Zeitschrift für Geophysik, 1970, Band 36, Seite 299—311. Physica-Verlag, Würzburg

Crustal Investigation from gravity measurements at the scarp of the Ethiopian Plateau

By J. MAKRIS[1]), P. THIELE[2]) and J. ZIMMERMANN[1])

Eingegangen am 16. Dezember 1969

Summary: Models of the crust have been constructed from gravity traverses across the escarpment of the Ethiopian Plateau and the northern part of the East African Rift near Addis Ababa. The densities used for the computations are closely related to seismic results obtained at the western part of the Rift, the Red Sea and the Gulf of Aden. They are:

2.65 g/cm^3 for the upper part of the crust,
2.85—2.95 g/cm^3 for the "intermediate" layer,
3.00—3.10 g/cm^3 for the mantle material.

The main results are:

The crustal thickness decreases to the north from 38 km under Addis Ababa to 15 km under Asmara at the edge of the Plateau;
the gravity anomaly obtained in the Rift can be explained by mantle material rising under the Rift;
the major tectonic fracture between the Ethiopian Plateau and the Depression of Afar seems to be located just in front of the escarpment on the side of the Depression;
the "intermediate" layer rises at the edge of the Plateau towards the Depression to a depth of about 10 km.

Zusammenfassung: Aus Schweremessungen am Abfall des Äthiopischen Plateaus und im nördlichen Teil des ostafrikanischen Grabensystems wurden Krustenmodelle entwickelt. Die für die Modellberechnungen eingesetzte Dichteverteilung lehnt sich eng an seismische Resultate aus dem westafrikanischen Grabensystem, dem Roten Meer und dem Golf von Aden an. Die angenommenen Dichtewerte sind:

2,65 g/cm^3 für den höheren Teil der Kruste,
2,85—2,95 g/cm^3 für die „intermediäre" Schicht,
3,00—3,10 g/cm^3 für das benachbarte Material des oberen Mantels.

Die Hauptergebnisse der Untersuchung sind:

Die Krustenmächtigkeit nimmt nach Norden von 38 km unter Addis Abeba auf 15 km unter Asmara am nördlichen Ende des Plateaus ab;
die Schwereverteilung im nördlichen Rift kann durch ins Rift eindringendes Mantelmaterial gedeutet werden;
die tektonische Hauptstörung ist dem Abfall des Äthiopischen Plateaus auf der Seite der Depression vorgelagert;
der „intermediäre" Horizont steigt am Rande des Äthiopischen Plateaus auf ca. 10 km Tiefe an.

---

[1]) Institut für die Physik des Erdkörpers, Universität Hamburg, D 2 Hamburg 13, Binderstraße 22, Germany

[2]) Geodätisches Institut, Universität Karlsruhe, D 75 Karlsruhe, Englerstraße 7, Germany

1. Introduction

It is widely accepted from geological and geophysical evidence that the Red Sea and the Gulf of Aden have originated as a consequence of the drifting of the Arabian peninsula off of Africa. This movement implies a translation to the north, combined with an anticlockwise rotation of approx. 8° [GIRDLER 1965; LAUGHTON 1965]. LAUGHTON [1965], reconstructing the conditions prior to seperation, placed parts of Yemen (Arabian peninsula) over a part of East Africa. The supposed area of superposition is now emerged land, known as the Depression of Afar. Laughton suggests that the Afar Depression might be new basaltic crust.

MOHR [1962] describes Afar as "a downfalted and downwarped triangular area of the original Arabo-Ethiopian Swell at the intersection of three units of rifting". He concludes from geological observation that the hypothesis of superposition is untenable. GOUIN [1969] reinforces MOHR's geological interpretation with geophysical data (gravity observations, attenuation and dispersion of surface waves travelling through Afar) and considers the area as a continental structure of average thickness.

The contradicting opinions make it clear that more geophysical and geological investigations in Afar are necessary, before the physical conditions and structure of this area can be understood. Since the beginning of 1969 the Deutsche Forschungsgemeinschaft is supporting a scientific program in Afar. At a first stage geology and gravity observations are being conducted. For the future explosion seismology, magnetic deep-soundings and magneto-telluric measurements are planned. In this paper the results obtained from a short gravity survey early in 1969 at the scarp of the Ethiopian Plateau will be presented.

2. The Geography of Afar

The lowland of Afar is located in Northeast Ethiopia, extending approximately from 10 to 15° N and 40 to 43° E (Fig. 1). In the west and south it is bounded respectively by the scarps of the Ethiopian and Somali Plateaus. In the northeast the Danakil Alps, extending from the Gulf of Zula to the Gulf of Tadjura, border the area. Afar is funnel-shaped opening to the south. Large parts of the land, particularly the north, are as deep as 200 m below sea level. The southwest has larger elevations, between 300 to 400 m above sea level, and is dominated by the river Awash with her swamps and lakes. The river terminates at Abhe Lake at the border of Ethiopia and French Somalia.

Plateau-basalts and recent volcanic rocks cover much of the floor in the north, obscuring the geological past. Volcanism in the south is lined up as an extension of the Wonje Fault Belt of the East African rift, striking to NE and changing to NNW through North Afar. The hostile interior of the region with extreme climatic conditions and difficult communications makes scientific investigations very problematic. It was one purpose of this short survey, apart from the scientific program, to explore the local terrain in order to be able to plan major geophysical investigations.

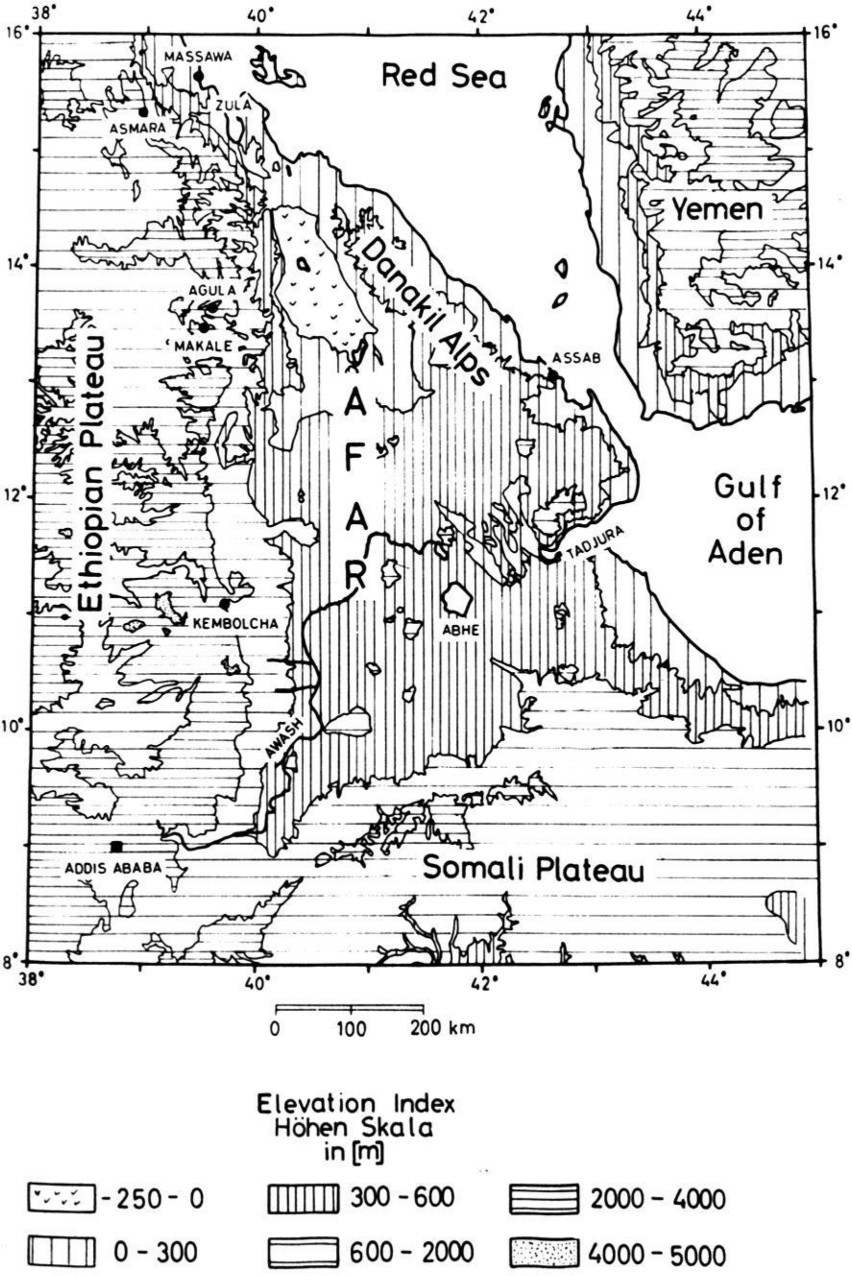

Fig. 1: Topography of Afar and adjacent areas.

3. The measurements

The measurements include:

1. Gravity observations.
2. Observations of the vertical component of the earth's magnetic field.
3. Barometric elevation measurements.

3.1 The gravity observations

One hundred new gravity stations along three traverses with a total length of three hundred kilometers were established at the escarpment of the Ethiopian Plateau (Fig. 2, profiles I, II, III).

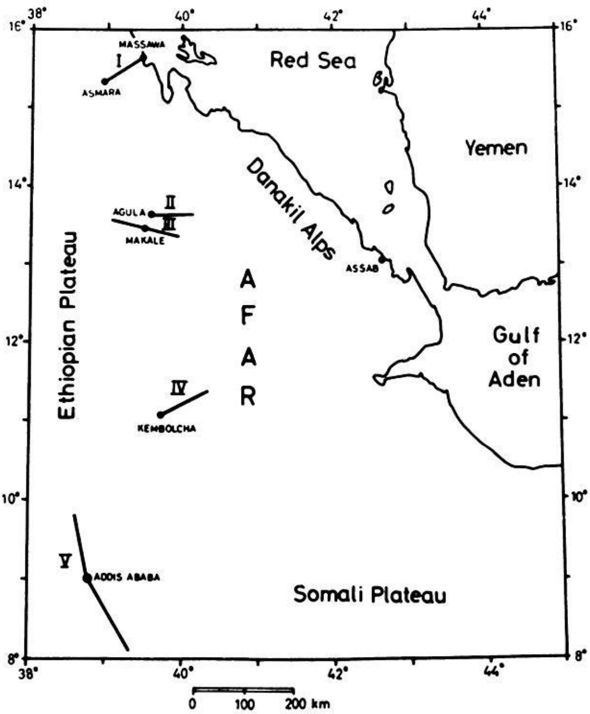

Fig. 2: Geographic position of gravity traverses used for this paper.

The measurements were conducted with two La Coste and Romberg gravity meters No. 87 and No. 115. Both instruments worked very reliably, and their field-readings agreed always better than 0.1 mgal. Their drift was linear and did not exceed the magnitude of 0.15 mgal/month. Figure 3 shows the long-range results and the position of the profiles.

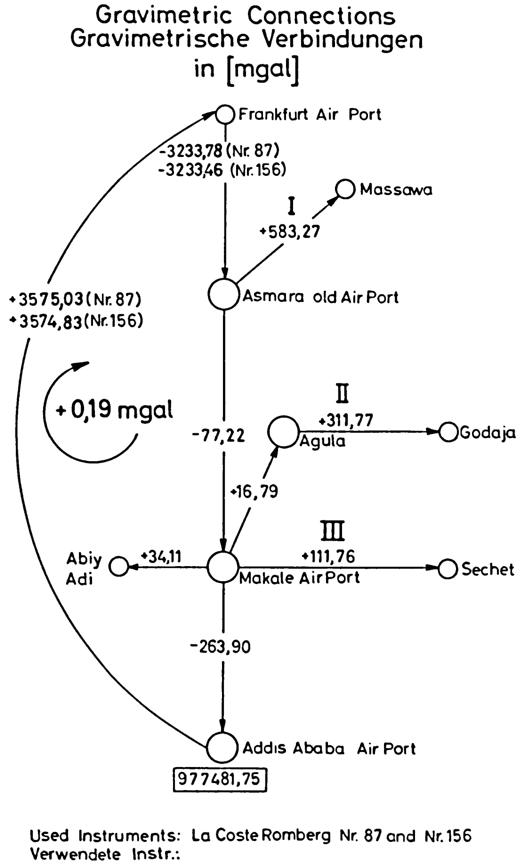

Fig. 3: Long-range gravimetric connections and relative positions of gravity profiles measured in 1969.

The field measurements were referred to the basic gravity point

$$\text{Addis Ababa K: } g = 977481{,}75 \text{ mgal.}$$

The results were corrected for tide effects.

3.2 The magnetic measurements

The vertical component of the magnetic field was observed with an Askania GfZ-torsion balance, No. 661034, at all gravity stations. The instrument was calibrated several times during the campaign. Daily variations were corrected from registrations obtained at the Geophysical Observatory, Addis Ababa.

The accuracy of these measurements is not better than $\pm$ 20 to 30 γ. The field conditions in our area of investigation require a greater density of observations than was achieved, since basaltic extrusives may locally influence the measurements. For this reason the magnetic profiles should not be used for a detailed interpretation. At the present stage we are satisfied if the trend of the field can be obtained.

3.3 The barometric elevation measurements

The elevations of the gravity stations were measured by altimeters, type: Thommen, 3 B 4.02. A set of four instruments was used simultaneously in order to eliminate instrumental errors and to increase the accuracy. Each field-point was repeated at least twice, on the average three times. Daily pressure variations were locally recorded by a barograph. Air-temperature and humidity were measured by means of a psychrometer at every point.

The accuracy of elevations varied from profile to profile between three to five meters, according to experimental conditions and differences in elevation. We consider this accuracy as sufficient for the purpose of our investigation.

4. Evaluation and representation of the measurements

The gravity, magnetic and altimetric measurements are presented in Fig. 4, 5, 6. For each profile:

curve H is drawn along the altitudes measured at each station.

curve $\Delta g'$ is the free-air anomaly reduced to sea level.

curve $\Delta g''$ represents the Bouguer anomaly, which is reduced to sea level for elevation, up to Hayford zone O_2 (0 to 167 km) for the mass reductions with density = 2,67 g/cm^3. The accuracy of the Bouguer anomalies is not better than $\pm$ 5 mgal on the average. This accuracy could only be achieved after the topographic corrections were calculated.

curve ΔZ shows the magnetic anomaly referred to the first point of each traverse. The values are corrected for the daily variations, and the accuracy is not better than 20—30 γ.

Short dashes beneath the distance-axis indicate the locations of observation points.

The terrain corrections were calculated as follows: From topographic maps of 1 : 500.000 a grid of geographic coordinates $\delta\varphi \cdot \delta\lambda = 2{,}5' \cdot 2{,}5'$ was constructed and the average height of each compartment estimated. With the help of these average heights the topographic corrections from Hayford zone O_2 up to 10 km around each station were calculated. For the rest of the topography a geographic grid, $\delta\varphi \cdot \delta\lambda = 1{,}25' \cdot 1{,}25'$, of average heights was photogrammetrically evaluated. For this purpose areal photographs of 1 : 50.000 were used. The terrain corrections varied between 5 to 20 mgal.

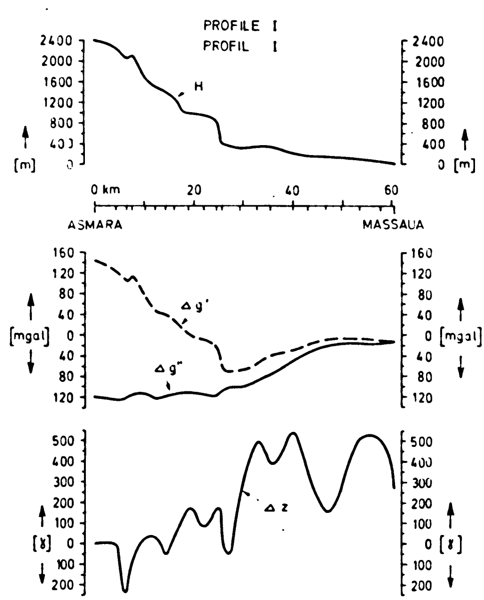

Fig. 4: Profile I.

H = Terrain elevation; $\Delta g'$ = Free-air anomaly; $\Delta g''$ = Bouguer anomaly; ΔZ = Magnetic anomaly of the vertical component; Density of reductions = 2.67 g/cm^3.

Reference level: H_0 = 0 m (Red Sea); Terrain and Bouguer corrections spherical from zone A to O_2 (0 to 166.7 km).

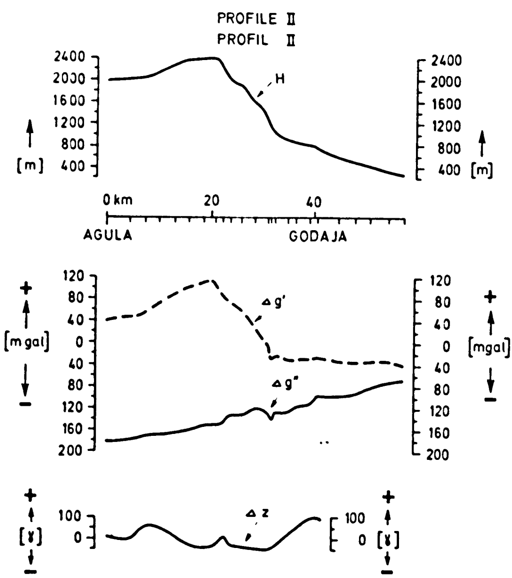

Fig. 5: Profile II. Explanations see Fig. 4.

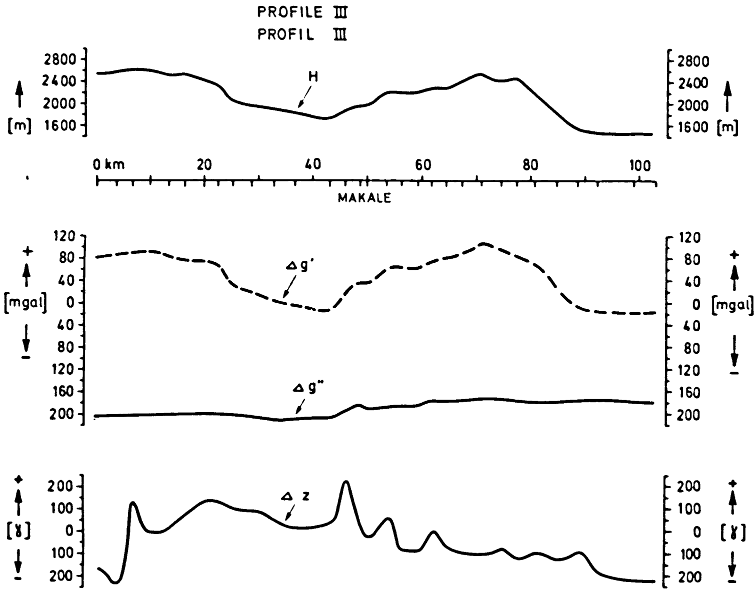

Fig. 6: Profile III. Explanations see Fig. 4.

5. Interpretation

The gravity traverses measured by the authors cover only a small part of the escarpment at the Ethiopian Plateau. In order to obtain a better picture of this structure, we used two more profiles further south (Fig. 2 profiles IV and V) for the interpretation.

Profile IV from Kembolcha to the Depression of Afar was measured by GOUIN and MOHR [1964], and profile V crossing the Rift from the Ethiopian to the Somali Plateau at Addis Ababa was measured by MOHR and ROGERS [1966]. The Bouguer values of both traverses have not been corrected for topography, and the elevations of the gravity stations are single-measured with only one altimeter. The accuracy expected cannot be better than approx. 10% of the total anomaly. The average distance between the gravity stations along these traverses is about 5 km.

As a first approach of an interpretation we assumed a density difference $\delta\varrho = +0{,}3\ g/cm^3$ (2,9 to 3,2 g/cm^3) between crust and mantle. The results are given in Fig. 7, 8 and 9. These crude models had to be rejected, since they lead to quite unrealistic dimensions of the crust. The only information they give is the approximate location of the major tectonic fracture which has to be placed just at the end of the escarpment towards the Depression.

These first results and the fact that the gravity gradients observed are fairly steep require a more complicated crustal model with a shallower anomalous mass distri-

PROFILE I
PROFIL I

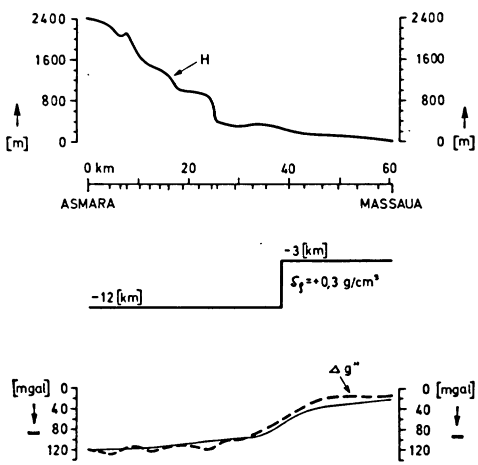

Fig. 7: Profile I showing the topographic relief, the model causing the anomaly and the measured anomaly $\Delta g''$ compared to the calculated one.

PROFILE II
PROFIL II

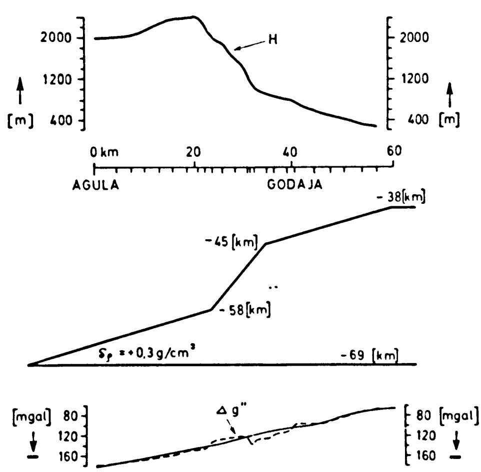

Fig. 8: Profile II—see Fig. 7.

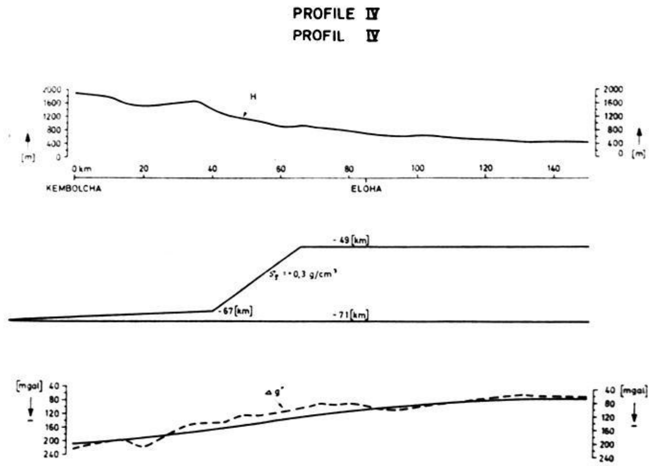

Fig. 9: Profile IV—see Fig. 7.

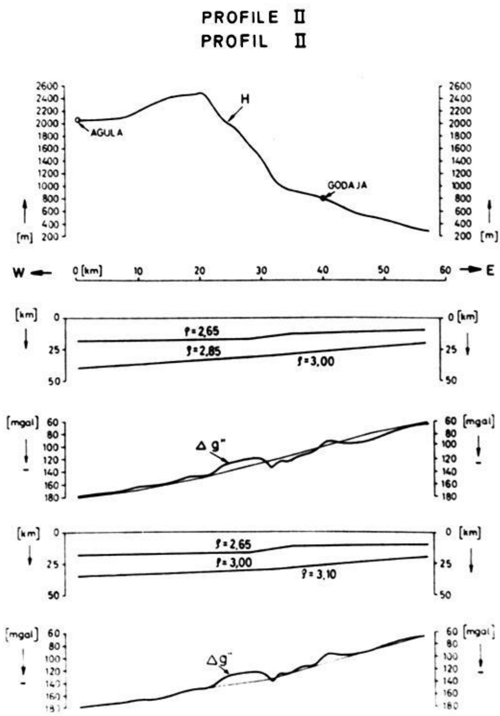

Fig. 10: Profile II showing two-layer crustal models. $\Delta g''$ represents the measured Bouguer anomaly compared to the computed one.

bution. A series of several models was computed for profiles II, IV and V. The results are given in Fig. 10, 11 and 12. Profile I was excluded from these calculations due to the fact that the horizontal gradient of about 15 mgal/km and the gravity anomaly of more than 100 mgal observed between the end of the escarpment and the coast of the Red Sea can only be simulated by a vertical displacement of 9 km, at shallow depth. The similar trends of the gravity and the magnetic field lead to the conclusion that the material causing the anomaly must have greater density and magnetization than the granites composing most of the escarpment between Asmara and Massawa. The local conditions are too complicated to permit more detailed models, since the available geological and geophysical informations are inadequate.

The density-combinations shown in Fig. 10, 11 and 12 are closely related to the crustal models proposed by Dopp [1964] for the western Rift Valley of Africa. The only significant modification introduced is lower density within the upper mantle, which is also postulated by Girdler [1965] and Laughton [1965] for the Red Sea and the Gulf of Aden. From our models obtained so far, we conclude:

The crust beneath the Ethiopian Plateau thins towards the Red Sea from a thickness of about 38 km under Addis Ababa to about 15 to 20 km under Asmara at the northern edge of the Plateau.

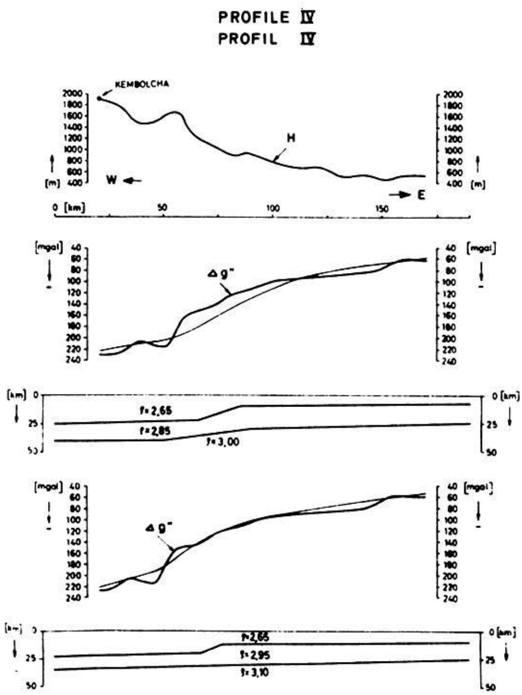

Fig. 11: Profile IV—see Fig. 10.

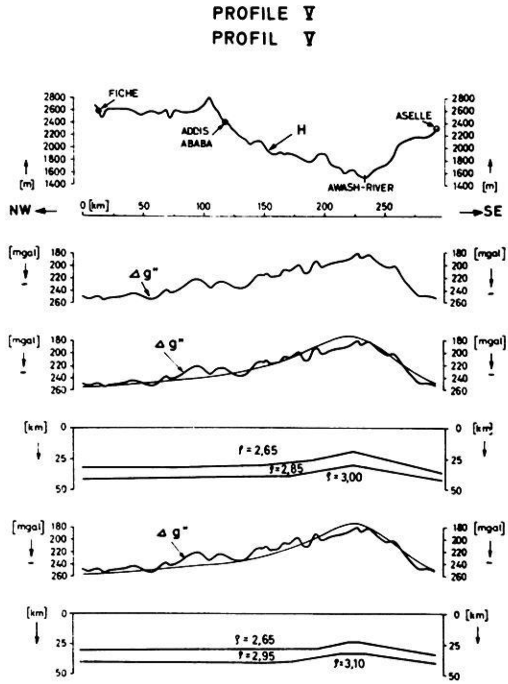

Fig. 12: Profile V—see Fig. 10.

The gravity high observed at the Rift near Addis Ababa is caused by mantle material rising under the Rift.

The crust of the Plateau thins towards the Depression, and the "intermediate" layer of 2.95 g/cm³ rises at the edge of the escarpment to a depth of about 10 km.

Apparently the major tectonic fracture does not coincide with the escarpment but is slightly displaced toward the Depression.

BONJER, FUCHS and WOHLENBERG [1969] derived a crustal model for Addis Ababa from a study of crustal response ratios of long-period body waves. Implications will be discussed in a joint communication.

6. Acknowledgements

The authors thank the following institutions for their kind support:

The Imperial Ethiopian Ministry of Mines introduced us to local authorities and permitted us to conduct our investigations in Ethiopia.

The Geophysical Observatory, Haile Sellasie I University, Addis Ababa, supplied us with corrections of the daily magnetic variations.

The Salzdetfurth AG branch in Ethiopia supported us most generously during the field measurements.

The Deutsches Geodätisches Forschungsinstitut, Munich, placed at our disposal the La Coste and Romberg gravity meter No. 87.

The Deutsche Forschungsgemeinschaft sponsored this investigation.

The computations were partly conducted at the Rechenzentrum, University of Hamburg, and at the computing facilities of the Institut für die Physik des Erdkörpers, Hamburg. Mr. W. Kaminski supported us with technical advice and fruitful discussions during the computations.

We thank Prof. H. Menzel and Prof. H. Lichte for their geophysical and geodetic guidance. Dr. R. Gutdeutsch read the manuscript critically.

References

Bonjer, K.-P., K. Fuchs, and J. Wohlenberg: Personal communication, 1969

Dopp, S.: Preliminary Note on an Refracted P Phase in the Western Rift Valley of Africa. J. Geophys. Res. 69, 3027—3031, 1964

Drake, C. L., and R. W. Girdler: A Geophysical Study of the Red Sea. Geophys. J. 8 473—495, 1964

Girdler, R. W.: The Role of Translational and Rotational Movements in the Formation of the Red Sea and Gulf of Aden. Report of Symposium, Ottawa, Canada, 4.—5. 9. 1965

Gouin, P.: Seismic and Gravity Data from Afar (Abstract). Meeting of the Royal Society, London, 27.—29. 3. 1969

Gouin, P., and P. A. Mohr: Gravity Traverses in Ethiopia (Interim Report), Haile Sellasie I University, Bulletin of the Geoph. Observ. 7, 1964

Laughton, A. S.: The Gulf of Aden. In: Relation to the Red Sea and the Afar Depression of Ethiopia, Report of Symposium, Ottawa, Canada, 4.—5. 9. 1965

Mohr, P. A.: The Ethiopian Rift System. Haile Sellasie I University, Bulletin of the Geoph. Observ., 1962

—: The Geology of Ethiopia, University College of Addis Ababa Press, 1962

Mohr, P. A., and P. Gouin: Gravity Traverses in Ethiopia (Third Interim Report). Haile Sellasie I University, Bulletin of the Geoph. Observ. 10, 1967

Mohr, P. A., and A. S. Rogers: Gravity Traverses in Ethiopia (Second Interim Report). Haile Sellasie I University, Bulletin of the Geoph. Observ. 9, 1966

Runcorn, S. K.: Satellite Gravity Observations and Convection in the Mantle. Report of Symposium, Ottawa, Canada, 4.—5. 9. 1965

Sowerbutts, W. T. C.: Crustal Structure of the East African Plateau and Rift Valley from Gravity Measurements. Nature 223, 143—146, 1969

Talwani, M., Le Pichon, X., and M. Ewing: Crustal Structure of the Mid-Ocean Ridges: Computed Model from Gravity and Seismic Refraction Data. J. Geophys. Res. 70, 341 to 352, 1965

Woollard, G. P., and J. C. Rose: International Gravity Measurements. Society of Exploration Geophysicists, 1963