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Continental-Oceanic Crustal Transition Off Southwest Africa[1]

JAMES A. AUSTIN, JR.,[2] and ELAZAR UCHUPI[3]

ABSTRACT

More than 1,426 mi (2,300 km) of 48-trace, 12-fold seismic reflection profiles were used to examine the nature of the continent-ocean boundary off southwest Africa. South of the Orange River, faulted blocks, which we interpret as rifted continental crust, can be traced seaward to the 3 km isobath. The transition to oceanic basement occurs in a zone 19 to 25 mi (30 to 40 km) wide beneath the continental rise. Although structural details are obscured by a thick, seaward-dipping wedge of pre-AII (pre-late Early Cretaceous) overburden, oceanic crust at the presumed contact is not older than magnetic anomaly M9 (126 to 121 m.y.B.P.).

North of the Orange River, a pronounced hinge in continental crust correlates with magnetic anomaly G of Rabinowitz (1976). Seaward of the hinge, a complex fault-block terrane is evident. Oceanic basement can not be traced with any certainty landward of anomaly M4.

Intracontinental stretching and associated volcanism appear to have been important in the early history of the Cape Basin. Rifting and local dike intrusion may explain the presence of some lineated magnetic anomalies previously attributed to sea-floor spreading. Related extrusives form at least part of the pre-AII wedge just seaward of the hinge zone. Our interpretation of the seismic data suggests that the initiation of normal spreading in the Cape Basin postdates by 4 to 9 m. y. the Valanginian age derived from prevailing plate tectonic reconstructions of the South Atlantic.

INTRODUCTION

Since the early 1960s, the theory of plate tectonics has been substantially supported. One of the fundamental geologic problems that remains concerns the location and nature of the continental-oceanic crustal transition off passive continental margins. Numerous studies have focused on this crustal boundary, and many structural models have been proposed based predominantly on geophysical measurements.

Rabinowitz (1974) placed the transition off the southeastern United States along the trend of the Blake Spur magnetic anomaly , a feature located near the base of the Blake Escarpment in water depths of more than 14,500 ft (4.5 km). Recently collected multichannel seismic reflection profiles seem to support this hypothesis, and also show that the Blake Plateau is underlain by rifted and intruded continental crust (Dillon et al, 1979a, b).

North of the Blake Plateau from the Carolinas to the Canadian Maritime provinces, the East Coast magnetic anomaly appears to mark the transition from rifted continental to oceanic crust (M. J. Keen, 1969; Emery et al, 1970; Luyendyk and Bunce, 1973; Grow et al, 1979; Grow, 1980). In this region, the width of the transition varies but is relatively narrow, ranging from 9.3 to 12.4 mi (15 to 20 km) beneath the Baltimore Canyon Trough (Grow, 1980) to 43.4 mi (70 km) southeast of Nova Scotia (Keen and Keen, 1974). The slope anomaly off eastern Canada exhibits two peaks with a massive diapiric ridge located between them. Landward of the inner peak, velocity gradients characteristic of continental crust occur, whereas seaward of the outer peak the velocity structure is more typical of oceanic crust. Beneath the diapirs, crust with a velocity of 4.6 mi/sec (7.4 km/sec) is detected. Keen and Keen (1974) postulated that this crust consists of intrusive basic and ultrabasic rocks, perhaps now metamorphosed, that were emplaced in a zone 6.2 mi (10 km) wide during initial continental separation prior to the onset of normal sea-floor spreading.

In contrast, the ocean to continent transition in the Orphan basin north of the Grand Banks of Newfoundland is very wide, occurring at a water depth of 13,000 ft (4 km) and at a distance of more than 186 mi (300 km) from the shelf's edge. Keen and Barrett (1981) estimated a 50% thinning of continental crust as a result of rifting. Additional evidence for stretching is available from the Labrador Sea margin to the northwest, where geophysical data suggest a zone of rifted continental crust 62 mi (100 km) wide with its seaward edge in approximately 6,500 ft (2 km) of water (Hinz et al, 1979).

On the eastern side of the North Atlantic, faulted, thinned continental crust is in sharp contact with oceanic crust off Norway (Talwani and Eldholm, 1973), in the Bay of Biscay (Montadert et al, 1979), and off northwestern Spain, where a serpentinite diapir apparently emplaced along a fault marks the boundary west of Galicia Bank (Boillot et al, 1979, 1980). In the Rockall Trough, however,

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[2] The University of Texas at Austin Institute for Geophysics, Galveston, Texas 77550.

[3] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543.

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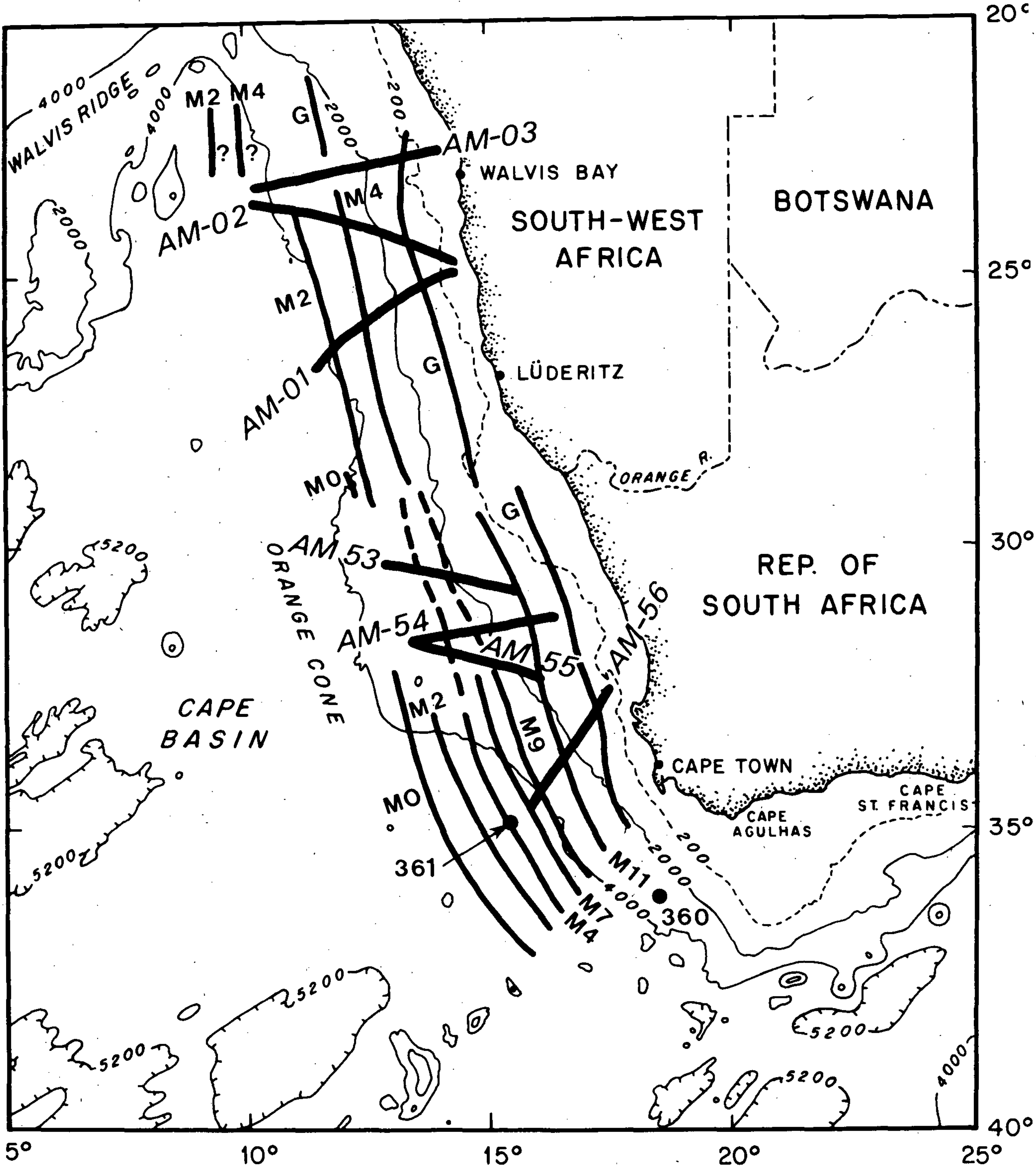

FIG. 1—Bathymetric map of Cape Basin and adjacent continental margin off southwest Africa (modified from Emery et al, 1975). AM 53 to 56 and AM 01 to 03 are 48-trace, 12-fold seismic lines collected by University of Texas. Supposed Mesozoic sea-floor spreading magnetic lineations M0 to M11 and G (M13) are after Rabinowitz (1976); 360 and 361 are drill-site locations from Leg 40 of Deep Sea Drilling Project (Bolli et al, 1978).

crustal relationships are obscured, perhaps because of an early rifting episode that produced not only minor block faulting but extensive volcanic activity (Roberts and Montadert, 1980).

The passive margins of South America and Africa are structurally diverse. Northwest of Morocco, the continental-oceanic basement boundary is probably located near the western edge of a diapiric field in water depths in excess of 13,000 ft (4 km). Like the Nova Scotian margin, the magnetic slope anomaly here has two peaks, with the inner peak over "continental" crust, the outer peak over "oceanic" crust, and the intervening diapirs underlain by crust with a velocity of 4.3 mi/sec (7 km/sec) (Uchupi et al, 1976; K. Klitgord and H. Schouten, personal commun.). If the parallel with the Canadian margin holds, then this 4.3 mi/sec(7 km/sec) material is ductile lower continental crust exposed either by listric faulting or creep, and evaporites in both regions were originally deposited on continental crust.

Off Mauretania, at 19° N, seismic refraction data indicate that no standard Layer 2–Layer 3 oceanic crustal sequence occurs for 84 mi (135 km) west of the continental slope (Weigel and Wissman, 1977; Goldflam et al, 1980). A layer with a velocity of 4.4 mi/sec (7.1 km/sec) is present from the upper rise to the base of the continental slope, however, and may once again represent lower continental crust exposed during initial rifting by either faulting or ductile creep. In contrast, off southern Senegal and Gambia, seismic reflection profiles indicate the presence of oceanic basement at the base of the continental slope (Beck et al, 1975; Lehner and De Ruiter, 1977). This is also the case along the translation margins of the Gulf of Guinea and northern Brazil (Houtz et al, 1977; Lehner and De Ruiter, 1977).

From Gabon to southern Angola, the transition from continental to oceanic basement probably takes place at the Angola Escarpment, a salt front (Lehner and De Ruiter, 1977). Seismic refraction data suggest that the same crustal boundary off eastern Brazil may also be located along the seaward edge of a salt diapiric field (Leyden et al, 1976). This crustal transition along the salt front is marked in places by a structural high having a relief of several kilometers.

While ocean-continent boundaries beneath the slope off Argentina and beneath the outer shelf-slope off southwestern Africa have been inferred by Rabinowitz (1976) and Rabinowitz and LaBrecque (1977, 1979) using lineated magnetic and isostatic gravity anomalies, Argentine seismic refraction and reflection profiles can also be interpreted to show that the slope magnetic anomaly there is along a hinge in subsided continental crust (Figs. 2, 5, 6, of Ludwig et al, 1979). In the Cape Basin, too, a combination of single-channel seismic and gravity data can also support the presence of an ocean-continent boundary in water depths greater than 9,800 ft (3 km) everywhere north of the Agulhas fracture zone (Emery et al, 1975; Scrutton, 1978).

PRESENT INVESTIGATION

The controversy over the interpretation of lineated potential field anomalies off southwestern Africa has developed because of a lack of seismic reflection information concerning the structure of the upper crust (Rabinowitz, 1978; Scrutton, 1978). In an effort to provide subsurface seismic control, The University of Texas Institute for Geophysics collected approximately 1,426 mi (2,300 km) of 12-fold common-depth-point (CDP) profiles in the Cape Basin in 1979 as part of an extensive site survey effort for the International Phase of Ocean Drilling (IPOD) in the South Atlantic. Seven traverses of the African margin were made during two different legs, one set west of Walvis Bay and the other west of Cape Town (Fig. 1). A 48-trace, 1.74 mi (2.8 km) streamer was used as a receiver, while the sound source consisted of four modified Bolt 1,500 in.^{3} air guns fired simultaneously at 500 psi (3,450 kPa). Incoming data were digitally sampled at 4 msec intervals, filtered (8 to 62 Hz), and then recorded in multiplexed format on 1-in., 21-track field tapes. All CDP processing was carried out ashore. The air-gun profiles were supplemented by continuous 3.5/12 kHz data and total-field magnetic intensity measurements made with a Varian proton precession magnetometer. Speed of the R/V *Fred H. Moore* was maintained as closely as possible at 5.6 mi/hour (9 km/hour). Navigation was by satellite.

SOUTHERN CAPE BASIN

Stratigraphy

Multichannel profiles AM-56-53 (Figs. 2 to 6) illustrate the development of the southwest African passive continental margin south of the Orange River. Well control in this region is sparse, consisting of DSDP sites 360 and 361 (Fig. 1) and a number of exploratory holes drilled on the shelf by SOEKOR, the South African national oil company (Bignell, 1977; Figs. 3, 4 of Gerrard and Smith, in press).

The profiles clearly show three major stratigraphic sequences separated by two prominent unconformities, D and AII, previously identified on single-channel profiles (Emery et al, 1975). Horizon D is the shallower of the two erosional surfaces. At site 361, it separates lower Eocene calcareous ooze and mud from upper Paleocene carbonate-poor clays (Bolli et al, 1978) (Fig. 7). D is a continuous, high-amplitude seismic reflector that can be traced from the inner shelf to the lower rise. Beneath the slope off Cape Town, it attains a maximum local relief of 0.2 sec in the vicinity of cut-and-fill structures (Figs. 2, 3). Basinward, D becomes smooth and conformable (Figs. 2 to 6).

The D-AII sequence of Paleocene-Late Cretaceous age is recognizable as a series of highly discontinuous, low to moderate amplitude reflectors (Figs. 2 to 6) that are produced by fine-grained, carbonate-poor distal fan turbidites at site 361 (Fig. 7) (Bolli et al, 1978). On the Orange Cone, these sediments are extensively faulted and slumped (Figs. 1, 6) (Emery et al, 1975; Dingle, 1980), but neither D nor AII seems to be directly affected. Farther south, major sediment deformation is restricted to the post-D (Tertiary) section (Figs. 2 to 4).

At site 361 on the lower continental rise, horizon AII sep-

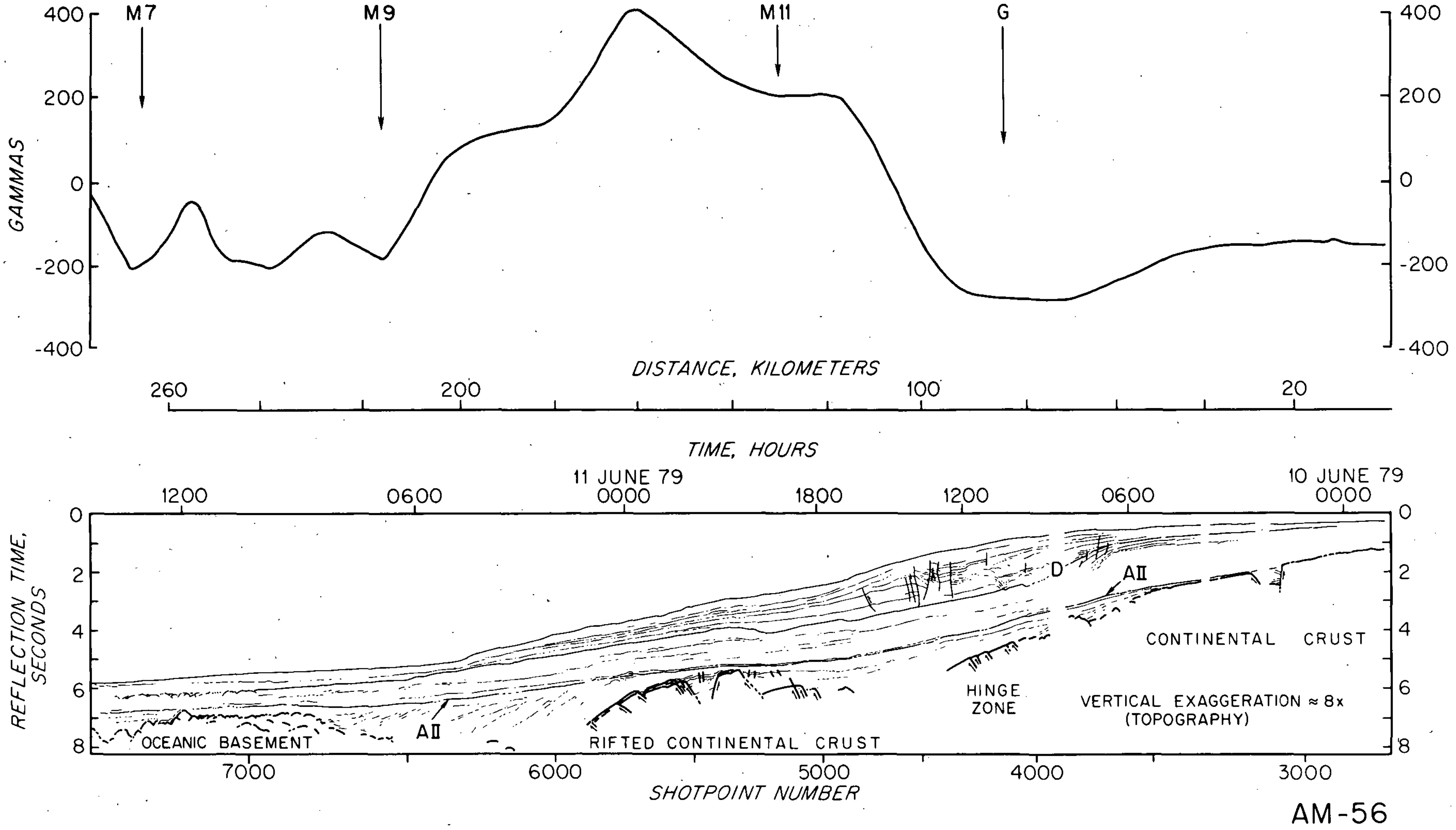

FIG. 2—Line interpretations of profile AM-56. See Figure 1 for location of profile. Figure 3 is uninterpreted, annotated version of line AM-56. Major features are identified for ease of comparison with line drawing. All data are 48-trace, 12-fold. Normal CDP processing has been completed (except migration). Reflector identifications and their significance are discussed in text. Superimposed magnetic anomaly profile for this line only is from *Vema* cruise 22, Leg 4 (Rabinowitz, 1976). Identifications of supposed Mesozoic sea-floor spreading anomalies on Figures 2, 4, 5, and 6 are based on direct comparison with model published in Rabinowitz (1976, Fig. 6). No further modeling was felt to be necessary as part of this investigation.

arates Upper Cretaceous turbidites from rapidly deposited (more than 164 ft/m.y., 50 m/m.y.) Lower Cretaceous carbonaceous quartz-sand turbidites interbedded with pelagic sapropelic shales (Fig. 7) (Bolli et al, 1978). On the seismic profiles, the pre-AII sequence resembles a wedge of seaward-dipping, variable amplitude reflecting horizons that reaches its maximum thickness (1.5 to 2.0 sec.) beneath the rise (Figs. 1 to 6). Similar features have been noted on other passive margins (Hinz, 1981). AII itself is a regionally smooth, high-amplitude reflector package capping the wedge, and does not appear to have been affected by subsequent tectonism in the southern Cape Basin (Figs. 2 to 6).

Basement

Acoustic basement displays three distinct morphologies, one beneath the rise, another on the slope, and a third beneath the shelf. Underlying the continental rise is a rough surface that exhibits the complex hyperbolic returns normally ascribed to oceanic basement. At the base of the slope, this surface appears to turn downward before disappearing beneath the prograded wedge of pre-AII material (Figs. 2 to 4). The landward limit of the hyperbolic basement coincides approximately with a magnetic anomaly identified as M9 along lines 56 and 55 and M4 along lines 54 and 53 (Rabinowitz, 1976) (Figs. 2, 4, 5, 6).

Under the continental slope 19 to 25 mi (30 to 40 km) east of the limit of "oceanic" basement lies a complex, blocky terrane dominated by broad highs and lows that are particularly evident on line 56 (Figs. 2, 3) and on a profile published by Beck et al (1975, Fig. 1, profile 4). This terrane everywhere underlies the pre-AII wedge of seaward-dipping reflectors. The strike of the buried topography cannot be determined from the available data, but trends roughly parallel with the present bathymetric contours seem justified based on mapping of more well-defined graben structures beneath the shelf (Gerrard and Smith, in press). Some of the interpreted normal fault scarps face the continents, implying minor seaward rotation of some blocks during subsidence (Figs. 2 to 4). None of the scarps are obviously listric in character.

A complicated, very long (more than 62 mi, 100 km) wavelength positive magnetic anomaly overlies the rifted zone (Figs. 2, 3, 5, 6). This multipeaked anomaly has been previously correlated with Mesozoic sea-floor spreading anomalies M8 to M11 (Rabinowitz, 1976), but on line AM-56 the anomaly overlies a broad, buried high that resembles a faulted horst (Figs. 2, 3; km 120 to 180) more than oceanic crust. Continental rifts produce similar "oceanic"-looking magnetic anomalies along the margins of the Red Sea (Cochran, 1981).

Basement beneath the shelf is generally smooth and unbroken except for a few small graben structures (see Figs. 2 and 3 between km lines 20 and 40). The topography of the rifts on the inner shelf appears to be truncated (see Figs. 2 and 3 landward of the 60 km line). North of line AM-56, the AII horizon either very closely overlies or merges with the basement surface (Figs. 5, 6). Where the graben fill beneath the truncating unconformity has been sampled south of the Orange River, it consists of Lower Cretaceous red beds and volcanics overlying a foundation of Precambrian metamorphic rocks and possible Permo-Carboniferous ("Karroo") clastics (Bignell, 1977; Gerrard and Smith, in press).

Separating the relatively smooth basement beneath the shelf from the broken terrane under the slope and upper rise is a prominent basement hinge or scarp. On line 56, the top of the scarp is beneath the outer shelf and on lines 54 and 53 beneath the mid-slope (Figs. 2, 3, 5, 6). Most of the pre-AII sequence pinches out against this basement hinge. A SOEKOR exploratory well recently drilled just seaward of the top of the hinge zone in the vicinity of lines 56 and 55 penetrated the onlapping pre-AII strata and recovered Aptian volcaniclastic sandstones and siltstones and Jurassic (?)-Early Cretaceous basic and acid alkaline lavas with associated pyroclastics that are not oceanic in character (Gerrard and Smith, in press). Both this SOEKOR well and the top of the hinge zone are located along the axis of magnetic anomaly G off Cape Town (Figs. 2, 3). Gerrard and Smith (in press) have suggested that anomaly G is the result of the regular pinchout of Mesozoic volcanics against older rocks east of the hinge zone.

NORTHERN CAPE BASIN

Stratigraphy

North of the Orange River, there is virtually no subsurface control. However, based on similarities in acoustic character, both the D and AII unconformities can be identified on lines AM-01-03 (Figs. 1, 8 to 12). D is traceable from the inner shelf (where it onlaps the basement surface) to the rise as a continuous, high-amplitude reflector whose unconformable nature is most pronounced beneath the slope. On line 01 (Figs. 8, 9, 13), D outlines a buried shelf-edge with more than 1.0 sec of relief.

The post-D (Tertiary) section is everywhere affected by massive slumping. There are at least two episodes of cutting and filling above D (Figs. 9 to 12). Unlike the extensively tectonized Upper Cretaceous section farther south, however, the D-AII sediments here are undeformed (Fig. 6). In the vicinity of the Orange Cone (Fig. 6), maximum thicknesses of the D-AII interval are over 3.0 sec, representing at least 1.9 mi (3 km) of open marine shales and sandstones (Gerrard and Smith, in press). Farther north, however, Upper Cretaceous thicknesses are always less than 2.0 sec (about 1.9 mi, 3 km; Figs. 8 to 12).

The AII horizon is less continuous and harder to trace in the northern Cape Basin, but there is still good seismic evidence for a pre-AII wedge of seaward-dipping reflectors beneath the slope and rise (Figs. 8 to 12). On line AM-01 (Figs. 8, 9), apparent normal faults that originate in a poorly defined basement complex beneath the wedge propagate upward into it. At one location farther seaward along the same line (Fig. 8, shotpoints 1300 to 1900; Fig. 9, km 210-240), an uplifted block prevents direct correlation of AII and older material basinward. This block is fault-controlled, and its top appears truncated, perhaps by the same erosional episode that carved the AII horizon. This high occurs in the right position to be the "outer high" composed of altered continental crust that is postulated by

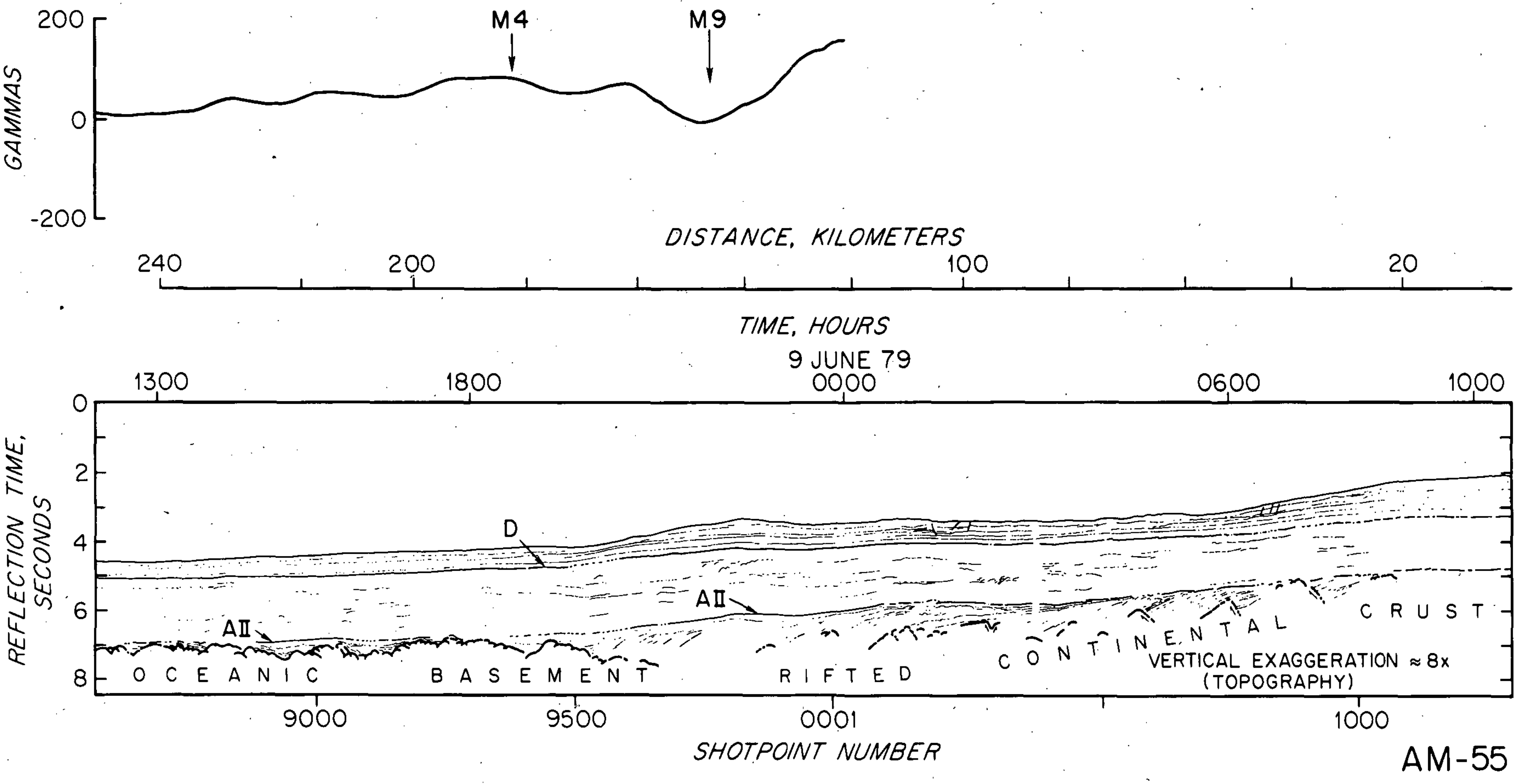

FIG. 4—Line interpretation of profile AM-55 (see Fig. 2 caption). Location of profile is shown on Figure 1.

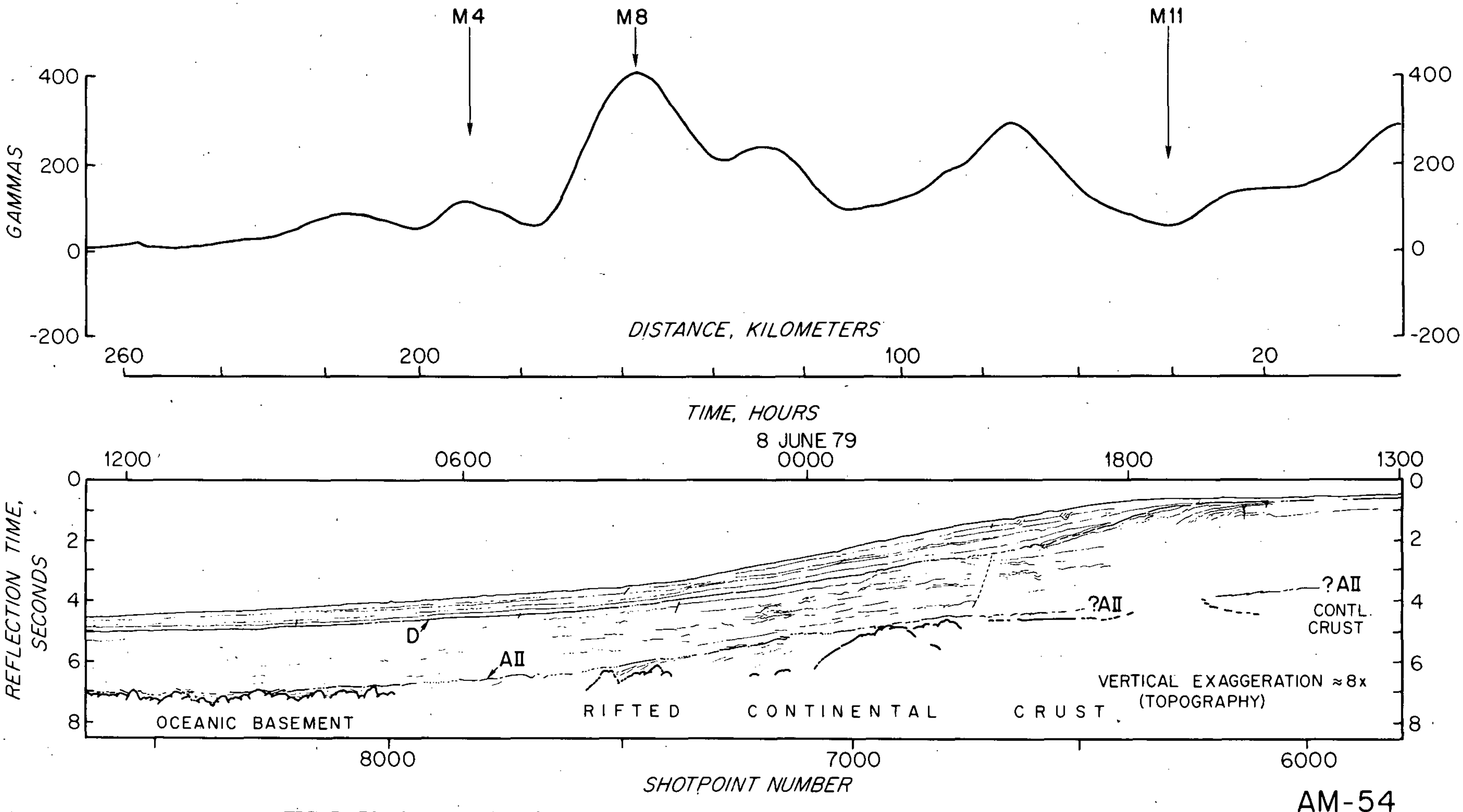

FIG. 5—Line interpretation of profile AM-54 (see Fig. 2 caption). Location of profile is shown on Figure 1.

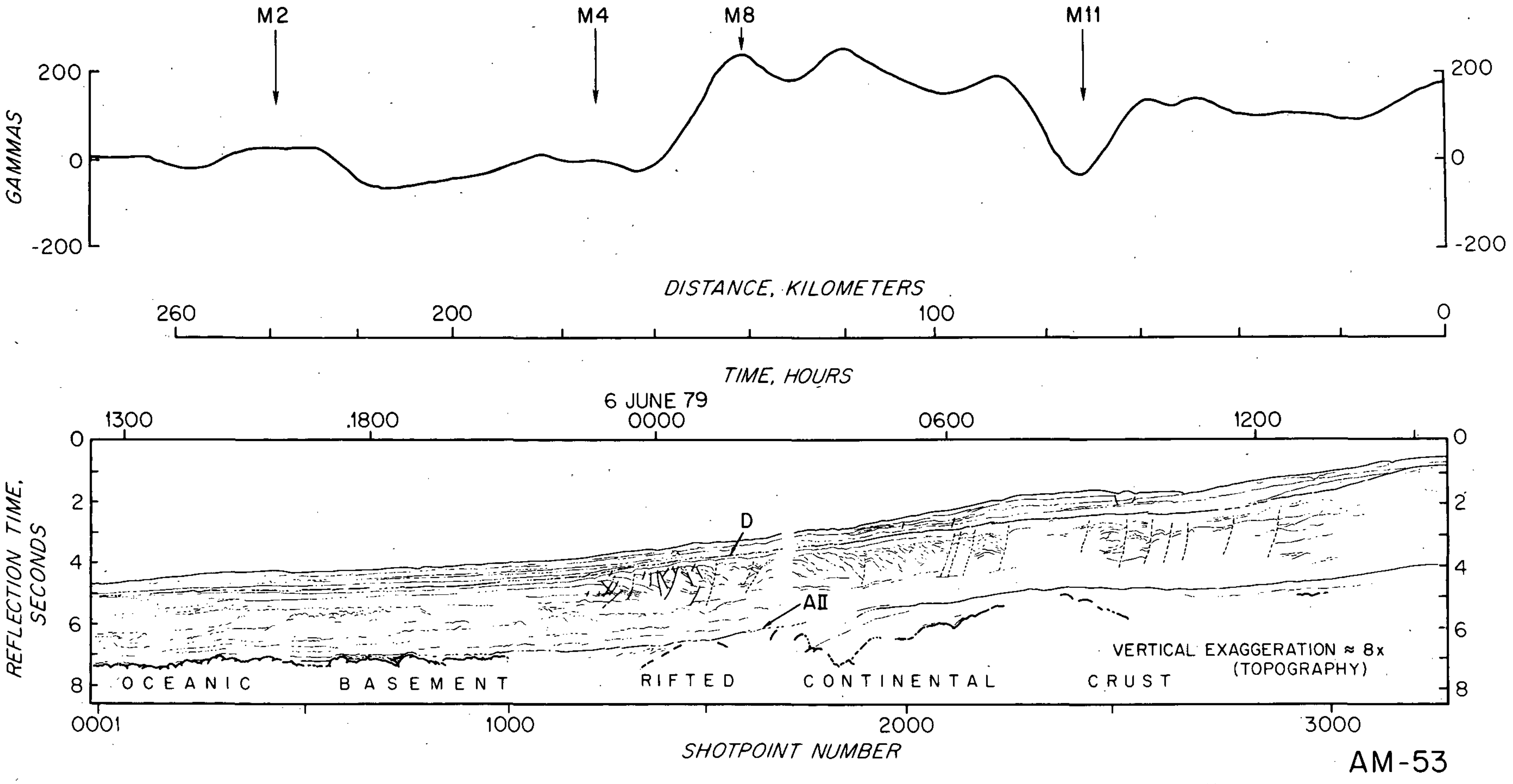

FIG. 6—Line interpretation of profile AM-53 (see Fig. 2 caption). Location of profile is shown on Figure 1.

Schuepbach and Vail (1980) to occur immediately landward of the ocean-continent transition on some passive margins. However, the persistence of the high along the strike of the margin cannot be demonstrated, as it occurs only on line AM-01. On all three of the northern Cape Basin lines (Figs. 8 to 12), the interpreted AII surface onlaps oceanic basement seaward of Rabinowitz's (1976) anomaly M2 (Figs. 8 to 11), substantiating its Aptian age at site 361 (Fig. 7).

Basement

The acoustic basement surface north of the Orange River is somewhat different from that to the south, but the three morphologic types previously described can still be recognized. The nested hyperbolae commonly identified as the top of oceanic basement extend from the deep basin to the mid-rise (Figs. 8 to 12). Relief of this surface averages 0.5 sec locally, but there is no pronounced landward hinge as there is beneath the rise off Cape Town (Figs. 2, 3). Instead, oceanic basement either disappears without a significant change in gradient (Fig. 10, shotpoints 1500 to 400; Fig. 11), or comes into direct contact with more rugged basement resembling uplifted blocks (Fig. 8, shotpoints 500 to 1900; Fig. 9). The contact occurs in approximately 11,500 ft (3.5 km) of water in the vicinity of magnetic anomaly M4 (Rabinowitz, 1976).

Between anomalies M4 and G, a zone more than 62 mi (100 km) wide, basement consists of a series of irregular blocks tilted along normal faults, which also occasionally cut overlying pre-AII material (Figs. 8 to 12). These faults do not appear to be listric, but some flattening with depth could occur because subbasement resolution in this zone is poor. Most of these faults dip seaward, but a few dip landward (Figs. 8, 9). Several of the blocks have beveled crests, suggesting erosion either before or during tilting (Fig. 8, shotpoints 1600 to 1800; Fig. 9). However, well-defined rifts are not apparent. Instead, complex faulting produces a chaotic arrangement of highs and lows with 0.5 to 1.0 sec of relief (Figs. 8 to 12). At the presumed ocean basement contact on line AM-01, the outer high is more than 6.0 sec below sea level but buried by less than 2.0 sec of overburden (Fig. 8, shotpoints 1700 to 1800; Fig. 9). It is often difficult to identify a basement surface beneath the faulted cover (Figs. 8 to 12), and the pre-AII wedge may consist of highly reflective syn-rift sediments and/or volcanics. Similar complexes exist off Cabinda (Cochran et al, in press) and in the Bay of Biscay (Montadert et al, 1979). Whether the pre-AII sequence off southwest Africa is continental, marine, or a combination of both is not known.

Beneath the continental slope, the rifted terrane is less than 5.0 sec deep at the base of a very prominent hinge zone. On lines AM-01 (Figs. 8, 9, 13) and 02 (Figs. 10, 11), this hinge exhibits more than 3.0 sec of relief. As it does farther south, the hinge separates a smooth crustal ramp beneath the shelf from complexly deformed fault blocks on the west. Only one small graben is discernible landward of the hinge (Fig. 8, shotpoints 4800 to 5100; Fig. 10, shotpoints 8000 to 7600; Figs. 9, 11, 13). The entire pre-AII sequence, which exceeds 2.0 sec in thickness, onlaps the hinge (Figs. 10, 11). Rabinowitz's (1976) anomaly G and its associated isostatic gravity anomaly overlie the hinge zone (Figs. 8 to 11).

Line AM-03 (Fig. 12), the northernmost of the University of Texas multichannel lines in the Cape Basin (Fig. 1), looks different from lines AM-01 and 02 (Figs. 8 to 11) (see Lehner and De Ruiter, 1977, Fig. 17, profile V' V for an interpreted profile with almost the same trend). First, the wedge of pre-AII material is thicker and more uniform. Basement in the rifted zone (landward of shotpoint 8300) seems less rugged, too, although this could be an artifact of poorer data quality. Finally, the hinge is not as prominent. Instead, the outer shelf seems to be underlain by a faulted(?), westward-tilted basin flanked by basement highs. Unfortunately, data gaps and poor resolution obscure the basement configuration beneath the mid-shelf. An examination of Figure 1 shows that AM-03 was shot along the trend of a large fracture zone that intersects the margin (Rabinowitz, 1976), and this may explain many of the structural differences from the lines farther south.

Anomaly G along line AM-03 occurs at approximately shotpoint 2600 (Fig. 12), directly over the landward flank (hinge zone?) of the large basin underlying the outer shelf. Seaward of anomaly G, the magnetics are confused, perhaps reflecting the tectonism associated with the fracture zone postulated to be in the vicinity. However, as on line 56 (Figs. 2, 3), a broad, multi-peaked positive magnetic anomaly overlies the zone of broken crust between the outer shelf and upper rise.

DISCUSSION

A map of the basement configuration of the continental margin off southwestern Africa can be constructed from the interpreted multichannel seismic data (Fig. 14). Beneath the inner shelf, acoustic basement is a generally smooth, gently dipping ramp. Occasional truncated graben structures entrained within the basement ramp occur. Their cross sections range along the strike of the margin, from as narrow as 6.2 mi (10 km) (Figs. 2, 3, 8 to 11) to as wide as 18.6 mi (30 km) or more (Fig. 12; see also Gerrard and Smith, in press, Fig. 11). Although a complete correlation of individual rift structures was not attempted because of the large line spacing of the survey, the outer shelf rift on lines AM-01 (Figs. 8, 9) and 02 (Figs. 10, 11) is probably the same feature, implying a minimum length of 43 mi (70 km). In the northern part of the Cape Basin (Figs. 8 to 11), the high-amplitude, narrow wavelength magnetic anomalies over the shelf landward of anomaly G may pinpoint the location of Late Cretaceous–Tertiary alkaline volcanics that intrude the older basement complex (Moore, 1976; Gerrard and Smith, in press).

A prominent hinge zone separates the relatively undisturbed shelf platform from intensely disturbed blocks. In the northern Cape Basin, the hinge exhibits more than 3.0 sec of relief on line AM-01 (Figs. 8, 9, 13) and perhaps 4.0 sec on line AM-02 (Figs. 10, 11). Based on average stacking velocities just seaward of the hinge and refraction results from Rabinowitz (1976), vertical offsets across the feature of from 2.5 to 3.7 mi (4 to 6 km) are possible.

In the southern Cape Basin, the hinge is not as easy to trace. On line AM-56 (Figs. 2, 3), anomaly G overlies the

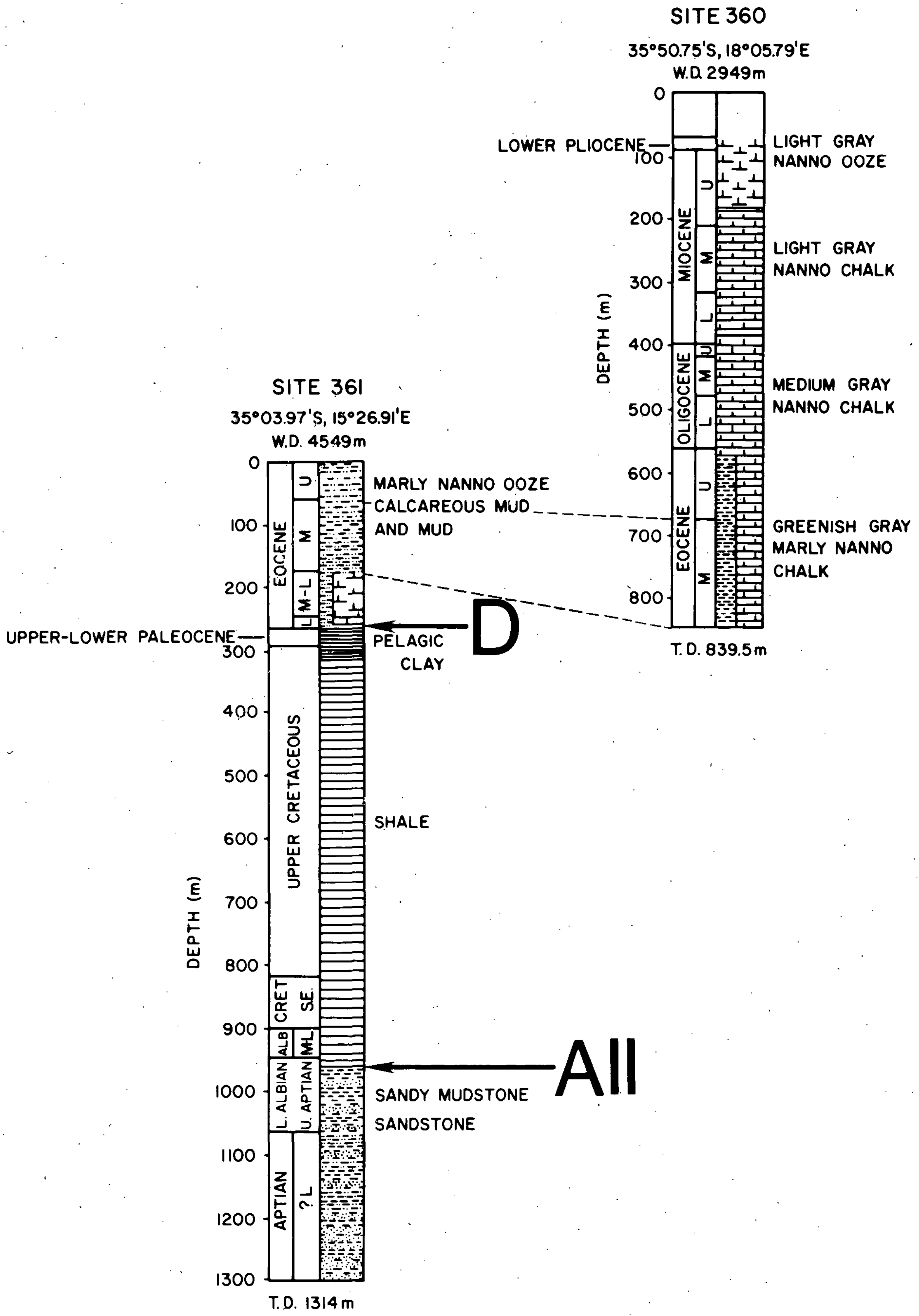

FIG. 7—Lithologic logs from DSDP Sites 360 and 361, and projected correlation with major seismic unconformities in Cape Basin. After Bolli et al (1978).

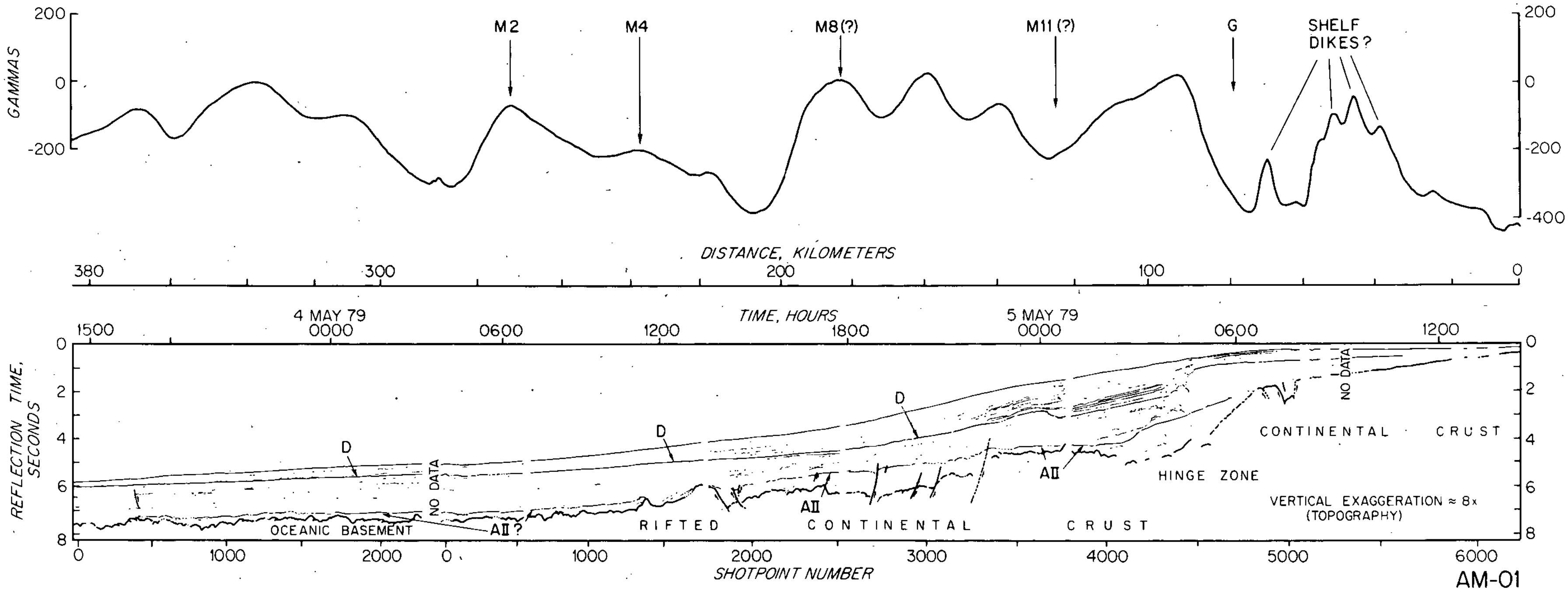

FIG. 8—Line interpretation of profile AM-01 (see Fig. 2 caption). Figure 9 is uninterpreted, annotated version of line. Major features are identified for ease of comparison with line drawing.

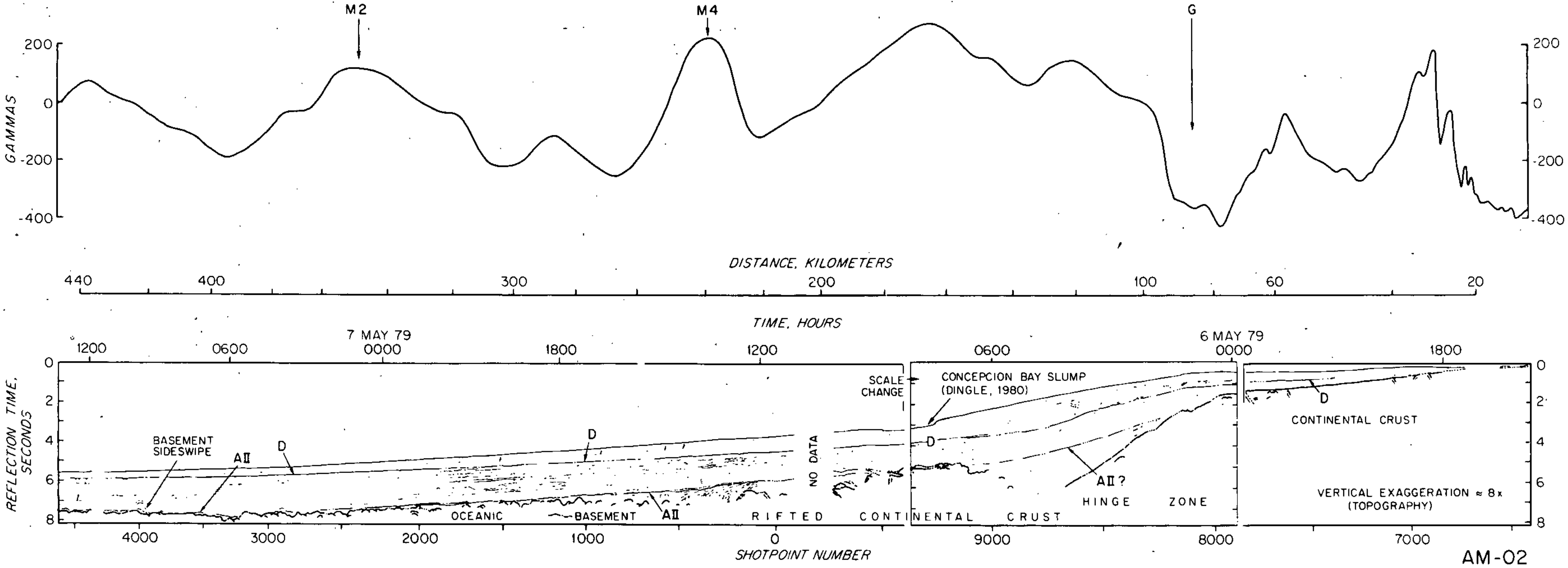

FIG. 10—Line interpretation of profile AM-02 (see Fig. 2 caption). Figure 11 is uninterpreted, annotated version of line. Major features are identified for ease of comparison with line drawing.

landward flank of a large depression that cannot be mapped farther north because of insufficient data coverage. The trend of anomaly G between line 56 and the Orange River suggests that the hinge may extend north-northwest along the edge of the shelf, not northwest across the trend of the continental slope as it is presently mapped (Fig. 14).

Basinward of the hinge zone is a region of irregular blocks tilted both landward and seaward by normal faults (Figs. 2 to 6, 8 to 12). The most prominent feature of this zone occurs west of Cape Town, where a faulted high 37 mi (60 km) wide is associated with a broad, multi-peaked positive magnetic anomaly (Fig. 2, shotpoints 4800 to 5900; Fig. 3). In the northern part of the Cape Basin, the pre-AII seaward-dipping reflector wedge is also faulted with the crust. Some of the blocks are flat-topped, implying erosion before and during their formation (see Figs. 8, 9). Individual rifts could not be mapped, in part because of the low data density, but also because of their high degree of structural variability (Figs. 2 to 6, 8 to 12).

The boundary between broken crust and the nested hyperbolae normally ascribed to oceanic basement occurs in approximately 10,000 ft (3 km) of water (Fig. 14). Its structural expression is dissimilar along the strike of the margin. Off Cape Town, the broad horst previously described abuts an interpreted oceanic crustal surface that appears to be approximately 2.0 sec deeper in the section (Figs. 2, 3). In contrast, west of Luderitz an interpreted oceanic basement surface adjoins a faulted, beveled block with a total relief across the contact of less than 1.0 sec (Figs. 8, 9).

The pre-AII wedge of seaward-dipping reflectors overlies the broken terrane on all of the profiles (Figs. 2 to 6, 8 to 13). It reaches thicknesses in excess of 2.0 sec (approximately 2.5 mi, 4.0 km, based on refraction velocities from Rabinowitz, 1976) both north (Figs. 10, 11) and south (Figs. 2, 3) of the Orange River. In the northern Cape Basin, the wedge pinches out against the hinge zone, and the AII horizon either very closely overlies or merges with the smooth acoustic basement ramp and truncated rift structures beneath the shelf. The seaward edge of the wedge is hard to pinpoint, but on lines AM-02 (Figs. 10, 11) and AM-03 (Fig. 12), AII appears to onlap interpreted oceanic basement in the vicinity of anomaly M2 (Rabinowitz, 1976). Only on line AM-01 (Figs. 8, 9) does AII appear to pinch out against an outer high, which we interpret as a continental block.

Farther south, the most well-defined pre-AII wedge occurs on line AM-56 (Figs. 2, 3). Once again, the AII surface merges with the ramp beneath the shelf and buries an interpreted oceanic basement high between magnetic anomalies M7 and M9 (Rabinowitz, 1976) beneath the rise.

CONCLUSIONS

The passive margin off southwestern Africa appears to have evolved as follows. During the Jurassic(?) and Early Cretaceous, an intracontinental rift developed between Africa and South America, in crust composed of an assemblage of Precambrian to Permo-Carboniferous granitic, metamorphic, and sedimentary rocks (Emery et al, 1975; Bignell, 1977; Gerrard and Smith, in press). Eventually, a complex series of arches and basins was produced (Veevers and Cotterill, 1978). One such arch is still visible along line AM-56 (Figs. 2, 3, km 120 to 180), and basins are particularly well-defined beneath the modern shelf (Figs. 8, 9, 13; see km 60 to 70). Major decoupling of continental crust resulted in large vertical offsets along the present hinge zone (Figs. 8 to 11).

We do not believe that the broken terrane seaward of the hinge zone represents either the top of thickened oceanic crust (Rabinowitz, 1976: Rabinowitz and LaBrecque, 1979) or a purely igneous contact between feeder dike complexes and extrusives (Hinz, 1981; Mutter et al, 1982). Based on a comparison with similar structures in the Bay of Biscay (Montadert et al, 1979; Roberts and Montadert, 1980), Orphan basin off eastern Canada (Keen and Barrett, 1981), off the east coast of the United States (Dillon et al, 1979 a, b; Austin et al, 1980; and others), and off Australia (Veevers and Cotterill, 1978; Talwani et al, 1979), we conclude that the fault blocks beneath the slope and rise off southwest Africa represent attenuated, subsided fragments of continental crust. Active tectonic readjustment of these blocks continued until at least the Aptian, as evidenced by basement faults that cut the pre-AII wedge on line AM-01 (Figs. 8, 9).

Syn-rift volcanism was widespread on this margin. The Hoachanas basalts sampled north of Walvis Bay and dated at 168 m.y.B.P. (av.; Gerrard and Smith, in press) may mark the onset of rifting in the Jurassic. In the immediate vicinity of the hinge, available drilling results have shown that Aptian and older alkaline volcanics form a major component of the pre-AII wedge (Gerrard and Smith, in press). Magnetic anomaly G and the associated isostatic gravity anomaly are here interpreted as products of the juxtaposition of the continental hinge and these volcanics, both of which were in turn responses to continental attenuation prior to the onset of sea-floor spreading. Volcanics have also been recovered by drilling seaward-dipping wedges on the Voring Plateau (Mutter et al, 1982) and off Rockall Bank (D. G. Roberts, personal commun.), but whether or not volcanics form a major component of the wedge off southwest Africa throughout its extent is not known. The presence of high-amplitude, complex magnetic anomalies (Figs. 2, 8) over the slope and rise supports the existence of some igneous material either within the seaward-dipping wedge or as a component of the rifted continental crust beneath.

At the same time, the margin was being eroded and syn-rift sediments were being deposited on both sides of the hinge zone. On the continental shelf, small grabens were filled with Early Cretaceous red beds as well as volcanics (Bignell, 1977; see Figs. 8, 9). Truncation of this shallow rift topography generated pre-AII sediments, which prograded westward and began to bury deeper rifts beyond the hinge zone. Lower Cretaceous sandstones and siltstones have been recovered at site 361 (Fig. 6) and near the top of the hinge zone south of the Orange River (Gerrard and Smith, in press).

Erosional (subaerial?) beveling of fault blocks now underlying the slope and rise must also have accompanied

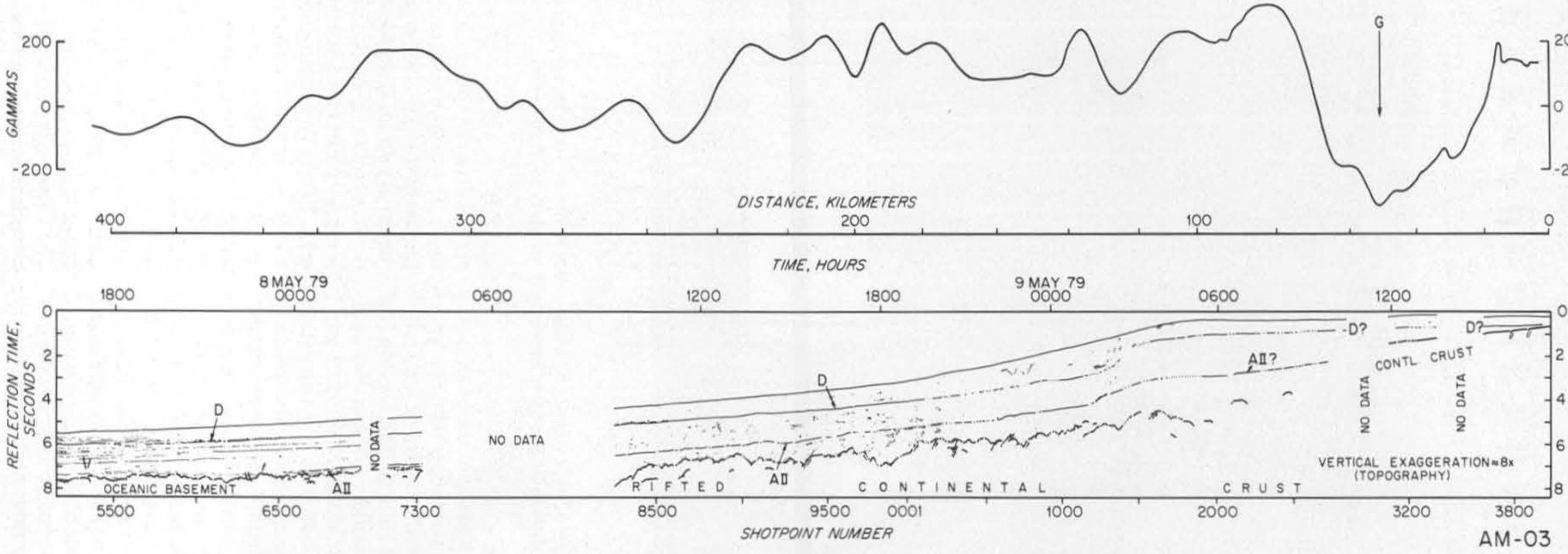

FIG. 12—Line interpretation of profile AM-03 (see Fig. 2 caption).

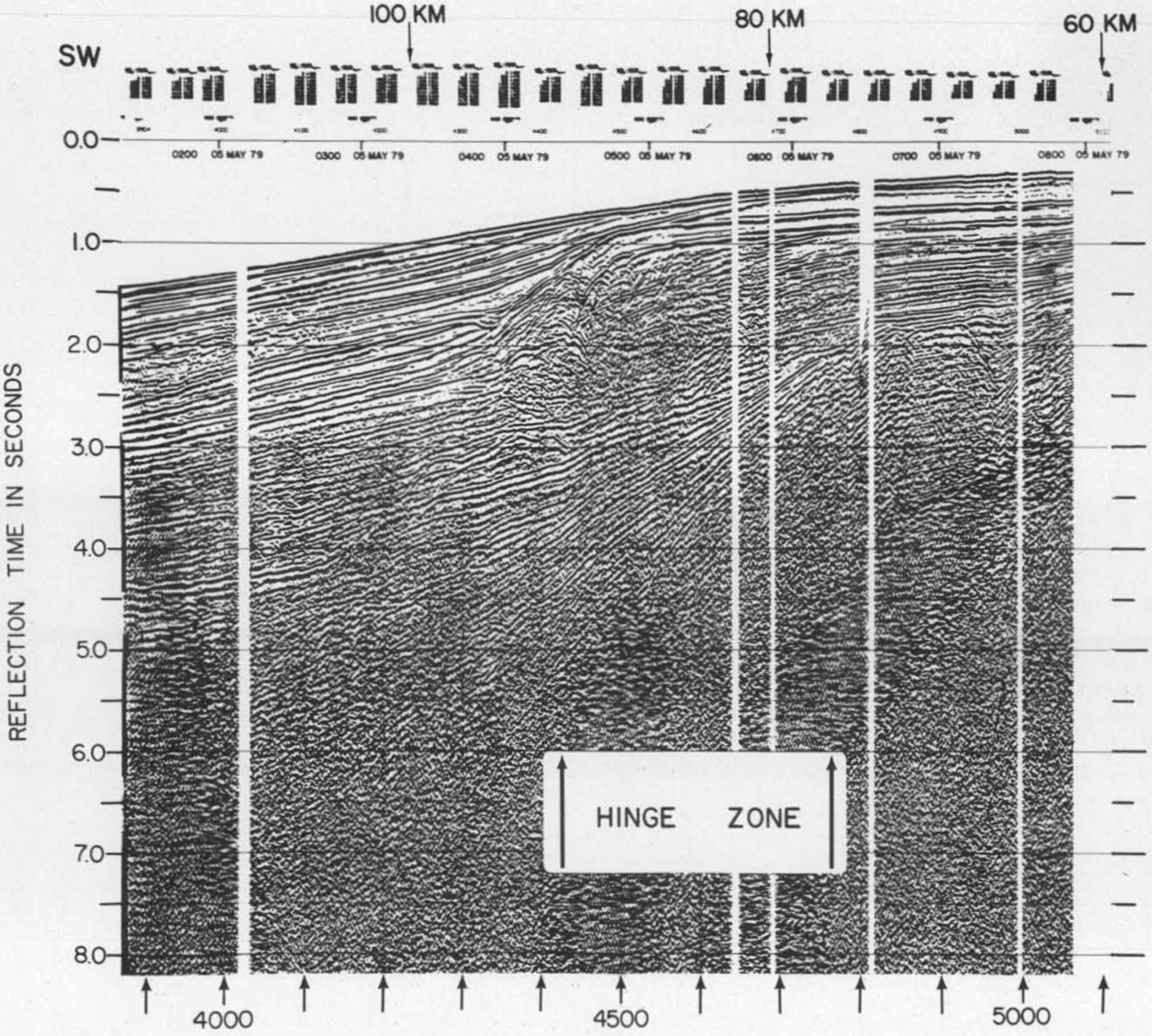

FIG. 13—Portion of AM-01 (see Figs. 8, 9) in vicinity of hinge zone. Relief of hinge here is approximately 3.0 sec. Note also small graben entrained into interpreted continental platform between shotpoints 4900 and 5000.

early crustal extension. The flattened top of the outer high on line AM-01 (Figs. 8, 9; km 220) coincides with the Aptian AII horizon, which also caps the wedge of seaward-dipping reflectors. According to Hinz (1981), the top of the oceanward-dipping layers should represent Falvey's (1974) breakup unconformity and mark the onset of sea-floor spreading. AII does coincide with the truncated basement surface beneath the shelf, but it onlaps and therefore must be younger than interpreted oceanic basement in more than one location beneath the rise (see Figs. 2, 3). AII could be time-transgressive, becoming younger basinward as the seaward-dipping wedge was eroded and redeposited downslope during rifting (Hinz, 1981). It might, therefore, coincide with a breakup unconformity landward of the hinge zone, yet be slightly younger than the oldest oceanic basement generated in the Cape Basin.

Based on our interpretation of the seismic data, sea-floor spreading began in the southern Cape Basin at approximately the time of anomaly M9—126 to 121 m.y.B.P. (respective ages of M9 from van Hinte, 1976; Larson and Hilde, 1975), perhaps 40-45 m.y. after the initiation of rifting. The oldest ocean floor off Cape Town is consequently 4 to 9 m.y. younger than the Valanginian age previously estimated (Larson and Ladd, 1973; Rabinowitz, 1976). The ocean-continent boundary gets progressively younger northward. Anomaly M4 (123-117 m.y.B.P.; van Hinte, 1976; Larson and Hilde, 1975) is the oldest sea-floor spreading anomaly west of Walvis Bay. Relief at the contact varies greatly along the strike of the margin, suggesting a variety of crustal responses to thinning, extension, and early sea-floor spreading.

Following the initiation of drift in the Early Cretaceous, sediment input primarily from the ancestral Orange River began to bury the rifted terrane and older oceanic crust. The Upper Cretaceous-Holocene Orange Cone sequence extends from the inner shelf to the continental rise and is

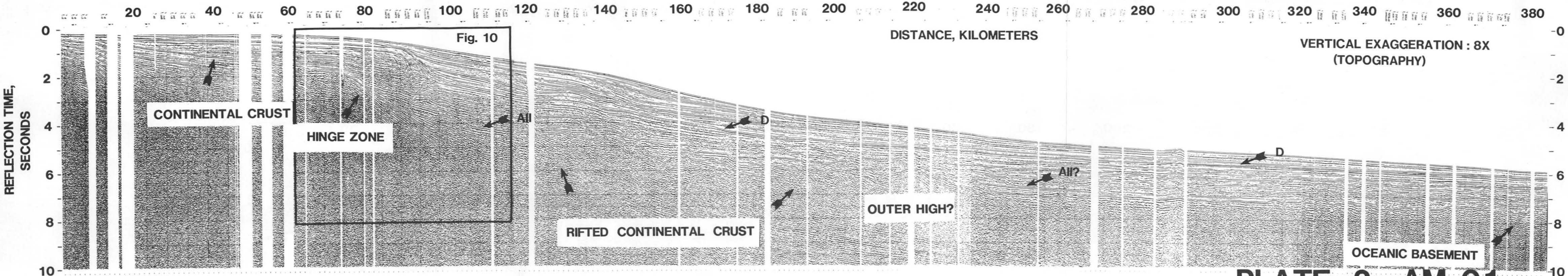

PLATE 2: AM-01

FIG. 9—Uninterpreted, annotated version of line AM-01. Compare with Figure 8.

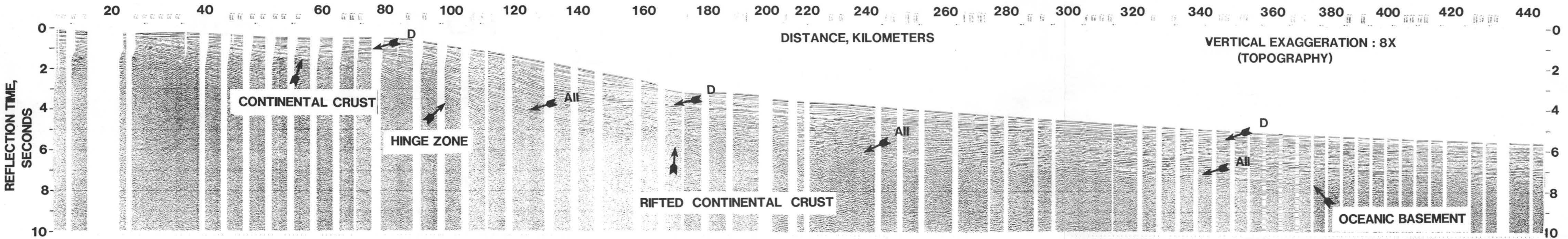

PLATE 3: AM-02

FIG. 11—Uninterpreted, annotated version of line AM-02. Compare with Figure 10.

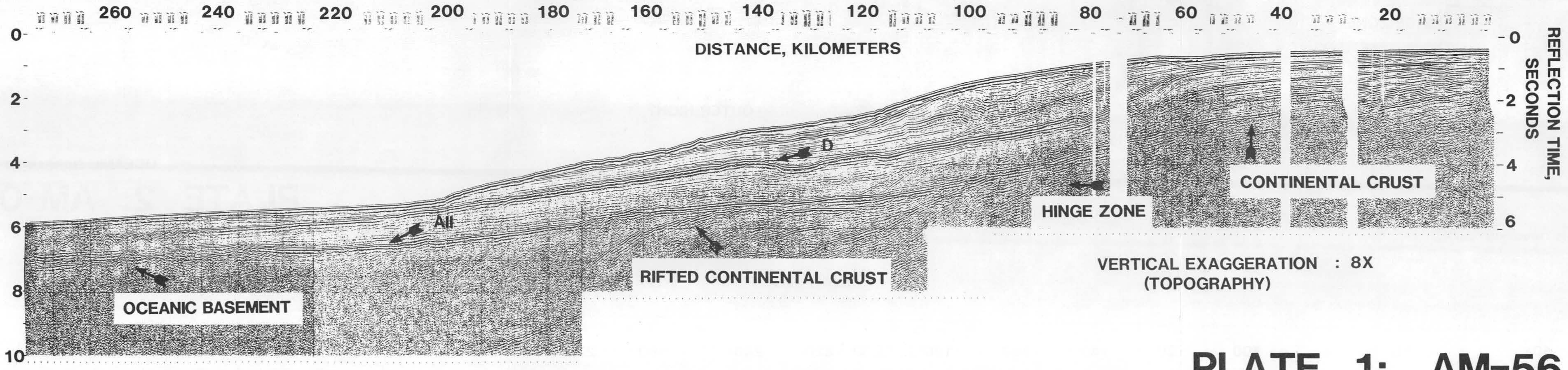

FIG. 3—Uninterpreted, annotated version of line AM-56. Compare with Figure 2.

PLATE 1: AM-56

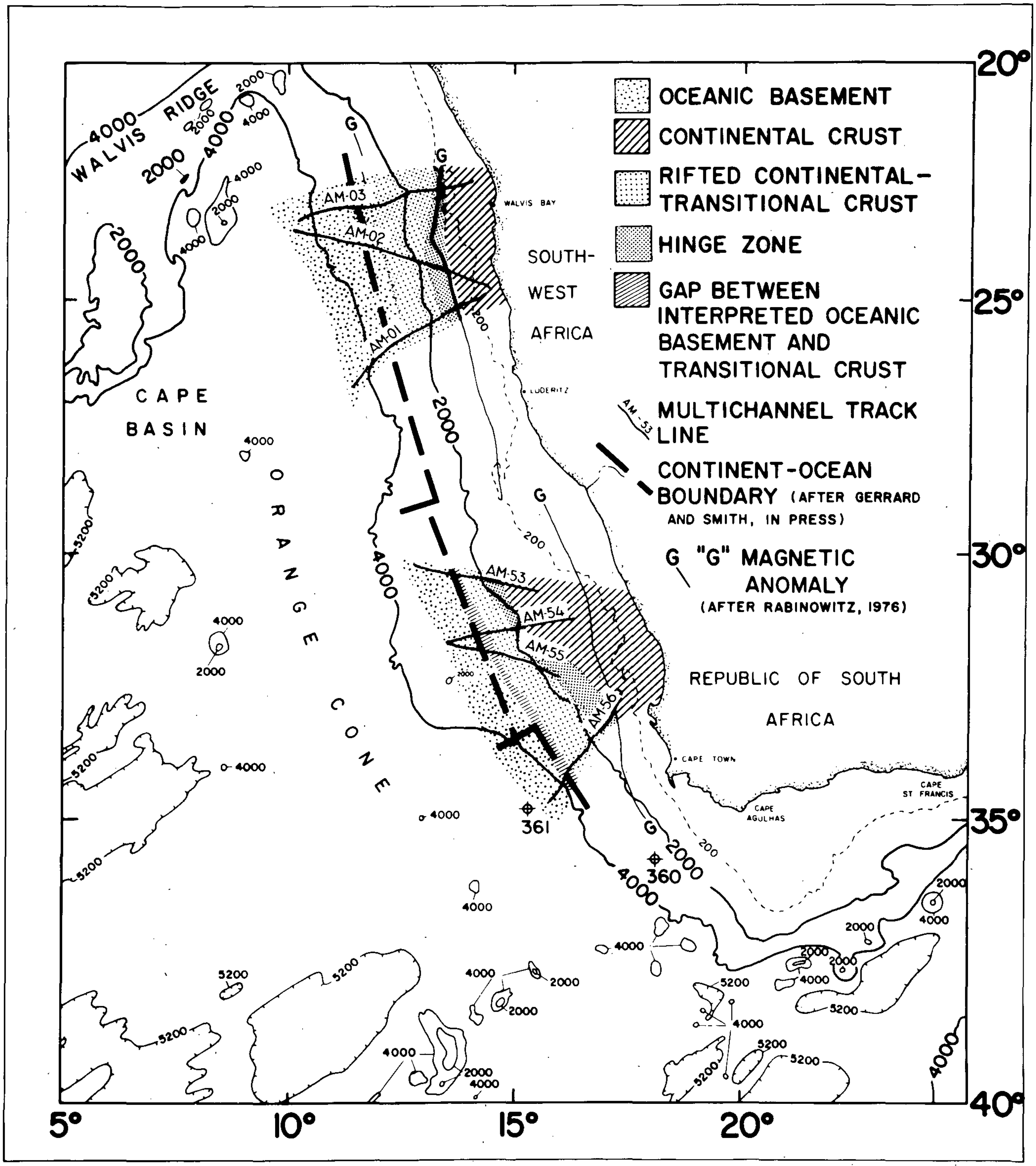

FIG. 14—Map showing basement configuration of passive margin off southwestern Africa. Bathymetry is that shown in Figure 1. Gerrard and Smith (in press) identify horizon AII as breakup unconformity (Falvey, 1974). Their ocean-continent boundary is defined by onlap of AII onto acoustic basement. Our interpretation of multichannel data suggests that AII is too young to be breakup unconformity, at least beneath continental rise, and that real ocean-continent boundary is buried by pre-AII overburden (see Figs. 2 to 6, 8 to 12). Magnetic anomaly G (Rabinowitz, 1976) overlies hinge zone in northern Cape Basin, but south of Orange River anomaly G cannot be consistently correlated with hinge because of insufficient data coverage.

disrupted by massive slumps (Figs. 1 to 6, 8 to 12). These structures have been attributed to a combination of seismic activity associated with uplift of the adjacent African coast, undercutting by bottom currents, sea level changes, and high pore-fluid pressures (Moore, 1976: Summerhayes et al, 1979; Dingle, 1980).

In conclusion, the multichannel profiles demonstrate the difficulty of applying simple geologic models to the evolution of passive continental margins. These models do not adequately consider the wide range of basement structures evident in the Cape Basin and the heretofore unexplained orthogonal basement trends observed on the conjugate margin off Argentina (Ludwig et al, 1979). More detailed geologic histories should be possible as deep penetration seismic reflection survey efforts expand to include more passive margins around the world.

REFERENCES CITED

Austin, J. A., Jr., et al, 1980, Geology of New England passive margin: AAPG Bull., v. 64, p. 501-526.

Beck, R. H., et al, 1975, New geophysical data on key problems of global tectonics; panel discussion 1; global tectonics and petroleum occurrence: 9th World Petroleum Cong. Proc., p. 1-14.

Bignell, R., 1977, Petroleum developments in central and southern Africa in 1976: AAPG Bull., v. 61, p. 1746-1794.

Boillot, G. , et al, 1979, The northwestern Iberian margin; a Cretaceous passive margin deformed during Eocene, *in* M. Talwani, W. Hay, and W. B. F. Ryan, eds., Deep drilling results in the Atlantic Ocean; continental margins and paleoenvironment: Amer. Geophys. Union, Maurice Ewing Ser., v. 3, p. 138-154.

——— et al,1980, Ocean-continent boundary off the Iberian margin: a serpentinite diapir west of the Galicia Bank: Earth and Planetary Sci. Letters, v. 48, p. 23-34.

Bolli, H. M., et al, 1978, Initial reports of Deep Sea Drilling Project: v. 40, 1087 p.

Cochran, J. R., 1981, The Red Sea; implications for the early development of Atlantic-type continental margins: EOS (Am. Geophys. Union Trans.), v. 62, p. 407.

Cochran, M. D., et al, in press, Tectonics and sedimentation of the South Atlantic rift sequence, *in* J. S. Watkins and C. L. Drake, eds. , Hedberg Research Conference on Continental Margin Processes: AAPG Mem. 34.

Dillon, W. P., et al, 1979a, Structure and development of the Southeast Georgia Embayment and Northern Blake Plateau; Preliminary Analysis, *in* J. S. Watkins, L. Montadert, and P. W. Dickerson, eds., Geological and Geophysical Investigations of continental margins: AAPG Mem. 29, p. 27-41.

——— et al, 1979b, Structure of the continental margin near the COST GE-1 drill site from a common depth-point reflection profiles, *in* P. A. Scholle, ed., Geological studies of the COST GE-1 well, United States South Atlantic outer continental shelf area: U. S. Geol. Survey Circ. 800, p. 97-107.

Dingle, R. V., 1980, Large allochthonous sediment masses and their role in the construction of the continental slope and rise off southwestern Africa: Marine Geology, v. 37, p. 333-354.

Emery, K. O. et al, 1970, Continental rise off eastern North America: AAPG Bull., v. 54, p. 44-108.

——— et al, 1975, Continental margin off western Africa; Cape St. Francis (south Africa) to Walvis Ridge (southwest Africa): AAPG Bull., v. 59, p. 3-59.

Falvey, D. A. , 1974, The development of continental margins in plate tectonic theory: APEA Jour., v. 14, p., 95-106.

Gerrard, I., and G. C. Smith, in press, The post-Paleozoic succession and structure of the southwestern African continental margin, *in* J. S. Watkins and C. L. Drake, eds., Hedberg research conference on continental margin processes: AAPG Mem. 34.

Goldflam, P., et al, 1980, Some features of the northwest African margin and magnetic quiet zone: Royal Soc. London Philos. Trans., v. 294, p. 87-96.

Grow, J. A., 1980, Deep structure and evolution of the Baltimore Canyon trough in the vicinity of the COST no. B-3 well, *in* P. A. Scholle, ed., Geological studies of the COST no. B-3 well, United States mid-Atlantic continental slope area: U.S. Geol. Survey Circ. 833, p. 117-126.

——— R. E. Mattick, and J. S. Schlee, 1979, Multichannel seismic depth sections and interval velocities over outer continental shelf and upper continental slope between Cape Hatteras and Cape Cod, *in* J. S. Watkins, L. Montadert, and P. W. Dickerson, eds., Geological and geophysical investigations of continental margins: AAPG Mem. 29, p. 65-83.

Hinz, K., 1981, A hypothesis on terrestrial catastrophes; wedges of very thick oceanward dipping layers beneath passive margins—their origin and paleoenvironmental significance: Geol. Jahrb. Reihe E, v. 22, p. 5-28.

——— et al, 1979, Geophysical transects of the Labrador Sea; Labrador to southwest Greenland: Tectonophysics, v. 59, p. 151-183.

Houtz, R. D., et al, 1977, Structure of the northern Brazilian margin: Geol. Soc. America Bull., v. 88, p. 711-719.

Keen, C. E., and M. J. Keen, 1974, The continental margins of eastern Canada and Baffin Bay, *in* C. A. Burk and C. L. Drake, eds., The geology of continental margins: New York, Springer-Verlag, p. 381-389.

——— and D. L. Barrett, 1981, Thinned and subsided continental crust on the rifted margin of eastern Canada; crustal structure, thermal evolution and subsidence history: Royal Astron. Soc. Geophys. Jour., v. 65, p. 443-465.

Keen, M. J., 1969, Possible edge effect to explain magnetic anomalies off the eastern seaboard of the U.S.: Nature, v. 222, p. 72-74.

Larson, R. L., and T. W. C. Hilde, 1975, A revised time scale of the magnetic reversals for the Early Cretaceous and Late Jurassic: Jour. Geophys. Research, v. 80, p. 2586-2594.

——— and J. W. Ladd, 1973, Evidence for the opening of the South Atlantic in the Early Cretaceous: Nature, v. 246, p. 209-212.

Lehner, P., and P. A. C. De Ruiter, 1977, Structural history of Atlantic margin of Africa: AAPG Bull., v. 61, p. 961-981.

Leyden, R., et al, 1976, South Atlantic diapiric structures: AAPG Bull., v. 60, p. 196-212.

Ludwig, W. J., et al, 1979, Structure of Colorado basin and continent-ocean crust boundary off Bahia Blanca, Argentina, *in* J. S. Watkins, L. Montadert, and P. W. Dickerson, eds., Geological and geophysical investigations of continental margins: AAPG Mem. 29, p. 113-124.

Luyendyk, B. P., and E. T. Bunce, 1973. Geophysical study of the northwest African margin off Morocco: Deep-Sea Research, v. 20, p. 537-549.

Montadert, L., et al, 1979, Northeast Atlantic passive continental margins; rifting and subsidence processes, *in* M. Talwani, W. Hay, and W. B. F. Ryan, eds., Deep drilling results in the Atlantic Ocean, continental margins and paleoenvironment: Am. Geophys. Union, Maurice Ewing Ser., v. 3, p. 154-186.

Moore, A. E., 1976, Controls of post-Gondwanaland alkaline volcanism in southern Africa: Earth and Planetary Sci. Letters, v. 31, p. 291-296.

Mutter, J. C., M. Talwani, and P. L. Stoffa, 1982, Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by "subaerial seafloor spreading": Geology, v. 10, p. 253-257.

Rabinowitz, P. D., 1974, The boundary between oceanic and continental crust in the western North Atlantic, *in* C. A. Burk and C. L. Drake, eds., The geology of continental margins: New York, Springer-Verlag, p. 67-84.

——— 1976, Geophysical study of the continental margin of southern Africa: Geol. Soc. America Bull., v. 87, p. 1643-1653.

——— 1978, Geophysical study of the continental margin of southern Africa—reply: Geol. Soc. America Bull., v. 89, p. 793-796.

——— and J. L. LaBrecque, 1977, The isostatic gravity anomaly: key to the evolution of the ocean-continent boundary at passive continental margins: Earth and Planetary Sci. Letters, v. 35, p. 145-150.

——— ——— 1979, The Mesozoic South Atlantic Ocean and evolution of its continental margins: Jour. Geophys. Research, v. 84, p. 97-103.

Roberts, D. G., and L. Montadert, 1980, Contrasts in the structure of the passive margins of the Bay of Biscay and Rockall Plateau: Royal Soc. London Philos. Trans., v. A294, p. 97-103.

Schuepbach, M. A., and P. R. Vail, 1980, Evolution of outer highs on divergent continental margins, *in* Continental tectonics, studies in geophysics: Washington, D.C., Natl. Research Council, p. 50-61.

Scrutton, R. A., 1978, Geophysical study of the continental margin of southern Africa—discussion: Geol. Soc. America Bull., v. 89, p. 791-793.

Summerhayes, C. F., B. D. Bornhold, and R. W. Embley, 1979, Surficial slides and slumps on the continental slope and rise off southwest Africa; a reconnaissance study: Marine Geology, v. 31, p. 265-277.

Talwani, M., and O. Eldholm, 1973, Boundary between continental and oceanic crust at the margin of rifted continents: Nature, v. 241, p. 325-330.

——— et al, 1979, The crustal structure and evolution of the area underlying the magnetic quiet zone on the margin south of Australia, *in* J. S. Watkins, L. Montadert, and P. W. Dickerson, eds., Geological and geophysical investigations of continental margins: AAPG Mem. 29, p. 151-175.

Uchupi, E., et al, 1976, Continental margin off western Africa; Senegal to Portugal: AAPG Bull., v. 60, p. 809-878.

van Hinte, J. E., 1976, A Cretaceous time scale: AAPG Bull., v. 60 p. 498-516.

Veevers J. J., and D. Cotterill, 1978, Western margin of Australia evolution of a rifted arch system: Geol. Soc. America Bull., v. 89, p. 337-355.

Weigel, N., and G. Wissmann, 1977, A first crustal section from seismic observations west of Mauretania: Polska Acad. Sciences Inst. Geophys. Pub., v. A-4 (115), p. 369-380.