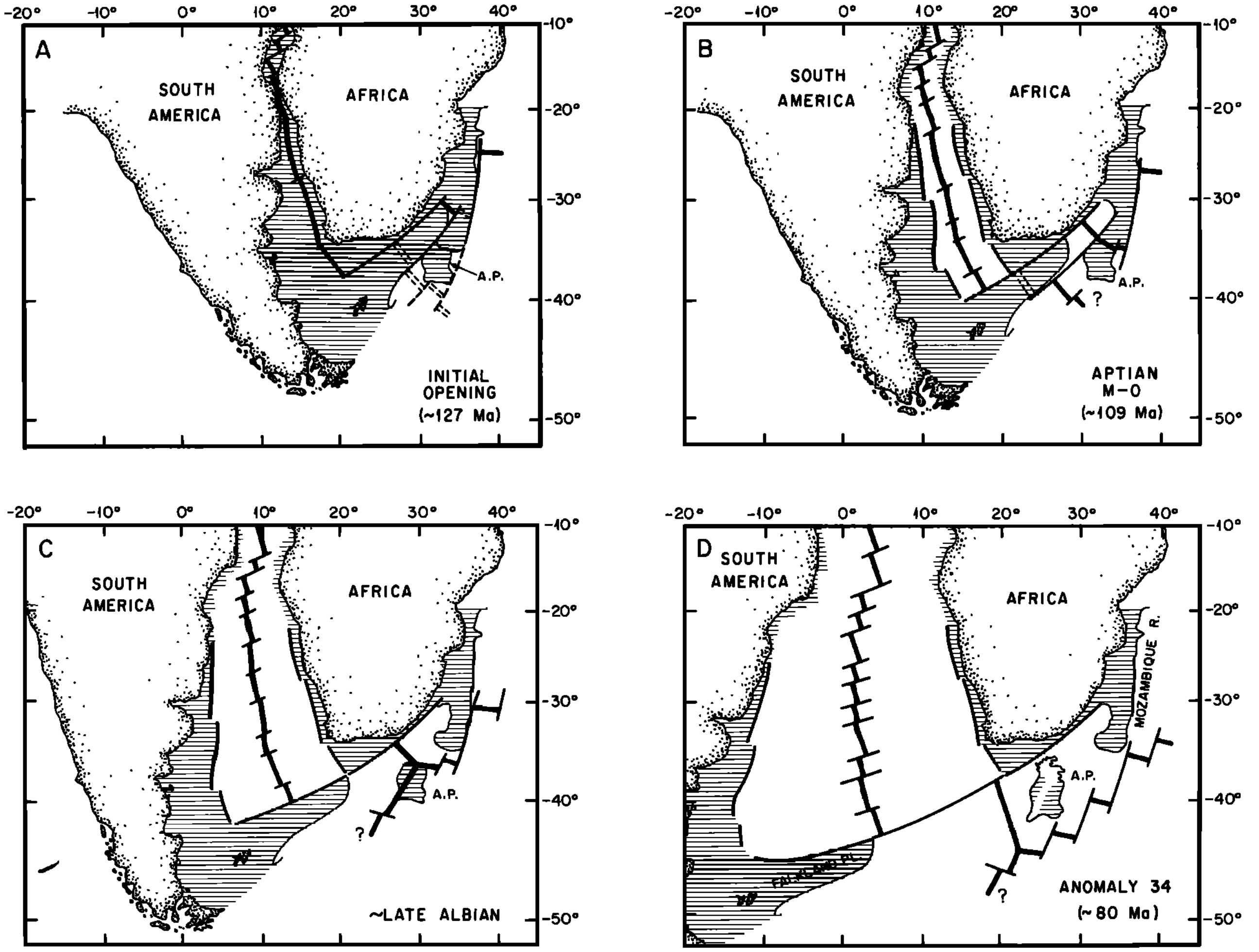

Fig. 9. Possible plate tectonic model for evolution of the Agulhas Plateau and seafloor south of Falkland-Agulhas Fracture Zone, with Africa held fixed. Shaded areas show presumed continental crust. The Falkland Plateau and Mozambique Ridge are approximately outlined by the present 3000-m bathymetric contours and the Agulhas Plateau by the 4000-m contour of basement depth. Zones of possible extension are dashed parallel lines. A. P. is Agulhas Plateau. Based on data in this paper and from *Rabinowitz and LaBrecque* [1979], *LaBrecque and Hayes* [1979], *Baker* [1979], *Simpson et al.* [1979], and *Bergh and Norton* [1976].

Fracture Zone [*Larson and Ladd,* 1973; *Rabinowitz and LaBrecque,* 1979], and it also is reasonably well defined at the eastern end of the Falkland Plateau, where magnetic anomalies M-0 to M-4 have been identified [*LaBrecque and Hayes,* 1979] and M-5 to M-10 also may be present [*Barker,* 1979]. The spreading center in the northern Mozambique Basin, east of the Mozambique Ridge, is defined by anomaly M-11 [*Simpson et al.,* 1979]. It presently is difficult to define a more detailed picture of the initial pattern of spreading ridges because of the lack of identified M-series anomalies south of the Agulhas-Falkland Fracture Zone. It is possible that crustal extension and thinning may have occurred beneath the central Falkland Plateau because analysis of recent refraction data suggests the presence there of oceanic crust (W. J. Ludwig, personal communication, 1980). On the Mozambique Ridge, Lower Cretaceous(?) basalts and Neocomian volcanic siltstones were drilled at DSDP site 249 [*Simpson et al.,* 1974], and they indicate that at least local crustal extension and volcanism occurred in that region. Similar extension also may have occurred across the Agulhas Plateau. This stretching could explain the ill-defined northwest trending faults mapped in Figure 2 and the also poorly defined and patchy southeasterly trend of irregular, possibly thickened oceanic crust across the southern plateau (Figure 6).

By the time of anomaly M-0 (~109 Ma; *Larson and Hilde* [1975]) the Agulhas Plateau may have been rifted from the Mozambique Ridge, although this interpretation is not constrained by geophysical observations (Figure 9*b*). Formation of an RRR triple junction by a small ridge jump to the northern end of the Agulhas Plateau, possibly about late Albian time, is a plausible means of explaining the formation and trends of the rugged crust composing the northern Agulhas Plateau as well as the zone of irregular basement and thick oceanic crust trending south-southwest across the southern plateau (Figure 9*c*). Intrusion of basalt and formation of zones of thickened oceanic crust would have both widened and lengthened the plateau at this time. It is possible that the triple junction could have formed slightly earlier (latest Aptian), when a change occurred in the location of the Africa-South America pole of rotation [*Rabinowitz and LaBrecque,* 1979]. Formation of smooth acoustic basement beneath the southern plateau by the processes described earlier probably continued

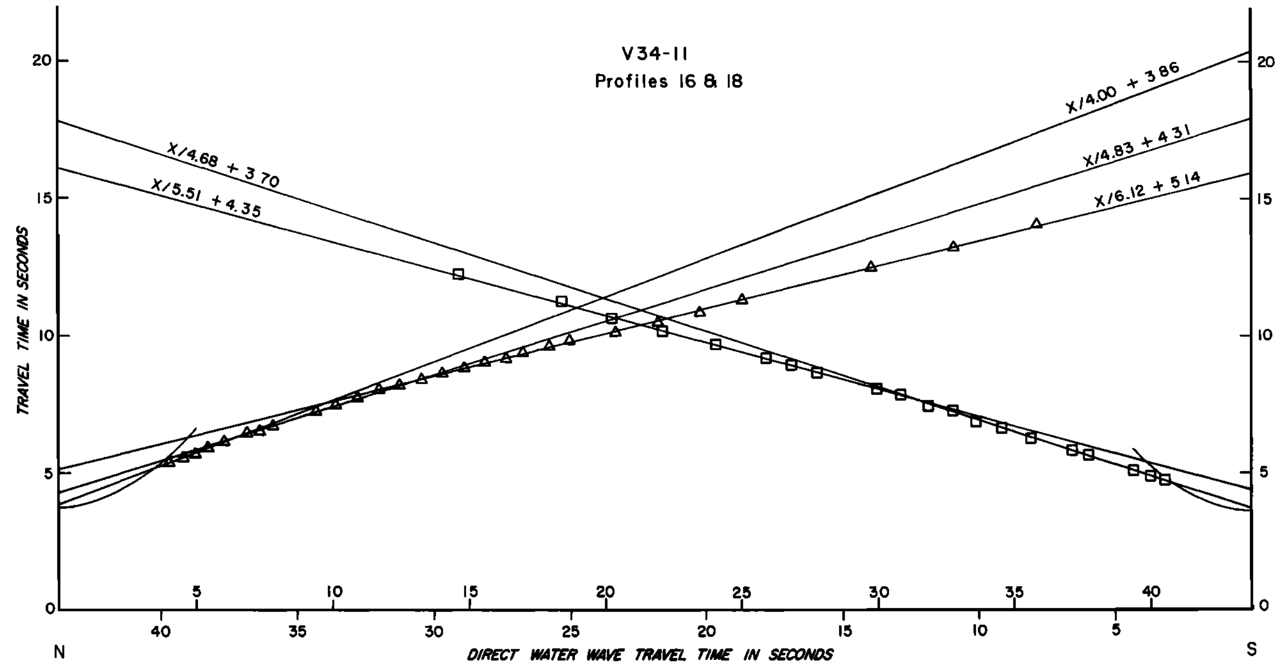

Fig. 10. Travel time graph for reversed long-range sonobuoy profiles 16N and 18S.

from the time of initial rifting at least through the time when this triple junction was active.

Another ridge jump may have displaced the triple junction to the southwestern edge of the Agulhas continental crust, and by about 80 Ma (anomaly A-34) the triple junction had migrated to a point southwest of the plateau (Figure 9*d*). The magnetic bight in anomaly A-34 that forms the eastern and northern limbs of this triple junction has been documented by *LaBrecque and Hayes* [1979]. The irregular crust comprising the 'southwest spur' of the Agulhas Plateau (Figures 2 and 6) could trace the migration of this triple junction.

Although the plate tectonic evolution outlined above may seem complex, it is not unrealistic. Both preexisting lineaments in the original continental crust of southern Gondwanaland and the subsequent tectonic fabric created by spreading patterns probably had significant effects on the location of spreading ridges and transform faults. Furthermore, because the very large original offset along the Falkland-Agulhas Fracture Zone (1400 km) presently is reduced to about 200 km [*Barker*, 1979; *LaBreque and Hayes*, 1979], it is clear that strongly asymmetric spreading or significant ridge jumps occurred during the spreading history of the basin south of the Falkland-Agulhas Fracture Zone. One ridge jump has been documented at about the time of anomaly A-29 (~64 Ma), and another jump may have occurred about 58–60 Ma [*LaBrecque and Hayes*, 1979; *Barker*, 1979]. However,

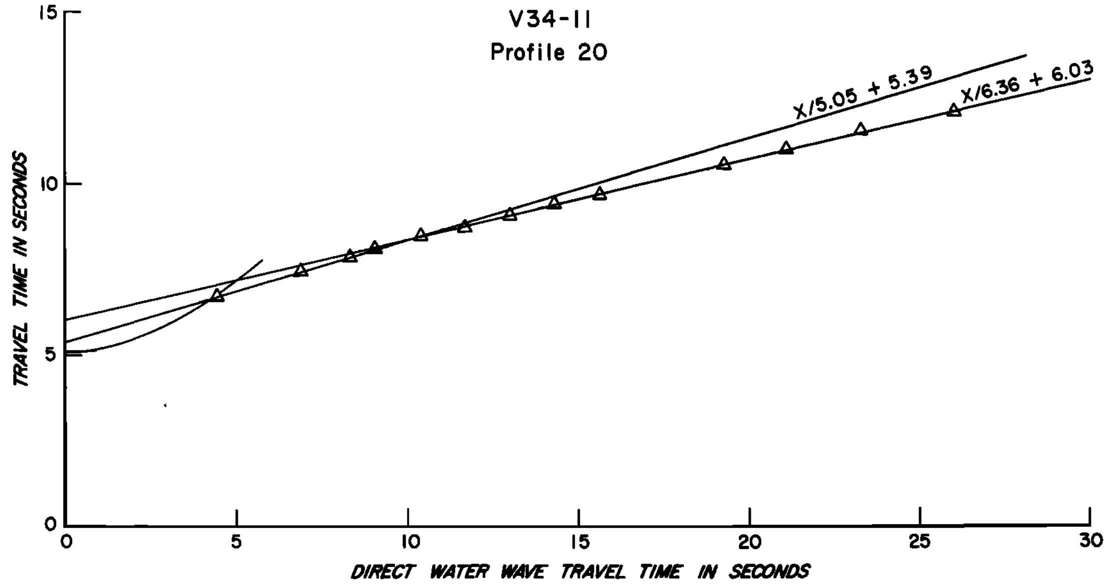

Fig. 11. Travel time graph for long-range sonobuoy profile 20.

these jumps still leave up to 400 km of offset unaccounted for. It is likely that one or more ridge jumps reduced the remaining offset within the Cretaceous quiet zone, when possibly less stable tectonic patterns prevailed before final separation of the Falkland Plateau and South Africa. Considering the complex structure of the Agulhas Plateau alone, it would not be surprising to find that the model we have outlined is overly simplified.

Although the early spreading history presently is not well defined, it is apparent that continental crust beneath the Agulhas Plateau and beneath part or all of the Mozambique Ridge must be accounted for in reconstructions of southern Gondwanaland. There are several clearly testable aspects to the model we have outlined, such as the required presence of M-series anomalies in the northeastern Transkei Basin and the degree of similarity in deep seismic structure and structural fabric of basement among the Mozambique Ridge, Agulhas Plateau, and Falkland Plateau. It also is noteworthy that many of these small and presumably continental fragments, including the Agulhas Plateau, are not covered by thick sediment accumulations. This fact makes them more readily accessible to seismic investigation and drilling, and they may ultimately prove to be ideal targets for studying the processes and results of early rifting of continental crust.

APPENDIX: SEISMIC REFRACTION DATA ACQUISITION AND REDUCTION

Field Techniques

Our wide-angle reflection and refraction measurements included the use of an ocean bottom hydrophone (OBH), commercial long-range sonobuoys (LRSB), and short-range military sonobuoys (SB). Explosives served as a sound source for the OBH, all the long-range sonobuoys, and one military sonobuoy (Table 1). A small airgun (328 cm^3) sound source was used for the other military sonobuoys. Explosive charges ranged in size from 2.5 to 100 kg and provided refraction data out to a maximum range of 63 km with the long-range sonobuoys and 72 km with the OBH. A maximum range of 19 km was achieved with the airgun and military sonobuoys; profile 113-V34 was extended to a range of 27 km with 25-kg explosive charges. Eight tons of SUBAQ explosives with PENTOLITE boosters, both supplied by AECI, Ltd., of Johannesburg, were used, and they proved to be easy to handle and exceptionally reliable. The explosives are designed and packaged specifically for marine work. Shot instants, time code, and seismic arrivals were recorded on a 12-channel SIE Dresser recorder. Charge sink rates were measured precisely by jettisoning several unarmed charges and measuring the time of descent with a 50-m length of thread.

The field work was hampered by bad weather, which occasionally degraded the quality of the sonobuoy data. At one point the weather deteriorated so rapidly that it was not possible to shoot to an OBH that had just been launched. Violent rolling made the OBH operations difficult and resulted in damage to the hydrophones so that only the first OBH record was usable. Over the crest of the plateau we had surprisingly little difficulty with currents causing sonobuoy drift in long-range profiles, but off the west flank of the plateau currents as fast as 6 knots (11 km/hr) made refraction and station work nearly impossible.

Data Reduction

Sonobuoy and OBH refraction solutions are listed in Table 1, and selected travel time graphs are shown in Figures 10-15.

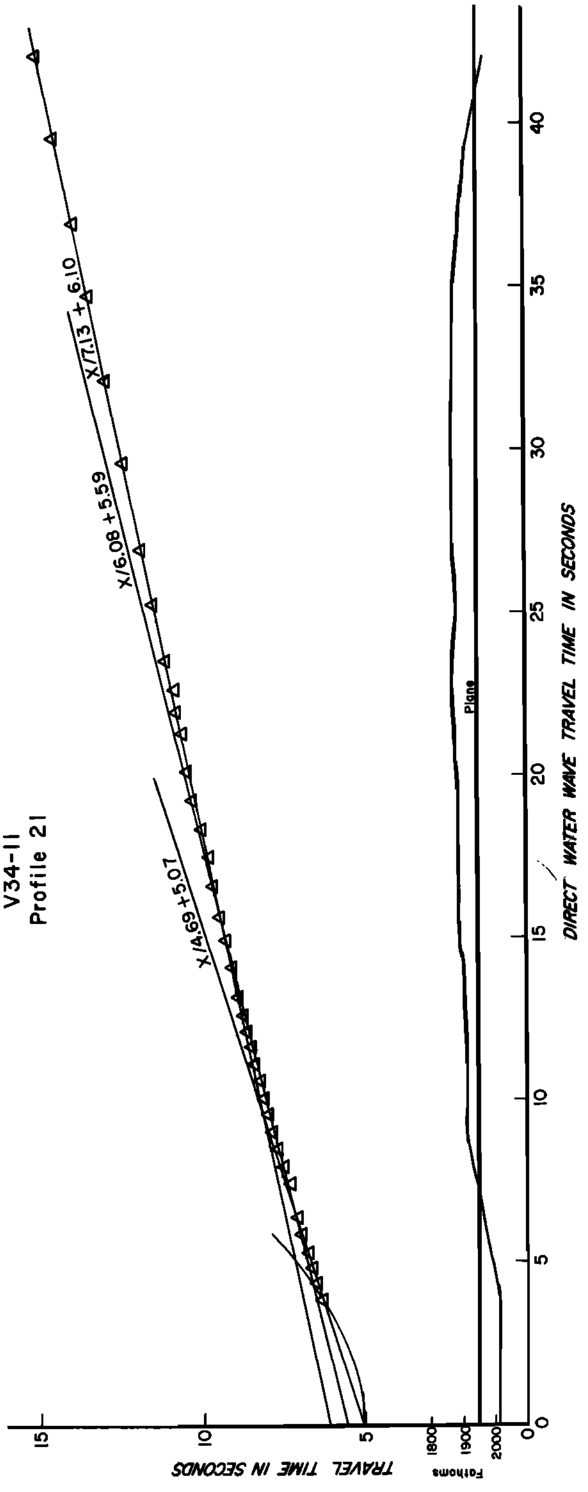

Fig. 12. Travel time graph for long-range sonobuoy profile 21.

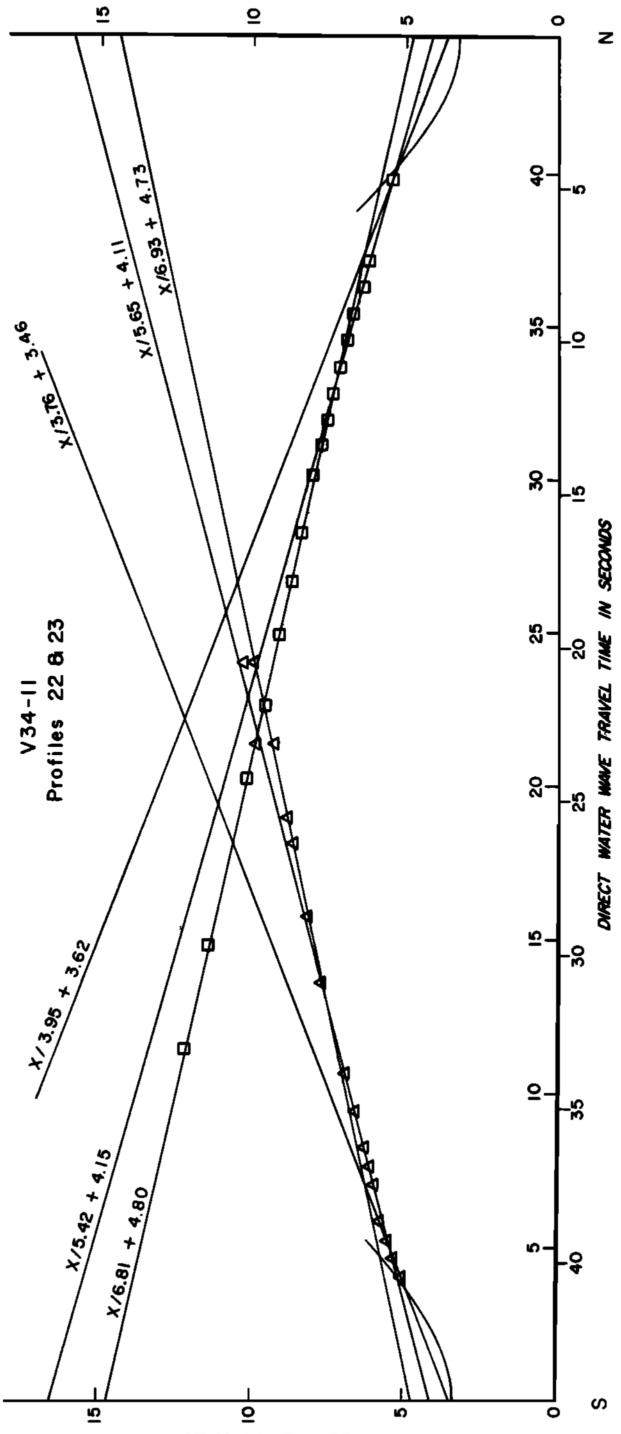

Fig. 13. Travel time graph for reversed long-range sonobuoy profiles 22S and 23N.

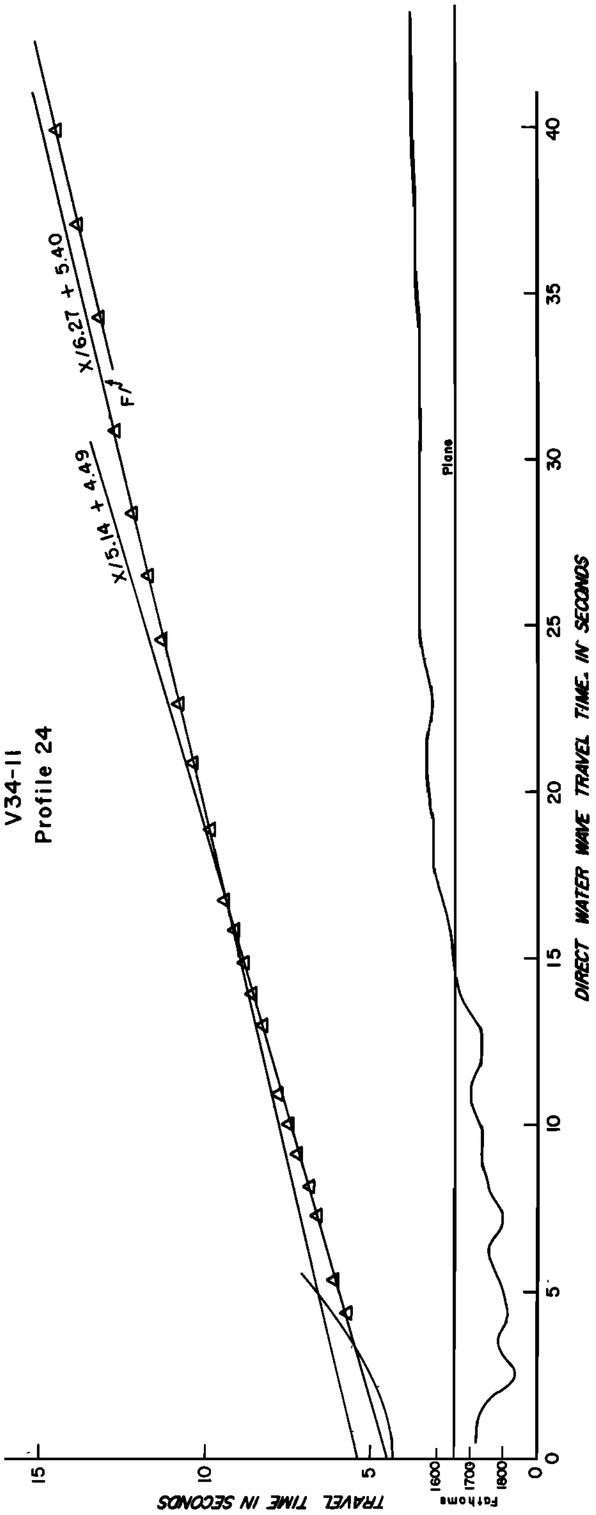

Fig. 14. Travel time graph for long-range sonobuoy profile 24.

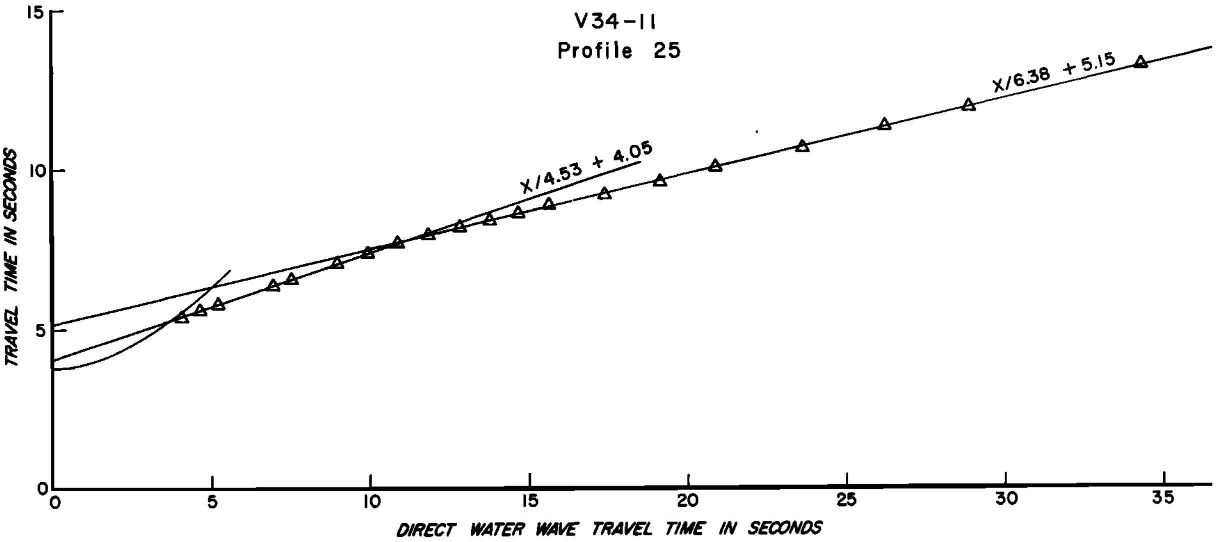

Fig. 15. Travel time graph for long-range sonobuoy profile 25.

In those cases where the range was at least 40 km, minimum thicknesses were calculated for the deepest layer recorded. The calculation of minimum thickness is based on construction of a deeper, hypothetical refraction line that is presumed to pass through the most distant observed refraction arrival. Whenever the deepest observed refraction line represented a velocity less than 6.5 km/s, the minimum depth was computed using an assumed 7.2-km/s line. If the observed refraction line was greater than 6.6 km/s, the assumed line was 8.1 km/s. Topographic corrections were applied to all profiles, but topography has a significant effect only in profiles 21 and 24, where relief exceeded 50 fm (Figures 12 and 14).

Two profiles, 16N/18S and 22S/23N, are reversed (Figures 10 and 13). Minimum thicknesses were computed here from the maximum range and extended to the opposite leg by use of the reverse times. The 3.9-km/s refraction line was observed clearly only on one side of profile 22S/23N, and it was constructed to reverse. Similarly, the 4.00-km/s line on profile 16N is not observed on profile 18S, but in this instance the data do not allow reversal, and the 4.0-km/s layer therefore must pinch out at the south end of the profile.

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