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J. GOSLIN*
J. MASCLE
J. C. SIBUET
Centre National pour l'Exploitation des Océans, Centre Océanologique de Bretagne, Boite Postale 337, 29.273 Brest Cedex, France
H. HOSKINS Woods Hole Oceanographic Instituion, Woods Hole, Massachusetts 02543

Geophysical Study of the Easternmost Walvis Ridge, South Atlantic: Morphology and Shallow Structure

ABSTRACT

—The landward termination of Walvis Ridge consists of two east-trending basement ridges of probable basaltic composition enclosing a relatively important sedimentary basin. East of long. 10° E., the southern ridge disappears under the sediments of the continental margin.

The trends of the basement ridges are in good agreement with the inferred direction of initial opening. Since its formation, the Walvis Ridge has probably dammed sediment coming from the south. The proposed identification of layer A, a very strong horizon over which the reflectors are nearly undisturbed, may indicate that no major tectonic phase has affected this area since the shift of the pole of opening for the south Atlantic in Late Cretaceous–early Tertiary time.—

INTRODUCTION

The Walvis Ridge is one of the most conspicuous features of the south Atlantic. It is an aseismic ridge, more than 3,000 km long, extending from the Mid-Atlantic Ridge (near Tristan da Cunha and Gough Islands) to the African coast, which it intersects near Cape Frio (lat 18° S.). Its general trend is southwest-northeast, but a closer examination of the bathymetric maps of Simpson (1970a; Fig. 1) and Uchupi (1971) shows at least three main sections: (1) An eastern segment extending from the African margin to long. 6° E. (600 km long) and trending east-northeast–west-southwest. Its width varies between 90 and 200 km. (2) A second segment oriented roughly north-south, which has a length of ~500 km, and is narrower than the eastern segment. (3) A third, somewhat discontinuous, segment, notably marked by seamounts, which connects the Walvis Ridge to the Mid-Atlantic Ridge in the vicinity of Tristan da Cunha and Gough Islands.

The relatively good fit between the coastlines of South America and Africa led to the first precontinental drift reconstructions. Wegener (1929), Carey (1958), Bullard and others (1965), and Funnel and Smith (1968) used 500- and 1,000-fm isobaths and proposed different models of the south Atlantic *prior to its opening*. Though details of this opening are not well known, it would be difficult to envisage an origin for the overlapping structures of the Walvis Ridge and the Rio Grande Rise other than an oceanic origin. Several hypotheses for the origin of the Walvis Ridge have been presented. They differ and can be divided into two main groups: (1) those which imply a formation of the Walvis Ridge synchronous with the opening of the south Atlantic and related to mantle "hot spots" (Wilson, 1965; Dietz and Holden, 1970; Morgan, 1971, 1972) or to transform directions and marginal offsets (Le Pichon and Hayes, 1971; Francheteau and Le Pichon, 1972); and (2) those favoring a creation posterior to, and independent of, the opening. This would involve, for example, a major uplift (Ewing and others, 1966). Maxwell and others (1970) suggest such an uplift and a rejuvenation for the Mid-Atlantic Ridge during Miocene time.

Several papers have dealt with the continental margins adjacent to the area where the Walvis Ridge meets the African continent, including those of Simpson (1970b), van Andel and Calvert (1971), Du Plessis and others (1972), Leyden and others (1972), Francheteau and Le Pichon (1972), Rabinowitz (1972), and Pautot and others (1973). During 1970 to 1972, three surveys were made in the area (Fig. 2). Continuous seismic profiles, magnetic profiles, and gravity and bathymetric measurements were made. Ten piston cores, five heat-flow stations, three dredging stations, bottom photograph stations, and unreversed oblique reflection-refraction profiles were made with expendable sonobuoys.

Using these data, we will describe here only the shallow structure of the eastern portion of the Walvis Ridge between long. 8° E. and the African coast. We have attempted to establish the relation between the basement of the ridge itself and its continuation under the adjacent continental margin and oceanic basins. We also consider the sedimentary processes that have been operative on the ridge itself and in the adjacent Cape and Angola basins. A second paper will deal with the deep structure of the area and discuss its probable origin.

DATA SOURCES

Three maps (Figs. 3, 4, 5) are compiled from all the data available to us in the summer of 1972, particularly, data from cruises of the Woods Hole Oceanographic Institution (R/V *Atlantis II, Chain,* and others) and data from the Centre National pour l'Exploitation des Océans (R/V *Jean Charcot*). Figure 2 displays the track lines. Supplementary bathymetry data (Fig. 3) were obtained from the General Bathymetric Chart of the Oceans (GEBCO) plotting sheets. Data for the continental margin are from maps published by van Andel and Calvert (1971), by Simpson (1970b), and by Uchupi (1971).

The preliminary map of the acoustic basement (Fig. 9) and the isopach map of the total sediments above basement (Fig. 10) are based only on the seismic profiles obtained on the Walda cruise. Because different seismic sources were used (Flexotir during the Walda cruise, sparker and air gun during the Woods Hole Oceanographic Institution [WHOI] cruises), correlation of the reflectors proved difficult. Moreover, penetration was not always comparable.

The free-air gravity anomaly map (Fig. 4) was drawn from the following sources: data collected by the R/V *Jean Charcot* (Walda cruise, legs CH 18 and CH 19), the R/V *Chain* (cruise 99, leg 4), and the R/V *Atlantis II* (cruise 67; legs 4, 5, 6); data from the R/V *Akademik Kurtchatov* (1968 cruise); map published by Rabinowitz (1972); and several pendulum measurements (Worzel, 1965). The mean and standard deviation of the crossover errors are 4 and 3 mgal, respectively. An Askania GSS2 gravimeter mounted on a stabilized platform was used aboard the *Jean Charcot.* Cross-coupling corrections were made automatically (Sibuet, 1972). A vibrating string accelerometer (Bowin and others, 1972) was used aboard the *Atlantis II* and the *Chain.*

Bathymetry and magnetic profiles were recorded with similar equipment on the

* Present address: Institut de Physique du Globe du Paris, Laboratoire de Géophysique Marine, 4 Avenue de Neptune, 94100 Saint Maur des Fosses, France.

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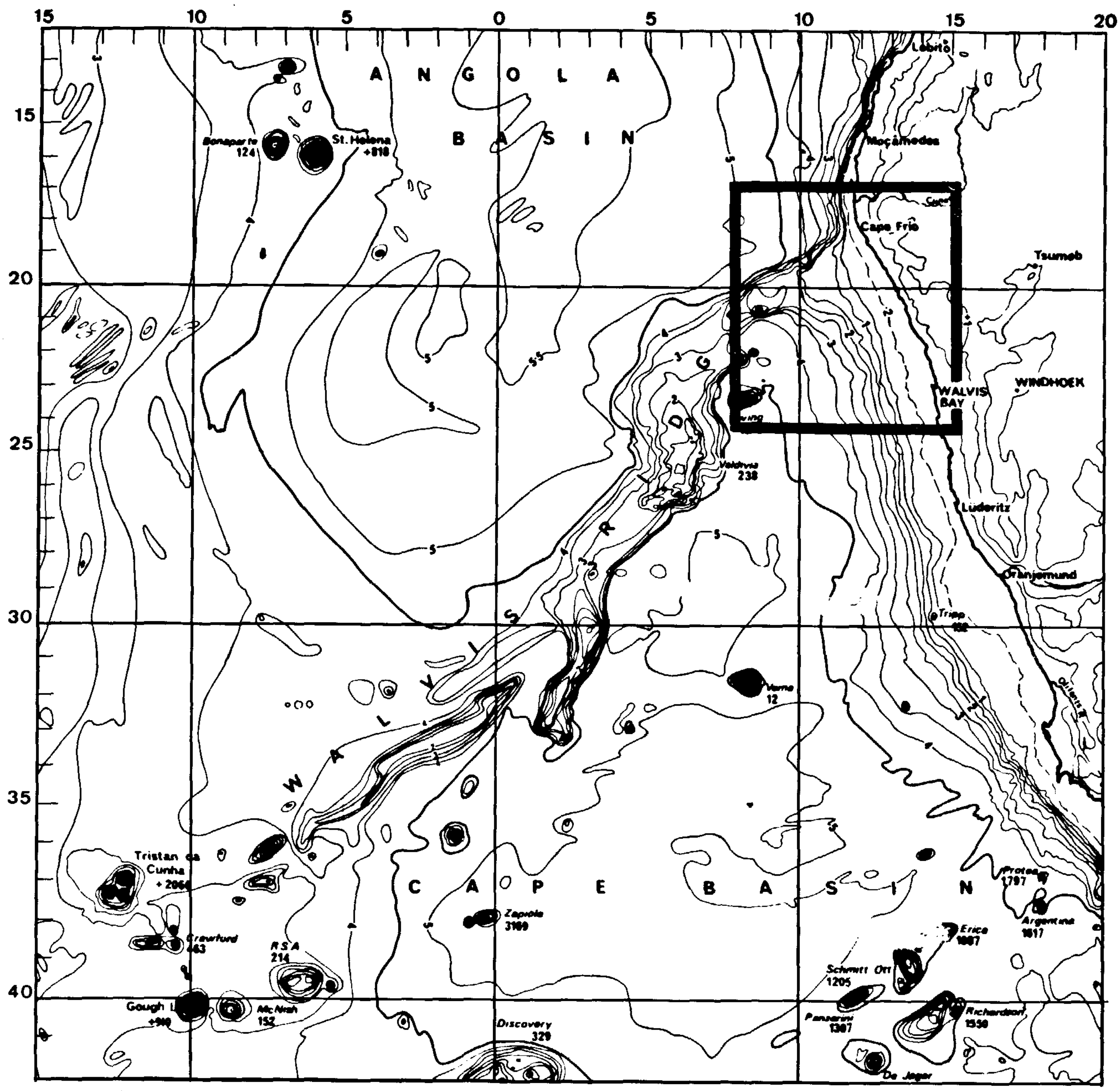

Figure 1. Bathymetric map of the southeast Atlantic from Simpson (1970a), showing Walvis Ridge divided in three main segments. Inset corresponds to area studied.

three ships. Satellite navigation systems were employed on the *Chain*, *Atlantis II*, and *Jean Charcot*. Precision can be estimated to be ~1 km.

BATHYMETRY

As shown on the general map of Simpson (1970a; Fig. 1), the easternmost part of the ridge is a continuous, almost linear topographic feature more than 600 km long that trends roughly perpendicular to the present coastline and continental margin. The ridge is surrounded by deep oceanic basins (4,000 m as an average on the north side and >3,000 m on the south side). The northern part of the Cape Abyssal Plain, wedged between the continental margin and the north-south portion of the Walvis Ridge, is much narrower than the southern part of the Angola Abyssal Plain adjacent to the ridge's northern flank. The continental shelf, on the other hand, is much more developed south of the ridge.

Three major topographic features can be observed on the ridge itself. A cross section from north to south reveals:

1. A steep northern wall apparent as far east as long. 11°30′ E. Its slope ranges from 6 to 10°. In detail, this wall seems to be longitudinally offset by small transverse features, particularly near long. 9°30′ and 10°30′ E. Several highs also mark the crest of the wall. The average height of the crest above the floor of the adjacent basin is more than 2,000 m.

2. A valley with a smooth topography to the south of this flank. The mean width is about 70 km. It slopes gently downward toward the north, west of long. 9° E., and toward the south, east of long. 9° E. The basin continues onto the margin as a large and almost flat plateau dipping toward

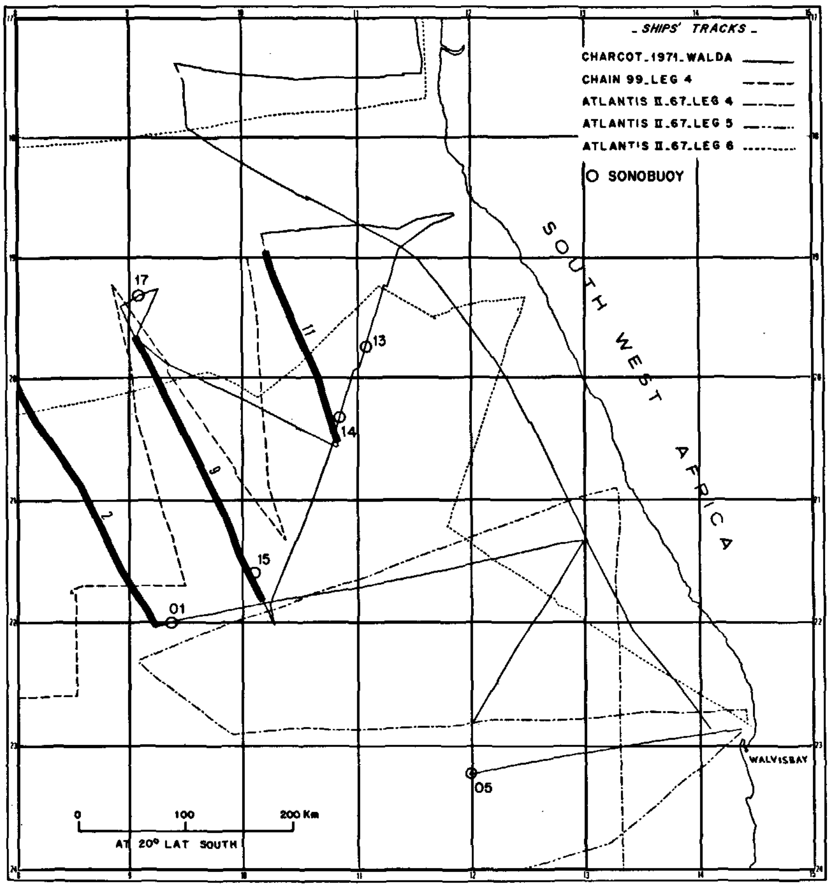

Figure 2. Index map of the area surveyed. Heavy lines indicate seismic reflection profiles shown in this paper. Open circles indicate position of the seismic refraction sonobuoys.

the southwest between depths of 400 and 2,000 m.

3. A southern flank, well developed westward of long. 10° E. and forming the highest crest line of the Walvis Ridge. Toward the Cape Abyssal Plain, this flank shows a sharp break in its slope. The upper part is steep (around 5°), while the lower is more gentle (seldom more than 1°). Several small hills (2,000 m wide, 150 m high on the average) can be seen mostly on the seismic profile 9 of Figure 6.

Aside from the prominent dissymmetry between the two flanks of the ridge, an important difference exists between the continental margins north and south of the ridge. The mean width of the continental margin north of the Walvis Ridge is ~70 km, whereas it reaches 200 km south of the Walvis Ridge. The difference may be explained both by difference in the sediment supply and by the difference in the depth to the basement as we shall see later. This observation also applies to the width of the continental slope of both margins; the northern one is about twice as steep. Separation of the 400- and 4,000-m isobaths is ~250 km in the south and <120 km in the north.

The bathymetric map (Fig. 3) shows that the average depth of the Cape basin is ~4,000 m and that of the Angola basin ~4,800 m. The floors of both basins are nearly flat. This map allows us to compare accurately the topographic trends with the theoretical directions of early opening as proposed by Le Pichon and Hayes (1971) and Francheteau and Le Pichon (1972). It suggests also that, at least in the eastern part, the Walvis Ridge is a continuous dam, both for flow of the deep water and for the transport of sediment.

SEISMIC PROFILES

We shall describe and discuss here three profiles (profiles 2, 9, 11; Figs. 6, 7) perpendicular to the axis of the Walvis Ridge. We consider them typical of the evolution of the structure of the ridge, going eastward toward the continent. Together with the remaining Walda profiles, three seismic profiles from *Chain* cruise 99 (tracks shown on Fig. 2) have been also used for this discussion.

Three main structures can be distinguished on all profiles (Fig. 7): the northern flank of the ridge, between long. 8° and 11° E.; the southern flank between long. 8° and 9°30′ E.; and an elevated sedimentary basin enclosed by the two crest lines. In addition to the three units, we shall briefly discuss the northern and southern extensions of the Angola and Cape Abyssal Plains.

Basement

All profiles (Figs. 6, 7) display a very strong reflector which merges with the exposed walls of the Walvis Ridge. We will refer to it as the acoustical basement.

Northern Flank. As pointed out above, this flank is particularly steep. Profiles 2 and 9 (Figs. 6 and 7) show that this flank is composed of two parallel ridges. The inner ridge, well developed to the west (see profile 2), becomes buried eastward toward the margin under a thick sedimentary cover. East of profile 2, between long. 8° and 9° E., *the inner ridge no longer appears on the topography.* This change in structure is shown on profiles 9 and 11 (Figs. 6, 7), and can be seen on the three *Chain* cruise 99 profiles (not shown in this paper).

The basement of the Walvis Ridge appears to be continuous with the acoustical basement of the Angola Abyssal Plain to the north. The strong diffraction of the seismic waves and the rough topography are generally considered as typical of the oceanic basement. Refraction data on the Walvis Ridge itself (sonobuoys 13 and 14, Table 1) yield velocities ranging from 5.24 km per sec to 5.49 km per sec, which are within the range of those encountered in basaltic layers (Le Pichon, 1969). Below, we shall interpret this layer as the basaltic basement layer. Two dredge hauls made on the *northern flank recovered altered alkali* basalts (Hekinian, 1972), suggesting that the flank is of volcanic origin.

The northern flank is covered locally by a thin sedimentary cap (see profile 9, Figs. 6 and 7), but in most cases it is almost totally devoid of sediments, even near the margin (see profile 11, Figs. 6 and 7), where this ridge has dammed the sediments coming from the south.

Southern Flank. The southern flank has a more developed topographic elevation than the northern flank (see profiles 2 and 9, Figs. 6 and 7) in the western part (west of long. 10° E.). The southern flank becomes buried when it approaches the continental margin. In contrast with the northern flank, the southern slope is less steep. In any case, there exists a 3° change in slope between the *steep upper part and the more gentle lower* part.

The seismic profiles show that the relief of the southern flank is almost entirely due to the rise of the acoustical basement. Profiles 2 and 9 (Figs. 6, 7) show a small cover of sediments overlying a massive ridge.

At about long. 10° E., this ridge is no longer expressed in topography and has gradually changed to a large basement rise covered by more than 2 sec of sediment, as

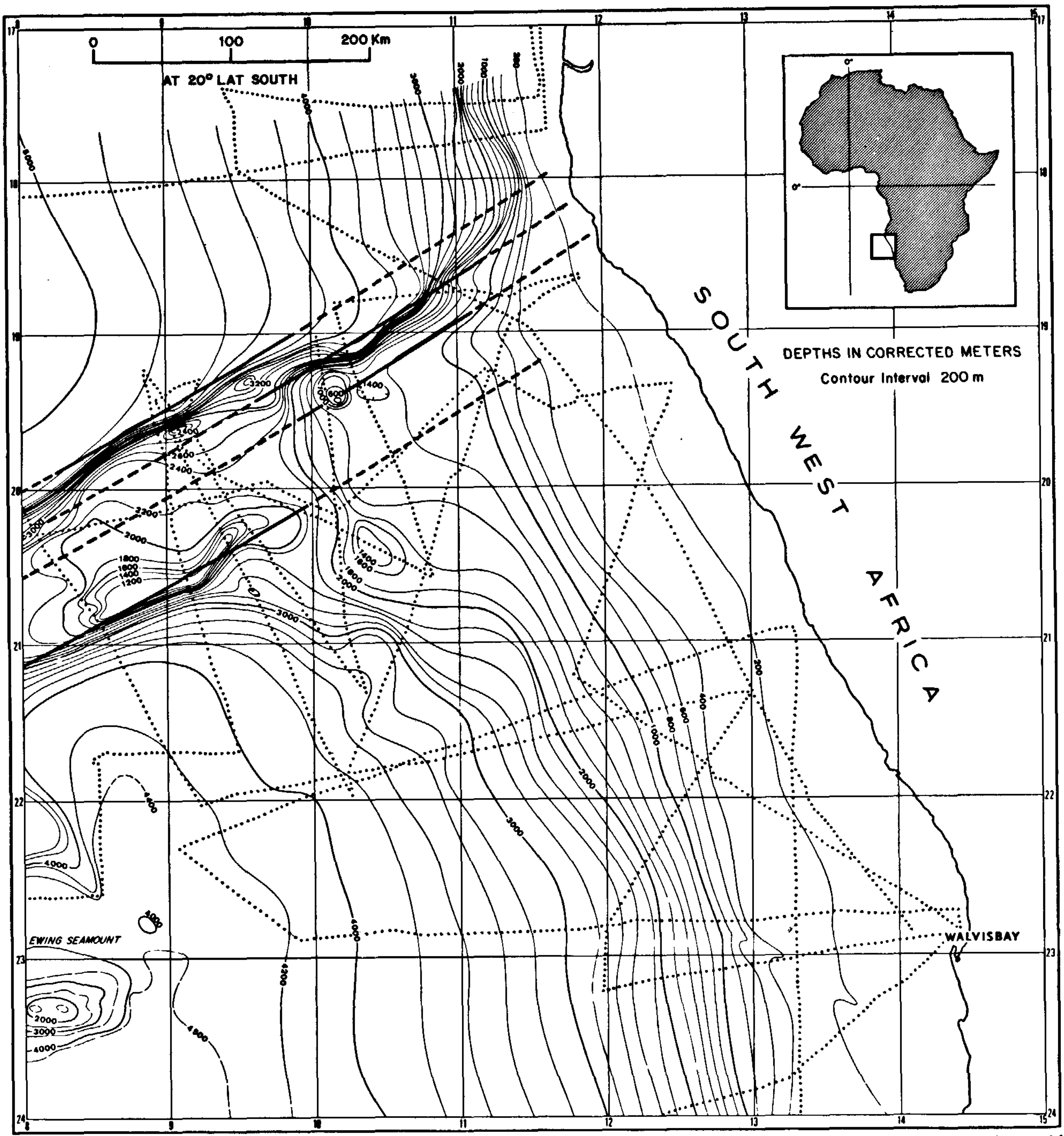

Figure 3. Bathymetric map of the area compiled from the profiles of Figure 2. Data from the GEBCO plotting sheet and maps published by Simpson (1970a) and van Andel and Calvert (1971). Depths are corrected meters according to Matthews' (1939) tables. Solid and dashed lines indicate small circles about the pole of early opening at lat 21°5′ N. and long 14° W. (Le Pichon and Hayes, 1971). Dotted lines indicate our surroundings.

shown on profile 11 (Figs. 6, 7). One of the *Chain's* profiles also records this change. The sediments are continuous with sediments filling a large basin on the continental shelf (Fig. 10).

The steepness of the walls, their linearity, and the shape of the basement highs forming the two ridges are not indicative of an origin as a chain of volcanoes, but rather suggest that the structure of the ridge is controlled by tectonic processes.

Internal Basin. Reflection profiles 2 and 9 also delineate an internal basin containing a large thickness of sediment (more than 2.0 sec two-way travel time — at least 2.5 km) between the two ridges, which is not apparent from bathymetric records. A tentative mechanism for the filling of the internal basin is shown in Figure 8 and will be discussed later. Basement was consistently recorded in profiles 9 and 11 (Figs. 6, 7) even in the deepest part, and the valley floor narrows gradually westward.

Adjacent Angola and Cape Basins. In the Angola Abyssal Plain, the average penetration is 1.2 sec. The topography is rough and consists of hills and troughs

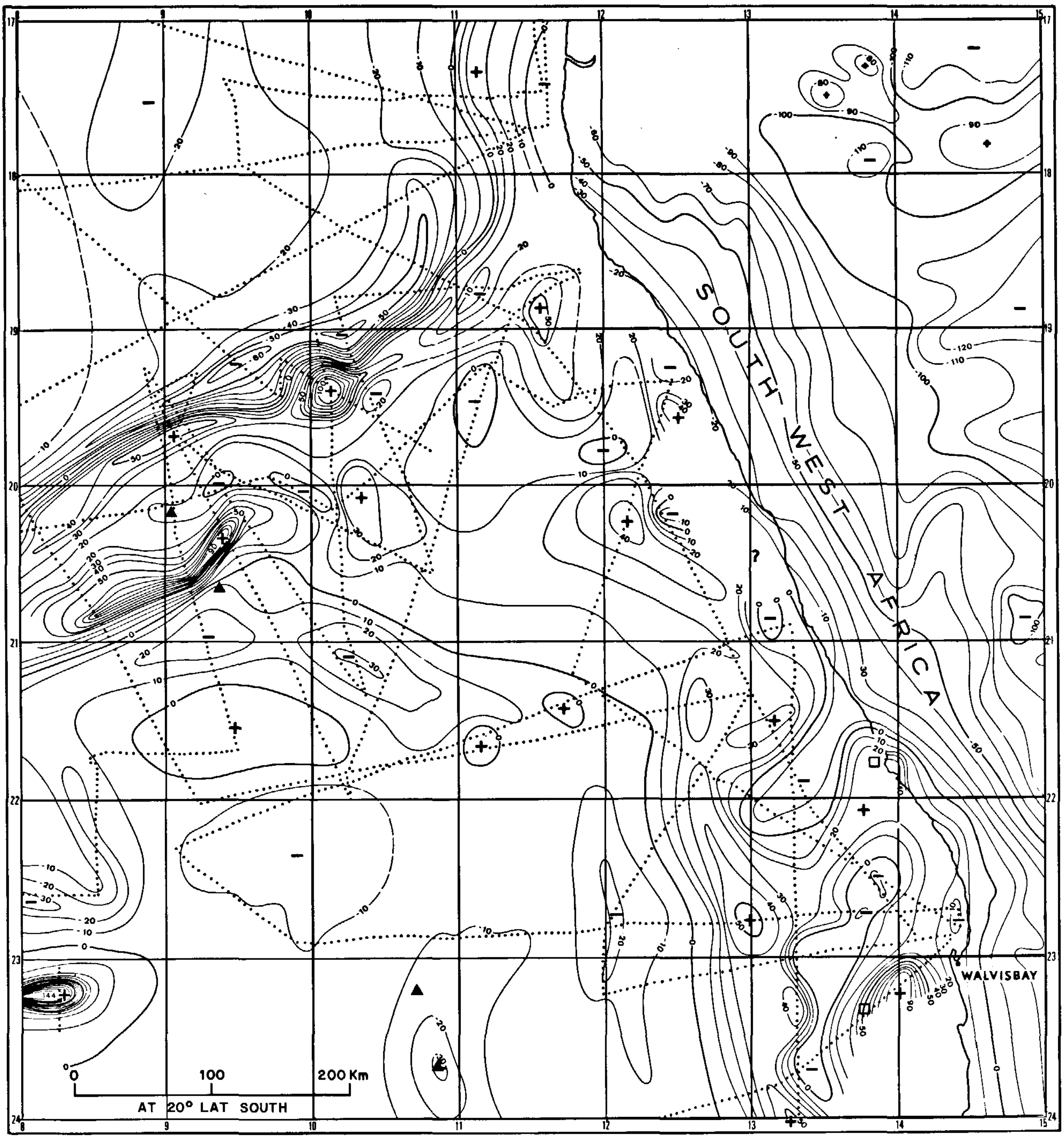

Figure 4. Gravity anomaly map (contour interval 10 mgal). Free-air anomalies in ocean and Bouguer anomalies on land (from the Geological map of South West Africa, 1963). Triangles indicate station pendulum measurements (Worzel, 1965), and open squares indicate station measurements from the R/V *Akademik Kurtchatov*.

filled by sediments up to 1.5 sec thick. In the Cape basin, the basement displays similar characteristics. Here also (see results of sonobuoys 01 and 05, Table 1), the velocities are well in the range of those of oceanic basalts (5.2 to 6.0 km per sec). One should note that along the same profile, the basement is consistently deeper on the northern side. The average difference between both basin basements is ~0.4 sec and will increase if the isostatic adjustment (due to the weight of the sediments) is taken into account.

The small difference in age of the crust north and south of the Walvis Ridge cannot explain the change in level of the basement, as theoretically proposed by Sclater and Francheteau (1970) and Sclater and Detrick (1973).

The subsidence might have been "lessened" in the south by the presence of an important topographic and basement high (Valdivia bank). The northern part of the Cape basin is an enclosed basin wedged between the wide margin and the north-south section of Walvis Ridge, whereas the Angola Abyssal Plain is an open basin.

A comparison of the depth of the acoustic basement (Fig. 9) with the bathymetry (Fig. 3) shows a direct relation between topography and basement relief. This is especially striking for the northern flank, where the influence of sedimentary processes was of lesser importance.

Sedimentary Cover (Fig. 10)

Walvis Ridge. On the northern flank, sedimentary cover is thin (only occasionally up to 0.5 sec on profile 2, Figs. 6 and 7) on the crest itself. The wall is devoid of sediments (profiles 9 and 11, Figs. 6 and 7), evidently due to its slope (>6°). The reflectors display some apparent deformation which can be related more to basement relief than to postdepositional tectonic processes. Sediment reflectors also cap the southern crest. On profile 11 (Figs. 6, 7), the sedimentary cover on the probable prolongation of the southern flank is more than 1.5 sec thick. In the internal basin, the sedimentary filling is more than 2.5 sec thick near the margin on profile 11. It thins westward, but is still 1.5 sec on profile 2. This implies that most of these sediments were brought from further east.

Two main sedimentary units can be traced by both their reflective properties and their morphology; the reflection sequence from the deepest unit is diffractive and shows examples of deformation. The thickness of this series in the midvalley area is about 0.8 sec and is quite constant. On profile 11, the unit is continuous to the south-southeast over the basement rise toward the southern margin. The upper reflectors are well stratified. They are almost seismically transparent near the margin where their thickness reaches 1.5 sec in the axis of the basin. The reflectors display some evidence of small faulting on profile 11, particularly over the basement rise. Following the basin westward, this unit thins and becomes more opaque, but remains well stratified. Some evidence of faulting is expressed in the sea-floor topography (see profile 2).

Some problems regarding the thickness of sediments in such an internal basin arise: we can imagine either that tectonic movements could have uplifted both the ridge and a pre-existing basin, or that recent sedimentary supply filled this basin in its present position. Older sediments may also have been protected from bottom-current erosion by the lateral ridges. They would have been covered by thick, recent sediments continuous with those of the southern margin (see profile 11, Figs. 6 and 7).

Angola and Cape Basins. In the Angola basin, the sedimentary cover varies in thickness and is typically 1.5 sec thick. Two main units can easily be distinguished. The upper unit is formed of well-stratified reflectors; its thickness is quite constant (~0.5 sec). This layer shows very little evidence of deformation, and strata rest horizontally. The contact with the basement below the northern wall is abrupt. On profile 11 (Figs. 6, 7), some deformation is related to slumping. The lower unit, indicated by very strong reflectors, has filled basement troughs. It is thus of variable thickness (locally up to 0.5 sec). The two units are separated by a series of very strong reflectors, ~0.2 sec thick. Above these reflectors, deformation disappears almost completely. Inspection of profile 2 (Figs. 6, 7) suggests that some of the deformation is related to diapirism; the smooth magnetic pattern does not contradict such a possibility. A large diapiric field has also been described off the western coast of Africa, just north of Moçamedes (Leyden and others, 1972; Emery, 1972; Pautot and others, 1973). This field is situated on the continental rise, but diapirism may occur in deep-sea areas (Pautot and others, 1970).

The Cape basin is marked by a much more complicated sedimentary pattern (as shown by comparison of the results of sonobuoys 01 and 17, Table 1). Sedimentary thickness is always greater than in the Angola basin. On profile 2, three sedimentary units can be traced, the lowest one being comparable to that of the Angola basin. A series of strong reflectors overlies it, similar to the one found on the northern side. The upper sediments thin toward the southern flank of the ridge. Some slumping may have occurred on the slope. Closer to the continental margin, the sedimentary pattern becomes more complicated (see profile 9, Figs. 6 and 7). Sediment thickness reaches 2 sec, and several units can be discerned. The thin series of strong reflectors described above is not apparent. On the slope, a series of hills appear between 0000 and 0400 hr, (profile 2, Figs. 6, 7) that is, between lat 21° S., long 9°45′ E. and lat 20°40′ S., long 9°30′ E. They are formed of acoustically transparent layers that rest unconformably on the deeper layers, and they are separated from the steep upper slope of the ridge by a region of smooth topography. They may be similar in origin to the so-called "abyssal anti-dunes" described by Fox and others (1968), Johnson and Schneider (1969), and Ewing and others (1971) and interpreted as bottom-current structures. In this case, they could be related to the Antarctic bottom-water flow (Neumann and Pierson, 1966).

Hypothesis on the Sedimentary Mechanism. We shall now try to give an explanation for the differences in sediment thickness between the Angola and Cape basins and for the filling of the internal basin.

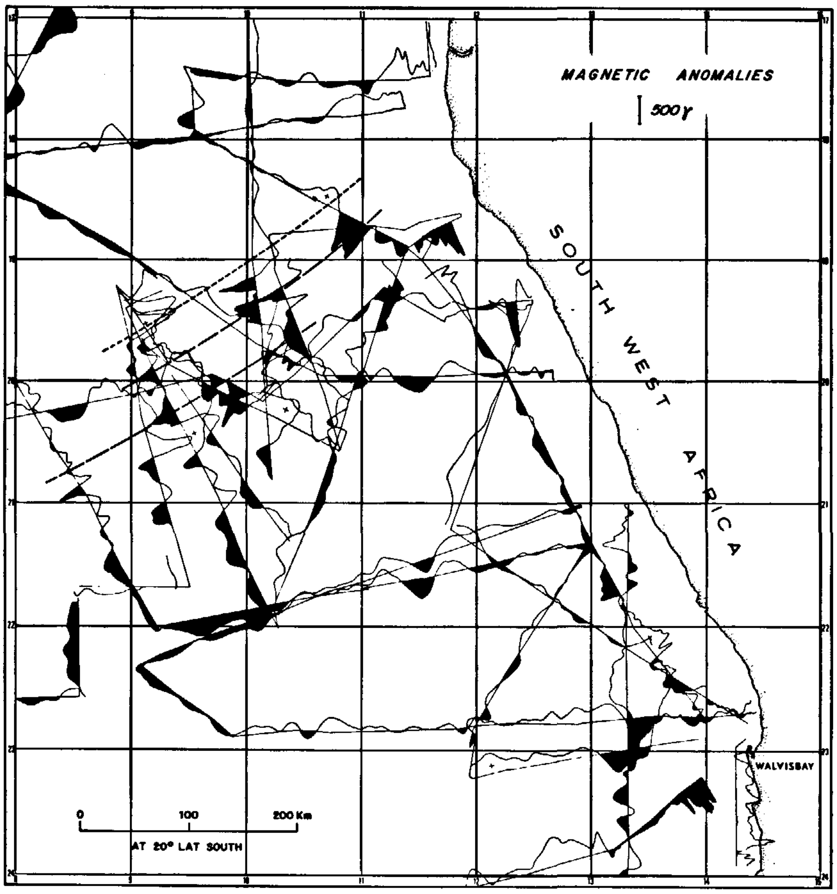

Figure 5. Magnetic anomalies along the ships' tracks. Black areas indicate negative anomalies. Dotted lines show tentative correlations.

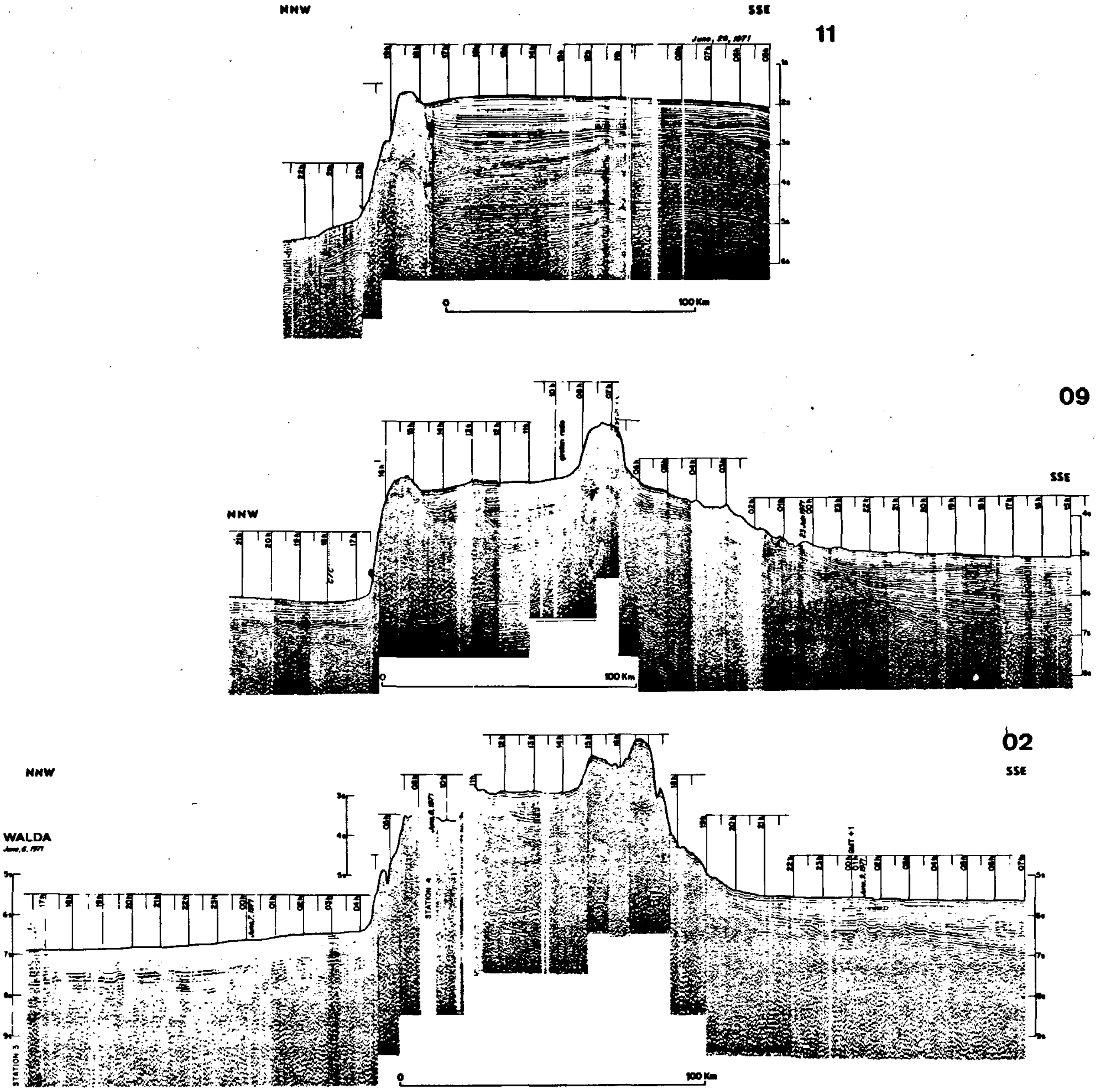

Figure 6. Original sections 2, 9, and 11 (position given in Figure 2). Vertical scale is in seconds of two-way travel time. Horizontal tick marks every half hour. The ship's speed was ~6 knots on all profiles. Vertical exaggeration, 15 to 20×.

First of all, as noted above, the sediments in the southern basin are thicker; the north-northwest–south-southeast traverses over the Walvis Ridge, like profiles 9 and 11, are relatively nearer to the continental margin of the Cape basin. Moreover, the Cape basin is confined between the coast and Valdivia Bank. This may account for the fact that the difference is still noticeable on the westernmost profile. Another mechanism can also be called upon to account for this difference. Van Andel and Calvert (1971) pointed out that the shelf sedimentary wedge near Walvis Bay has been the location of alternating periods of erosion and major sedimentary upbuilding and outbuilding. They suggested that the erosion is due to bottom currents. Du Plessis and others (1972) believe that a major period of erosion occurred along the southwestern African shelf after Mesozoic and early Tertiary deposits. Emery (1972) confirmed the existence of a large delta off the mouth of the Orange River, built during the Paleogene. We suggest that the sediments were moved by currents along the shelf and slope during the Tertiary. The sediments may have come from the Orange River; however, from the preliminary shipboard examination of piston cores, recent sedimentation on the Walvis Ridge appears to be of pelagic nature. If that has been always the case, a high rate of sedimentation in the central basin of the Walvis Ridge could be related to important biologic activity; upwellings are known all along the coast of South West Africa (Sverdrup and others, 1942; Neumann and Pierson, 1966). The filling of the central valley may be explained by the process proposed

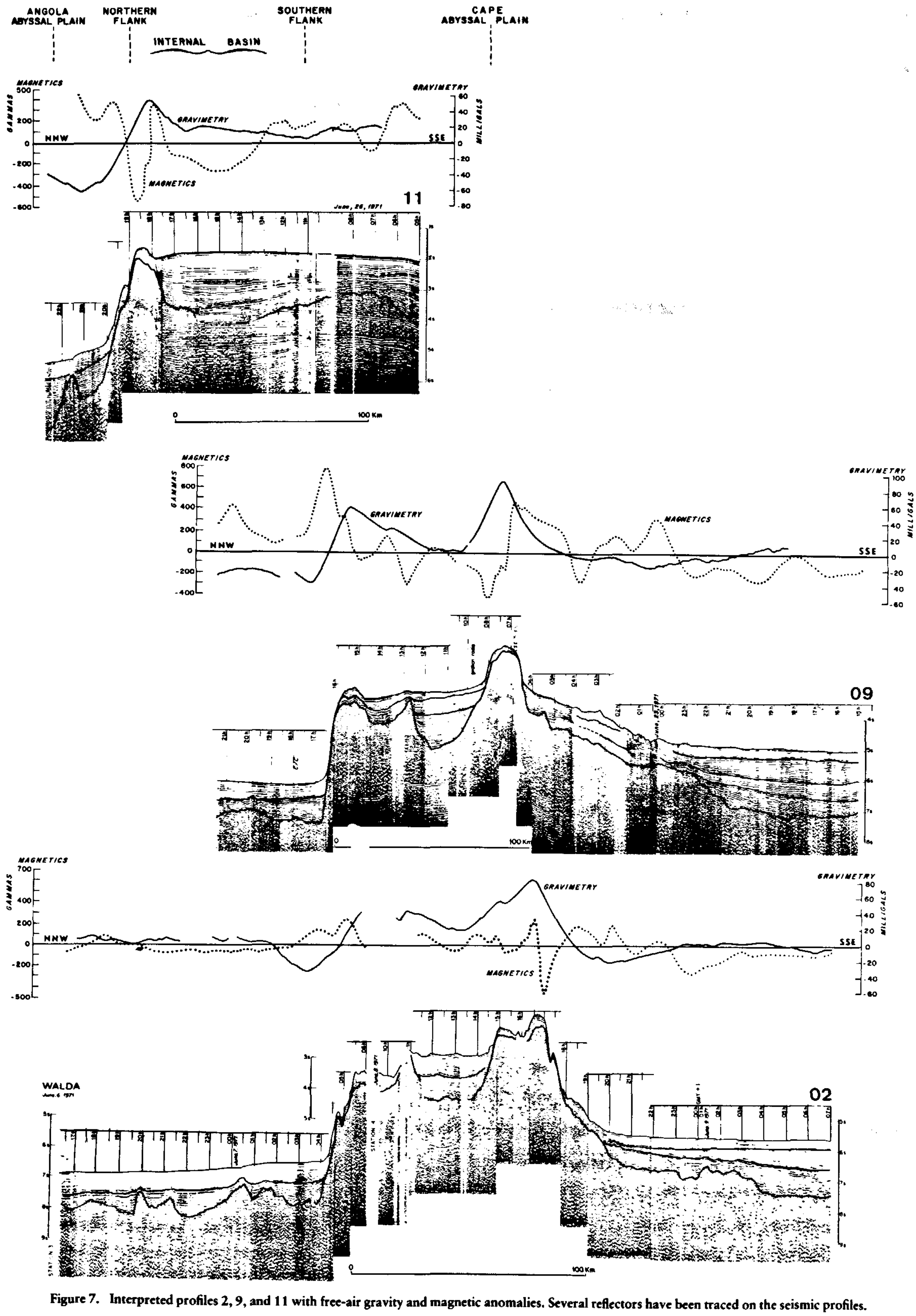

Figure 7. Interpreted profiles 2, 9, and 11 with free-air gravity and magnetic anomalies. Several reflectors have been traced on the seismic profiles.

TABLE 1. SONOBUOY REFLECTION-REFRACTION RESULTS ON WALVIS RIDGE AND ADJACENT BASINS

Sonobuoy no.	HO	V1	H1	V2	H2	V3	H3	V4	H4	V5	H5	V6	Position of launching	Mean ship's heading (degrees)
01	4.06	1.8	0.95	2.56	0.38	3.01	1.05	4.71	0.38	5.21	0.75	6.06	21°59'5" S., 09°27'0" E.	080
05	2.67	1.8	1.2	2.87	0.63	3.42	1.23	5.05					23°09'0" S., 11°57'6" E.	180
13	1.12	1.8	0.4	2.56	0.67	3.97	1.97	5.24	0.97	5.49			19°44'0" S., 11°01'0" E.	195
14	1.44	1.8	1.4	4.42	3.57	5.52							20°24'6" S., 10°49'9" E.	195
15	3.67	1.8	0.92	2.83	0.64	3.65	1.72	5.83					21°36'3" S., 10°04'0" E.	310
17	4.60	1.8	0.26	2.90	1.46	3.15	0.31	5.64					19°19'5" S., 09°03'4" E.	060
46	0.23	1.6	0.36	2.3	0.24	2.6	1.00	3.6	1.10	5.2	1.32	6.2	22°23'3" S., 13°18'3" E.	000
47	0.16	1.8	0.05	2.0	0.32	2.6	0.80	3.8	0.44	4.6	2.2	7.0	21°49'8" S., 13°17'0" E.	000
48	3.03	1.9	0.41	2.0	0.21	2.7	1.10	2.8					21°37'3" S., 11°04'3" E.	245
49	4.33	2.0	0.31	2.1	0.57	2.3	0.21	2.5	1.00	4.8			22°19'3" S., 09°05'2" E.	131
50	3.99	2.1	0.33	2.2	1.40								22°51'5" S., 10°18'4" E.	090
51	2.87	2.0	1.00	2.6	0.84	3.5	1.20	5.2					22°49'1" S., 11°53'0" E.	087
52	0.30	1.6	0.40	1.9	0.47	2.6	2.00	5.3					22°45'7" S., 13°03'5" E.	086
53	2.00	1.9	1.02	2.8	0.42	3.0	0.27	3.5	3.0	4.6?			23°56'7" S., 12°36'5" E.	248
70	1.27	1.6	0.28	2.1	1.32	3.6	1.50	5.4					21°26'3" S., 12°08'0" E.	310
71	0.94	1.9	0.95	2.8	0.90	3.0	0.78	3.7	0.34	4.9	1.42	5.7	19°15'7" S., 11°09'3" E.	223
72	2.28	2.4	0.81	2.0	0.40	4.5							20°08'0" S., 08°56'0" E.	258
58	1.45	2.3	0.39	2.6	0.30	4.3	1.20	5.0	1.2	5.4			19°33'9" S., 10°08'2" E.	179
59	1.79	1.7	0.18	2.2	0.40	2.0	0.40	4.8	1.3	5.8?			20°19'0" S., 10°11'2" E.	176
62	3.44	2.3	1.16	2.5	1.4	4.3							21°11'2" S., 10°16'5" E.	321
63	1.92	1.8	0.33	3.4	0.79	4.4	0.5	5.0					20°18'6" S., 09°37'8" E.	323
66	4.78	1.8	1.07	5.7?									19°12'3" S., 08°52'2" E.	165
73	2.63	1.7	0.30	2.2	0.13								22°49'5" S., 05°40'4" E.	121

Note: V = velocities; H = thicknesses of layers.

in Figure 8. Note that the northern wall is continuous to the margin. According to Sverdrup and others (1942), the denser water of the northward-flowing Benguela current is close to the Africa coast. We believe that the Benguela current may have been responsible for the shelf erosion and for the accumulation in the central basin of the Walvis Ridge.

Characteristics and Identification of Two Reflection Series. As shown above, there exist two main sedimentary units; the lower one, which rests on the acoustical basement, can be seen on all profiles in both basins and perhaps even in the central valley. It is quite diffractive and seems to have been deformed. The upper unit shows greater variety on the different profiles, but is well stratified, acoustically more transparent, and nearly undeformed. A thin series of strong reflectors lies locally between the two units (in both basins on profile 2, in the Angola basin on profile 9).

Apart from the topmost undisturbed layer (probably consisting of recently deposited pelagic sediments), there are large differences in the upper unit on the seismic reflection records. It is therefore difficult to determine whether the lower unit is the same in all areas. We should note that the lower unit nevertheless displays similar seismic characteristics. In the Argentine basin, south of Rio Grande Rise, Ewing and Lonardi (1971) have identified a strong reflector, 0.5 sec under the sea floor and of 0.25 sec average thickness. Generally, this horizon is considered to be of Late Cretaceous to early Eocene age. Moreover, Du Plessis and others (1972) and Emery (1972) suggest the possible presence of horizon A in the Cape basin. We propose that the thin series of strong reflectors mentioned above may be correlated with horizon A. If this interpretation is correct, some important event may have occurred between Late Cretaceous and early Eocene time.

MAGNETIC PROFILES

Several authors (Dickson and others, 1968; Ladd and others, 1973; Mascle and Phillips, 1972) have published magnetic profiles along the length of the Walvis Ridge. Our data, similar to their data from other portions of ridge to the southwest, show that the magnetic pattern over the Walvis Ridge is distinctly different from the pattern in the adjacent oceanic areas (Fig. 5). The rough topography of the basement, which is apparently of volcanic origin, creates short wave-length anomalies of high intensity. The northern flank is associated with an important positive anomaly situated northward of the crest on the profiles. In the central basin, the anomalies are generally negative. On the southern flank, several large-amplitude anomalies can be correlated. A positive anomaly coincides with the top of the southern flank and separates two negative anomalies, the southern one being of higher amplitude. Between lat 18° and 19° S., the large anomalies are probably related to widespread inland basaltic flows near Cape Frio (Geological Map of South West Africa, 1963).

Press and Ewing (1952) and Talwani and Heirtzler (1964) showed that depth and relief of the magnetic basement are the main factors governing amplitude as well as shape of the anomalies. As pointed out by Rabinowitz (1972), magnetic anomalies off the Angola margin are also evidently related to basement relief and magnetization contrast rather than to geomagnetic reversals.

Over the adjacent abyssal plains, particularly the Angola basin, magnetic anomalies are less prominent and their wave lengths much longer. Over the Walvis Ridge, the linearity, comparable to the basement linearity, is well expressed on the map of Figure 5, for which anomalies have been calculated using the international geomagnetic reference field (Cain and others, 1968) and projected along the ships' tracks. Because of the small wave lengths and strong gradients of the anomalies compared to the spacing of the ships' tracks, we do not feel confident in drawing a magnetic anomaly contour map.

On the margin and slope, only few anomalies are recorded. The generally low amplitude pattern might be due to demagnetization by "burial metamorphism" under more than 3 sec of sediment (Taylor and others, 1968). On the other hand, magnetic crust could have been emplaced under a thick sedimentary cover and undergone a slower cooling, thus acquiring a smaller remanent magnetization (Vogt and others, 1971). It has further been postulated that a thick blanket of sediment with a low susceptibility may act as a "magnetic shield" in which the field lines close themselves inside the sediment (B. Sichler, 1972, oral commun.). Applying the reasoning of Talwani and others (1971), we do not feel that the marginal anomalies are generally deep-seated features.

GRAVITY

The data are sufficient to contour with some confidence the free-air gravity anomaly seaward of the continental shelf (Fig. 4). On the shelf itself, the contours are only

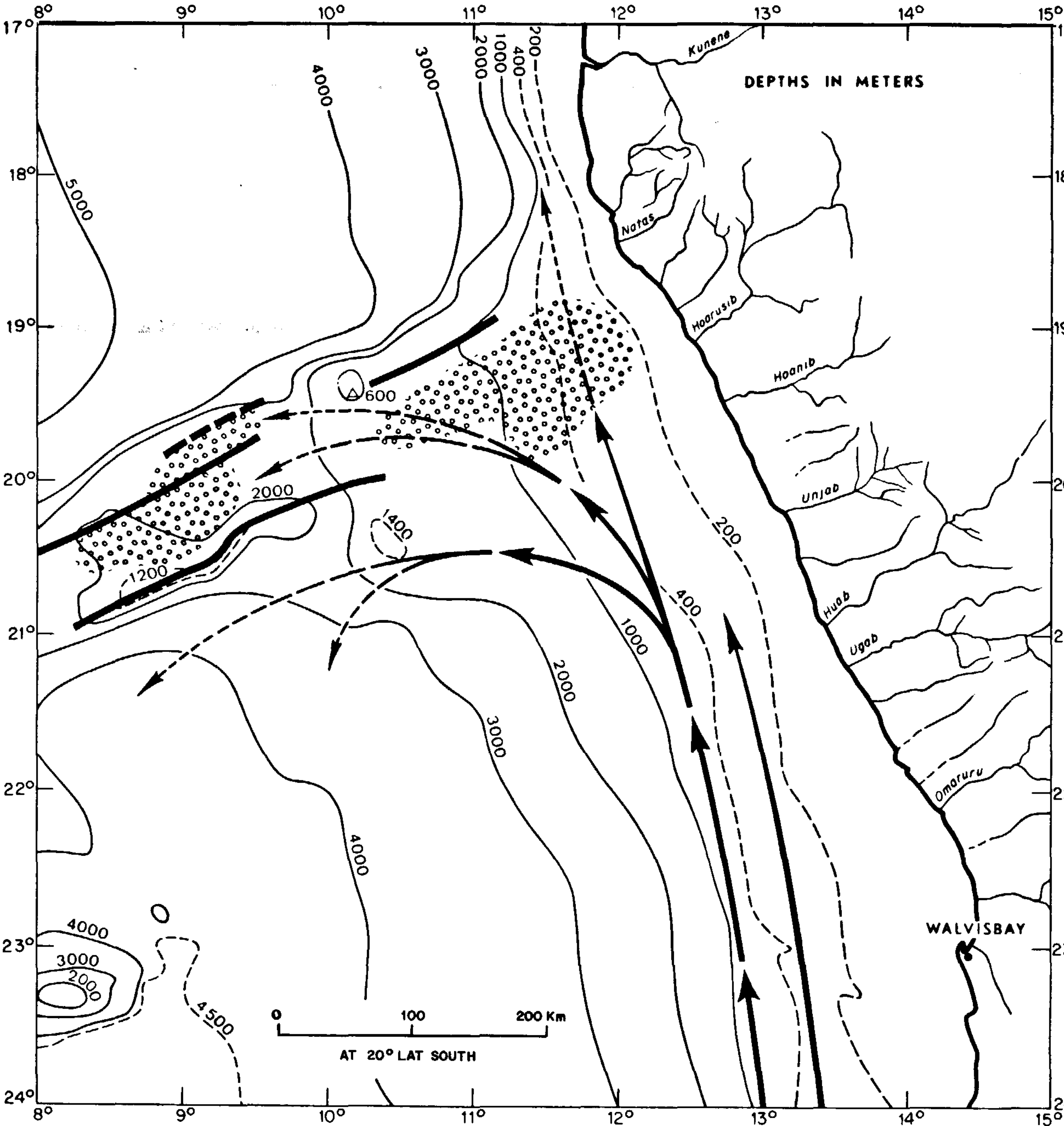

Figure 8. Tentative diagram for the filling mechanism of the internal basin. Small circles indicate regions of thick sediments. Light lines are simplified bathymetric contours (in meters). Heavy lines show approximate positions of basement highs as inferred from Figure 9. Arrows show tentative direction of sediment transport.

tentative and suggest a greater complexity, due both to the shallowness of the basement and its structure. The map was continued on land using the Bouguer anomalies given on the Geological Map of South West Africa (1963). Because the shelf is wide and shallow and the relief on land is small, there should exist only a small discontinuity between the two types of anomalies when one is crossing the shore. South of lat 20° S., the tracks were too far offshore to allow interpolation between the two sources of data.

If the Walvis Ridge is in isostatic equilibrium, the existence of weak negative anomalies at the bottom of the slopes of the flanks suggests the presence of an edge effect. Therefore, a root of light material may exist under the Walvis Ridge. On the continental margin, the slope is not very steep, and there is practically no edge effect. Both the Angola and the Cape basins display negative anomalies of low amplitude (-10 to -20 mgal) and large wave length.

It is difficult to trace the extension of the two crests from the gravity map because the crests deepen toward the margin (and are lost on the seismic records). The negative, or only slightly positive, marginal anomalies between lat 19° and 20° S. seem nevertheless related to an eastward extension of the cen-

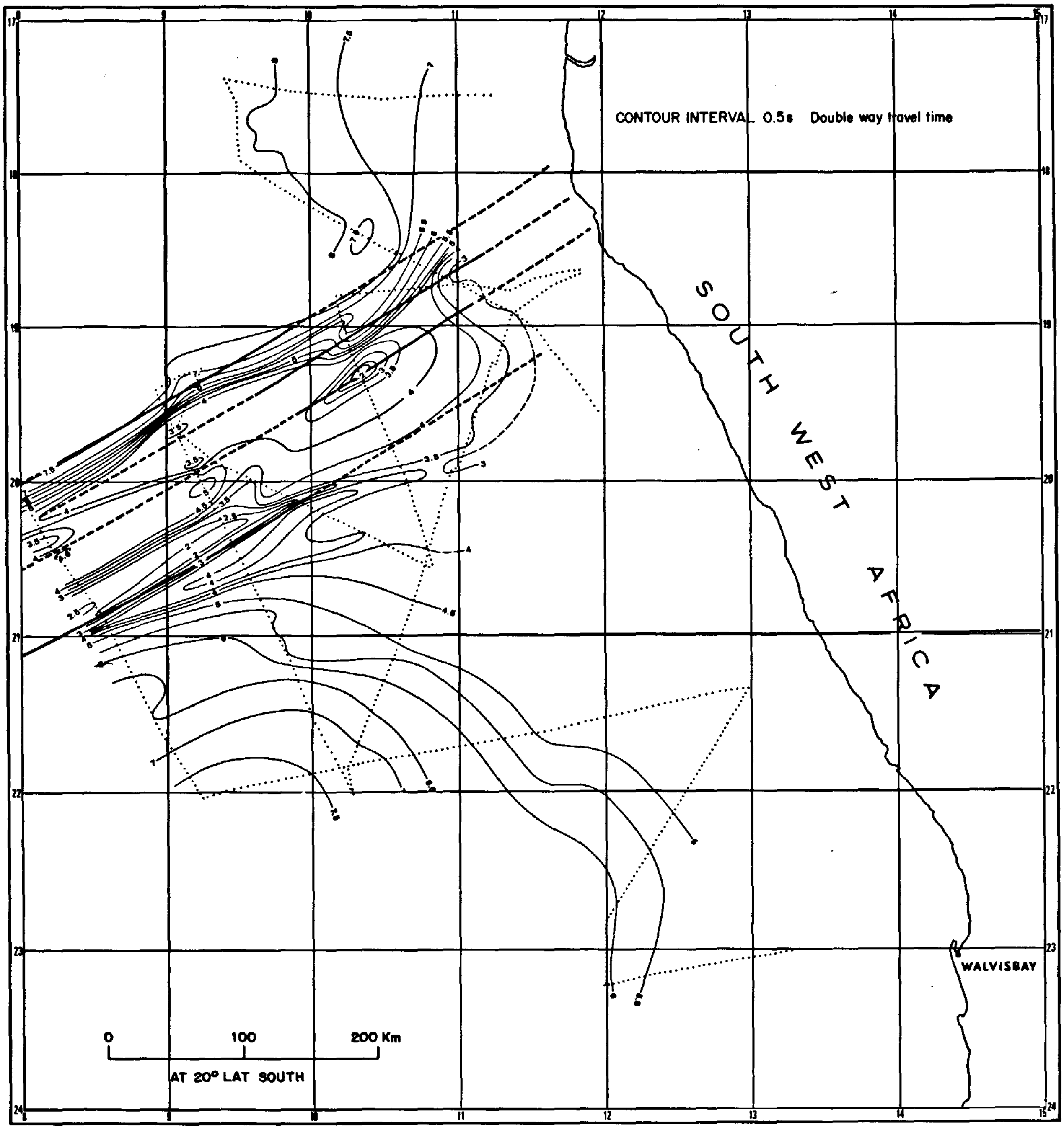

Figure 9. Map of the depth to the acoustical basement. Values are in seconds of two-way travel time from the sea surface. R/V *Jean Charcot's* tracks are shown as dotted lines. Heavy solid and dashed lines indicate small circles of early opening.

tral sedimentary basin. However, the Bouguer anomaly map does not indicate continuation of the central basin on land. The shelf itself, between lat 18° and 24° S., is a complex zone with no apparent gravimetric trend. The exceptions are two negative anomalies around lat 21° to 24° S., which stretch roughly southwest-northeast approximately perpendicular to the margin and the anomalies on land. These two anomalies, together with the positive anomaly between them, are the only gravimetric trend that can be followed for a short distance on land. There seems to be very little other relation between the anomalies found on the shelf and the ones found on land.

Several positive anomalies run along the edge of the continental shelf south of the Walvis Ridge, in depths between 400 and 800 m (Fig. 4). If these anomalies are caused by the same process, they cannot be due to an edge effect. The edge effect alone cannot account for more than 10 mgal because the continental slope is very gentle and regular over a few hundred kilometers (Fig. 3). This is supported by comparing the amplitudes

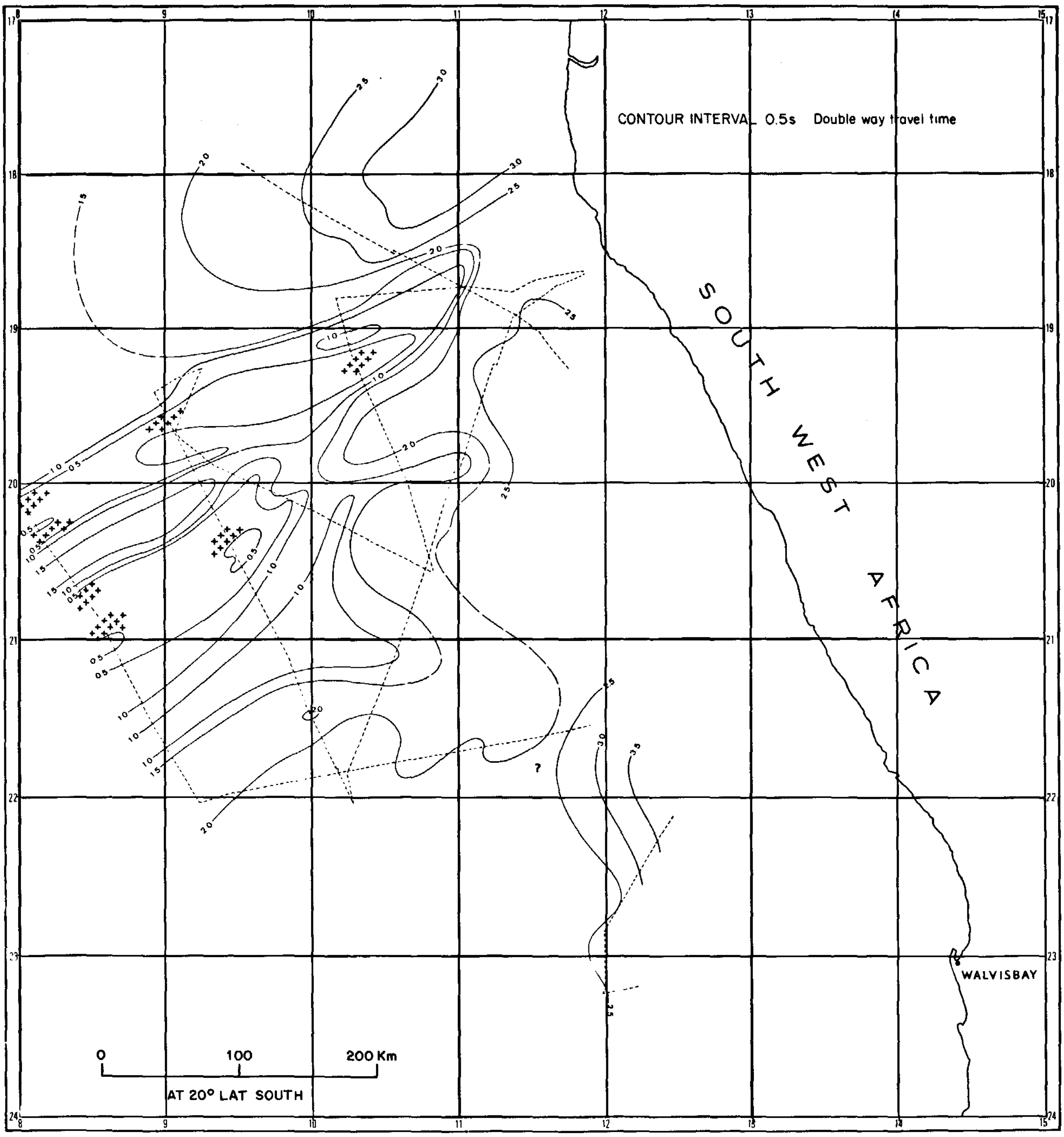

Figure 10. Map of the sedimentary filling above the acoustical basement. Crosses indicate basement outcrops. Dotted lines show R/V *Jean Charcot's* tracks.

of these anomalies to those recorded above the shelf north of the Walvis Ridge, which reach only 20 mgal where the slope is twice as steep as it is south of the Walvis Ridge. No more can they be related to basement highs because only some of them coincide with marked magnetic anomalies (Fig. 5).

On the other hand, the deep sedimentary layers thicken greatly to the east between the 800- and 200-m lines. The seismic velocity (and therefore, the density) quickly increases with depth (buoy 5, Table 1). This thickening of dense layers, together with the involved density contrast when compared to a normally layered margin, can account for 40 mgal free-air anomalies.

CONCLUSION

There are several aseismic plateaus and ridges in the world's oceans. Some are believed to be foundered continental fragments, for example, the Rockall bank in the North Atlantic (Roberts and others, 1970; Bullard and others, 1965). Others are of volcanic origin, such as the Hawaiian seamount chain (Malahoff and Woollard, 1970; Morgan, 1972) or are related to uplift of the oceanic crust. In their study on the evolution of the Indian Ocean, McKenzie and Sclater (1971) proposed as a general rule that "the aseismic volcanic ridges often mark plate boundaries and are formed during pauses in spreading." It seems difficult to apply this hypothesis to the south Atlantic. Magnetic data (Dickson and others, 1968; Ladd and others, 1973; Mascle and Phillips, 1972) do not show particular evidence of pauses in spreading, but little is known about the magnetic anomalies before anomaly 32 (around 77 m.y. B.P.).

We shall examine the collected data as they pertain to the origin and evolution of the easternmost portion of the Walvis Ridge and which of the following types of formation mechanism they seem to favor: (1) a hot-spot origin proposed by Wilson (1965), Dietz and Holden (1970), and Morgan (1971, 1972); (2) a transform-fault mechanism (Le Pichon, 1968; Le Pichon and Hayes, 1971) associated with a marginal offset (Francheteau and Le Pichon, 1972); and (3) an uplift along old lines of weakness, as suggested by Ewing and others (1966). The first two processes imply that Walvis Ridge and Rio Grande Rise were created with a topography and position close to that of the present day, synchronous with the opening. The third alternative of uplift would have occurred after the creation of the surrounding oceanic basins.

The easternmost portion of the Walvis Ridge is a continuous quasi-linear topographic feature more than 600 km long. The trends of topography, magnetic and gravity anomalies, and of the basement highs are perpendicular to the coastline. The continuity and linearity favor a fracture-zone origin, either a pure transform fault or some type of tectonic process following an older line of weakness. The hot-spot structures inferred in the Pacific (for example, the Emperor and Hawaii seamount chains) are less continuous and are a linear succession of seamounts and volcanoes. However, the formation of hot-spot structures could be much different in the Atlantic, perhaps only because of the smaller spreading rates. Another argument against a hot-spot origin for the Walvis Ridge is the difficulty in supposing a northward motion of the African plate over the hot spot sufficient to create the north-south segment of the Walvis Ridge. An alternative hypothesis for the creation of step-like structures such as the Walvis Ridge (and possibly, the Hawaiian seamount chain) by hot spots would be either a motion of the plate over the hot spot, oblique to the lines of weakness, or a slight motion of the hot spot itself (X. Le Pichon, 1973, oral commun.). The basalt flows would then concentrate along a line of weakness until the hot spot was too far away from it. The hot spot would then tend to pass to another line of weakness, thus creating segments perpendicular to the lines of weakness. Such an explanation will remain hypothetical until more is known about the deep structure of possible hot spots.

The ridge is a relatively wide feature (130-km average) surrounded by deep basins of different sizes and structures.

The east-west segment of Walvis Ridge is a double feature, even close to the continental margin where the basement of the southern flank is more subdued. This observation is not as valid for the north-south segment (Ewing and others, 1966). The small difference in depth of the basement in the two bordering basins, the existence of two bordering ridges, and the relatively steep walls remind us of the topography of other Atlantic fracture zones, such as parts of the Gibbs fracture zone (Fleming and others, 1970; Olivet and others, 1974, in press) or Vema fracture zone (van Andel and others, 1971). A comparable whole-structure elevation is not found in other areas and seems to be an indication of posterior uplift of the Walvis Ridge. Traces of faulting in the central basin and dissymmetry of the two crests may indicate either that an uplift has not been the same everywhere, or that some parts of the important sediment cover may have subsided slightly at a later time.

Comparison of the early opening flow lines proposed by Le Pichon and Hayes (1971) and the basement ridges direction (Fig. 9) suggest a correlation between the creation of the Walvis Ridge and the early phase of opening of the south Atlantic. As pointed out by Francheteau and Le Pichon (1972), no large offset appears on the coastline or on the shallow isobaths of the continental margin. The easternmost Walvis Ridge would then have to be the scar of a very small offset transform fault, active during a long period of time. It is therefore unlikely that a pure transform mechanism would create such an important topographic feature as the Walvis Ridge. Other tectonic processes, acting along a transform direction, would then have to be called upon, for example, posterior uplift of a less prominent relief or asymmetric spreading south of the Walvis Ridge–Rio Grande Rise line.

There is a marked contrast in sedimentation on the continental margin and in the adjacent oceanic basins north and south of the Walvis Ridge. This suggests that the Walvis Ridge has dammed sediment coming from the south during a long period of time. We feel confident of the identification between the lower series of reflectors in the basins on both sides of the Walvis Ridge (at least on the westernmost profile). The identification is no longer easy for the upper series. If the strong reflectors between the two series have been correctly interpreted as layer A, we can presume that an important tectonic event occurred contemporaneous with, or just after, the deposition of this layer, that is, Upper Cretaceous to early Eocene in the south Atlantic (Ewing and others, 1970). This episode could have been contemporaneous with the inferred migration of the pole of opening (~80 m.y. B.P.). The upper layers are nearly undisturbed in both abyssal plains (as well as in the central basin) of the Walvis Ridge. Consequently, only minor tectonic movements have affected the Walvis Ridge since the migration of the pole of opening. The Walvis Ridge, since the beginning of the opening of the south Atlantic, may have restricted the circulation of the equatorial south Atlantic and may have promoted the extensive evaporite deposits evident along the continental rise between Angola and Nigeria.

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