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Seismic and gravity data from Afar in relation to surrounding areas

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The Afar triangle is bordered, to the west, by a seismic belt running along and on top of the escarpment. Seventy-five per cent of the seismic energy of the area is released along this belt. The epicentre distribution along the western escarpment coincides either with major north–south marginal tectonic features or with cross-rift faulting. A second epicentre lineation runs at N 15° E through central Afar. To the south-east, in the region of the Gulf of Tadjura, epicentre locations offer no distinct lineation.

The sum of the free-air gravity anomalies over Afar is almost zero; Bouguer values are generally negative and strictly proportional to elevation. Absolute Bouguer positive values are found only over volcanic centres and along the northeastern coast; their maximum does not compare with the positive values found over the nearby Red Sea trough.

Evidence based on attenuation and dispersion of seismic surface waves and on gravity profiles suggests a continental crustal structure of relatively 'standard' thickness under the Afar triangle.

INTRODUCTION

The bulk of modern geophysical information on the Afar triangle and the Ethiopian–Somali swell is practically limited to:

(*a*) Eleven years of seismic observations recorded at the Geophysical Observatory AAE in Addis Ababa (09° 02′ N, 38° 46′ E).

(*b*) A network of some 2500 gravity stations. Naturally the density of stations is higher in areas of potential commercial interests, such as the northern half of Afar, the Eritrean coast of the Red Sea and the southeast sector of the Somali Plateau. Of these, 968 stations have been established by the Observatory and are used as a basis for this study. Whenever possible, stations established by previous authors (list given in Gouin & Mohr 1964, p. 188) have been reoccupied. Through the courtesy of the Ethiopian Ministry of Mines, the author had access to its confidential files but only as a help for controlling the interpretation of his own findings.

(*c*) A few ground magnetic Z profiles.

(*d*) A few aeromagnetic surveys.

The present paper is restricted to the analysis of the seismic and gravity data. The observations on the Afar triangle would not be seen in their true perspective if taken out of their natural context: the Ethiopian–Somali swell, of which Afar is the anomaly.

SEISMIC ACTIVITY IN ETHIOPIA

Frequency of occurrence and magnitude of seismic events

From the area under consideration, a surface of about 1000 km in radius centred on Addis Ababa (N 09°, E 39°) and located at the junction of the Red Sea, the Gulf of Aden and the East African rift system, an average of 1.5 seismic events per day have been recorded during seismically quiet years since 1958. As there is only one seismic station in the area, events happening beyond a maximum epicentral distance, corresponding to their magnitude, are naturally eliminated from these statistics. During the years of higher seismic activity the daily count reached 350, in May 1961 in Addis Ababa (Gouin 1963). In Asmara, 457 shocks (Conti

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Rossini 1947) were reported felt between January and May 1921 and similar figures were also reported during the swarms of quakes which destroyed Massawa in 1921 (Cavasino 1922).

The frequency–magnitude curve for the last 60 years gives the following yearly distribution (table 1). The yearly energy release in the whole area, during a seismically quiet year, corresponds to the energy released by an earthquake of magnitude 7.0 or so.

For the sake of comparison with a nearby sector of the mid-Indian Ocean ridge, the maximum magnitude reached in Ethiopia is 6.75 as compared with 8.3 in the Indian Ocean; and the yearly strain release is about one order of magnitude lower (compared with data given by Stover 1966).

The maximum computed focal depth does not exceed 60 km.

Table 1. Estimated frequency of events above a given M_0

magnitude, M_0	no. of events per year
6.5	0.165
6.0	0.4
5.5	1.1
5.0	2.8
4.5	6.0

Epicentral distribution

For the purpose of this study, where only large tectonic structures are to be investigated, epicentres have been classified in three categories according to the accuracy of their location:

(i) Epicentre location of higher accuracy; that is instrumental epicentres of the last ten years and some previous epicentres for which an electronic recomputation gave a circle of confidence of radius $\leqslant \pm 0.5°$.

(ii) Epicentre location of lesser accuracy, for which the radius of the circle of confidence does not seem to exceed $\pm 1°$.

(iii) Non-instrumental data based on felt reports and surface evidence.

Figure 1 shows the areal distribution of epicentres. It is understood that, for a detailed study, proper weight is to be given to each epicentre and to each centre of seismic activity. Figure 1 is presented here to illustrate the apparent random distribution of epicentres when all available data are used. It is of importance to note that discrete events selected only because of the higher accuracy of their location or because they happened during a selected recent period of time, say the last ten years, do not statistically constitute a valid criterion for the seismicity of a region.

(a) *Epicentre location along the western escarpment of Afar and of the Ethiopian rift*

The western escarpment of Afar and the adjoining crest province west of its outer margin and west of the Ethiopian rift (that is a belt of some 200 km in width), form the most seismically active zone of Ethiopia. 75 % of the total yearly energy is released along this belt.

Epicentres seem to be alined according to two major patterns: (i) along the marginal faults of the escarpment; (ii) along, or subparallel to, major cross faults. Naturally they appear to cluster at the weakest crustal points where cross-faults intersect major marginal faults or ‘grabens’.

This double pattern of epicentral distribution was well illustrated by the sequence of shocks and aftershocks of 1961 in the Wollo province (cluster of epicentres between 10–11° N and

39–40° E, figure 2) from where more than 3000 shocks originated (Gouin 1963). During these swarms of earthquakes, most epicentres were alined N 15–20° W, along the margin of the Robi–Borkenna 'graben', and also NW–SE, parallel to the regional trend of cross-rift faulting.

Centres of seismic activity have moved periodically along this belt during the last century. In 1842, the centre was located around 09.5° N, 40° E and Ankober, the capital of Shoa, was destroyed (Harris 1842); in 1853–4, it had moved 3° to the north along the same meridian and left substantial fissures near Lake Ashangui; in 1884, the epicentres were located off the coast of Massawa; in 1913–15, they were north of Asmara; in 1920–1 Massawa was completely

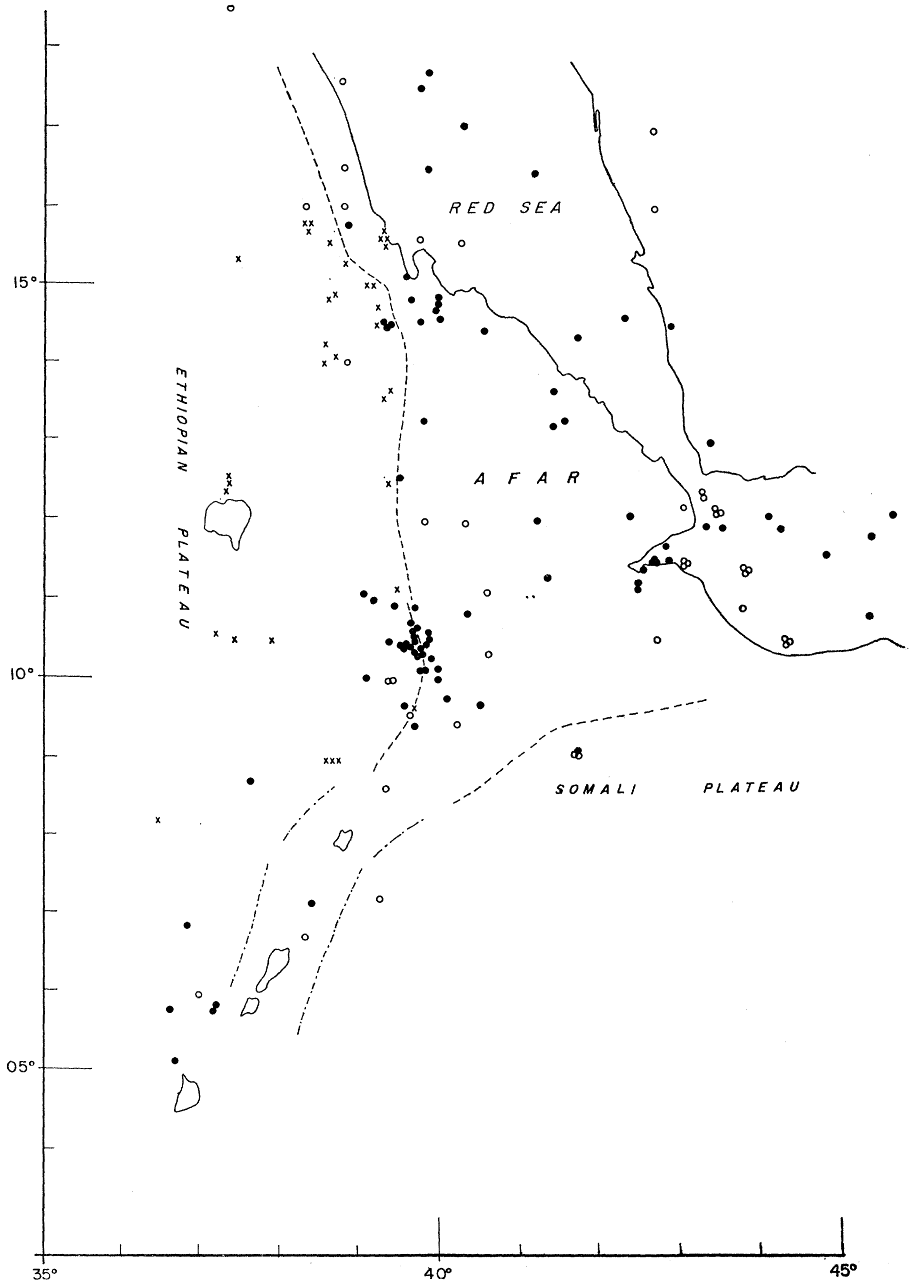

Figure 1. Location of epicentres in Afar and adjacent areas. •, location of higher accuracy; o, location of lesser accuracy; ×, location based on non-instrumental data.

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destroyed; and in 1961 the centre of seismic activity was located in the Wollo province (10–11° N, 39–40° E). This continuously moving activity is a strong argument in favour of an epicentre lineation coinciding with the western escarpment; at the same time it weakens the probability that some of these centres might be linked with other possible lines of activity, for instance the projection into Ethiopia of the Gulf of Aden central line of epicentres.

Figure 2. Location of epicentres along the escarpment of Afar and of the Ethiopian rift. •, location of higher accuracy; o, location of lesser accuracy; ×, location based on non-instrumental data; ▲, epicentre associated with volcanic activity; – – –, outer rift margin; —, major fault line; ▦, graben associated with rift margin; ●, focal mechanism. (Tectonic features after Mohr.)

Note that the western escarpment seismic belt appears to continue northwards towards the central trough of the Red Sea, as suggested by the apparent lineation of epicentres north of 15° N. The only fault-plane solution available for this zone is that of an event which occurred on 11 November 1962, at 17.05° N and 40.58° E, computed by Sykes (1968). The solution indicates a left-lateral strike-slip movement in the general direction of the western escarpment of Afar. The focal-mechanism solution, however, is not unambiguous (private communication, 1968).

By contrast with the Ethiopian plateau, the seismicity of the Somali plateau and of the southern escarpment of Afar is very low. Only one series of earthquakes was recorded: that of 1953 in Harar province (09° N, 42° E).

(*b*) *Location of epicentres in the Ethiopian rift and in Central Afar*

Other epicentres are located in the rift valley and in Afar. They seem to follow an important fracture zone known as the Wonji Fault Belt (Mohr 1960), and its postulated prolongation through central Afar where it enters the Red Sea at 14° N, 42° E. Through central Afar, the Wonji Fault Belt is thought to be characterized by a line of alkaline silicic volcanoes (Mohr 1968), although, north of the 12th parallel, it is not self evident that the major fault pattern trends also in the direction of this volcanic lineation (unpublished tectonic map by Mohr 1967).

In contrast with the western escarpment, the seismic activity along the Wonji Fault Belt is far smaller, and many of the shocks located north of the 12th parallel are known to have been associated with volcanic activity: Dubbi, 1861; Afdera, 1907; Erta-ale, 1906–7.

(Note added to the original text: from 29 March 1969 until mid-April—date that this paper was given for printing—swarms of earthquakes shook central Afar along the 12th parallel between 41° and 42° E. The maximum magnitude reached 6.3. Faults striking either N 40° W or N 60–70° W developed; these two directions correspond to the regional surface faulting trends. Left-lateral shear displacements up to 50 cm, striking N 40° W, were observed; the vertical displacement reached 75 cm).

On the northeastern and eastern border of Afar, epicentres appear to be related either to the western marginal fault scarp of the Danakil 'horst' or to that of the Haïsha horst, south of the Gulf of Tadjura.

(*c*) *Location of epicentres at the junction of the Red Sea and Gulf of Aden*

In the sector located between 10–13° N and 43–45° E, at the extreme west end of the Gulf of Aden and its junction with the Red Sea, the percentage of epicentres for which the coordinates are inaccurate is high. Nevertheless, the scattering of the more accurately located epicentres is such that, in all probability, those of less accurate or doubtful location would not, even if properly relocated, fall on a single line. Similar scattering also appears in the Red Sea itself south of 17° N (see figure 1).

In contrast with the relatively linear distribution of epicentres along the main axis of the Gulf of Aden trench, such a scattering, if real, suggests that seismic activity is not associated there with simple linear tectonic patterns but corresponds to a grid pattern of lines of weakness as is normally expected in a region under horizontal tension from more than one direction.

INFORMATION ABOUT CRUSTAL STRUCTURE UNDER AFAR FROM SEISMIC RECORDS

A preliminary study of the dispersion of first mode Rayleigh and Love waves from an event which took place on 16 November 1967 in northern Afar (15.9° N, 39.82° E) indicates that along the wave path from the north end of the Danakil Horst to Addis Ababa (that is, through the western section of Afar), the dispersion curves for group velocities closely correspond to the standard curves presented by Oliver (1962) for continental paths.

The surface-wave dispersion curves for seismic events originating at the south end of the

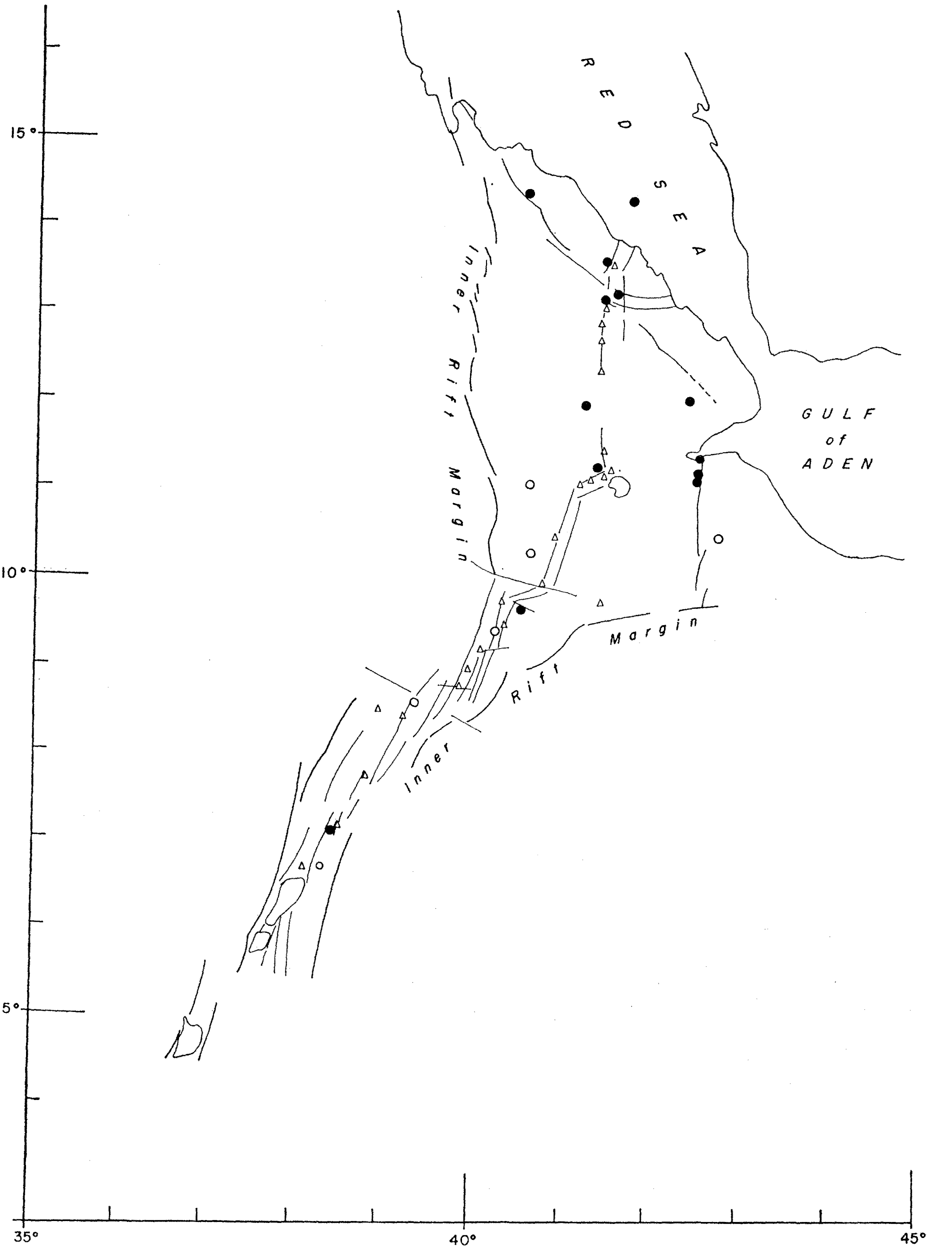


FIGURE 3. Location of epicentres along the axis of the main Ethiopian Rift and in central Afar. •, location of higher accuracy; ○, location of lesser accuracy; △, volcano; ——, major fault (after Mohr).

Danakil horst (12.21° N, 42.58° E) or at the west end of the Gulf of Aden (12.00° N, 42.77° E) differ slightly from the previous ones, and point towards the presence of a small proportion of basaltic intrusion along the wave path from the junction of the Red Sea and Gulf of Aden to Addis Ababa (Jones 1968).

Although the transmission paths for these three shocks are undoubtedly too short to allow the development of well-dispersed surface waves over a wide range of periods, Jones's preliminary results are a good indication that the crustal structure under Afar is mainly of continental nature, although, in some areas, it is contaminated by a certain proportion of mantle material.

This assumption is confirmed by the presence of Lg waves ($T = 1$ s; $v = 3.54$ km s^{-1}) on the A.A.E. records for events originating at the west end of the Gulf of Aden. A group velocity

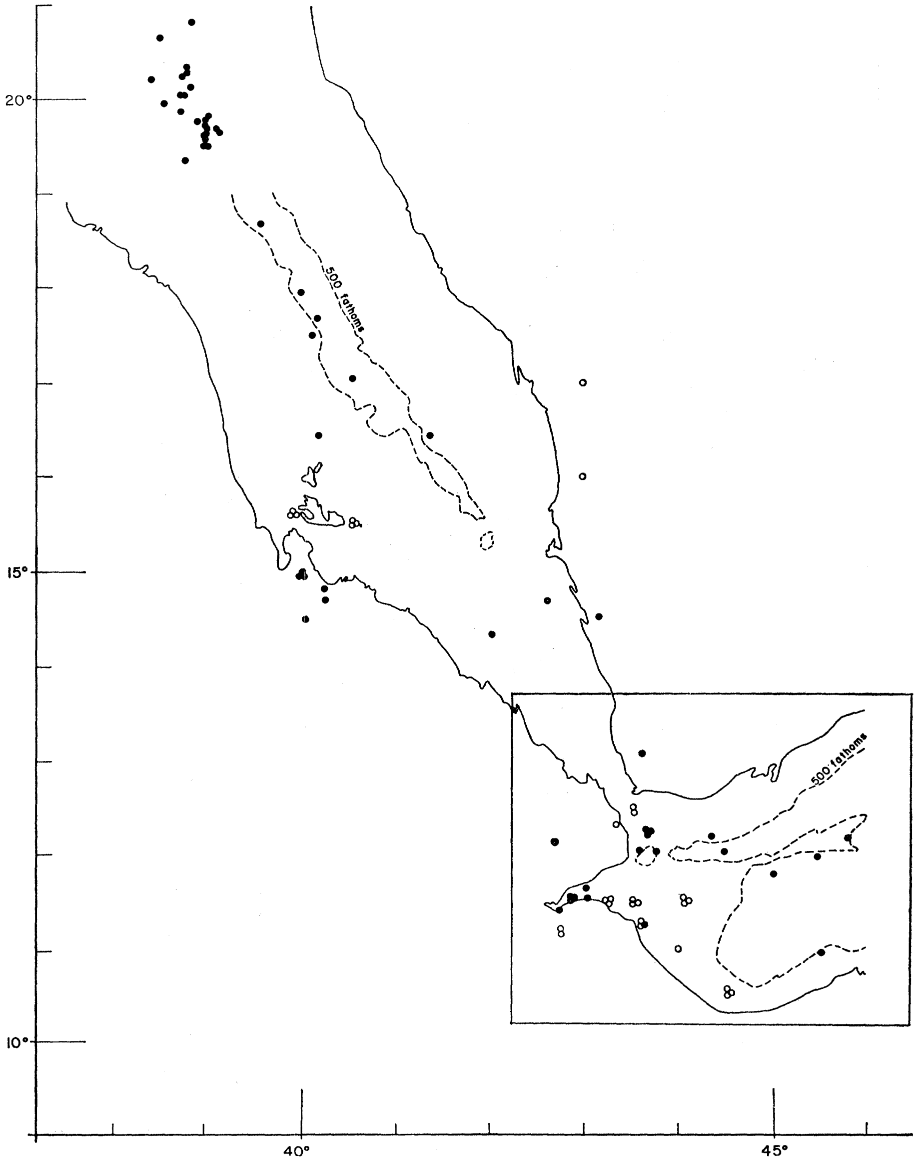


FIGURE 4. Location of epicentres at the junction of the Red Sea and the Gulf of Aden. •, location of higher accuracy; o, location of lesser accuracy.

of 3.54 to 3.55 km s^{-1} for Lg waves falls within the range of velocities (3.47 to 3.58 km s^{-1}) found by Pomeroy & Oliver (1967) for Africa. Press, Ewing & Oliver (1956) found a group velocity of 3.46 km s^{-1} for Lg waves along a north–south path through West Africa.

Gravity field over Ethiopia

Gravity data for some 1000 stations scattered over Ethiopia have already been published, as well as their probable correlation with geological and tectonic features of the Ethiopian–Somali swell and of Afar (Ballarin 1943; Pacella 1948*a*; Gouin & Mohr 1964, 1968; Mohr & Rogers 1966; Mohr & Gouin 1967). We will recall here, by means of a few typical traverses, only general gravity patterns. Due to the lack of accurate topographic maps, only free-air and simple Bouguer values have been computed. A location map (figure 6) indicates the geographic

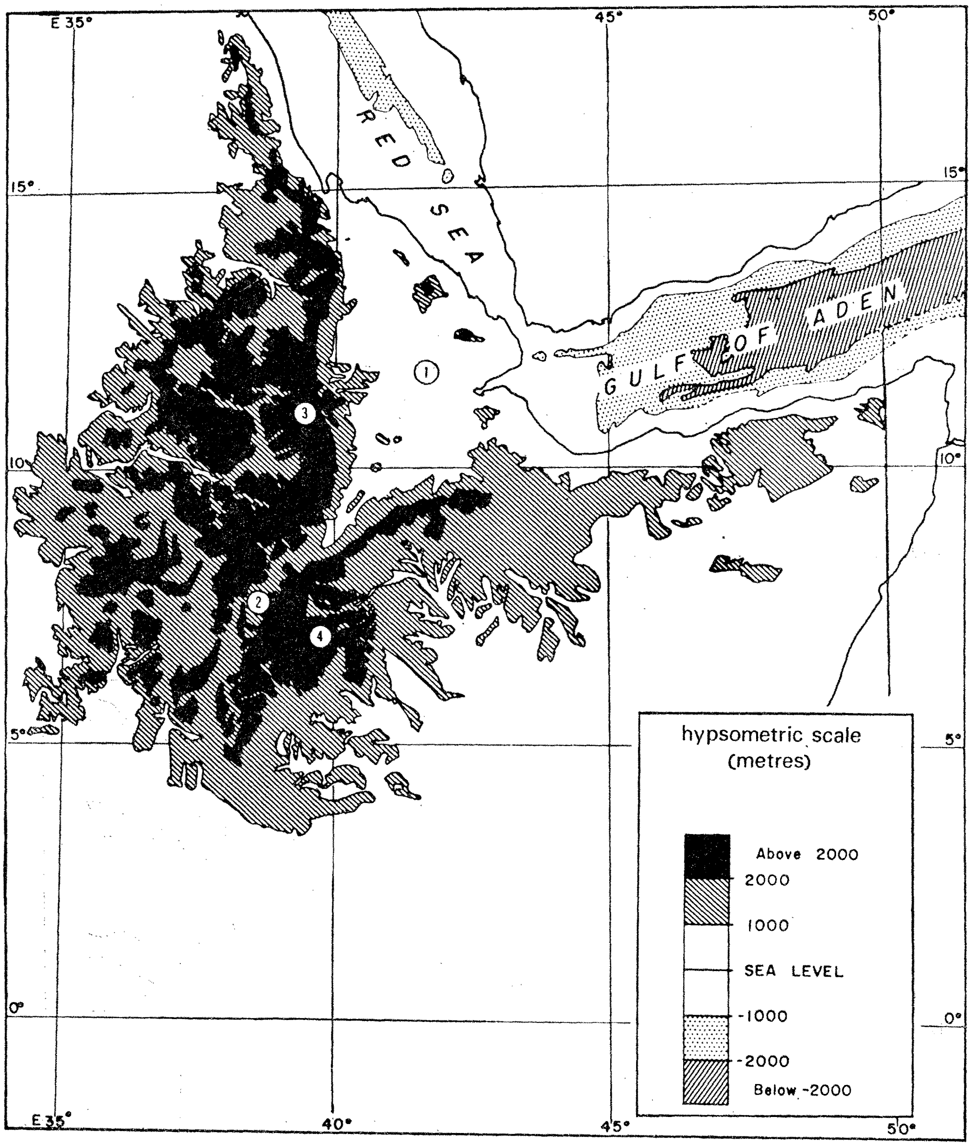


Figure 5. Outline physiographic map of Ethiopia. The numbered regions are: (1) Afar, (2) Main Ethiopian Rift, (3) Ethiopian Plateau and (4) Somali Plateau.

position of these traverses, and their corresponding profiles are to be found in figures 7 to 12 respectively.

The area is divided in three sectors (figure 5). (1) the Plateaux (Ethiopian and Somali); (2) the Ethiopian rift; (3) the Afar triangle.

Needless to say, all data do not carry the same weight, due to probable errors in position and elevation. Out of 968 stations, 128 were established on first-order elevation bench-marks (U.S. C.G.S. 1957–1961) and whenever possible the gravity survey loops were closed at these points. Other loops were closed on two railway level-surveyed lines (Asmara–Massawa and Addis Ababa–Djibuti) both linked to sea-level stations. A few loops close on Italian triangulation controls. All other elevations were obtained by altimeter readings. It is highly probable that on long profiles made in sectors and on different occasions, erroneous anomaly values due to errors in elevation (which in extreme cases reach a possible 20 to 30 m over a total range of 3500 m) do not alter the general attitude of the gravity curves.

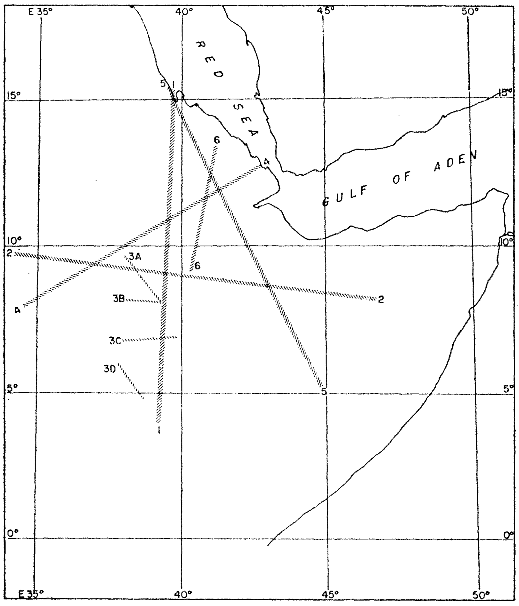


FIGURE 6. Location map of gravity traverses.

For practical purposes, all station values have been projected onto a meridian or a parallel rather than plotted against road distances as done in our previous reports. The distortion produced on the curves by such a projection does indeed change the apparent slope of some anomalies on the regional anomaly, but certainly does not significantly alter the general trend of a profile many hundreds of kilometres long.

(a) *Gravity anomaly over the plateaux*

Two traverses have been chosen (1 and 2 on figure 6, with corresponding profiles on figures 7 and 8), running across the entire Ethiopian–Somali swell at almost right angles to each other. They intersect on the Ethiopian plateau near Addis Ababa, somewhat south of the region of mean maximum elevation. The choice of these profiles was dictated by their geographic position and by the greater number of stations along their paths.

It is evident from these two profiles that the general Bouguer gravity pattern over the swell

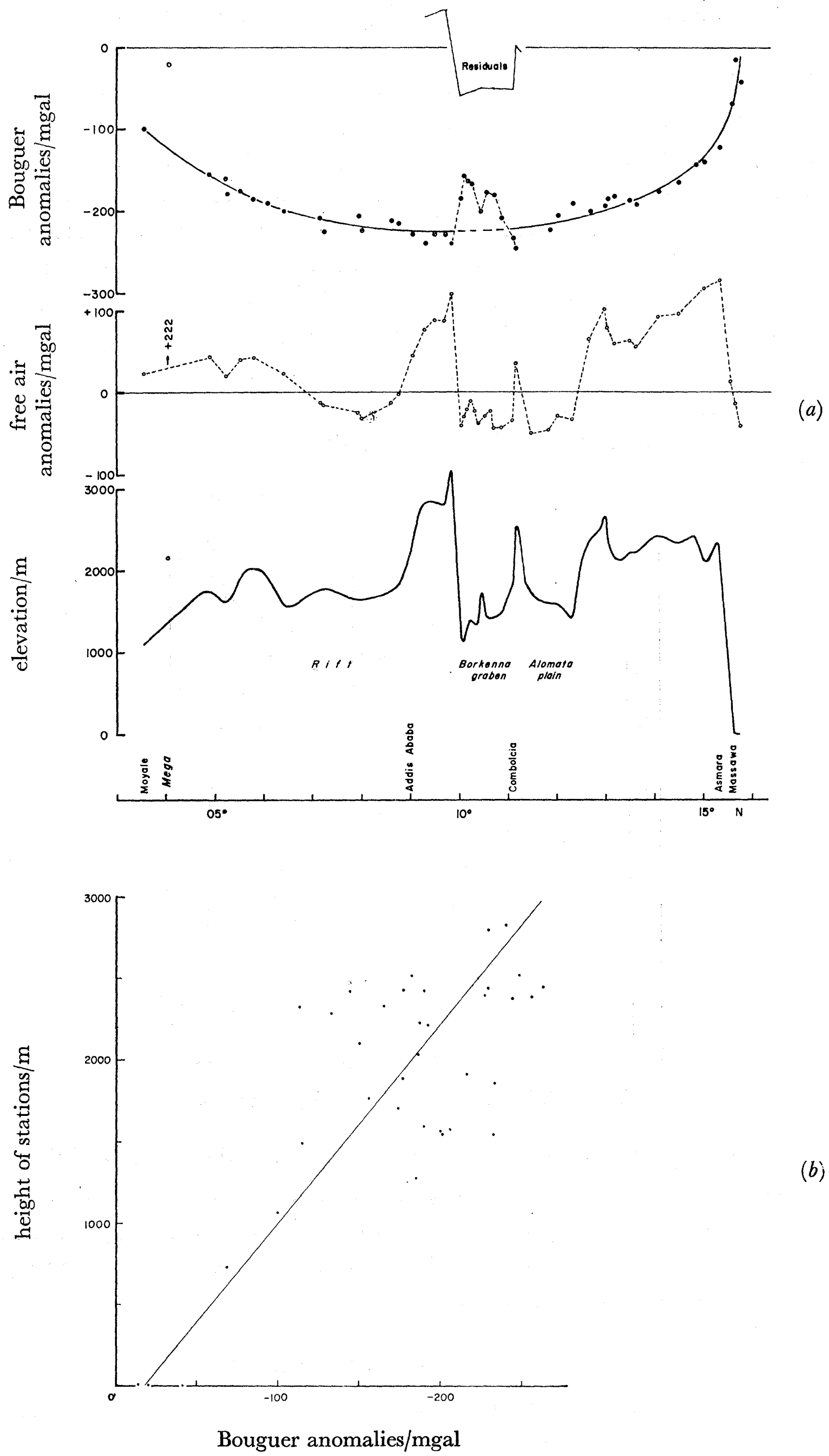


FIGURE 7. North–South gravity traverse across the Ethiopian plateau.

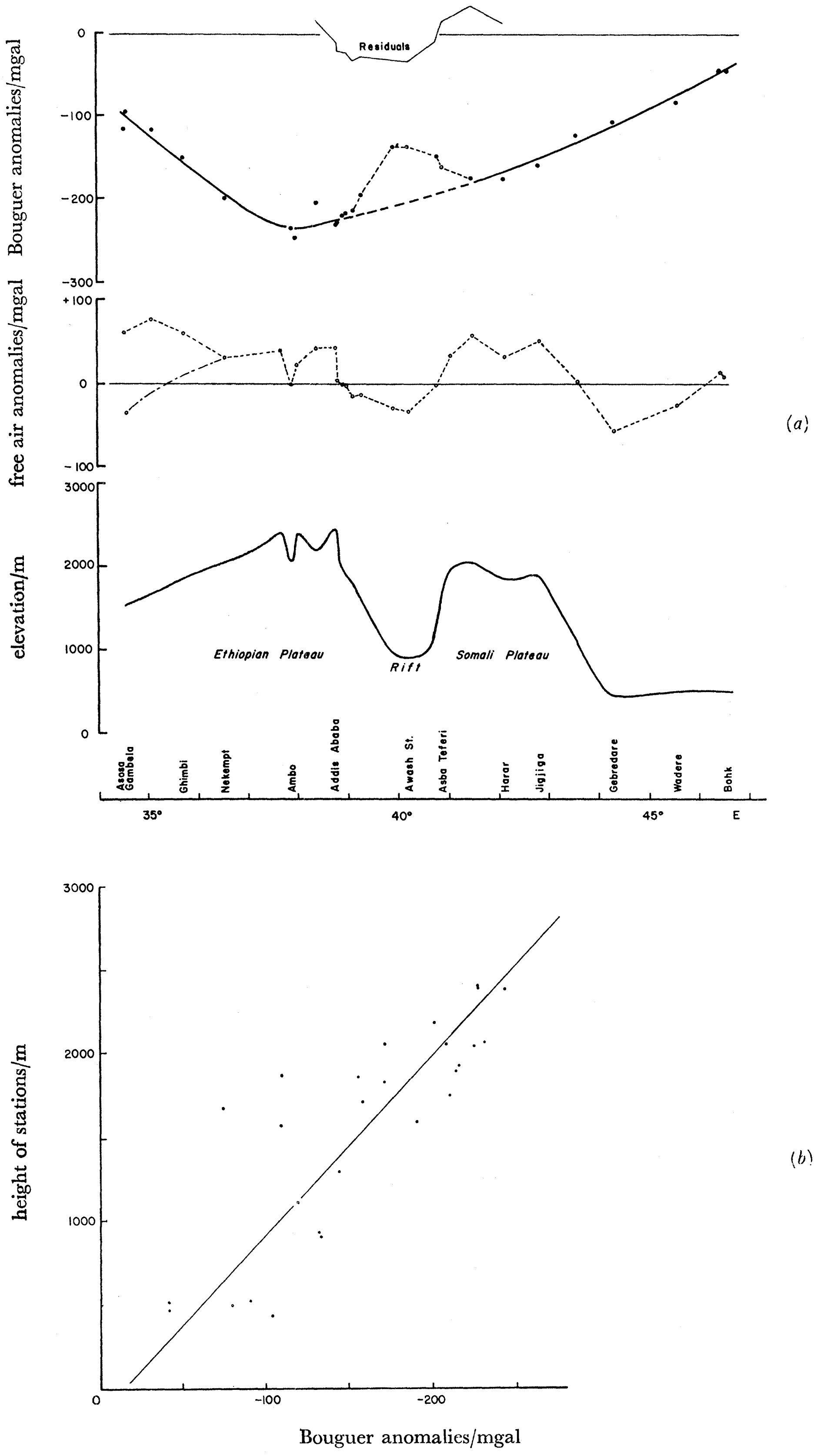
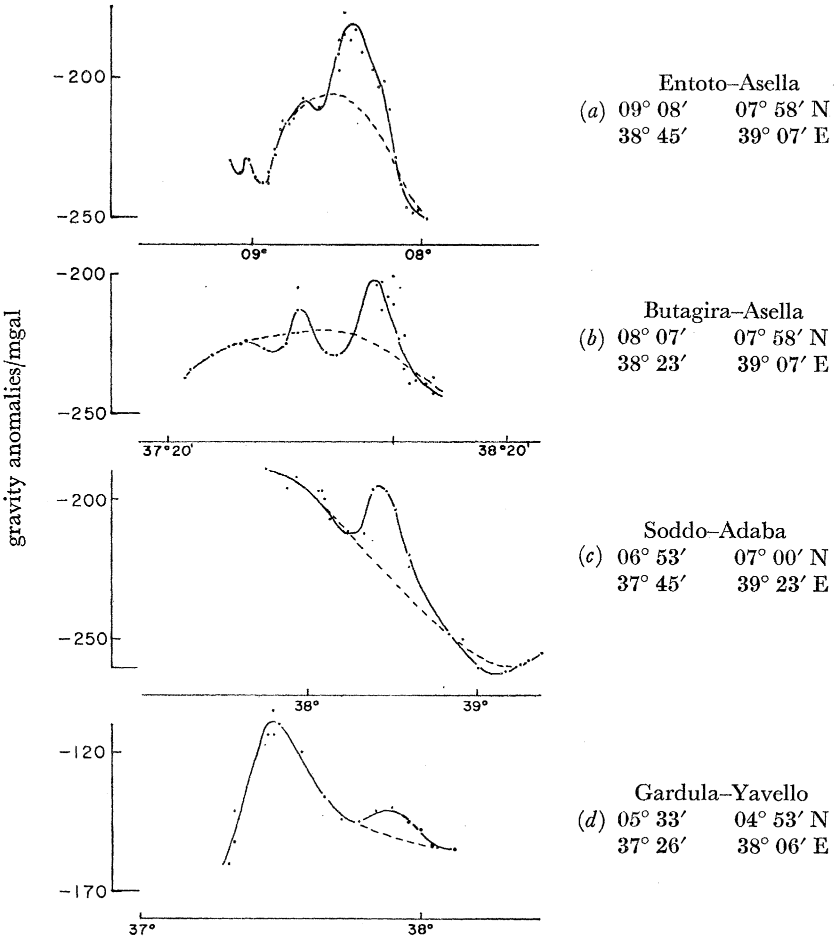


Figure 8. WNW–ESE gravity traverse across the Ethiopian–Somali swell.

resembles a huge negative concave dome reaching a minimum of some −270 mgal† under the Wollo province (10–12° N, 37–39° E). The gravity minimum occurs over the area of mean maximum elevation. The smoothness of the Bouguer anomaly indicates a much more regular distribution of the compensating deficiency in crustal density than the above sea-level topography would suggest (see scattering on graph 7*b*). The slope of the regression lines on both scatter diagrams 7*b* and 8*b* is about $0.09h$. Such a ratio, approximately equal to the Bouguer correction factor, suggests in a general way that the plateau is underlaid by a density deficiency nearly proportional to the attraction of the above sea-level topography, and that this deficiency is almost equal to zero at sea level at the margin of the swell.

The free-air profiles reveal nothing significant since they match too closely the topographic cross-sections. The only exceptions are the last three stations at the east end of figure 8*a*.



Entoto–Asella
(*a*) 09° 08′ 07° 58′ N
38° 45′ 39° 07′ E

Butagira–Asella
(*b*) 08° 07′ 07° 58′ N
38° 23′ 39° 07′ E

Soddo–Adaba
(*c*) 06° 53′ 07° 00′ N
37° 45′ 39° 23′ E

Gardula–Yavello
(*d*) 05° 33′ 04° 53′ N
37° 26′ 38° 06′ E

FIGURE 9. Gravity profiles across the Ethiopian rift.

(*b*) *Gravity over the Ethiopian rift*

The smooth regional trend of the Bouguer anomaly over the Plateaux is broken on both profiles by a sudden positive inflexion. That a positive inflexion happens to be located near the minimum on each profile is strictly accidental. The positive inflexion on the north–south

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† 1 mgal = 10^{-3} cm s^{-2} = 10^{-5} m s^{-2}.

profile (figure 7 *a*) occurs over the Robi-Borkenna 'graben' along the rim of the western escarpment of Afar. Its strike is thought to be parallel to the main axis of the 'graben'; its relative importance on the profile is highly exaggerated by the fact that the traverse runs at a very small angle to this axis. We simply note its presence and direction, since this 'graben' is not part of the Ethiopian rift proper.

The positive inflexion of +60 mgal on the Bouguer curve of figure 8*a* is relevant. At the latitude of Addis Ababa, the traverse runs almost normal to the axis of the rift and the positive anomaly does not correspond to the observations made by Bullard (1936) across the East African rifts, where the Bouguer anomaly was found to be negative and where free-air, Bouguer, and isostatic curves matched the topography of the land. Nor does it correspond to the ill-defined Bouguer profile over the Dead Sea rift (Knopoff & Belshe 1965).

For more details on the relative positive anomaly over the rift, four profiles for different latitudes are given in figure 9. In three of these profiles, over better defined topographic cross-sections of the Ethiopian rift, (9*a*, *b* and *d*), two characteristic features stand out:

(i) a smooth, convex, positive trend (dotted line), the exact magnitude of which cannot easily be determined,

(ii) a positive modulation of the regional trend.

The amplitude of the regional Bouguer anomaly (see table 2) can apparently be accounted for by the difference in elevation of the stations, the thickness of sedimentation on the rift floor, and terrain effect.

TABLE 2. GRAVITY DATA FOR PROFILE 9*a*

	mgal
estimated regional anomaly	+50 to +60
estimated Δg due to Δh Entoto side − floor = 1100 m Asella side − floor = 750 m anomaly/height ratio = 0.093 *h*	+80 to +90
estimated Δg due to sedimentation from profile 6 (figure 12)	−20 to −30
estimated topographic correction	up to −5 to −10

The positive convex shape of this anomaly, the relationship between anomaly and elevation, and the maximum amplitude of the anomaly suggest as a first approximation, provided the assumed mean density of 2.67 g cm^{-3} is valid, a valley simply cut through a swell. No corresponding crustal model with proper mass distribution has yet been computed.

Superimposed on four profiles of figure 9 is a secondary positive high which coincides on the surface with the Wonji Fault Belt. These 'highs' are thought to be connected with local basaltic dyke intrusions, very limited in width, along the axis of this important fracture zone (Gouin & Mohr 1964, 1968; Mohr 1967*a*). The steep gradients of these highs indicate a shallow origin.

(*c*) *Gravity anomaly over the Afar Triangle*

Afar as a whole—when the topography is not suddenly disturbed by important tectonic structures such as: (*a*) the Danakil depression rift in the north, (*b*) annular faulting in the south-east, or (*c*) volcanic centres—offers a rather monotonous gravity pattern in which the sum of the free-air anomalies is almost zero and the Bouguer anomaly is strictly proportional to elevation. The limiting marginal elevation of Afar was arbitrarily taken as 1000 m above sea level along the escarpments, and the density as a first approximation as 2.67 g cm^{-3}.

The main characteristic of the gravity pattern is a constant increase from a minimum of some -100 mgal along the escarpments, to near zero at sea level, regardless of whether sea level is reached inland or on the Red Sea shore. This trend is illustrated by figures 10 to 12. Each profile in these figures includes a sector of either the plateaux or of the rift floor in order to detect major gravity transition, if any, between the different surrounding regions and the Afar triangle.

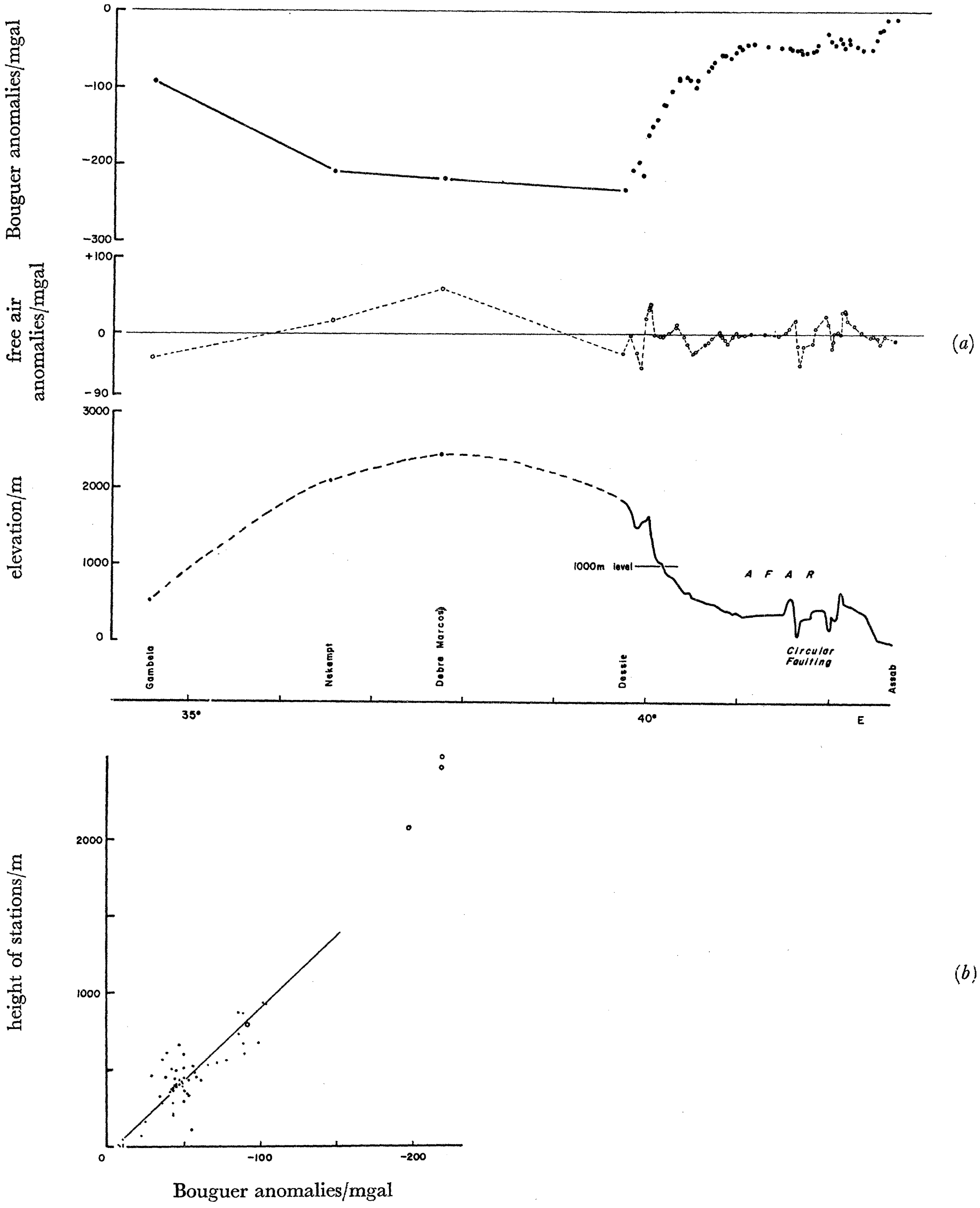

FIGURE 10. SW–NE gravity traverse across the Ethiopian Plateau and Afar. On scatter diagram (*b*): •, Afar stations below 1000 m; o, plateau stations.

Traverse 4, with corresponding profiles on figure 10, starts from the western rim of the Ethiopian Plateau at Gambela (08° N, 34° E) and crosses the region of mean maximum elevation at Debre Marcos before reaching Afar. It terminates on the Red Sea shore at Assab (13° N, 43° E). On this traverse, most gravity stations were established on first-order vertical control stations (U.S.C.G.S. 1957–61). In Afar itself the topographic cross-section is disturbed between 41.5° E and 42.2° E by important annular faultings (Mohr 1968). The free-air anomaly

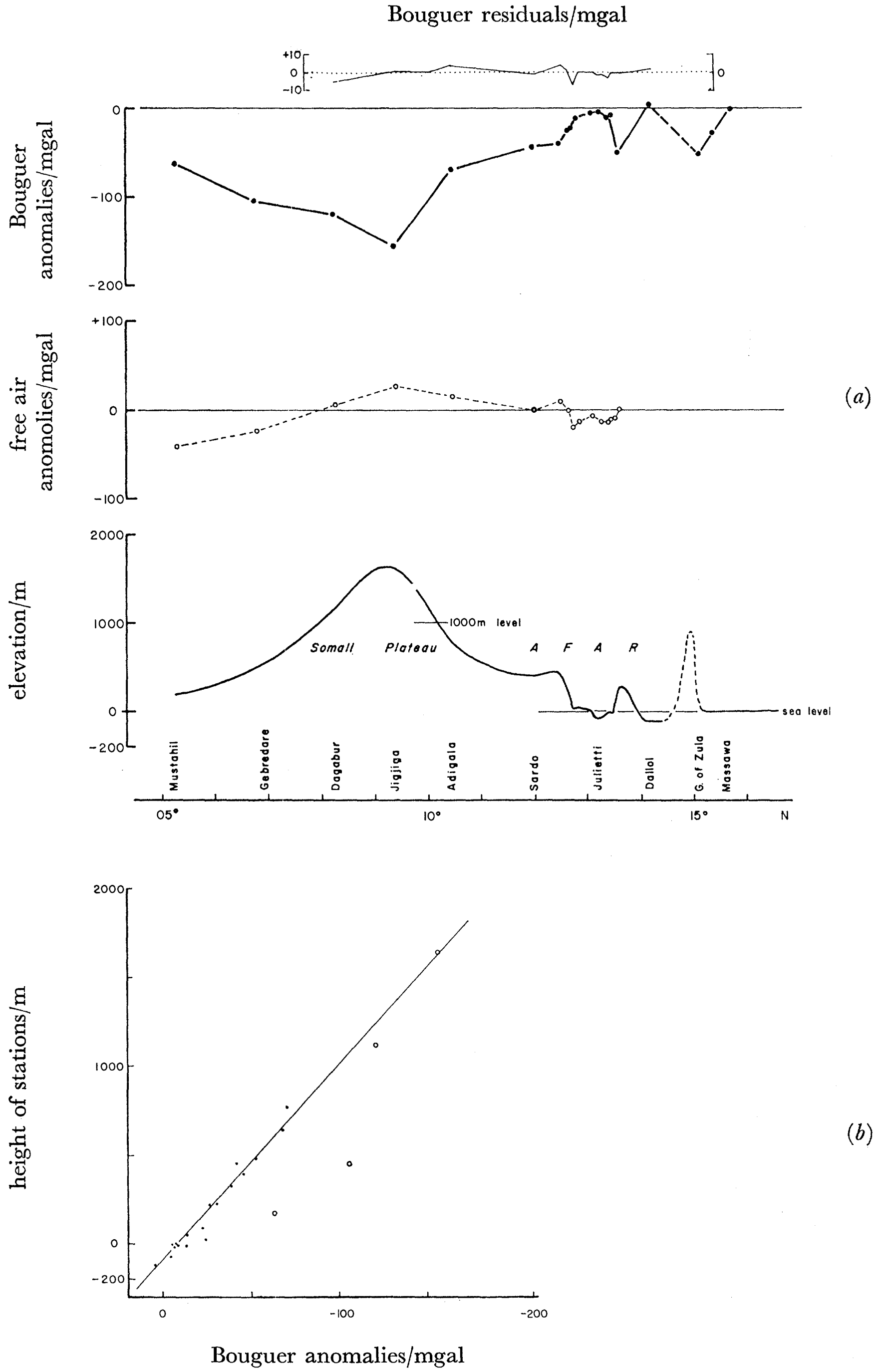

Figure 11. SSE–NNW gravity traverse across Somali Plateau and Afar. On scatter diagram: •, Afar stations below 1000 m; o, plateau stations.

closely matches the topography, except on the escarpment from 39.7° E to 40.5° E where amplified oscillations coincide with important marginal faulting and block tilting. The Bouguer curve, on the same scale, is much less disturbed and the amplitude–elevation correlation is evident on the graph 10*b*. Note that on this graph the Ethiopian Plateau Bouguer values appear to be relatively more positive than expected.

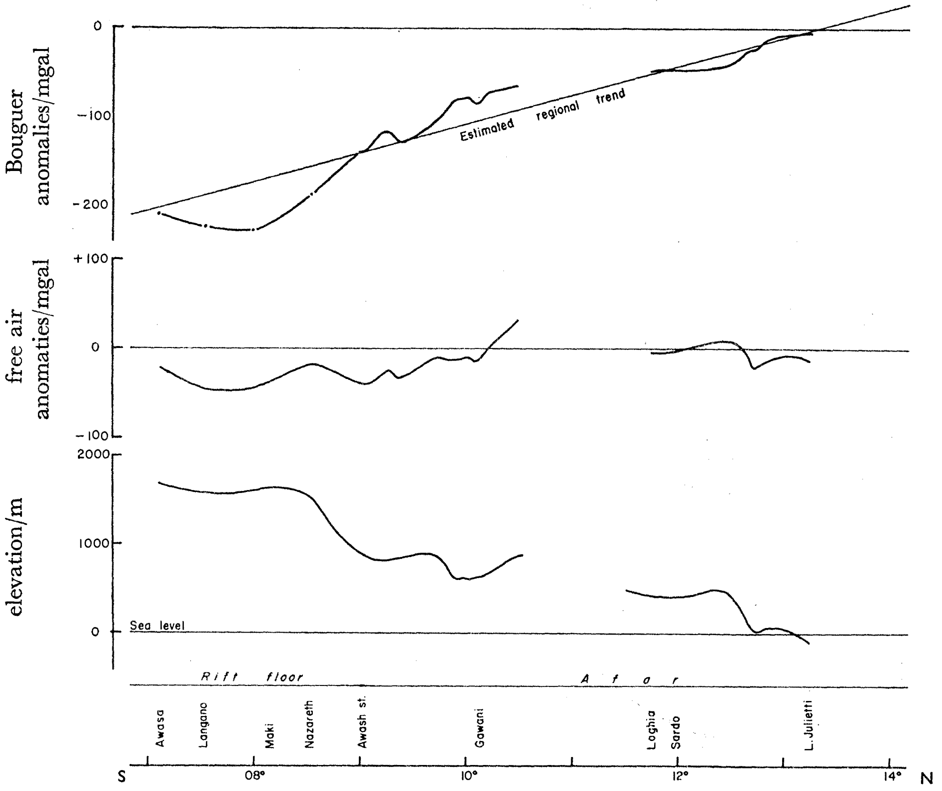

FIGURE 12. Gravity traverse from the rift floor into central Afar.

Traverse 5 on figure 6 (profiles of figure 11) starts from the southern limit of the Somali Plateau in Ethiopia at Mustahil (05.4° N, 44.8° E) crosses the Somali Plateau and Afar in a SSE-NNE direction and terminates on the Red Sea coast at Massawa (15.6° N, 39.5° E). The topography of the Afar floor is violently disturbed, north of 12.5° N, by the Danakil Depression rift which the traverse crosses lengthwise. This 'graben' is about 250 km long and 100 km wide and strikes in a NNW–SSE direction. It is marked in its central axis by a line of volcanic centres over which the Bouguer anomalies are positive. Traverse 5 avoids this volcanic line and runs mostly on the floor of the 'graben'. Such a profile, avoiding local anomalies which are very limited in width, offers the same general gravity picture as shown by traverse 4 (figure 10). The dispersion on the anomaly–height graph is smaller than on the previous one, but in this case, the Bouguer values for the Somali Plateau seem more negative than expected. These negative values are probably due to thick sedimentation in the Wabi Shebelli basin.

Details on the gravity pattern over the Danakil Depression rift are given by Holwerda & Hutchinson (1968) and in unpublished reports from mining companies.

Figure 12 shows profiles from the rift floor to the Afar sector (traverse 6 on figure 6). The estimated regional trend of the Bouguer curve, indicating an anomaly approaching zero at sea level, is simply modulated in the south by a 39 to 40 mgal negative trough where the thickness of the sediments in the rift lakes region is known to be relatively great, and by a small 10 to 15 mgal positive where the profile runs over the Wonji Fault Belt at the foot of the Ayelu volcano and along a 100 m fault uplift in the region of Gawani (09.5° N to 10.5° N). Here again, the Bouguer values are proportional to elevation.

Absolute positive Bouguer values in Afar were found to be restricted to:

(*a*) The top of the central volcanic line of the Danakil Depression rift where a few maximum values are known to reach $+65$ mgal when computed for a mean crustal density of 2.67 g cm^{-3}.

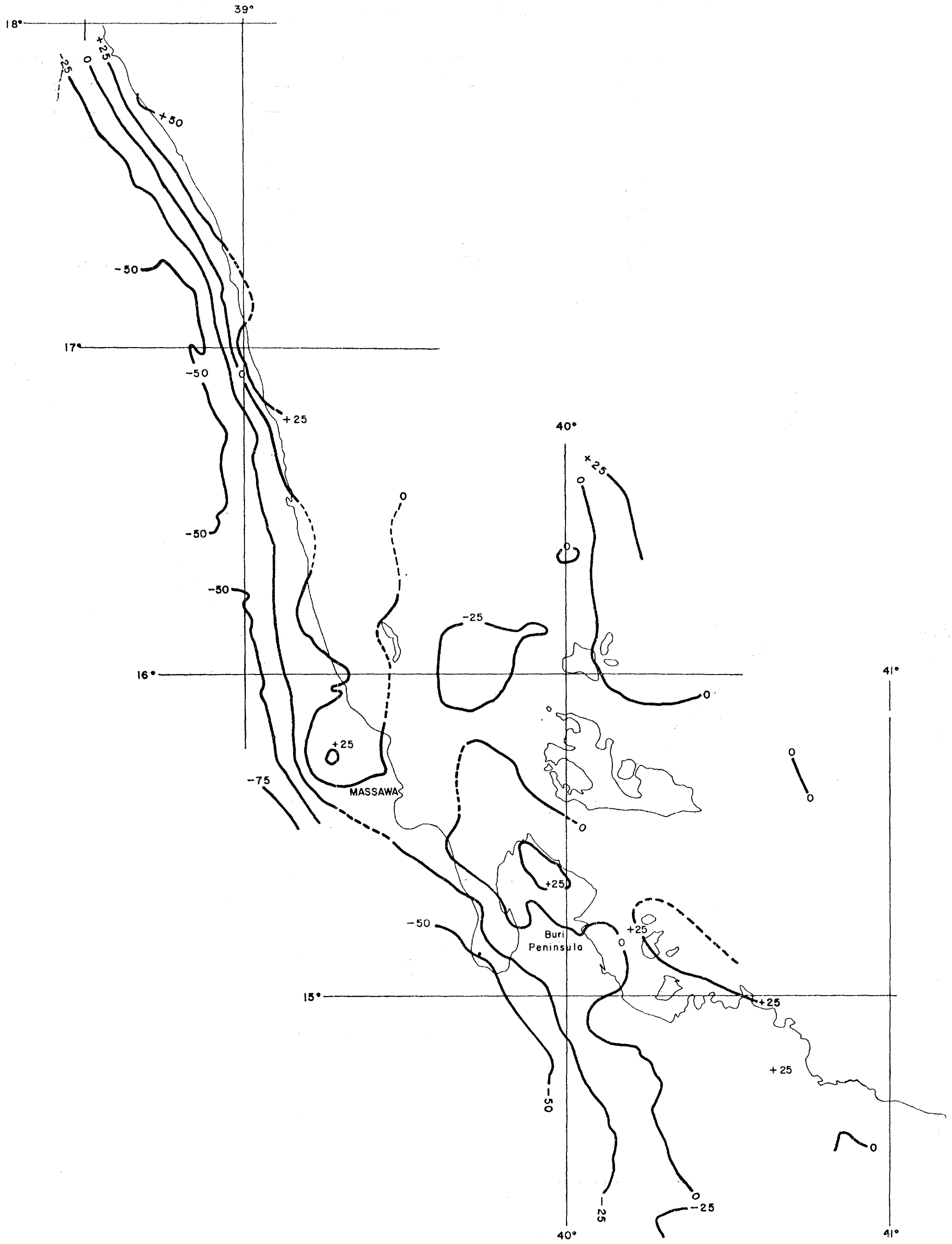

FIGURE 13. Final Bouguer gravity map of Eritrean coast of Ethiopia, after Naftaplin. Units are milligalileos. (By courtesy the Ministry of Mines and State Domain, Addis Ababa.)

(*b*) Along the coast, north of the Danakil Horst (Naftaplin 1959, 1960). On the Eritrean coast the positive anomalies are discrete and elongated in shape with their main axis parallel to the coast line (figure 13). The maximum values reach +50 mgal.

(*c*) South of 14.5° N. On the coast at the foot of the Dubbi volcano complex, values up to +7 mgal have been reported (Gouin & Mohr 1964).

None of these positive values compare with the +150 mgal found over the Red Sea central trough (Girdler 1958).

TABLE 3. PARAMETERS OF GRAVITY STATIONS FOR RANGES OF 500 m

range of h/m	N stations	mean h/m	mean FA/mgal	mean B/mgal
−500 to 0	6	−33	−11	−7
0 to 500	66	248	−7	−35
500 to 1000	86	772	−10	−98
1000 to 1500	121	1324	−8	−163
1500 to 2000	357	1831	−5	−196
2000 to 2500	252	2228	+43	−206
2500 to 3000	96	2661	+70	−228
3000 to 3500	3	3105	+108	−239

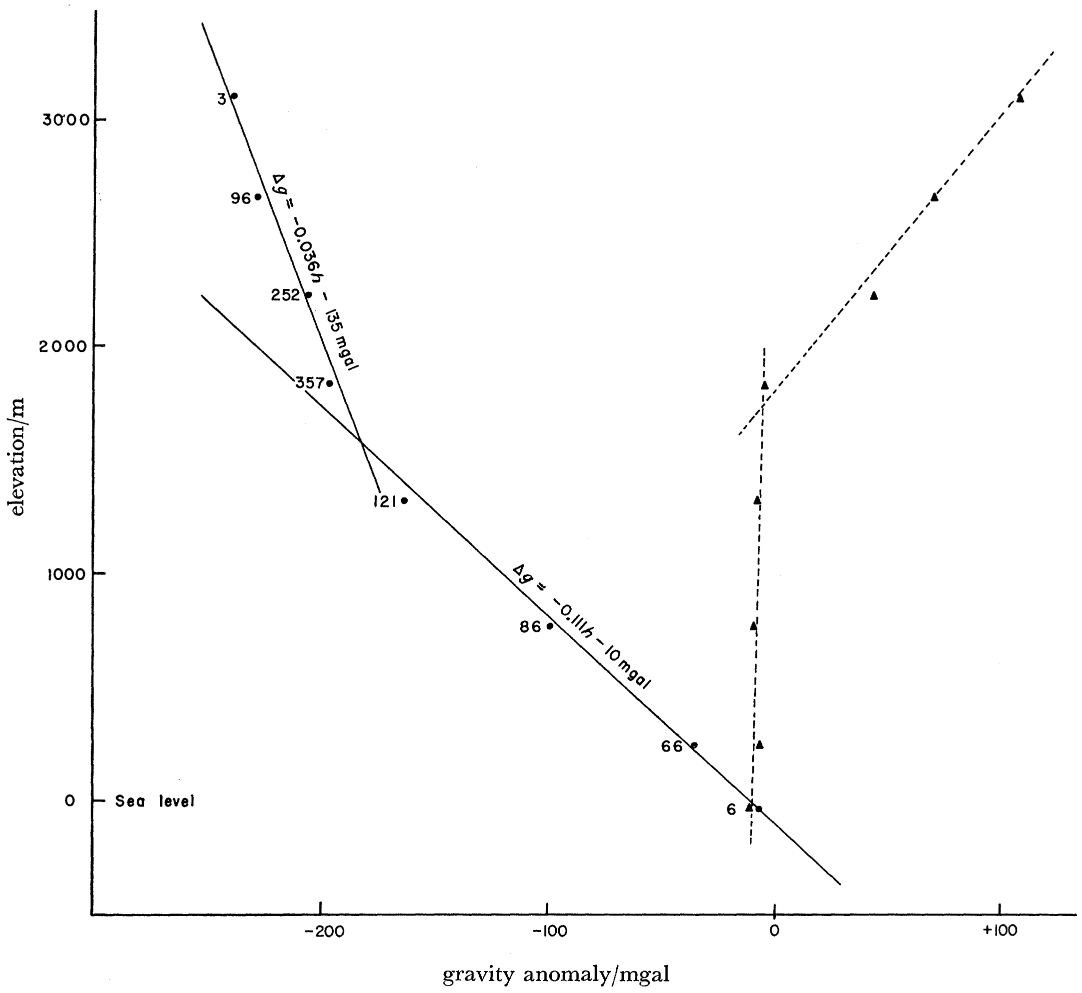

FIGURE 14. Mean gravity anomaly against mean elevation for ranges of 500 m. ——, simple Bouguer anomaly; – – – –, free air anomaly. The number of stations used is indicated besides each point.

ISOSTASY

Estimation of the isostatic equilibrium of a large sector of the Earth's crust is normally based on the sum of isostatic anomalies for an assumed crustal thickness. For the area under consideration, no isostatic anomalies have yet been calculated; moreover, the geology is barely known and no attempt has ever been made to determine inland crustal thickness from seismic reflexion surveys. Very few off-shore seismic profiles are available. Some indications of the isostatic balance could, however, be inferred from the degree of correlation between the Bouguer anomalies and the elevation of the stations.

As a first approximation, elevations from all stations were grouped in ranges of 500 m and the mean values of the anomaly were plotted against the mean elevation of each group. The results are shown in table 3 and figure 14.

The graph (figure 14) shows mean free-air and mean Bouguer values which aline much too well to be real. The exaggerated smoothing of the curve is no doubt due to the excessive range in elevation of each group. However, one important feature stands out: the knee in the two gravity curves at about $h = 1600$ m. Below 1600 m (that is most of Afar and the margins of the plateaux), the mean free-air values are near zero and the Bouguer–height ratio equals $-0.111\,h$; conditions found in continental crust in almost perfect equilibrium.

At elevations higher than 1600 m, the mean free-air anomalies become positive and proportional to elevation; their variations are too sensitive to elevation to be of interest. The Bouguer slope at that point suddenly passes from $-0.111\,h$ to $-0.036\,h$ as if the higher section of the swell was isostatically undercompensated.

CONCLUSIONS

Ethiopia as a whole, i.e. the Ethiopian–Somali swell and Afar, is seismically active but not to a degree comparable to that of the sector of the mid-oceanic ridge which bisects the nearby Indian Ocean and enters the Gulf of Aden. The epicentre locations, inland, are thought to follow two definite linear patterns and to be related: (1) to the western escarpment of Afar and of the rift where 75 % of the total energy is released; (2) to the central fracture zone of the rift and its prolongation through Afar.

At the transition between the plateaux and Afar or between the rift floor and Afar, no unexpected changes in Bouguer values are observed on individual profiles; on the graph of mean anomaly versus mean elevation, a sharp break appears. If the sudden change of slope on this graph is real (that is, if it is not caused by a large and thick superficial stratum of denser volcanic material which would not only cancel the negative effect of compensation but overcome it), then the seismic lineation along the escarpment might correspond to a sudden change in isostatic balance. One would therefore expect an accumulation of stress along that elevation level with an important vertical component. In connexion with this statement, it could be mentioned that appreciable tilt with a greater east–west component is observed on the seismic piers at Addis Ababa. Whether this tilt is superficial, deep-seated, or due to any other cause has not yet been ascertained.

In terms of crustal thickness, the gravity anomaly points towards a sial-sima horizon bulging downwards under the plateaus and tending towards 'normal depth' at its periphery. The author would like to emphasize here the limitations of such an interpretation when the gravity data are not controlled by seismic surveys. He has particularly in mind the recent observations made in Canada near Hudson Bay where a variation in crustal thickness from 42 to 24 km was found not to be accompanied by any positive increase in gravity (Ruffman & Keen 1967).

The surface wave dispersion curves through Afar, the presence of Lg waves along the same paths, the sum of free-air anomalies approaching zero, and the absence of absolute positive Bouguer values suggest under Afar a continental crust structure, contaminated by both high density basaltic material and low density silicic welded tuffs (and sediments) in proportions at present difficult to assess. From seismic phase velocities along the wave path from Addis Ababa to Shiraz (Iran), Niazi has suggested a continental-crust model for the whole path including Afar and Saudi Arabia. His crustal model is that of a normal, double-layered continental crust of 35 km thickness overlaid by 0.5 km thick unconsolidated sediments (Niazi 1968). Niazi's conclusions are, no doubt, to be taken as suggestions only when applied to the African section of the path since the Afar sector corresponds to 20 % only of the total Addis–Shiraz arc.

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