Geophysical Studies of the Seychelles Bank

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Geological studies of the islands on the Seychelles Bank, and the results of seismic refraction experiments made on the bank, are reviewed. They show that the crust is of continental type under the centre of the bank. Gravity measurements confirm that the thick crust extends to the northern edge of the bank and show that the Mohorovičić discontinuity slopes upward at an angle of about 19° under the peripheral cliff. Large narrow magnetic anomalies occurring in the central area of the bank are ascribed to minor intrusions of dolerite found in the Precambrian granites, and it is suggested that the edge of this area may mark the limit of the granite mass. Magnetic anomaly profiles of the Mascarene Ridge are similar to those over the Seychelles Bank and could result from a similar structure.

Introduction and geology of the islands

The Seychelles Bank is situated midway between the coast of Africa and the Carlsberg Ridge, about 950 mi. east of Mombasa. The bank has an almost flat top which lies at a depth of about 30 fm. below sea level. The oval area enclosed by the 100 fm. line measures about 200 × 100 mi. (figure 1). The edge of the bank is clearly defined by steep sides which drop away to depths greater than 2000 fm. in all directions except towards the west and the southeast. At its western end the Seychelles Bank is connected by a saddle with a sill depth of 1200 fm. to the shallow bank on which the Amirante Islands stand, and at its southeastern end the bank is joined at a depth of about 1000 fm. to the flat-topped Mascarene Ridge which curves southwards for 1000 mi. through the Saya de Malha Bank, Nazareth Bank and the Cargados Carajos Shoals towards islands of Mauritius and Reunion (Heezen & Tharp 1964).

The islands on the Amirante Bank are coral atolls and sand cays. No volcanic rocks are exposed on them but magnetic anomaly profiles obtained by H.M.S. *Owen* (Admiralty 1963) suggest the presence of basaltic foundations at a depth of less than 1 km beneath the atolls. On the west side of the Amirante Bank (beyond the limits of figure 1) is a curved trench, convex towards Africa (Loncarevic 1963). The Amirante Bank and trench together have many of the characteristics of a young volcanic island arc and, as such, are probably geologically dissimilar from the Seychelles Bank.

The geology of the islands of the Seychelles Group has been described and mapped by Baker (1963). Two small islands, Bird Island and Dennis Island which lie on the Seychelles Bank near its northern margin, are coral sand cays. The remainder of the islands and islets on the bank are granitic. They occupy an area 40 × 50 mi. in extent in the centre of the bank. The three largest islands are Mahé, Praslin and Silhouette. The petrology of the igneous rocks has been described by Bauer (1898), by Baker, and by Frankel & Kent (1964). Radioactive age determinations have been reported by Miller & Mudie (1961) and Baker & Miller (1963). Granite of late Precambrian age (*ca.* 650 My) makes up the islands of Mahé and Praslin and the associated islets. In some places the granite is crowded with basic xenoliths of amphibolite and diorite. On Silhouette Island and nearby Ile du Nord the rocks belong to a syenite-microgranite ring complex of early Tertiary age, about 50 My. The Precambrian granites of the Mahé–Praslin group, are cut by altered basaltic dykes and sills belonging to two groups: a more altered group of metadolerites of

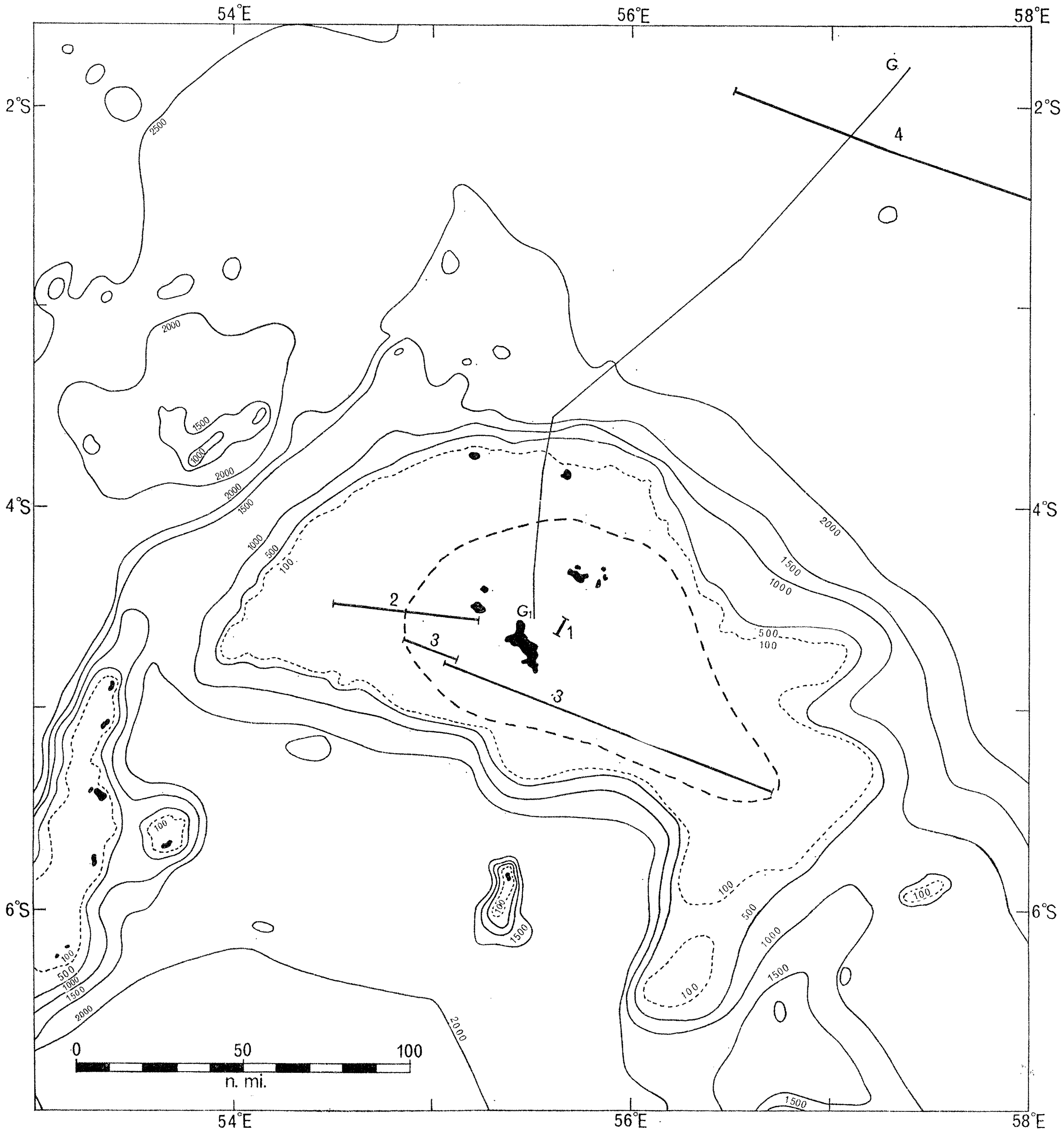

Figure 1. Topography of the Seychelles Bank. Contours at 500 fm. intervals, plus the 100 fm. contour (dashed). Simplified from Dr A. S. Laughton's 1:1000000 bathymetric chart by omission of intermediate contours. GG_1, line of gravity profile shown in figure 8. 1 to 3, seismic refraction lines referred to in text: 1, H.M.S. *Challenger*; 2, R.V. *Argo* and R.V. *Horizon*; 3, R.R.S. *Discovery* and H.M.S. *Owen* (station 5210); 4, *Discovery* stations 5170 and 5176. Broken line enclosing inner islands on the Seychelles Bank marks limit of narrow magnetic anomalies.

late Precambrian age, and a less-altered younger group of alkali olivine-dolerites of early Tertiary age which are probably associated with the syenite-microgranite complex of Silhouette. The dykes show some preferred trend in west to northwesterly directions, parallel to the elongation of the larger islands.

As Baker & Miller have written (1963, p. 348), 'The Mahé–Praslin granite is almost certainly a single plutonic mass of anorogenic character, and must have been emplaced in a crust at least 1 mi. thick', but almost no trace has been found of the country rocks into which the plutonic masses were intruded. Loose blocks of andalusite-hornfels have been described by Bauer, and similar rocks were collected on Cerf Island by Kent who believed them to be *in situ*. Apart from this occurrence which probably represents a roof pendant (Kent & Frankel, personal communication) there is no sign of the original cover of the granites, or of any younger sedimentary rocks, except those which are forming at the present time, and the geological survey by Baker makes it unlikely that any large outcrops remain to be found on the islands.

The Seychelles Bank is surrounded by the deep ocean, and the presence of substantial masses of granite of continental aspect and Precambrian age in such an environment is entirely anomalous. Similar granites do not occur on any oceanic islands of comparable size and we are forced to compare the Seychelles Bank with Madagascar which is known to be a small continent or continental fragment. Gardiner (1906) and Willis (1932) invoked the hypothesis of isthmian links to explain the anomaly, but such a hypothesis is now plainly inadmissible. Baker & Miller (1963, p. 348) mentioned the intermittent down flexuring of the Mozambique geosyncline and suggested that 'the eastern part of the continent of Africa once extended as far as the line of the Mascarene Ridge', but subsequent seismic work and gravity profiles (Francis, Davies & Hill, this volume) indicates the presence of normal oceanic crust in places between the Seychelles and Africa. Du Toit (1937, p. 125), discussing the theory of continental drift and the northward migration of peninsular India, visualized the crystallines of the Seychelles 'as fragments left behind in the rear of India'. The geophysical work summarized here was undertaken to test the idea that not only the granitic islands but also the whole Seychelles Bank represents a small continental fragment.

SEISMIC REFRACTION RESULTS

Three sets of seismic refraction experiments have been carried out on the Seychelles Bank: a short line was shot in 1953 by H.M.S. *Challenger* between Mahé and Praslin islands (Gaskell, Hill & Swallow 1958), a line of moderate length was shot west of Silhouette Island by R.V. *Argo* and R.V. *Horizon* in 1962 (Shor & Pollard 1963), and a line more than 100 mi. in length was shot by R.R.S. *Discovery* and H.M.S. *Owen* in 1963 (Davies & Francis 1964). The positions of these lines are marked on figure 1, and the layering deduced from them is shown in figure 2. In the *Discovery*/*Owen* profile the velocities 6·26 and 6·78 km/s are particularly well determined, but the 8·1 km/s velocity is assumed. On the time–distance diagram this line was fitted through one reliable point; the other points on this line were mediocre and so a typical upper mantle velocity of 8·1 km/s was assumed.

The velocities 5·72 and 6·26 km/s are typical of granitic rocks. The division into two layers may well be more apparent than real and this result could represent the velocity gradient in the granite. The layer with velocity 6·78 kms could be a continuation of layer 3 of the typical oceanic crust (Raitt, p. 101, in Hill 1963). Typically oceanic crustal sections including the 6·8 kms layer have been found at stations shot in deep water to the northeast and east of the Seychelles Bank. The interface between the 6·26 km/s layer and the 6·78 km/s layer, found here at a depth of about 15 km, corresponds to the postulated Conrad discontinuity under the continents. The depth of 33 km to the interface between the 6·78 km/s layer and the 8·1 km/s layer which we interpret as the Mohorovičić discontinuity is, of course, only determined for a relatively small area near the middle of the *Discovery–Owen* line. However, gravity profiles permit us to determine how far the thick crust extends in a northward direction. We conclude from the seismic results that the granitic rocks extend to a depth of about 15 km in the central part of the bank and that the crust there has both a continental character and a continental thickness. We shall return to discuss the superficial layers after considering the magnetic results.

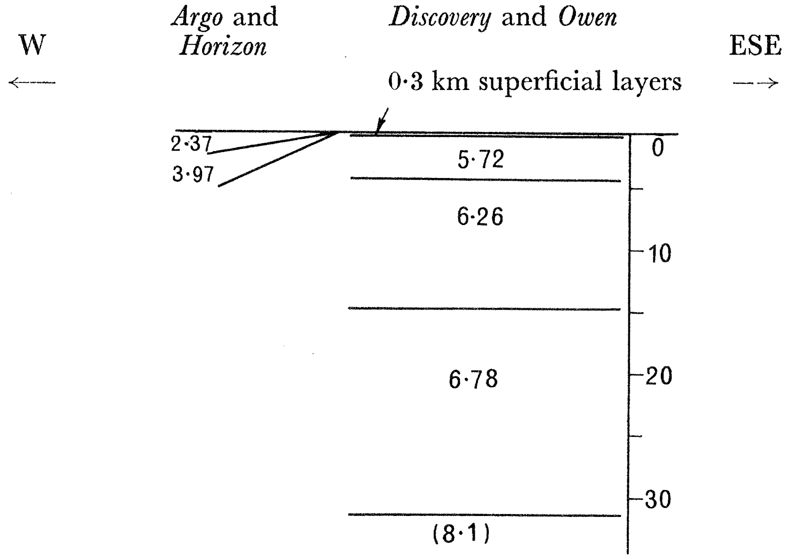

Figure 2. Velocity structure of the Seychelles Bank. Depths in kilometres, seismic velocities in km/s. (After Davies & Francis 1964.)

Gravity profiles

Gravity profiles across the edge of the Seychelles Bank were obtained aboard H.M.S. *Owen* by Loncarevic in 1961 and by Matthews and Chaplin in 1962 (Admiralty 1963, 1965). All the profiles show the very substantial free air anomaly which results from the abrupt change in water depth at the edge of the bank, but there is no large anomaly over the central part of the bank. It follows that the bank is a compensated feature not greatly out of isostatic equilibrium. If we assume that compensation takes place at the Mohorovičić discontinuity, and choose appropriate densities for the crustal rocks in the light of the seismic results, it is possible to use the gravity profiles to calculate the shape of the Mohorovičić discontinuity under the edge of the bank.

The position of the profile chosen for study is shown in figure 1. It passes within 10 mi. of the centre of a reversed seismic refraction profile (*Discovery* stations 5170, 5176, Royal

Society 1964). This refraction station was shot in order to provide a reference section for the gravity computations. The resulting time–distance diagram can be confidently interpreted and gives the following average structure near 2° 12′ S, 57° 18′ E (Francis 1964; and p. 257 below).

layer	km/s	thickness
water	1·54	4·38
1	1·78	0·30
2	4·86	1·72
3	6·86	4·7
4	8·14	—

This velocity structure is typically oceanic. Several reconnaissance tracks pass within 40 mi. of the position of the seismic profile and show that it lies in an area of abyssal hills and occasional small seamounts and on the lowest part of the western flank of the Carlsberg Ridge. On all these profiles the gravity field (free air anomaly) is relatively smooth, with excursions less than 15 mgal, giving confidence that the observed seismic structure can be projected on to the line of the chosen gravity profile.

Computations to interpret the gravity results were made by M. Takin utilizing computer programs adapted by him and by F. J. Vine for use on EDSAC 2. His results are described in the next few paragraphs. For the main calculation two-dimensional models were employed, assuming the structure to be infinitely extended perpendicularly to the line of the profile. Two of the models used are shown in figure 3. Densities were assigned to the crustal layers utilizing the data presented by Nafe and Drake (p. 807 in Hill 1963). The 6·78 km/s layer under the bank was assumed to be identical with the third layer observed at the oceanic station, 6·86 km/s, and was assigned a mean density 2·99 g/cm^3. Layers 1 and 2 of the oceanic structure were assumed to wedge out against the granite. The granite was treated as two distinct layers having densities 2·71 and 2·83 g/cm^3 respectively; a model simulating a linear increase in density downwards through the granite was also tried and gave results which differed by less than 10 mgal. In view of the uncertainties in the seagravimeter observations (±5 mgal) and in the assumed densities this difference is not significant.

Figure 3 shows two models which simulate the observed gravity profile and which differ in the shape assumed for the edge of the granite. Both models indicate a depth of about 26 km to the Mohorovičić discontinuity under the Seychelles Bank. This result is in general agreement with the depth of about 33 km obtained from the seismic refraction work. Both models require a very steep rise in the crust/mantle interface under the edge of the bank. The interface rises 14 km in 42 km, a slope of about 19°.

The two models on figure 3 differ grossly in the distance by which the granite is assumed to extend oceanwards. Since both models produce a fair approximation to the observed gravity it is clear that gravity measurements alone cannot solve this question. This is because the granite must be assumed to wedge out against both layers 2 and 3 of the oceanic crust but has a density intermediate between them, so that geologically very dissimilar models can give very similar gravity effects.

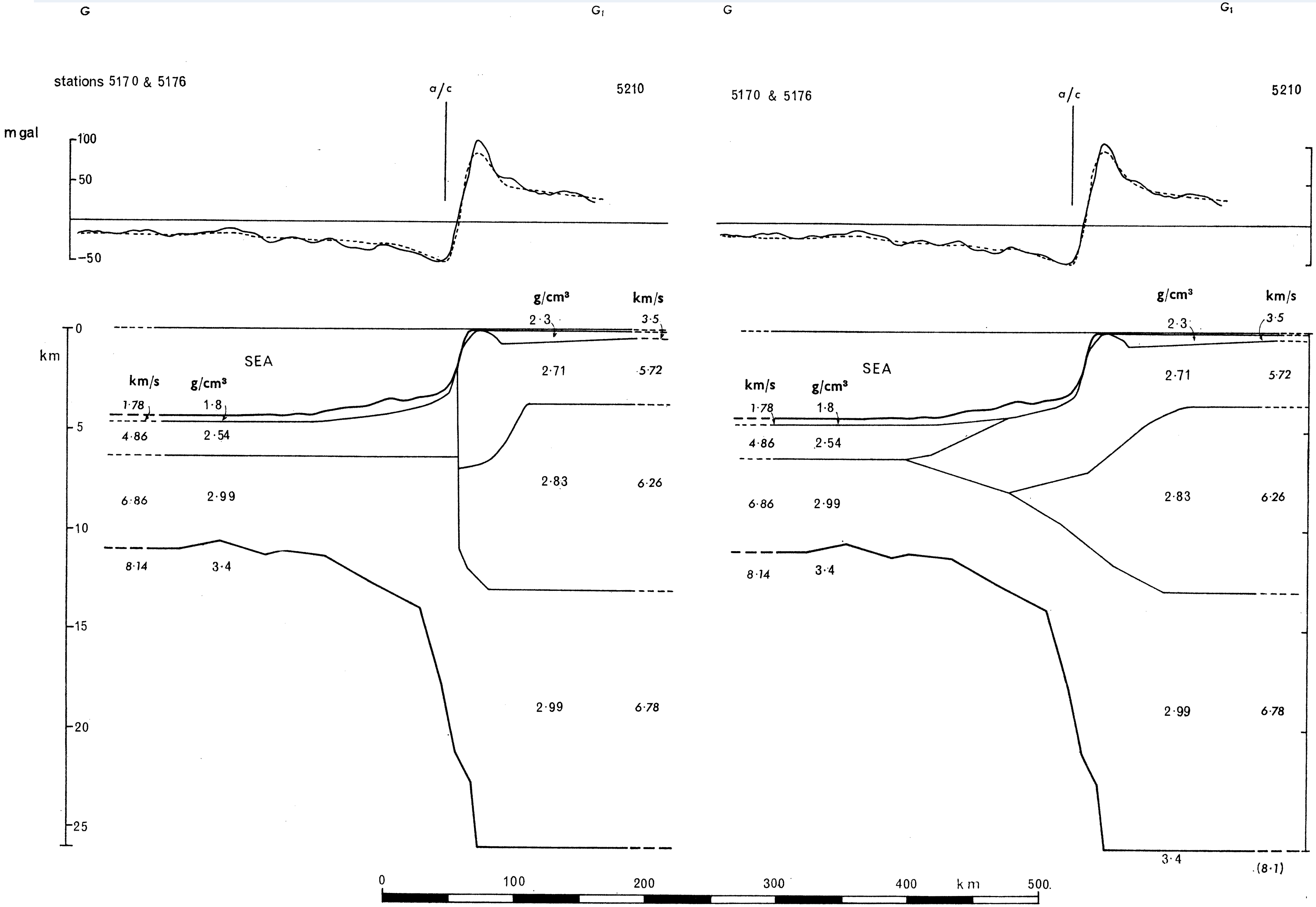

FIGURE 3. Gravity profiles across the northern edge of the Seychelles Bank, and crustal structure models used for calculations. *Top left* and *right*: free air gravity anomaly profiles between seismic stations 5210 and 5170 along the line drawn on figure 1; *continuous line* observed anomalies, *dashed line* computed anomalies. *Bottom left and right*: structure models used in computations. Figures in italics are observed seismic velocities (V_p) in km/s, figures in Roman numerals are corresponding densities in g/cm³. Thin superficial layers of water and mud on the Seychelles Bank are not shown in the diagram but were included in the calculations. Depth to Mohorovičić discontinuity fixed at the northeast end of the line by results at seismic stations 5170 and 5176 but calculated from gravity results along

Magnetic anomaly profiles

Fourteen magnetometer profiles across the edge of the Seychelles Bank have been obtained by H.M.S. *Owen* and R.R.S. *Discovery* (Admiralty 1963, 1965; Vine 1964). Their positions are marked on figure 4 and two composite profiles are illustrated in figure 5.

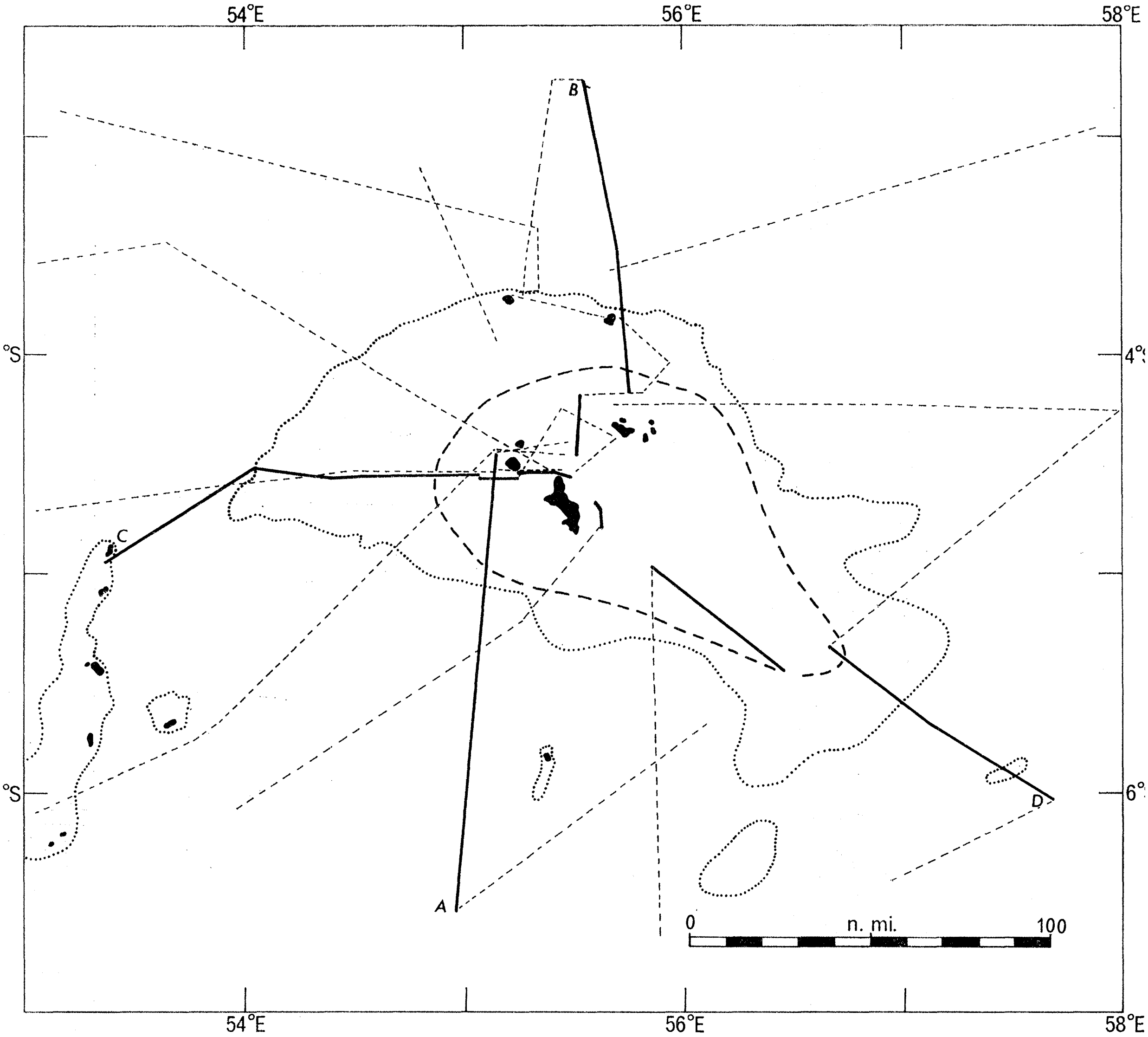

Figure 4. Position of magnetic anomaly profiles. The 100 fm. contour around the Seychelles and Amirante Banks is marked with a dotted line. Dashed lines show tracks along which magnetic anomaly profiles have been obtained. Profiles illustrated in figure 5 are indicated by the discontinuous heavy lines *AB* and *CD*. Broken line rings area within which sharp anomalies are found (see text).

At the time that the first magnetometer traverses were made it was expected that when the ship passed from the relatively magnetic volcanic rocks of the oceanic crust over the weakly magnetized granites the magnetometer record would become quiet. This was not the case; instead the central part of the Seychelles Bank, over the shallow water, is characterized by narrow total field anomalies which frequently exceed 1000 γ in range and are crossed in less than 1 mi. It is natural to interpret these large narrow

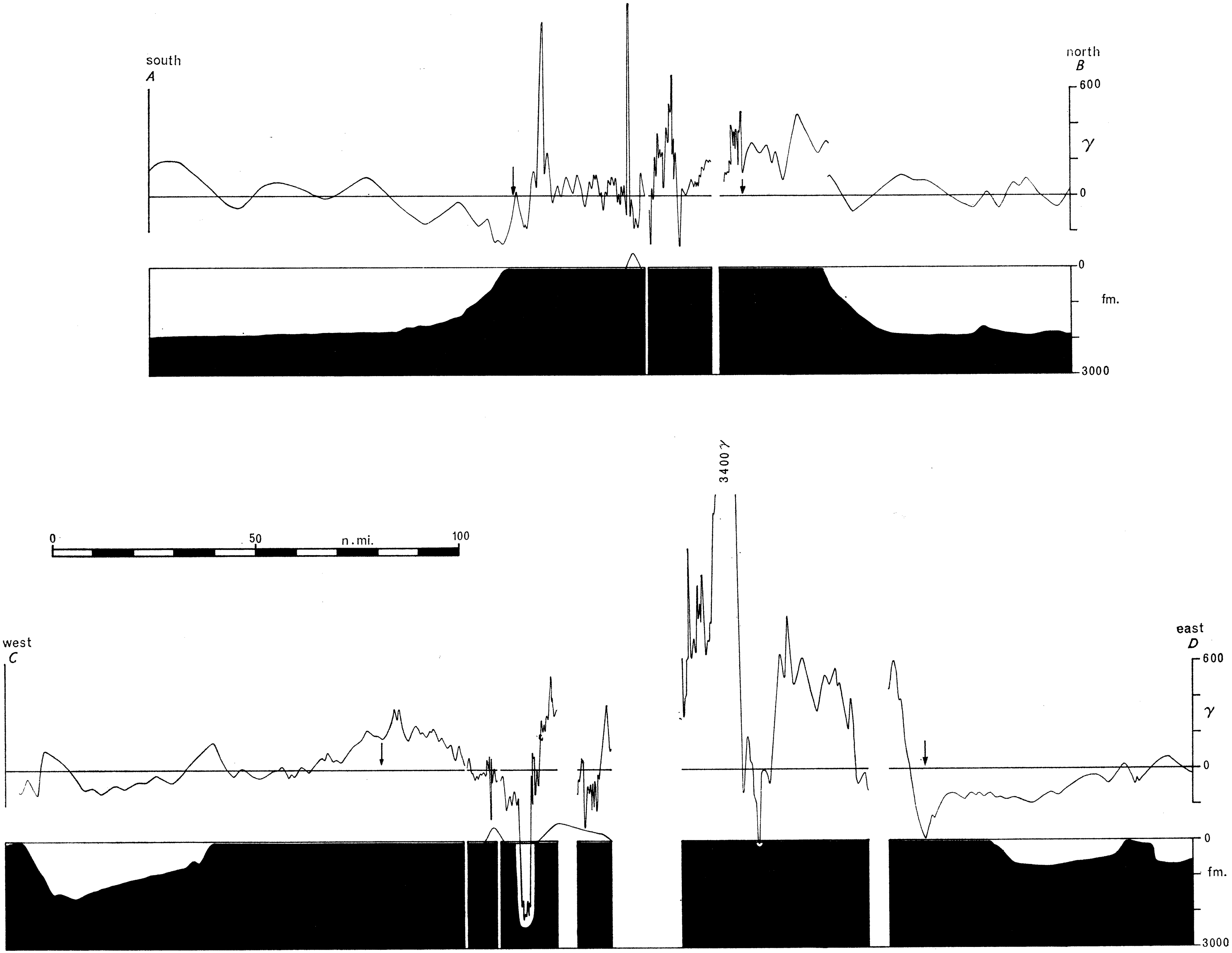

FIGURE 5. Comparison profiles across the Seychelles Bank showing magnetic anomalies and topography along the lines *AB* and *CD* shown on figure 4.

anomalies in terms of the basaltic dykes which can be seen to cut the granites on the islands. It was hoped that correlations would be found between adjacent profiles, at least in the centre of the bank where the tracks of the ships converge on Port Victoria, but this has proved impossible so that, if the anomalies are elongated, their trend remains unknown. A partial explanation of this lack of correlation is provided by palaeomagnetic results (Matthews & Reilly 1964). Measurements by Reilly of the natural remanent magnetization of samples collected from dykes on the islands showed that although the rocks are strongly magnetized (median intensity 10^{-2} e.m.u./g, maximum intensity about 0·5 e.m.u./g) the directions of their magnetization are widely scattered. If the rocks which give rise to the observed anomalies are the same it is clear that the anomaly profile must vary from place to place along any particular dyke.

The very sharp magnetic anomalies are confined to the central area of the bank. The approximate limits of this area, indicated by arrows on the profiles (figure 5), are shown in plan on figure 4. (This fact was first pointed out by Dr T. F. Gaskell who directed a magnetic survey of the bank aboard H.M.S. *Owen* in 1962.) On the islands the basic dykes generally follow the direction of the prominent tension joints in the Precambrian granites (Baker 1963, p. 9). They are not found cutting the Tertiary plutonic rocks. It is possible, although by no means necessary, that the line marking the limit of the narrow anomalies also marks the line of the outcrop of the original roof of the granite or of younger sedimentary formations overlying the granite. In this context it may be significant to note that this line passes between the two end stations of the *Argo–Horizon* seismic line (figure 1). At the eastern end, station L.S.D. 20 near Silhouette Island, Shor & Pollard (1963) found only a thin veneer, less than 200 m thick, of mud and coral overlying the granite. This superficial structure is very similar to that found at the *Challenger* and *Discovery–Owen* stations which also lie within the area of large narrow magnetic anomalies. At the opposite end of the line, 80 km westward at station L.S.D. 21, Shor & Pollard report layers with velocities 2·37 and 3·97 km/s overlying the granite (velocity 6·22 km/s) which they found at a depth of 2·9 km below sea level. They interpret these superficial layers as 0·79 km of coral, overlying 2·06 km of volcanic rocks, but these layers could equally well be interpreted as a cover of consolidated sedimentary rocks thickening towards the west above the granite. On the magnetic profiles the characteristic short-wavelength high-amplitude anomalies die away quite abruptly in a distance of 10 to 15 km. If this effect is due to the blanketing of narrow dykes within the granite by overlying strata then the depth to the top of the dykes must increase by 1 to 2 km in this distance, i.e. the top contact of the granite must dip at an angle of 5 to 10°. It would be worthwhile to dredge for these sedimentary rocks on the southwest slopes of the bank and to look for them on seismic reflexion profiles taken west of Silhouette Island.

Calculations have been made to confirm that strongly magnetized basic igneous rocks do not make up a large proportion of the upper part of the bank. If such rocks did occur in large quantity and were exposed in the steep peripheral cliff of the bank then there would be a substantial magnetic anomaly associated with the bank edge. The magnitude of this anomaly has been estimated by F. J. Vine using a computer program written for EDSAC 2. Six profiles were chosen for computation and comparison with the observed total field magnetic anomalies. Their positions, and the results of two typical computations, are shown in figure 6. The model assumes that the topographic profile extends to an infinite distance perpendicular to the track and that the rocks (solid black in the figure) are magnetized with intensity 5×10^{-3} e.m.u./cm^3, as if the Seychelles Bank were a planed off basaltic volcano rather like Bikini Atoll. There is no similarity between the calculated profiles over the edge of the bank and the observed ones. It follows that the bulk intensity of magnetization of the rocks which form the upper layers of the bank must be very much less than 5×10^{-3} e.m.u./cm^3, and we may infer that basic igneous rocks are not exposed in large masses in the cliffs around the bank.

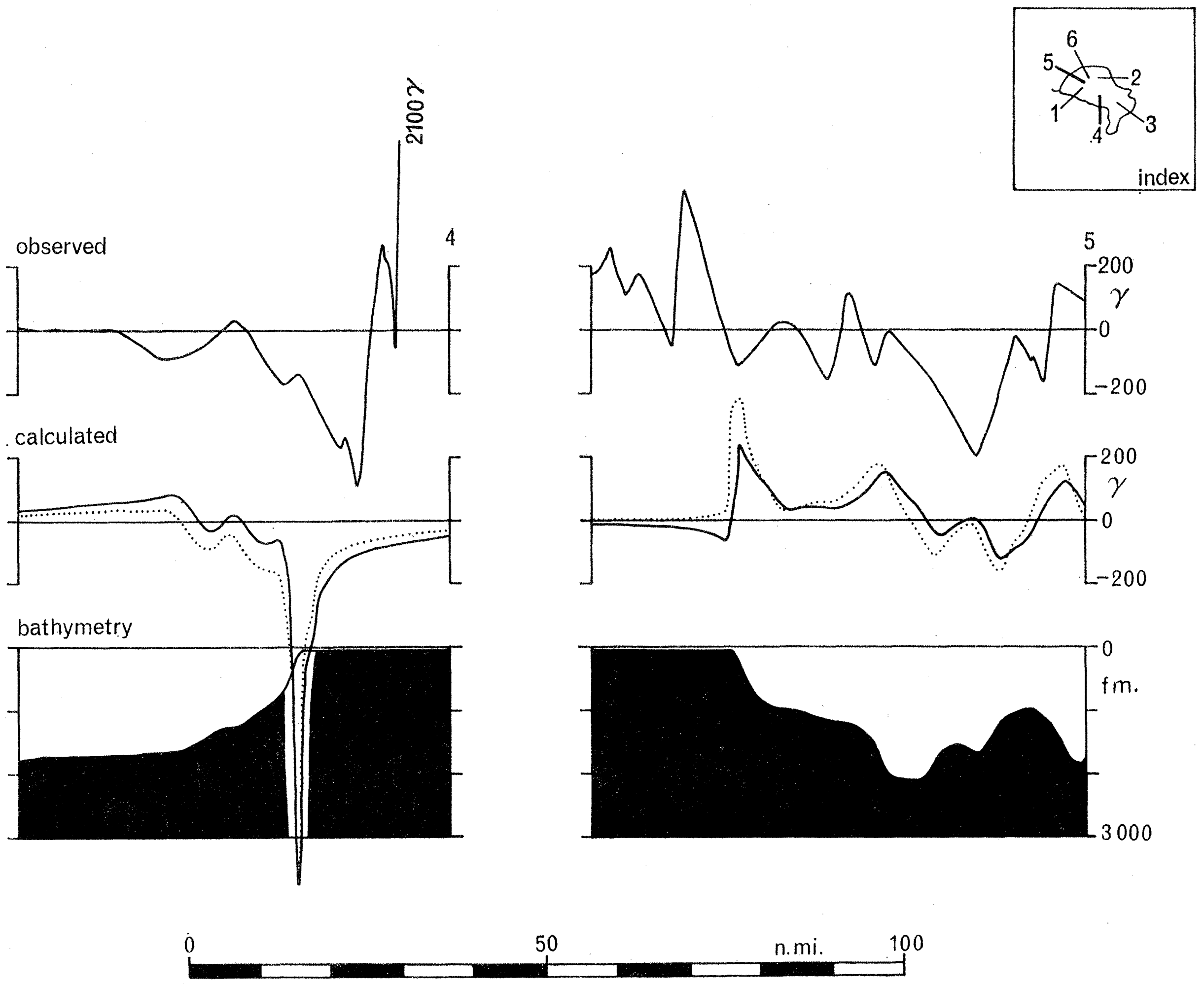

FIGURE 6. Magnetic effect of the edge of the Seychelles Bank. Magnetic anomalies observed over the edge of the bank (*top row*) plotted for comparison with anomalies (*middle row*) calculated on the assumption that the rocks comprising the topography (*lower row*) are uniformly magnetized (—, normal dipole; . . . , induced). Computations were made for six profiles at positions shown in index map. Results for profiles 4 and 5 are illustrated.

The Seychelles Bank lies at the northern end of the Mascarene Ridge, and the volcanic islands of Mauritius and Reunion lie at its southern end. It is of interest to inquire whether the structure of the ridge is essentially continental like the Seychelles or volcanic like Reunion. A magnetometer profile which runs obliquely across the Cargados Carajos Shoals near 16° S, 61° E shows large narrow anomalies over the western part and smaller

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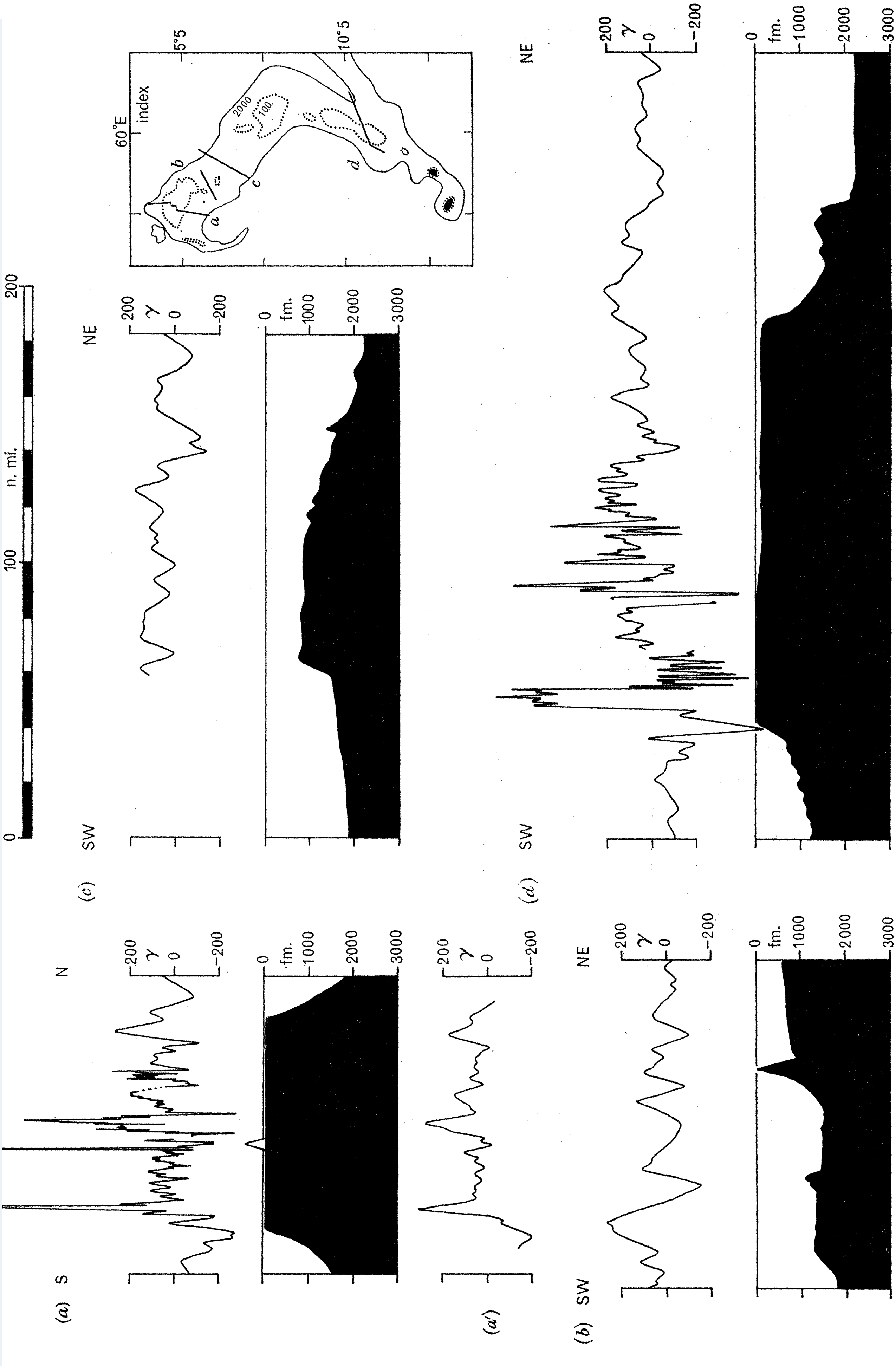

FIGURE 7. Topography and magnetic anomalies along four tracks which cross the Mascarene Ridge at positions shown on index map. (*a*) North–south across Seychelles Bank, (*b*) and (*c*) across saddle between Seychelles and Saya de Malha Banks, (*d*) obliquely across Cargados Carajos Shoal. Index map shows 2000 and 100 fm. contours.

broader anomalies over the eastern part (figure 7, profile *d*). This profile is closely similar to those obtained in a similar depth of water over the Seychelles Bank and, like them, could be produced by dykes cutting continental rocks. However, seismic refraction work on the Saya de Malha Bank (near 11° S, 61° E) indicates that the central part of the Mascarene Ridge is not like the Seychelles Bank but is 'probably a volcanic ridge capped with coral and crystalline debris and resting on oceanic crust' (Shor & Pollard 1963). Magnetic anomaly profiles across the saddle between the Seychelles and Saya de Malha banks are illustrated in figure 7 (profiles *b* and *c*), where they are compared with one of the composite profiles across the Seychelles Bank. The profile *a*, across the Seychelles Banks, is clearly much rougher than that across the saddle, but this difference could be due solely to the difference in water depth between the two. In profile *á* of the figure allowance has been made for this effect by recomputing profile *a* as it would appear were the water depth comparable with that over the saddle. It will be seen that there is then no essential difference in character between the two. We conclude that the magnetic anomalies observed on crossings of the Cargados Carajos Shoals and the northern end of the Mascarene Ridge could be produced by a structure similar to that of the Seychelles Bank, in which abundant basic dykes transect weakly magnetized non-volcanic rocks.

SUMMARY

Seismic refraction studies and gravity measurements confirm that the crust under the flat-topped Seychelles Bank is of a continental type. The thickness of the crust is about 30 km (± about 3 km) under the central part of the bank and this thick crust extends as far as the edge of the bank, defined by the 100 fm. contour. Under the steep northern cliff of the bank the Mohorovičić discontinuity slopes upwards at an angle of about 19°. Magnetometer traverses reveal the presence of an abundant basic dyke swarm which is confined to the central part of the bank. It is possible that these dykes are confined within the Precambrian granites and that other rocks, perhaps representing the original roof or wall of the granite intrusion, are exposed beneath the seabed in the peripheral parts of the bank. Comparisons with other parts of the Mascarene Ridge made on the basis of magnetometer traverses alone, indicate that the ridge could have a structure similar to the central part of the Seychelles Bank, although evidence presented by Shor & Pollard (1963) indicates that the Saya de Malha Bank, like Mauritius and Reunion, has volcanic foundations. This problem requires further study.

In addition to the people mentioned in the text we wish to thank Mrs Susan Vine who has carried out much of the data reduction, computation and drawing. We are grateful to the Hydrographer of the Navy and the Officers and men of H.M.S. *Owen* and to the Director of the National Institute of Oceanography and the Officers and men of R.R.S. *Discovery*. Much of the work has been financed by grants from the Royal Society and from the U.S. Office of Naval Research under contract no. N62558-3883 with the University of Cambridge.

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