PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

An Interpretation of Gravity Anomalies in the Eastern Mediterranean

J. C. Harrison

Phil. Trans. R. Soc. Lond. A 1955 **248**, 283-325
doi: 10.1098/rsta.1955.0017

AN INTERPRETATION OF GRAVITY ANOMALIES IN THE EASTERN MEDITERRANEAN

By J. C. HARRISON

(*Communicated by Sir Edward Bullard, F.R.S.—Received* 26 *October* 1954—*Revised* 16 *March* 1955)

CONTENTS

This paper gives an interpretation of the results of the 1950 British Submarine Gravity Survey. The area covered by the survey is divided into four separate problems: the environs of Malta, the Crete island arc, Cyprus, and the Nile delta. A 2000 ft. submarine scarp south of Malta is associated with a change in the Bouguer anomaly of about 34 mgal. This scarp is interpreted as a fault scarp, and geological sections consistent with the gravity and seismic data are drawn. The positive anomalies in the southern Aegean Sea and the negative anomalies outside the Crete island arc lead to the hypothesis that, in this area, the granitic and intermediate layers are of constant thickness, the Mohorovičič discontinuity remaining parallel to the surface topography. Large positive anomalies on Cyprus indicate the presence of a large buried basic or ultrabasic mass; this mass is discussed with relation to the geological structure of the island. The thickness of sediments on the Nile delta and the crustal sag caused by them are estimated from gravity anomalies and topographic considerations.

1. Introduction

This paper is concerned with an interpretation of the gravity results obtained by H.M. Submarine *Talent* in the eastern Mediterranean during 1950 (Cooper, Harrison & Willmore 1952). Much further geological and geophysical field work is necessary before the problems discussed can be settled with any finality, and it is hoped that this paper may stimulate such work by increasing interest in the area.

The Mediterranean Sea is, in general, a region of large isostatic anomalies and may be divided into three portions on the basis of the character of these anomalies. The western portion, consisting of the Tyrrhenian Sea and the basin west of Sardinia, is characterized by positive anomalies of the order of +50 mgal. These are well illustrated in the map given by Hoffman (1952). The central portion consists of the foot of Italy, Sicily, the Ionian Sea and the area between Sicily and Tripolitania. It is characterized by the alternation of areas of positive and negative anomalies; sometimes the anomalies are large, as in Sicily (±100 mgal), and sometimes small, as in the neighbourhood of Malta (±15 mgal). The eastern portion is characterized by an extensive strip of large negative anomalies (down to −150 mgal) which is balanced by large positive anomalies (+100 mgal) in the southern Aegean. There are also very large (+200 mgal) positive anomalies on Cyprus and smaller ones (+50 mgal) on the Nile delta.

These three divisions correspond, on a broad view, to regions occupying different tectonic positions in relation to the mountain ranges. In the west, the Mediterranean lies between the Betic–Balearic orogenic belt of Europe and the Atlas system of North Africa, which ranges are thrust outwards from the sea and maintain a comparatively undisturbed ESE-WNW strike. In the central region, this relatively simple situation is disturbed and the NW-SE and SW-NE strike directions cut across those in the western portion. The predominantly east-west strike direction is recovered in the eastern Mediterranean, but both the northwards and southwards thrust ranges lie to the north of the Sea and there is no major range in Cyrenaica or Egypt.

The different gravimetric characteristics of the three portions are probably related to their tectonic positions, and the anomalies, if properly interpreted, should give information concerning the processes involved in their geological evolution. No stations were occupied in the western portion during the 1950 survey of H.M.S. *Talent* and this portion will not be considered here. It has already been discussed by Coster (1945), de Cizancourt (1948), Glangeaud (1951) and Van Bemmelen (1952), in addition to Hoffman.

The Cambridge gravity data throughout this paper are based on a value of 981·2685 cm/s^2 at Pendulum House, Cambridge, England (Cook 1953, pp. 519–520), apart from those on Cyprus for which the formerly adopted value of 981·2650 cm/s^2 is retained. The latter value was used by Cooper *et al.* (1952), but it is necessary to use the revised value whenever the Cambridge results are compared with those of other observers.

2. Central Mediterranean

The first section of the *Talent* survey was devoted to a detailed survey on the environs of Malta and Pantelleria. A bathymetric chart of this region is given in figure 1. The sea is generally shallow, mainly less than 400 fathoms deep, and large areas are less than 100 fathoms deep. The extensive area south-west of a line running roughly south-east from Cape Bon, is less than 100 fathoms in depth, and there are shallow platforms adjacent to the south-eastern and south-western tips of Sicily. An outstanding feature, however, is a trench of deep water, up to 900 fathoms deep, near Pantelleria, which stretches in a south-easterly direction from Pantelleria and ends just south of Malta. This trench divides about half-way between the islands, the northerly arm ending near Malta, the southerly one probably joining the deep water east of Linosa, though this cannot be definitely proved owing to lack of soundings. The area as a whole is bounded to the east by steep submarine cliffs running approximately north-south, across which the depth increases rapidly to about 2000 fathoms.

Considerable interest is attached to these bathymetric features, for there is palaeo-zoological evidence of land bridges connecting Italy, Sicily, Malta and North Africa during the Lower Pleistocene. In Calabrian (Lower Pleistocene) times the mammals in these localities appear to have been so similar that free passage between them must have existed. In later times the species in the various areas diverge and interbreeding must have ceased. It is possible to travel from Sicily to Tunisia, north of Pantelleria, without crossing sea deeper than about 200 fathoms, and from Sicily to Malta without crossing water more than 75 fathoms in depth. The changes in the relative levels of land and sea to allow connexions between these places are not large, and faults with vertical throws several times as great are known in the area.

There is some volcanic activity in the area. Pantelleria and Graham's reef both erupted in the later part of the last century, and two further submarine volcanoes have been

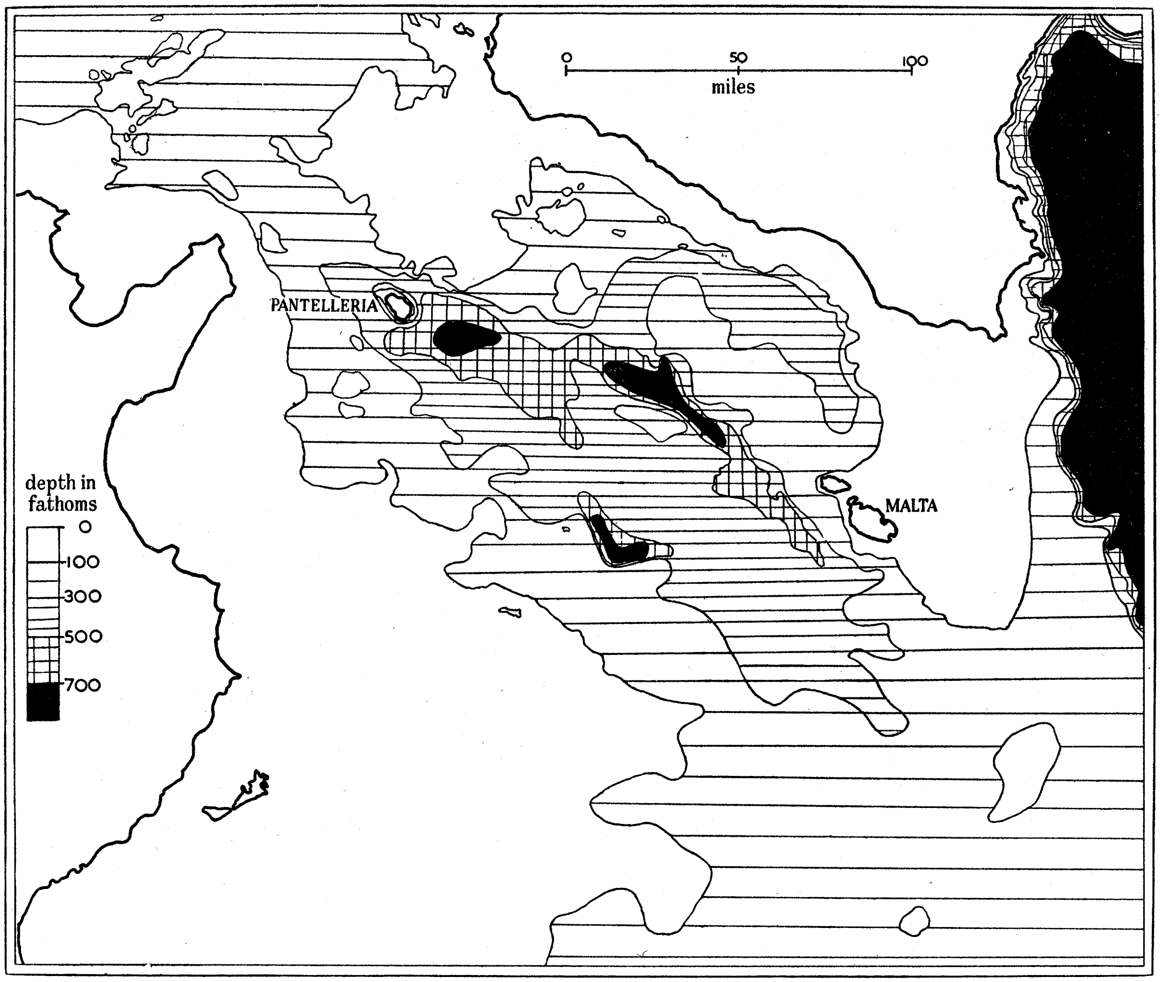


FIGURE 1. Bathymetric chart of the Malta–Pantelleria area.

reported between a line joining Malta and Pantelleria, and the Sicilian coast (Gutenberg & Richter 1949). Linosa is a volcanic island but has not erupted in historic times. The volcanism is not associated with important seismic activity.

The isostatic anomalies in this area are given in figure 2. The data for Sicily are taken from Medi & Morelli (1952) and those in Tunisia from Lagrula (1951). At sea, the data were obtained on two cruises by Cassinis (Cassinis 1935, 1942), by Vening Meinesz (1934) and by the *Talent* expedition. The isostatic reductions (Hayford $H = 113{\cdot}7$ km) were read from the *Isostatic isocorrection line maps* published by the European Society of Exploration Geophysicists. The patchwork nature of the anomalies is apparent. Large negative anomalies in central Sicily contrast strongly with the positive anomalies in the south-eastern part of the island. The shallow bank between Sicily and Malta is characterized by small positive anomalies, forming an extension of the area of much larger positive anomalies in south-eastern Sicily, and this bank is bordered on its western and southern sides by small negative anomalies. Pantelleria lies in a further area of positive anomalies and there are more negative anomalies just east of Cape Bon.

It is proposed to work outwards from Malta in the interpretation. Malta and its immediate neighbourhood are well surveyed topographically, geologically and gravitionally, so the interpretation at least starts from well-based premises.

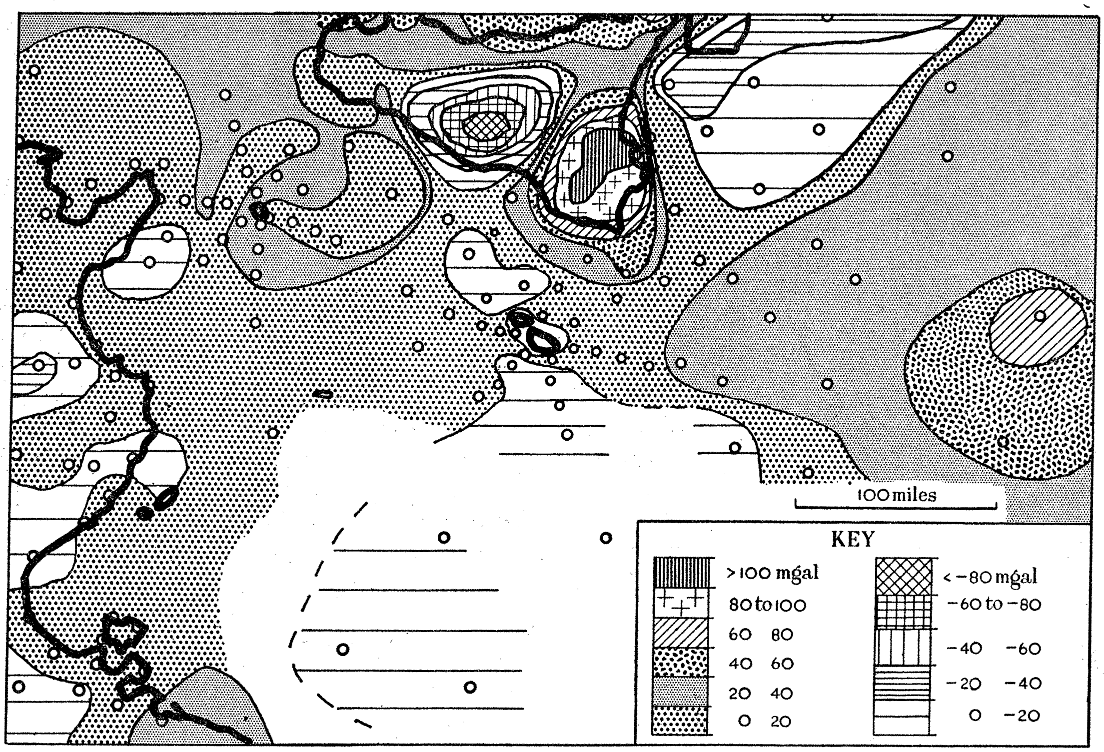


FIGURE 2. Hayford isostatic anomalies for $H = 113\cdot7$ km. Gravity stations used are shown by circles, except on Sicily and Malta. The white area on this figure covering Malta and Gozo should bear the shading corresponding to $+20$ to $+40$ mgal.

The Bouguer anomalies on Malta and in the sea nearby are given in figure 3. Twenty-two gravity measurements on Malta were made by the author, with the assistance of Lt-Comdr J. C. E. White, in 1952 (Harrison 1954), and eight stations had previously been occupied by Harding (Woolard, Harding, Muchenfuss, Bonini & Black 1952). The densities used in the Bouguer reductions are 2·25 for stations on land and 2·35 for sea stations.

The Bouguer anomalies on the island are remarkably constant, with an average value of about $+64$ mgal. There is a tendency for slightly higher anomalies to the north-east and for lower anomalies to the north-west and south-west. The greatest variation in Bouguer anomaly occurs between the submarine stations just south of Malta and the stations on the island itself. The differences between the two near-shore submarine stations and the nearest land measurements, less than 2 miles away, are greater than the total range of anomaly on the island.

Most of the high ground on Malta lies in the south-west, and the highest points (*ca.* 800 ft.) on the island occur some 600 yards from the coast. The land then falls away in several precipitous cliffs, and the British Admiralty Chart no. 3670 shows soundings of about 50 fathoms close in to the shore. This coastline is almost certainly faulted, though the only geological evidence for this occurs along a small length where the downthrown side is accessible. The north-western portion of the island is downfaulted along faults with NE-SW strike directions, so the decrease of anomaly in this direction is likewise associated with downfaulting. Reed (1949) gives a map of these faults which are the sole important tectonic features on the island. The strata are otherwise horizontal, or have only slight dips to the north-east, and are not folded to any important extent.

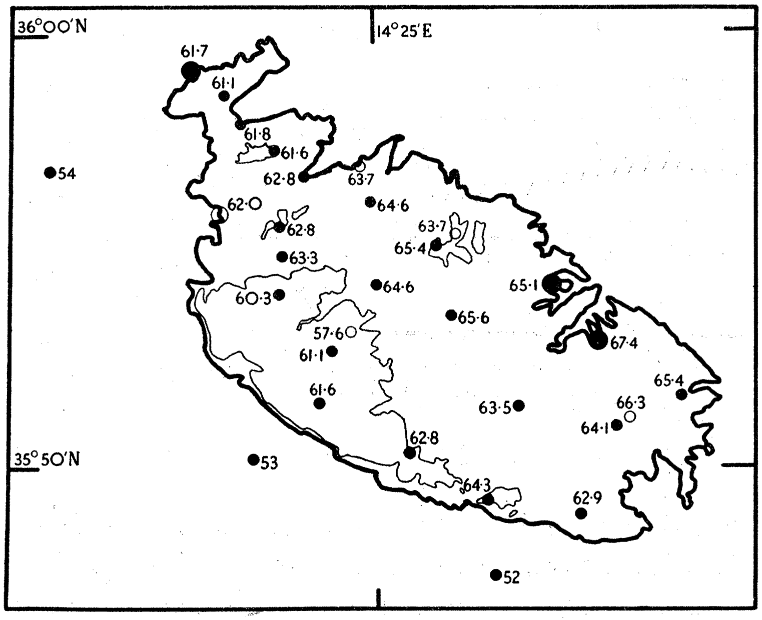


FIGURE 3. Bouguer anomalies on Malta (mgal). All anomalies positive. 400 ft. contour shown.

It is necessary to make assumptions for the densities of the underlying strata before the anomalies can be interpreted and a basement density of 2·67 has been assumed. Sediments between the basement and the base of the Malta limestones do not affect the interpretation, provided they do not vary across the faults. The Maltese strata are of Miocene and Oligocene age and the nearest pre-Oligocene strata, Upper Cretaceous to Oligocene marls with basaltic lava flows, outcrop in south-eastern Sicily.

The throw of the Malak fault on the south-west coast of Malta, deduced from the downthrown strata on Malta and Fifla, is 550 ft. The throw is probably generally greater than this, for the downthrown side normally lies some 300 ft. below sea-level, and it may be estimated at some 900 ft. The change in anomaly expected across such a fault, calculated from a density contrast of (2·67 − 2·35) over 900 ft., is 3·7 mgal. In fact, the observed changes in anomaly are 8 and 12 mgal for the two near-shore sea stations.

A very similar situation exists farther south, as shown in the profiles *AB* and *CD* in figure 4 (positions of profiles shown in figure 7). The cliff in profile *AB* was too steep for a continuous profile to be observed on *Talent's* echo sounder—a steady echo from 450 fathoms was suddenly lost and, by the time the sounder scale had been changed and the echo recovered, the sounding was 120 fathoms. The horizontal distance travelled in this time was about 1 mile, so the slope of the sea bottom is at least 1 in 3. The throw of this fault, as gauged from the topographic step, is about 330 fathoms or 2000 ft., and a fault of this magnitude should be associated with a change of anomaly of approximately 8 mgal. In fact, the observed change is 34 mgal.

Thus the changes in gravity across the NW-SE faults are much larger than expected from the throws of the faults. This is not so for the perpendicular set of faults. The northern part of the island is downfaulted by a series of faults, of which the most important is the

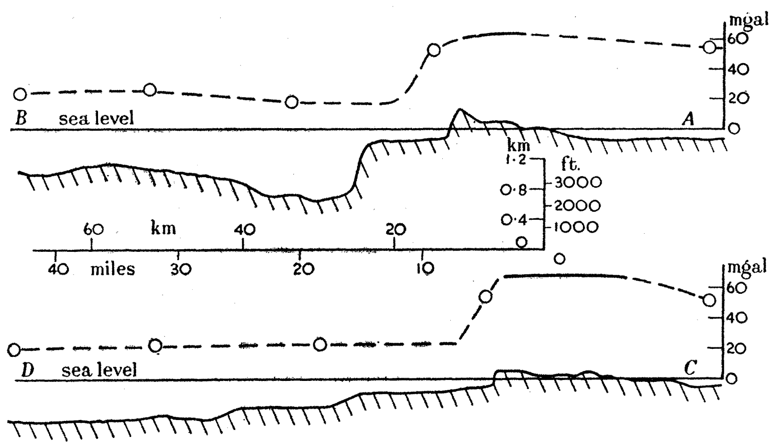


FIGURE 4. Topographic and Bouguer gravity profiles across Malta.

'Grand Fault' with a throw varying from 270 to 350 ft. The total downfaulting could easily be double this when the other lesser faults are taken into consideration. The mean Bouguer anomaly over the southern half of the island is about 64·5 mgal, and that over the northern half about 61·5 mgal. The 3 mgal change of anomaly corresponds to a throw of 730 ft., which is not significantly different from that deduced from the geology.

The excess change of anomaly, over that calculated from the topographic steps, across the faults south-west of Malta shows that there is either excess dense matter below the upthrown side or light matter on the downthrown side. It is possible that basaltic lava flows underlie Malta, and that these thin suddenly at the faults. There is, however, no reason why they should do this, and it is more reasonable to assume that there is low density material on the downthrown side. This material could be either light sediment covering the downthrown strata, reducing the apparent throw in addition to reducing the Bouguer anomaly by reason of their low density, or the limestone series itself could be increased in thickness.

In view of these considerations, Drs Gaskell and Swallow, on board H.M.S. *Challenger*, were asked to obtain seismic profiles in positions north of Malta, in a region where the Bouguer anomaly is about +60 mgal, and south-west of the main submarine cliff, where the anomaly is about +23 mgal (Gaskell & Swallow 1953). In the former profile (see figure 7 for positions of seismic profiles) a two-layer structure was found. The upper layer showed a sound velocity of 5440 ft./s and had a thickness of 650 ft. It is underlain by a layer with a velocity of 11400 ft./s and of unknown thickness. If the 11400 ft./s layer is underlain by material with a velocity of 22000 ft./s, its thickness exceeds 3000 ft. and, if the velocity in the underlying formation is 18000 ft./s, its minimum thickness is 2000 ft. In the line south of Malta, the arrivals indicated a velocity of 18750 ft./s, and this high velocity prevented pulses travelling through the overlying layers from being first arrivals. Weather conditions were not good, and second arrivals cannot be read satisfactorily on the records. The only information about the upper layers is given by the intercept of the 18750 ft./s line, and this information is summarized in table 1. Two cases are considered, one in which there is a single low-velocity layer overlying the 18750 ft./s layer and one in which there is a layer of intermediate velocity between the low-velocity and the 18750 ft./s layers. In the latter case it is not possible to determine the thickness of the two layers uniquely, and the solutions given are possible solutions only.

Table 1

upper-layer velocity (ft./s)	intermediate-layer velocity (ft./s)	Thickness of upper layer (ft.)	thickness of intermediate layer (ft.)
6000	—	1200	—
8000	—	1600	—
10000	—	2200	—
6000	12500	400	2100
6000	15000	850	2200
5440	11400	190	2200

Table 2

description of sample	specimen no.	sound velocity (ft./s)	dry density (g/cm^3)	saturated density (g/cm^3)
soft limestone with large mollusc casts, U. Coralline	I	10300	1·80	2·10
Globigerina Limestone	II	9270	1·90	2·12
L. Coralline Limestone	III	$\parallel$to bedding 18500 $\perp$to bedding 14900	2·29	2·36
'Malta Granite', hard crystalline limestone (probably L. Coralline)	IV	19000	2·44	2·53
Black Limestone, L. Coralline	V	14200	2·22	2·37

Mr A. S. Laughton kindly determined the seismic velocities in the samples of Maltese limestones collected for density determinations. These are given in table 2 with the dry and saturated densities. The difference in the velocities for specimen III arises because the specimen consists of two layers. The velocity perpendicular to the bedding plane is the mean of the two velocities, that along the bedding plane is the velocity in the faster layer.

An interpretation of profile *AB* can now be made employing the gravitational, seismic and geological information. The general lines of the interpretation are already known, the main features being two parallel faults striking at right angles to the profile. One of these faults coincides with the south-west coast of Malta, the other is marked by a submarine cliff and lies some 7·5 miles to the south-west. The problem is one of finding a combination of formation thickness and fault throws which is consistent with all the evidence.

The seismic line north of Malta showed a layer of thickness 650 ft. with a velocity of 5440 ft./s near the surface. This layer can be identified as unconsolidated sediments. A density of 1·90 is assumed for these sediments in the interpretation of the gravity measurements. The underlying layer has a velocity of 11400 ft./s, which is a possible velocity for limestones occurring on Malta. However, many of the limestone bands on Malta have very much larger velocities, in particular the lower part of the Lower Coralline Limestone probably has a velocity of about 19000 ft./s, and the upper part of the same formation at least 14000 ft./s (see table 2). The seismic results show that, if the 11400 ft./s layer is underlain by 18000 ft./s material, its thickness is greater than 2200 ft. In fact, the total proved thickness of limestones on Malta is not much in excess of 1000 ft., of which 500 ft. belong to the Lower Coralline Limestone. If the lower layer of the seismic profile were part of the Malta Limestone series, the Lower Coralline Limestone would definitely be expected to show up with a velocity of around 19000 ft./s, and the absence of such an indication suggests that the limestones are missing. It is probable that the 11400ft./s layer is a Cretaceous and Eocene calcareous marl series such as that found in south-eastern Sicily. The velocity is probably rather high for the actual marls, but thin layers of a more calcareous nature could have such a velocity and would mask the sound travelling through the body of the marl.

A layer with a velocity of 18750 ft./s was found south of Malta and, unfortunately, sound travelling through this masked all other arrivals. This layer can be identified as part of the Malta limestone series, the likely candidates being the Upper and Lower Coralline Limestones. Possibilities for the overlying layers have been listed in table 1.

One difficulty that arises in the interpretation of gravity profiles is the separation of deep-seated from shallow masses. Downfaulting has been postulated in the section *AB*, and there must be lateral movement of matter at depth to accommodate the downfaulted material. Some assumptions as to the masses displaced must be made before the anomaly profiles can be interpreted. The two faults divide the section into three portions, the two southern being downfaulted relative to the northern. It has been assumed in the computations that no matter is displaced from beneath the middle portion, for it is only 7·5 miles wide and may wedge out at depth, but that mass has been displaced from beneath the southern section.

Matter of density 3·3 has been supposed replaced by matter of density 2·67 at a depth of 20 km starting directly below the southern fault, the displacement being 4000 ft. for the first 12·5 miles in a south-westerly direction and 2000 ft. beyond this. The 'root' is supposed to extend indefinitely in a direction perpendicular to the section. These values were chosen, after preliminary calculations, to make the vertical displacements of the base of a hypothetical 'granitic' layer approximately equal to those of the limestone horizons. The observed anomalies were corrected for the attraction of this 'root' and the resulting anomalies interpreted as variations in mass per unit area in columns of the sedimentary strata down to a hypothetical 'granitic' basement. (This basement may be similar to the gneisses of the north-eastern corner of Sicily and of Calabria.) It was found that the gravity anomalies interpreted in this way lead to a thickness of about 1400 ft. of sediment covering the Maltese limestones in the position of the seismic profile on the downthrow side of the faults. This is consistent with the seismic results (table 1).

However, it is possible that the faults die out in the granitic basement and that no material of density 3·3 is displaced beneath the downthrown side. In this case the entire mass deficit indicated by the gravity anomalies must be placed in the near surface rocks

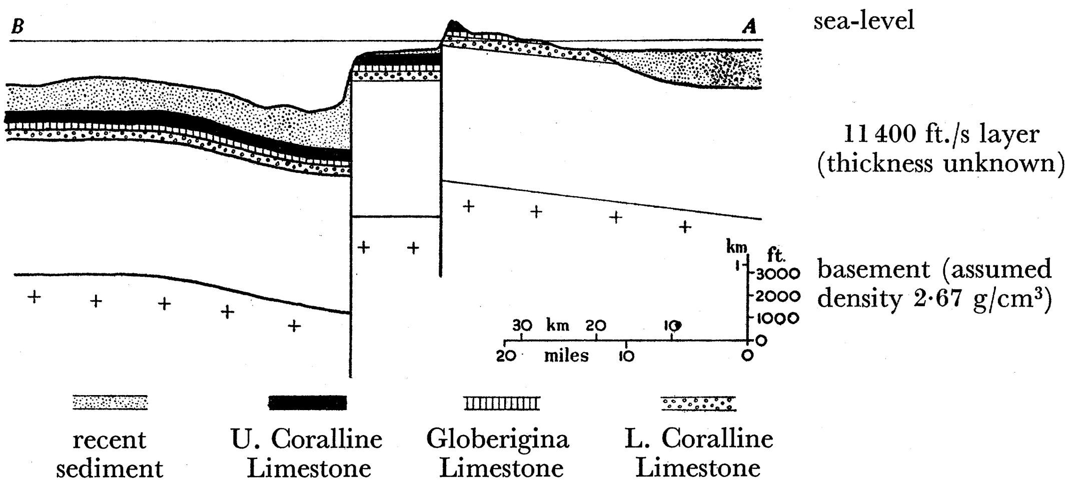


FIGURE 5. Geological section across Malta deduced from geophysical data, assuming matter displaced at depth.

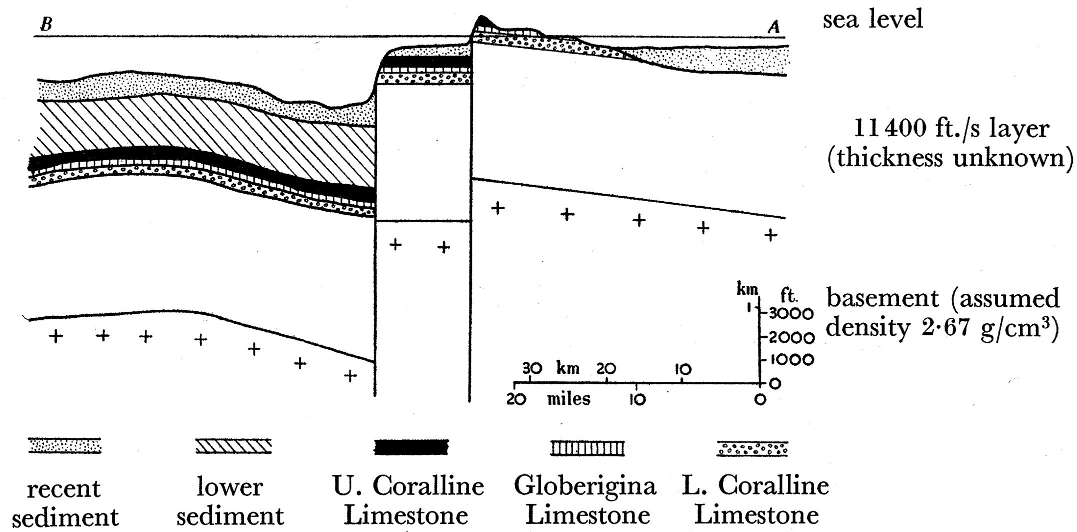


FIGURE 6. Geological section across Malta, assuming no matter displaced at depth.

and, thus, thicker sediments are deduced on the southern side of the faults. A possible geological section on this hypothesis is shown in figure 6. If the sediment has a density of 1·90, a thickness of some 2500 ft. is needed, and this is not consistent with the seismic evidence unless the seismic velocity in the lower part of the sediments is as high as 12500 ft/s. It is doubtful whether a material with such a high velocity would have a density as low as 1·90. In figure 6, an upper sediment thickness of 850 ft. is supposed underlain by 2600 ft. of lower sediment with a density of 2·1. This configuration is consistent with the seismic result if the lower material has a velocity of about 15000 ft./s. The lower sediment could be either Upper Coralline and Globerigina Limestones in a much thicker development than on Malta, or, alternatively, more recent compacted sediments. The total throw of the main fault in figure 6 is about 5000 ft., whereas in the interpretation offered in figure 5 this throw is only about 3500 ft.

The details in these sections are dependent on the assumptions made, but the main feature, that the area of low anomalies south and south-west of Malta has been downfaulted, the throw of the fault being considerably greater than that deduced from the

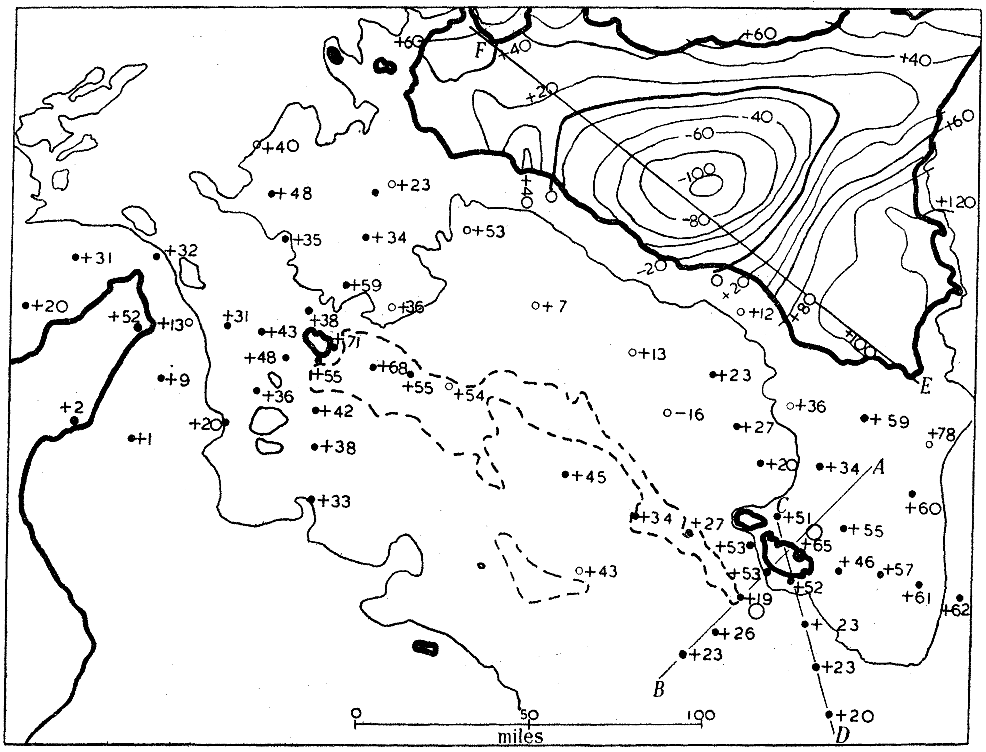


FIGURE 7. Bouguer anomalies in the vicinity of Malta and Pantelleria. Density 2·35 g/cm³. •, Cooper station; ∘, Cassinis station; ——, 100 fathom line; – – –, 500 fathom line; ○, seismic profile.

submarine topography because of increased sedimentation, is well established. The flatness of the shelf joining Malta and Sicily is a result, not of its being the upper surface of a hard limestone but, probably, of equilibrium between present sedimentation and the dispersive action of currents and waves.

The identification, south of Malta, of the submarine trough as a downfaulted area partially concealed by sediments and associated with negative gravity anomalies, suggests a similar interpretation for the rest of the trough in its north-westerly extension towards Pantelleria. The anomalies in figure 7 show that this is not the case. Unfortunately, there are no traverses across the trough, but near Pantelleria, the anomalies over the trough appear to be more positive than elsewhere in that neighbourhood. The low anomalies south of Malta extend northwards on the western side of the Malta shelf and join the very low anomalies in central Sicily. There is some uncertainty in comparing the results of

Cassinis with those of Cooper because of an apparent consistent difference between the surveys. Cassinis's measurements in figure 7 have been reduced by 16 mgal.

The low anomalies in central Sicily, with the extremely high anomalies in the south-east, provide a problem of long-standing interest. The most recent survey was made by Medi & Morelli (1952), who occupied some 300 stations on the island. The most probable explanation for the negative anomalies is that central Sicily is a tectonically depressed region filled in with sediments (Medi & Morelli). The positive anomalies in south-eastern Sicily could be the result of either a large basic intrusion (Hoffman) or to faulting which brings the dense rocks below the Mohorovičić discontinuity closer to the surface. The presence of Upper Miocene and Cretaceous basalt flows in the area support the former hypothesis, but there is no evidence for such exceptionally large basalt masses as are needed to account for the anomalies.

The thickness of the sediments and the amount of crustal depression in central Sicily can be estimated from the magnitude of the negative anomalies. If the 'granitic layer' is supposed to be of constant thickness along section *EF* (see figure 7) and to be depressed in central Sicily to form a trough which has been filled in with sediments of density 2·35, then the thickness of the sediments and the crustal depression relative to the south-eastern corner of the island must amount to about 20000 ft. (6 km) in central Sicily. This estimate was made on the assumption that the structures continued indefinitely in a direction perpendicular to the section, that the granitic layer has a normal thickness of 20 km, a density of 2·67, and that it rests directly on matter of density 3·3. The basalt flows in south-eastern Sicily were assumed to contribute 20 mgal to the positive anomaly there, implying a thickness of approximately 5000 ft. However, the granitic layer may be somewhat thicker in central Sicily than in the south-east, in which case the sediment thickness would be somewhat less than estimated above.

Beneo (1951, 1952) considers the whole of Sicily to be overriden by allochthonous material with the exception of the tabular limestones and basalts of the south-eastern corner, the lava flows of Etna and the gneissic rocks of Mt Peloritani. The allochthonous formation (known as Argille Scagliose) is predominantly clayey and contains elements from the Permo-Carboniferous to the Oligocene, sometimes even from the Miocene and Pliocene. It is covered in parts by autochthonous Upper Miocene, Pliocene and Quaternary deposits and is unmetamorphosed. The Argille Scagliose is supposed to have moved southwards from its original place of deposition in a series of landslips, and to contain limestone blocks torn from the floor over which it travelled, as well as material deposited on top of it during the movement. The motion is supposed to be due to gravity, and to have taken place mainly in the period between the Eocene and the Lower Miocene. All the limestones on the island, apart from those in the south-eastern corner, are considered to be allochthonous.

A less extreme view divides Sicily into three regions. The mountains in the north are characterized by folds in an autochthonous Permo-Carboniferous to Oligocene basement which have been partially overridden by the allochthon. These folds show a ENE-WSW or NE-SW strike direction whose consistency is a strong argument for the autochthonous role of the folded formations. A trough in central Sicily is filled in, partly by allochthonous Argille Scagliose and partly by autochthonous deposits. The Ragusa plateau, the third structural division, occupies the south-eastern corner of the island and is characterized by relatively undisturbed autochthonous limestones of Tertiary age. This latter picture is generally compatible with the interpretation deduced from the gravity results. The mountains in the north and the Ragusa plateau in the south-east are characterized by positive anomalies and the trough in central Sicily by negative anomalies. There is no geological reason, however, to expect a greater thickness of sediments in central Sicily than, say, beneath Etna, and this thickness would otherwise have been estimated as not exceeding 6500 ft. (2 km). The base of sediments, however, is not seen in central Sicily, and there is no proof that they have not the thickness of 20000 ft. (6 km) suggested by the gravity anomalies. The depression probably took place in the Lower Tertiary, and the Argille Scagliose may have slid down into the central Sicilian trough from the mountain and Tyrrenian areas. There is some evidence that the depression of the central Sicilian trough was produced by faulting. Beneo (1951, p. 11) describes a fault striking NE-SW through S. Croce–Camarina–Comiso–Chiaramonte, which bounds the foreland limestones of south-eastern Sicily to the north-west. This fault is supposed to continue beneath Etna to the Straits of Messina and the north coast of Calabria. A large part of the depression could, however, be the result of bending rather than faulting.

Figures 2 and 7 show that the low anomalies of central Sicily continue southwards, though much diminished in magnitude, to join those south-west of Malta. The positive anomalies around Pantelleria show that they do not join with the low anomalies in Tunisia and south-east of Cape Bon, as would otherwise have been anticipated from the general NE-SW strike directions in Sicily and Tunisia.

Little can be deduced from the anomalies in the neighbourhood of Pantelleria, which resemble random selections of numbers from a range 20 mgal each side of +50 mgal. The area may be crossed by Atlas–Apennine fold structures with dimensions roughly equal to the station spacing, which would lead to the apparently random variations in anomaly.

Discussion of the Malta–Pantelleria trench near Malta led to the conclusion that it is a result of faulting, and the bathymetric evidence favours the idea of a downfaulted strip. It is, therefore, difficult to explain why the anomalies in the trench near Pantelleria are more positive than is usual in that area. It is very unlikely that this could be explained by the use of too high a density in computing the Bouguer anomalies, but it may be due to the presence of dense basaltic lava flows on the floor of the trough. A thickness of some 4500 ft. would be required.

The sea floor drops very steeply from the shallow water of the Malta platform to the Ionian Sea. The shelf drops gradually from 100 to 200 or 300 fathoms and then plunges very steeply to about 2000 fathoms. The form of the slope varies in the different echo-sounder profiles taken across it. The first part of the drop, to approximately 1000 fathoms, occurs steeply and cleanly, but then the reflected echoes become faint and irregular and sometimes multiple. Interpretation of the sounder records is difficult when the sea floor slopes steeply, for the sound pulse sent out from the ship spreads over a wide angle (semi-angle of first lobe about 15°) and is scattered by irregularities over a wide area. Many echoes may return to the ship, and the first one to arrive, which is the depth recorded, may have been scattered from the side at a range quite different from the depth of water under the ship. Or, alternatively, no echo at all may return.

It has been assumed, in the interpretation, that all echoes are returned from points lying on the ship's course. Circles are drawn with centres at points corresponding to the ship's position at various times and radii equal to the echo range at these times. The envelope drawn tangent to these circles then represents the profile of the sea bed along the ship's course. Profiles thus drawn for the 300 to 1000 fathom cliff are given in figure 8, in which the horizontal and vertical scales are equal. The slopes are considerable, of the order of 45°. In the *Talent* profile, at 35° 40′ N, 15° 45′ E, there is a shelf 2 miles wide at 1100 fathoms and then a fairly rapid drop to 1800 fathoms, with an average slope of 8°. A profile taken by H.M.S. *Dalrymple* only a few miles away showed a single irregular slope averaging about 10° from 330 to 1730 fathoms. The form of the sounder profile depends on the

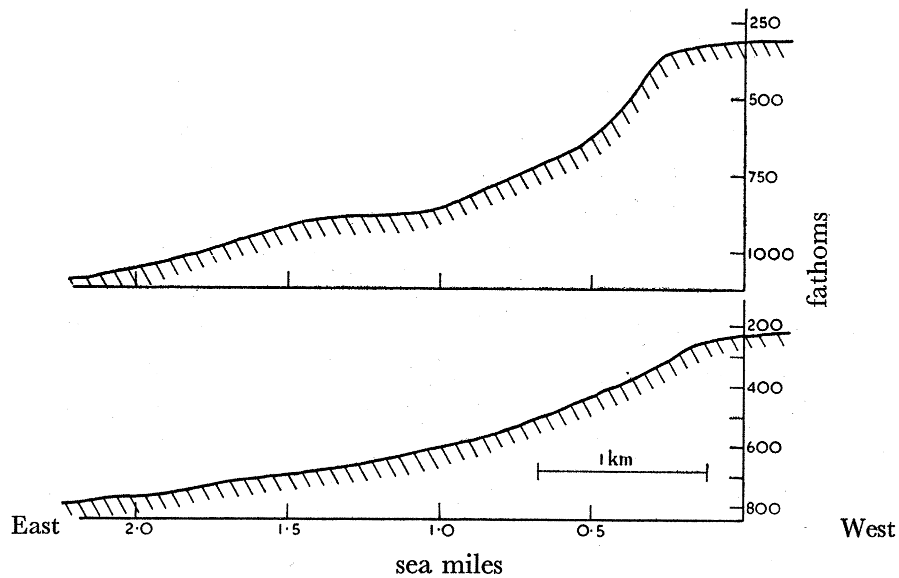


FIGURE 8. (Top) *Talent* profile and (bottom) *Challenger* profile across first portion of slope between Malta shelf and Ionian Sea. Horizontal and vertical scales equal.

angle at which the ship's course crossed the cliff, and the slopes deduced from the records are minimum slopes. There is good evidence that the slopes between the Malta platform and the Ionian Sea are too steep to be explicable otherwise than by faulting, as pointed out by Staub (1951, p. 68). The Ionian Sea has a fairly uniform depth of about 2000 fathoms.

Bathymetric charts provide the only evidence for the continuation of these scarps to the north and south. These are not altogether satisfactory, as errors of a few miles sometimes occur in the positions of soundings, and two widely differing soundings plotted close together are not conclusive evidence of a cliff between them; hence the importance of continuous profiles. The charts suggest that the cliffs cease to the south at about latitude 35° N, but there is evidence for continuous steep slopes northwards, off the eastern coasts of Sicily, the south-eastern coast of Calabria and in the Gulf of Taranto. Beneo (1951) marks faults along the whole of this coast in his tectonic map; two sets are involved, one striking NW-SE, the other NE-SW.

There is also evidence for faulting of the Ionian Sea margins on its eastern side. The outside of the Cretan island arc is faulted, and there are steep scarps off the western coast of the Peloponnesus and Greece (see §3). There are faults with NE-SW strikes in northern Cyrenaica, the downthrow being to the north-west. The sea deepens rapidly off this coast and these is a possibility of parallel faults at sea. The borders of the Ionian Sea are thus faulted over a considerable proportion of their length.

The isostatic anomalies in the centre of the Sea are positive, those at the edges of the Sea but still in deep water are negative, while the anomalies on the surrounding land or shallow water are generally positive. This picture is in agreement with the faulted character of the margins, positive anomalies occurring over the upthrown, negative over the downthrown, portions of the continental shelves. Positive anomalies in the centre of the Ionian Sea show that the basin as a whole is not downfaulted, but only its margins. This central part must be regarded as a basin of oceanic depth in essential isostatic equilibrium. The differences in anomaly across the faults at its edges is difficult to assess, as there are no traverses with close-station spacing. The isostatic anomalies, on the Airy hypothesis for $T=30$ km, are about $+120$ mgal in south-eastern Sicily and -25 mgal at sea immediately to the east; on the Hayford hypothesis for $H=113{\cdot}7$ km, the anomalies at sea are somewhat more positive. The difference due east of Malta is much smaller; on the Airy hypothesis the decrease across the fault is only about 10 mgal, while on Hayford's hypothesis there is a steady increase of anomaly towards the deep water. The east coast of Sicily is strongly faulted but the faults appear to die out to the south. There is some steepening of the continental shelf, but little gravitational effect, east of Malta and, south of latitude 35° N, the shelf is not exceptionally steep.

The Ionian Sea basin itself is apparently unaffected by the fault system of Sicily and southern Italy, and has an even, fairly flat bottom. It appears to have behaved as a rigid block whose edges have been faulted, but which has itself resisted the forces which deformed the neighbouring land areas.

The extensive NW-SE and NE-SW faults are a remarkable feature of the central Mediterranean, and faults with these perpendicular strike directions have been of prime importance in the formation of the Apennines, and in determining the shape of the coastline of peninsular Italy (for instance, see tectonic maps given by Staub (1951) or Beneo (1951)). This criss-cross pattern of faults is probably responsible for the patchwork nature of the gravity anomalies in the central Mediterranean area.

3. Crete island arc

The islands of Kithera, Crete, Scarpanto and Rhodes form a prominent, approximately semicircular, arc which separates the predominantly shallow water of the Aegean Sea from the deeper water of the eastern Mediterranean. This arc lies on the great mountain belt which extends from the east coast of the Adriatic through Turkey, Persia, northern India and Burma to the East Indian island arc, and it forms a link between the mountain ranges in Greece and Turkey. Many features of the East Indian arc are present, in a modified form, in this arc, and a comparison is of interest because structures of East Indian type have been recognized in many regions.

Both arcs lie on the Alpo–Himalayan mobile belt and are regions of Tertiary orogeny. Earthquakes are common in both areas, which suggests that orogenetic processes are still active. The East Indian arc is about 3500 miles in length from Sumatra to Ceram and has a very complicated shape, varying from the slightly curved Sumatra–Java–Flores portion to the sharply curved and highly complex Banda Sea–Celebes area; the Cretan arc approximates closely to an arc of a circle with radius 170 miles and centre near the island of Mykoni in the Aegean Sea.

The physiographic simplicity of the Crete arc is reflected in its gravity anomalies (figure 9). The southern Aegean Sea shows very uniformly high positive isostatic anomalies of about +100 mgal centred on Santorin, which appear to decrease gradually to the north, north-east and north-west, though there are practically no measurements in Greece, Turkey and the northern Aegean. The outside of the arc is characterized by very large negative anomalies which run in a strip, concentric with the arc as far as Rhodes, and then

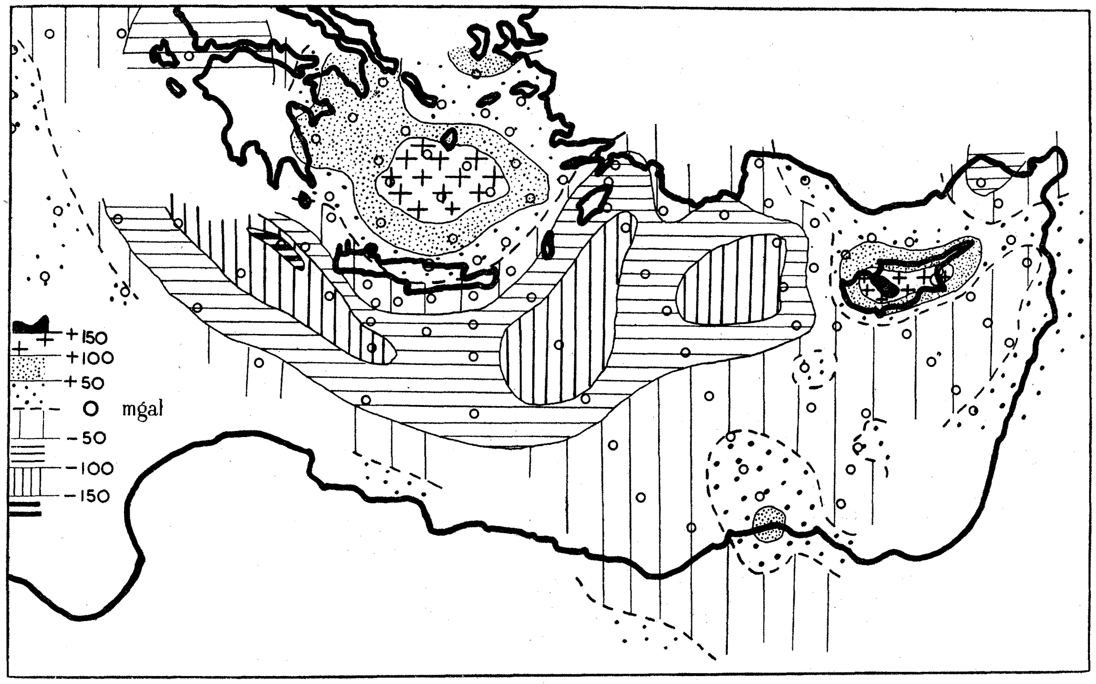


FIGURE 9. Isostatic anomalies in the eastern Mediterranean. Airy–Heiskanen hypothesis for $T = 30$ km. Gravity stations are shown by circles, except on Cyprus.

follow the south coast of Turkey as far as the Gulf of Iskanderun, though temporarily interrupted by the very large positive anomalies of Cyprus. This strip of negative anomalies continues throughout the surveyed area. It appears to strike into Turkey in a north-easterly direction by the Gulf of Iskanderun and, in the west, it is last traced striking in a north-westerly direction south of the Peloponnesus. Cassinis (1942) has measured anomalies of very nearly −100 mgal in the Gulf of Corinth which may belong to a northerly continuation of the strip. Alternatively, the anomalies measured by Cassinis may be associated with the graben structure of the Gulf of Corinth, and the negative strip may continue in a north-westerly direction off the west coast of Greece and the Peloponnesus. There is a large gradient of anomaly across the island arc, between the Aegean Sea and the negative strip.

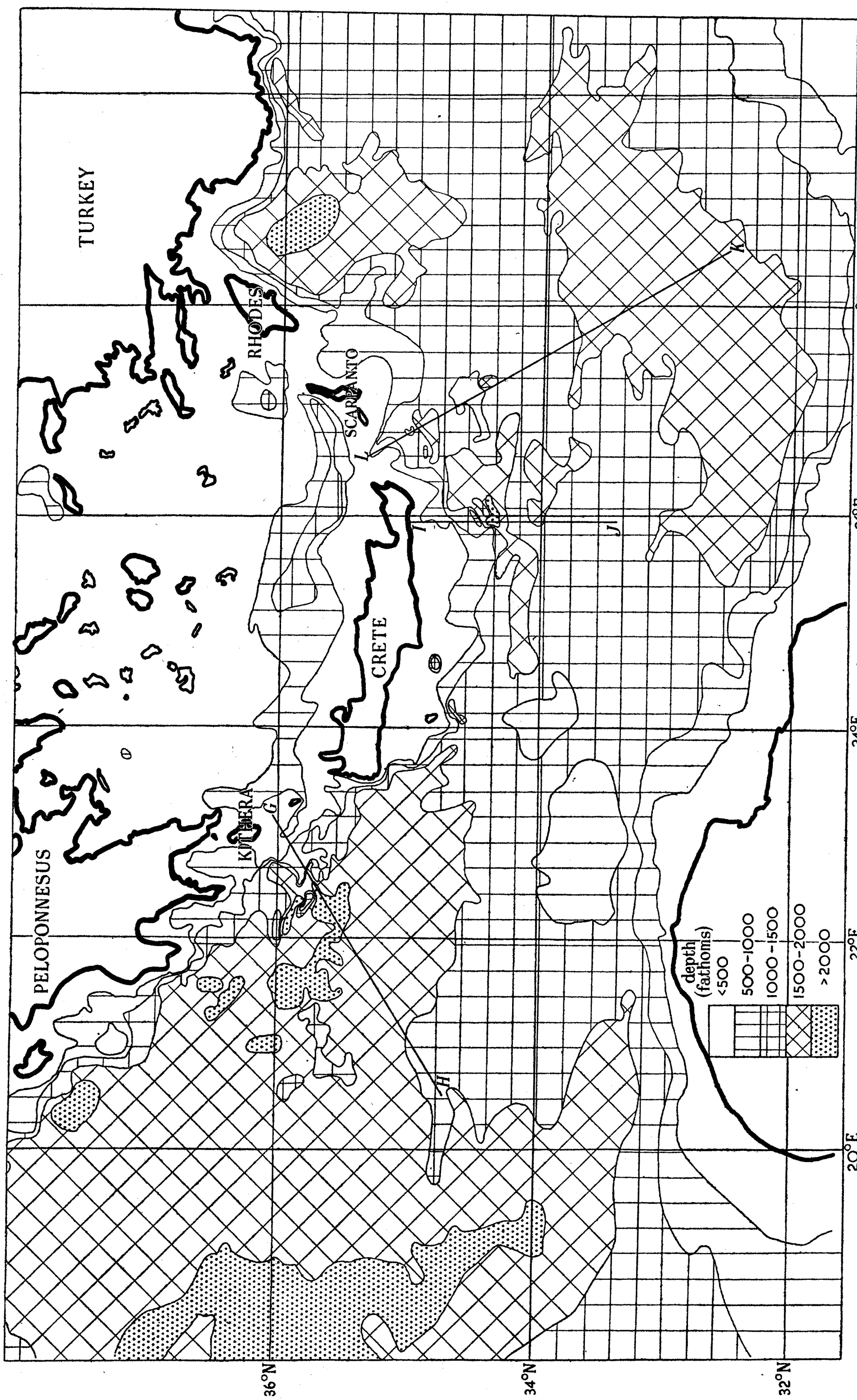


FIGURE 10. Bathymetric chart of the Crete island chart.

The gravity anomalies in the East Indies form a very much more complicated pattern. There is a strip of large negative anomalies outside the arc and a tendency for positive anomalies inside, but the positive anomalies occur in patches separated by secondary strips of negative anomalies and do not have the regular appearance of the Aegean anomalies.

The negative anomalies belonging to the Cretan arc are bounded to the south by the continent of Africa, and the eastern Mediterranean basin lies between the continents of Africa and Europe. The East Indian arc divides the continental mass of Eurasia from the Indian and Pacific Oceans, the islands surrounding the Banda Sea providing the only portion where a continental mass (Australia + New Guinea) lies on the outside of the arc.

There is a tendency for the Mediterranean to be deeper than usual just outside the island arc, but there are no features comparable in depth with the Java trench and the deeps outside the Pacific arcs. A bathymetric chart (figure 10) shows the sea floor to be very much simpler on the south-western side of the arc than on the south-eastern. There is a broad strip of deep water south-west of Kithera Channel which locally exceeds 2500 fathoms in depth. Profile *GH*, figure 11, shows that the slope of the sea floor from the shallow water of Kithera Channel to the deep water is extremely steep, whereas the water shallows gradually on the other side of the trough. Such profiles are typical of conditions off the western coast of the Peloponnesus and off the Kitheran and Antikitheran Channels. Profile *IJ* (figure 12) is typical of the type encountered on both of *Talent*'s north-south profiles south of Crete, but it is not known whether there is a continuous narrow trough or a number of local deeps. Profiles off the south-eastern side of the arc, such as profile *LK* in figure 12, are very irregular, but there again appears to be a fairly broad, simple trough, about 2400 fathoms deep, east of Rhodes.

The deep-focus earthquakes and volcanoes are two major features of the East Indian arc and both have parallels in the Cretan arc. No deep-focus earthquakes have been recorded in the Mediterranean area (using the classification of Gutenberg & Richter 1949, p. 10), but the Aegean, with the adjacent parts of Greece and Turkey, is a centre of shocks of intermediate depths (see figure 13). Both positions and depths are subject to considerable uncertainty—of the depths listed by Gutenberg & Richter, for only two is the 'probable limit of error' as low as 30 km. The epicentral positions are only rarely subject to as little as 1° 'probable limit of error' and 2° is a better average. The histogram would suggest a maximum activity at about 100 km depth but for the fact that nearly one-half of the intermediate depth earthquakes in this area have estimated depths of exactly 100 km. There has clearly been a strong bias in favour of the round number. No shocks have been reported with foci deeper than 180 km. There is no apparent correlation of the depth of a focus with its position and no indication that the foci lie on a dipping plane, as is the case in the Pacific.

There are several active volcanoes in the southern Aegean, and these, with other extinct volcanic islands, lie on the inner arc of the Cyclades, which parallels the main arc. The East Indian double-arc structure consists of an inner volcanic arc, and an outer sedimentary arc which coincides with the large negative anomalies. If the volcanic arc of the Cyclades is equivalent to the inner volcanic arc, then the Cretan arc should be equivalent to the East Indian outer sedimentary arc. The negative gravity anomalies, however, lie over the deep water outside the arc and not over the arc itself. Similarly, if the Cretan arc is compared with the inner East Indian arc, the volcanoes occur in the wrong position and there is no outer arc.

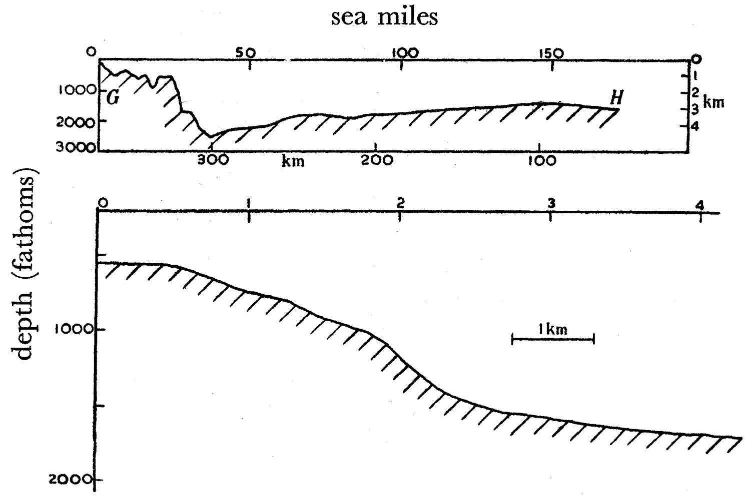


FIGURE 11. (Top) Profile *GH*. (Bottom) Enlarged portion of section *GH* showing the cliff with no vertical exaggeration.

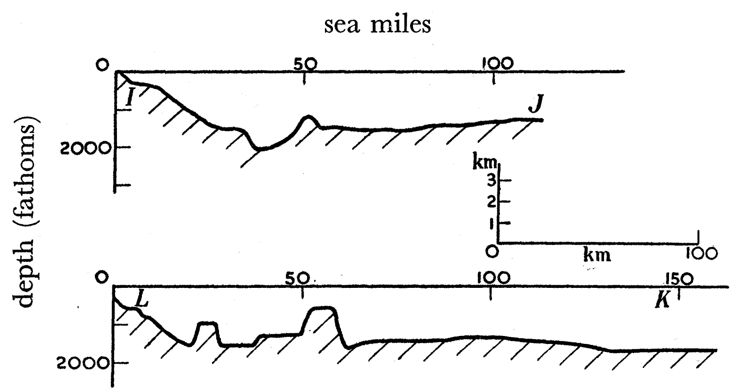


FIGURE 12. Profiles *IJ* and *LK*.

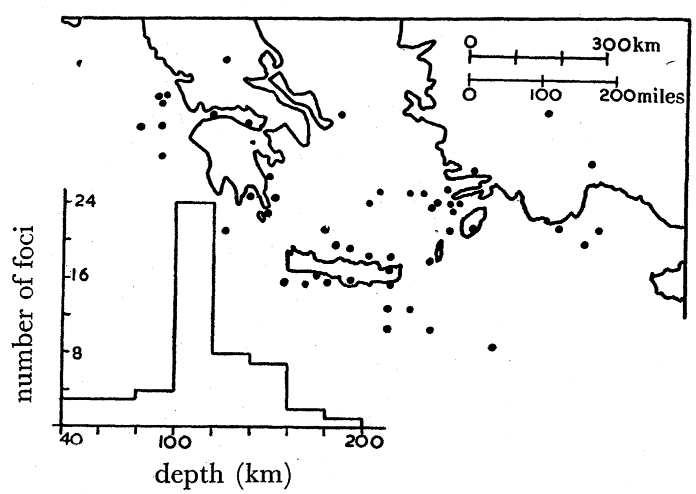


FIGURE 13. Earthquakes of intermediate depth near the Crete island arc.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Although the Cretan and East Indian arcs have several features in common, there is no exact correspondence between them and they differ in detail.

The gravity measurements in this area were obtained on two submarine expeditions, the British survey of 1950 and an Italian survey in 1935 (Cassinis 1942). There are also two measurements by Vening Meinesz near the African coast, several measurements in Athens and some measurements by Carnera (1915) in the Aegean Islands. The latter have not been used because their reliability is suspect. (There is a discrepancy of 164 mgal with Cassinis at Rhodes!) There may be a systematic difference of about 11 mgal between the British and Italian surveys (see Cooper *et al.* 1952, §3 (*d*)).

The gravity anomaly, at stations in the southern Aegean and in the negative strip south of Crete, is correlated with the depth of water at the station. The isostatic and free-air anomalies are positive over shallow water and negative over deep water, while the Bouguer anomalies are more positive in shallow than in deep water. Such a relation is very important and will be investigated statistically.

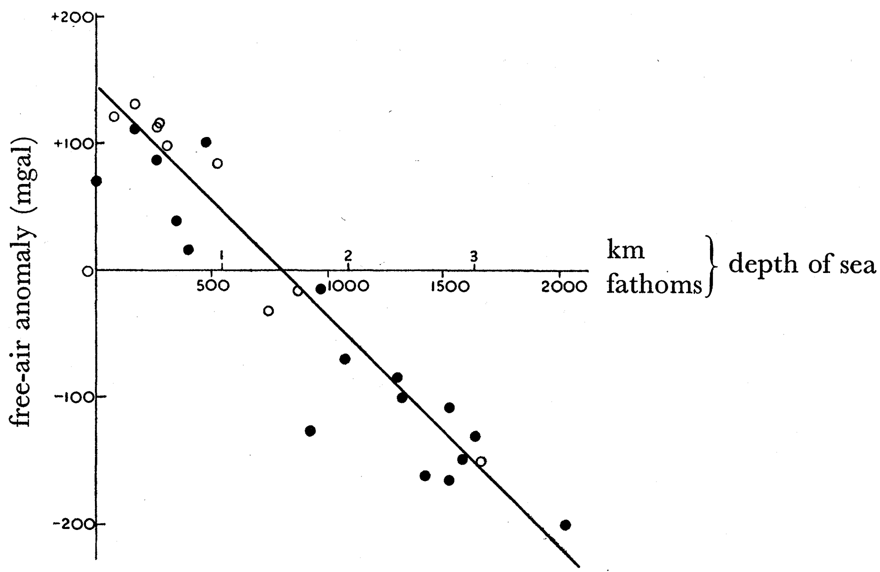


FIGURE 14. Free-air anomaly as a function of depth of sea in the vicinity of Crete island arc.

The data to be analyzed must be selected before statistical methods can be applied. The correlation does not hold generally, so the analysis must be restricted to observations in a limited area. Submarine cliffs, such as that illustrated in figure 11, occur on the outside of the island arc and are probably fault scarps. Such faults will locally disturb any simple relation between anomaly and depth, and it is, therefore, desirable to eliminate observations made near to the scarps before the statistical analysis. The following procedure was adopted.

A circular arc, which coincided well with the outer edge of the island arc, was drawn. Two concentric areas were drawn with radii 10 min of arc greater and 10 min less than that of the first arc. Radii were then drawn to exclude stations near the Greek and Turkish coasts, which are probably affected by the compensation of the mountain ranges in these countries, and the area was limited to the south by a further concentric arc with radius

4° 25′. Stations in the zone 10 min each side of the island arc are neglected, and the remaining twenty-seven observations investigated statistically.

The free-air anomaly is plotted as a function of depth of water at the station in figure 14. A linear relation is strongly suggested, and the straight line was fitted by the method of least squares. The anomalies in water shallower than about 800 fathoms (1·5 km) are positive, their magnitude increasing with decreasing depth; those in deeper water are negative, their size increasing with the depth of water. A relation of this type would result if the area had originally been in equilibrium with free-air anomaly everywhere zero and the depth uniform at 800 fathoms (1·5 km), and the topography had been built up by digging out matter in some places to make deeper sea and adding it in others to make the sea shallower. The variations of anomaly represent alterations in the mass per unit area, and sea made deeper in the way described would be associated with a decrease in mass per unit area. The change in mass per unit area for unit change in depth, and hence the density of the matter added or removed, can be found from the relation between anomaly and depth. This relation is conveniently expressed in terms of a density, which is 2·37 g/cm^3 for the relation of free-air anomaly with depth. This density is not that of the matter added or removed, because allowance must be made for the water, which is displaced when matter is added to make the sea shallower and flows in to fill the space formerly occupied by rock dug out to deepen the sea. The density of the matter added or removed is thus $2{\cdot}37+1{\cdot}03=3{\cdot}40$ g/cm^3, the density of sea water being 1·03 g/cm^3.

The relation between anomaly and depth was also investigated for the modified Bouguer anomaly, in which corrections were made for topography in the Hayford zones A to O and for topography and compensation in zones 18–1, using a density of 2·67 g/cm^3 and the Airy hypothesis for a crustal thickness of 30 km. A linear relation, $B=Dx+y$, was assumed, where B is the modified Bouguer anomaly (mgal) and D the depth (km). The method of least squares, when all twenty-seven stations were used, gave

$$x=-28{\cdot}63, \text{ r.m.s. error } 5{\cdot}35;$$
$$y=124{\cdot}8.$$
$$\text{Correlation coefficient } =0{\cdot}696.$$

The value for x corresponds to a density contrast of $0{\cdot}69\pm0{\cdot}13$ g/cm^3, or a density of $2{\cdot}67+0{\cdot}69=3{\cdot}36\pm0{\cdot}13$ g/cm^3. The correlation coefficient is used to test the significance of the apparent decrease of anomaly with depth. The probability, that the apparent decrease of Bouguer anomaly with depth, is spurious is much less than 1 % (Fisher 1950, p. 193). If allowance is made for a possible systematic difference of 11 mgal between the measurements of Cassinis and Cooper and the least-squares solution repeated, a density contrast of 0·63 g/cm^3 is obtained corresponding to a density of 3·30 g/cm^3.

In general surface features are compensated, mountains being associated with mass deficits at depth and oceans with mass excesses, so that the mass per unit area of the earth's crust remains approximately constant. Compensation is normally by no means exact, but it is very remarkable to find a consistent relation between Bouguer anomaly and topography in the opposite direction to that expected on any form of isostatic hypothesis. In this area, the base of the granitic layer, instead of showing an inverse correlation with surface features, shows a direct correlation with the topography. The Bouguer and free-air anomalies indicate that topography has been built up from a uniform level by the addition or subtraction of material with density 3·3 to 3·4 g/cm^3. The surface density cannot be as high as this, but the surface topography could have been formed by vertical movements of a uniform crust, the dense material being displaced or added at depth. The upper and lower surfaces of the crust would be parallel, the upper surface of the subcrustal material be parallel to the surface topography, and the density of 3·3 to 3·4 g/cm^3 would refer to subcrustal material. This estimate agrees well with the density deduced for this material by other methods. This hypothesis provides a very simple interpretation of the gravity anomalies and has been accepted.

Negative anomalies are sometimes associated with great thicknesses of light sediments but, in the eastern Mediterranean, the agreement between the density found from the anomalies and that deduced for the substratum by other means shows that an important quantity of sediment in the depressed area is unlikely, for this would disturb the anomaly-depth relationship. This relationship could, however, be explained if the depression of the crust were to displace material with a density less than 3·30 g/cm^3 and the thickness of sediment were proportional to the depth of sea; but the assumption of proportionality of sediment thickness to depth of sea is artificial, and it is even more unlikely that the constant of proportionality should be just right to make the apparent density given by the gravity anomalies equal to that generally accepted for subcrustal material.

An attempt to determine the crustal thickness was made by assuming a two-layer model, as in the Airy–Heiskanen isostatic hypothesis, and by computing a new type of anomaly, in which only topography outside zone O is assumed to be compensated, while inside the outer radius of zone O the upper layer is assumed to be of constant thickness. This anomaly, which was called a displacement anomaly, was computed for several normal thicknesses for the upper layer, the difference between the normal thickness and the thickness inside zone O being adjusted to make the mean anomaly zero. The mean-square displacement anomaly, however, did not vary sufficiently with the normal crustal thickness assumed to make a determination of crustal thickness possible.

The displacement anomalies in the 20 min strip near the island arc itself are strongly negative. This could be a result of either crustal thickening beneath the arc, or of thick sedimentation. The anomalies are negative on both sides of the scarps, which suggests that sedimentation is not the sole cause. The crustal thickening would amount to about 13 500 ft. (4 km) if it occurred over a horizontal distance of 18·6 miles (30 km), at a depth of 30 km, and if it were the sole cause of the negative displacement anomalies near the arc.

The island arc can be well accounted for by a reversed fault on its outer edge, the Aegean being pushed southwards and upwards over the eastern Mediterranean. The steep scarps outside the arc (figure 11) suggest a fault of some kind. The crustal thickening beneath the arc is of the same order as the vertical throw of the supposed fault, which would be the case for an overthrust fault dipping at 45° under the arc. A tensional fault would dip southwards from the surface scarps and be accompanied by thinning of the crust. The consistent negative displacement anomalies beneath the island arc itself, and the random nature of these anomalies south of the scarps, show that the fault is a compressional one dipping northwards. The concept of a single overthrust fault is of varying value along the arc. The south-western side can be well accounted for by such a fault, but the south-eastern is more complicated and there are probably several faults along this section.

The earth's crust has fractured along the Crete island arc, the Aegean area to the north being raised above its equilibrium position and the sea to the south depressed. These displacements are the cause of the large gravity anomalies. The fracture has involved crustal thickening beneath the island arc itself and is, therefore, a result of compression.

This interpretation is of importance in tectonic theory, for this type of depression is exactly what is needed in geosynclines. The eastern Mediterranean is an area of geosynclinal subsidence, and had been recognized as such geologically before any gravity measurements were made there (Seidlitz 1931, p. 57). It is not the geosyncline in which the sediments of the Greek and Turkish mountains were deposited, but a later depression farther south (Seidlitz, p. 187). The sediments of the Greek–Turkish geosyncline have been divided into zones depending on their facies and tectonic role (Seidlitz, figure 24). The zones are roughly parallel to the general topographic strikes, and those characteristic of the deeper, central, part of the geosyncline (East Hellenic and Parnass–Kiona Series) lie in the east of Greece and the Peloponnesus (Renz 1940). The tectonic situation in the Aegean is very complicated and is difficult to disentangle because only a small proportion of the area is above sea-level. The autochthonous material on Crete and Rhodes belongs to the outer margins of the main geosyncline which lay to the north, probably between the island arc and the Attic–Cyclades massif. Small fragments from the inner tectonic zones lie thrust on to these outer zones. The eastern continuation of this geosyncline is to be found in the Taurus Mountains of southern Turkey (Egeran 1947, map 2).

The formation of the present depression is difficult to date exactly. Late Tertiary–Quaternary faulting, which is still active, has been a very important influence in determining the present topography, and the faults on the outside of the arc belong to this group (Renz 1940, pp. 18–20 and 59–61). This faulting began after the main folding and thrusting in the Lower Miocene. It is probable that the northern geosyncline was destroyed and replaced by the southern, existing, depression during the Miocene folding, though a later date is possible.

The recent depression is a promising area to study the mechanism of crustal fracture and geosyncline formation, because of its simplicity and the absence of thick sediments, whose presence in other geosynclines confuse the interpretation.

The late Tertiary date for the origin of the east Mediterranean depression supports the field evidence for its compressional origin, for there is abundant evidence of compression in this area during the Miocene folding. The physical problem is, therefore, to study the effects of compression on a solid crust resting on a weak lower layer, which can be displaced to accommodate warping of the upper layer. The strength of the lower layer and the curvature of the earth are neglected and the problem is treated as two-dimensional.

Vening Meinesz (1934, pp. 44–53) proposed that compression in such a crust produces elastic instability and bends the crust into waves. This process would produce constant-thickness deformation of the crust, such as that observed around Crete, but has been rejected by Jeffreys on the grounds that the crust is elastically stable and would fracture before these waves could form (Jeffreys 1929, p. 228; 1932, 1952, pp. 311–314). Vening Meinesz recognized this objection but supposed that the crust consists of a number of layers which slide over one another during the bending, thus reducing the elastic potential energy in the waves and encouraging elastic instability.

Crustal waves contain potential energy which can be considered in two portions, elastic energy due to bending and gravitational energy due to distortion of the equilibrium surface of the substratum. This energy must be supplied by the compressive forces producing the waves. Even if the elastic energy is entirely neglected, this condition places an upper limit to the maximum wavelength that can be produced by compressive forces in a crust of given strength and thickness. It is easy to show that for any reasonable assumptions of crustal strength and thickness, this maximum wavelength is several times less than that observed in the neighbourhood of Crete.

The constant-thickness deformation of the crust in the southern Aegean and eastern Mediterranean cannot have been produced by a Vening Meinesz type wave, but the faulting along the Crete island arc, between the positive and negative anomalies, provides a possible solution. When the crust is compressed, the plane of maximum shear stress approximately bisects the angle between the maximum and minimum principal stresses, and is parallel to the direction of the intermediate principal stress. If the maximum principal stress is N-S, the intermediate E-W and the minimum vertical, the crust would be expected to fracture along a shear plane dipping at about 45° and cutting the surface

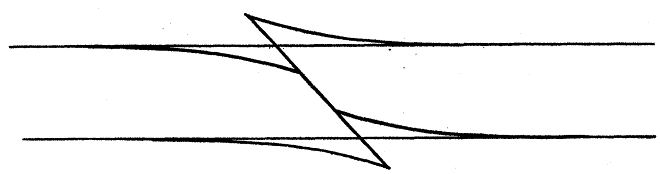
South  North

FIGURE 15. Type of crustal fracture postulated along Crete island arc.

along an E-W line. Suppose the plane to dip northwards. Then the northern section of the crust is pushed upwards over the southern and the crust each side of the fault is bent (see figure 15). The consequences of such a fracture have been investigated by Bullard (1936) and Gunn (1947). These authors agree that the equation of the deformed neutral axis may be sufficiently accurately represented by $y=(2Fq/\rho g)\exp(-qx)\cos qx$. F is the vertical force per unit length acting on the broken end of the section, g the acceleration due to gravity, ρ the difference between the densities of the substratum and of water and $q^4=3\rho g/Ed^3$. E is Young's modulus and d the thickness of the crust. q always has the same sign as x, which is measured from the centre of the fault. It may be shown that the energy conditions which ruled out a wave of Vening Meinesz type do not prevent a deformation of this type, provided that the total vertical throw at the fault does not exceed about 30000 ft. (9 km).

This, however, is probably not the limiting condition. The vertical throw of the fault is given by $4Fq/\rho g$. F is the vertical reaction between the two fractured portions of the crust and is limited by the maximum shearing forces the crust can stand. The shearing strength is about 3×10^8 dyn/cm^2, and this limits the vertical throw to 8200 ft. (2·5 km). If the compression is continued beyond this stage there will be a strong tendency for failure along vertical shear planes.

The energy considerations, which led to the rejection of the Vening Meinesz wave theory, do not prevent a somewhat similar wave being produced by faulting along a crustal shear plane. The fault is essential.

The vertical throw of this fault is $4Fq/\rho g$. The vertical displacements are greatest near the fault, decrease to zero when $x=\pi/2q$, then change sign and continue to oscillate. The equation is heavily damped, the second maximum is less that one-twentieth of the first and will almost certainly be disguised by other effects. This simple deformation is a good approximation to actual conditions on the south-western side of the Cretan arc, but the faulting is more complicated on the eastern side. However, this has little effect on the deformation away from the fractured zone itself.

The horizontal scale of the deformation enables the thickness of the solid crust to be estimated. The width of the strip of negative anomalies is about 150 miles or 250 km, and this, theoretically, is equal to $\pi/2q$. Hence the numerical value of q can be found and, by definition, q^4 is equal to $3\rho g/Ed^3$. Taking an average for E of 10^{12} dyn/cm^2, d may be estimated at 75 km. This value can only be regarded as an order of magnitude, as many approximations have been made in its derivation.

Estimates of the thickness of the granitic layer are considerably smaller than this, but the quantity measured here is not the thickness of the granitic layer but of the solid crust. Stresses of about 10^9 dyn/cm^2 down to depths of the order of 40 km, and finite stresses down to 50 km, are required to support the Himalayas, even on an isostatic hypothesis, and the crust must, therefore, be at least 50 km in thickness (Jeffreys 1952, pp. 196, 199).

4. Cyprus

The island of Cyprus provides a very complex and intriguing problem to the geologist and geophysicist. The first indication that the island is of special interest came in 1939 when Mace & Bullard published the results of gravity measurements on the island, which showed that it is characterized by some of the largest known positive anomalies. Until then very little geological attention had been paid to the island and, in particular, the only investigations of the Troodos igneous massif consisted of some rock descriptions published by Bergeat in 1892 and a reconnaissance by Bellamy (Bellamy & Jukes-Browne 1905), though Cullis & Edge (1922) had studied the pillow lavas fringing this massif in connexion with the associated copper deposits.

Fortunately, this situation has now improved and there have been two systematic investigations of the gelogy since the war, one concerned primarily with the sedimentary rocks and the other with the Troodos massif. The former, by Henson, Browne & McGinty, was published in 1949, the latter, by the Geological Survey of Cyprus set up in 1950 under the direction of D. W. Bishopp, is still in progress, though the principal results to date have been published in two papers (Bishopp 1952*a*, *b*). This paper contains only a summary of the geology, and the original works should be consulted for a more detailed account. It is derived from the papers by Henson *et al.* (1949) and Bishopp (1952*a* *b*).

Igneous rocks

Four different groups of igneous rocks have been encountered on the island. The boundaries in figure 16 are based largely on Bellamy's reconnaissance (1905) and are known to be incorrect in some places.

(*a*) *Folded Diabase*

This is the oldest of the igneous rocks, certainly older than the Upper Triassic, and is strongly folded along north-south axes. It probably consists of a series of basic lava flows with interbedded intrusive sheets and has suffered low-grade metamorphism to Epidiorite. In several places the series is severely shattered by faulting, and it is intruded by serpentine and gabbro. It is the most abundant rock outcropping in the Troodos igneous massif.

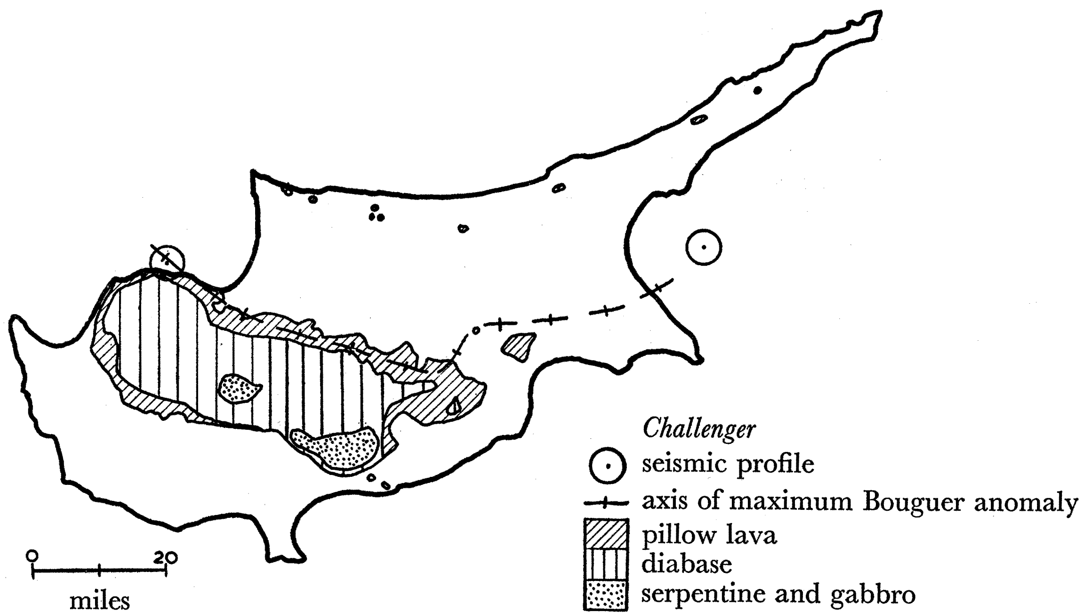


FIGURE 16. Igneous rocks on Cyprus.

(*b*) *Intrusions into diabase*

Gabbro and serpentine occur in association in plutonic intrusions into the diabase. Their relative and stratigraphical ages are unknown. The two intrusions are very probably continuous beneath the diabase, and these rocks may be more important at depth than near the surface. In one intrusion the serpentine is surrounded by a ring of gabbro and a narrow ridge of serpentine forms a core to the other, so that the serpentine is never in direct contact with the diabase. The serpentine is dunite-serpentine and the gabbro may have been produced by refluxing of the diabase.

(*c*) *The lavas*

The Folded Diabase is surrounded by a ring of andesitic lavas, mainly pillow lavas. Some of the lavas are interbedded with Triassic sediments, which are also extensively penetrated and baked by later extrusives. Some of the lavas are, therefore, certainly Triassic, and some belong between the Triassic and Upper Cretaceous; others may be older. In some places they were poured out over an eroded diabase surface. These lavas also outcrop in the Kyrenia range, where they are probably younger than the Jurassic limestones and are certainly older than Upper Cretaceous. There is also evidence of slight Tertiary igneous activity in this northern area.

(*d*) *Serpentine*

A borehole on the south coast struck serpentine after passing through nearly 4000 ft. of limestone. Bishopp considers that this serpentine is not comparable with the intrusive serpentine of the Troodos.

Sedimentary rocks

Renz has reported finding limestones with Permo-Carboniferous fossils, but this discovery was not confirmed by Henson *et al.* (1949). There is general agreement that any Palaeozoic limestones present exist as exotic blocks brought up by thrust sheets or extrusives.

The oldest sediments of known age in place are Upper Triassic. They are found mainly on the southern flank of the Troodos, where they are about 600 ft. thick, but also occur in isolated outcrops in the Kyrenia range. The succeeding deposits in the south are of Upper Cretaceous age, there being a considerable gap in the sequence, but, in the north, a hard, dense and often nearly vertical limestone forms the core of the Kyrenia range and is probably of Lower Jurassic to Lower Cretaceous age.

The succeeding Upper Cretaceous to Oligocene strata consist of globigerinal chalk marls changing to a flysch deposit near the Kyrenia range, showing that the Kyrenia uplift was beginning. The Miocene strata usually follow unconformably, but deposition was continuous in some local basins. They show the same facies change, the northern (Kythrean) facies consisting of over 10000 ft. of sandstones, with thin bedded limestones and marls, much disturbed by thrusting and folding. The transition to the much thinner, undisturbed, calcareous facies on the flanks of the Troodos is hidden beneath the later deposits of the Mesaoria plain. A volcanic bomb has been found in the Kythrean deposits, indicating some Tertiary igneous activity.

Structure

There are two mountain ranges on the island. The northern, Kyrenian, range, consists of sediments, with some lavas, thrust southwards during the Miocene. It extends along the entire north coast and forms the Cape Andreas peninsula which protrudes from the north-east corner of the island. The feature continues as a submarine ridge for about 20 miles in a north-easterly direction, but is then cut off sharply by water some 600 fathoms deep. It does not appear to continue out to sea in a westerly direction. The range is probably the result of basic rocks beneath the Mesaoria plain forming a rigid block against which the sediments were thrust by the Tauric compressions.

The Troodos range to the south is a much older igneous massif consisting of the basic rocks described above. It is probable that the basic rocks are bounded by faults, possibly on all sides, and that the lavas surrounding the massif were extruded through these faults. The gravity anomalies show that a large part of the basic rocks lie beneath the sediments of the Mesaoria plain, suggesting a fault along the northern edge of the Troodos. The borehole on the south coast, which passed through nearly 4000 ft. of limestone, is only slightly over a mile from the nearest outcrop of pillow lavas. The diabase shows marginal escarpments which are probably fault scarps. Further evidence for a very sharp cut off of the Troodos igneous rocks comes from a seismic profile obtained by H.M.S. *Challenger*

(Gaskell & Swallow 1953) in Morphou Bay. The position of the profile is 35·2° N, 32·7° E, in 75 to 140 fathoms of water, and just over a mile from the shore (see figure 15). The coast here is made of pillow lavas and the diabase outcrops about a mile inland. Three layers were found; surface sediments 1900 ft. thick with a velocity of 6000 ft./s, 2600 to 4600 ft. of a 9700 ft./s layer and a basement with a sound velocity of 13500 ft./s. The upper layer can probably be identified as Pliocene and more recent sediments. A velocity of 9700 ft./s is consistent with those found for Kythrean sediments on the Mesaoria plain. The most probable identification of the 13500 ft./s layer is with the pillow lavas, but the velocity could also match many other types of rock, including limestones. The shore geology suggests that the 9700 ft./s layer might be pillow lavas and the 13500 ft./s basement, the diabase. However, a velocity of 13500 ft./s is very low for diabase and 9700 ft./s is also rather low for andesitic lavas. The first, and more probable, interpretation of the seismic results implies 4500 to 6500 ft. of sediment hardly more than a mile from the pillow lavas. Faulting is strongly suggested, and the difficulty of estimating the geological corrections to the gravity anomalies is emphasized.

The gravity anomalies

In addition to the thirteen pendulum measurements made by Mace, parts of the island have been surveyed by the Iraq Petroleum Company with a gravimeter, and this survey was kindly made available by the Company and the Government of Cyprus. A number of stations were observed in the surrounding sea on the *Talent* survey, and a harbour station was occupied at Famagusta.

Mace's observations were made with the Cambridge pendulum apparatus, and experience elsewhere had led to the placing of considerable confidence in results obtained with this apparatus. The Iraq Petroleum Company made only relative measurements of gravity on the island, but a number of Mace's stations were occupied and there is good agreement between gravity differences found by Mace and by the Company. It is thus possible to base the gravimeter survey on a value of 981·265 cm/s^2 at Pendulum House, Cambridge, the base for the pendulum observations. A measurement by Bonini (Woolard *et al.* 1952) at Mace's station in Nicosia confirms the Pendulum House–Nicosia difference to within 1 mgal. The Iraq Petroleum Company made a check between Nicosia and the *Talent* station at Famagusta, and the measurements of Mace and Cooper are consistent to within 1 mgal. All the surveys used in the interpretation are well connected together and to Pendulum House.

The anomalies on Cyprus are very large and positive; Bouguer anomalies of over +200 mgal are found south of Kalokhorio. These anomalies are probably connected with the basic igneous rocks, which must be present in enormous quantity to produce such a large disturbance of gravity.

The first factor to be considered, when attempting to deduce the distribution of the basic rocks from the gravity data, is the density difference between the igneous rocks and the surrounding material. The basic rocks of Cyprus consist mainly of pillow lavas, diabase, serpentine and gabbro. A few specimens were collected by Cooper & Willmore in 1950 and, of these, the densest are the gabbro and diabase with densities of about 3·0. Though the number of samples collected was very small it is unlikely, on the basis of these

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

measurements and of the petrological descriptions of the rocks, that there is any substantial quantity of rock near the surface denser than 3·0. The serpentine, however, is ultrabasic dunite-serpentine, and there is a possibility of denser material at depth. A contrast of 0·33 g/cm^3, between the dense rocks and their surroundings, is first assumed and possible corrections to this discussed later.

The distribution of sediments provides a difficulty which is, at the moment, insuperable. Very thick Tertiary sediments cover parts of Cyprus, and these have low densities. Geological corrections should be made for these, after the manner of Evans & Crompton (1946) for India and Burma, but unfortunately very little is known about their thickness. The geological correction probably exceeds 40 mgal in some places.

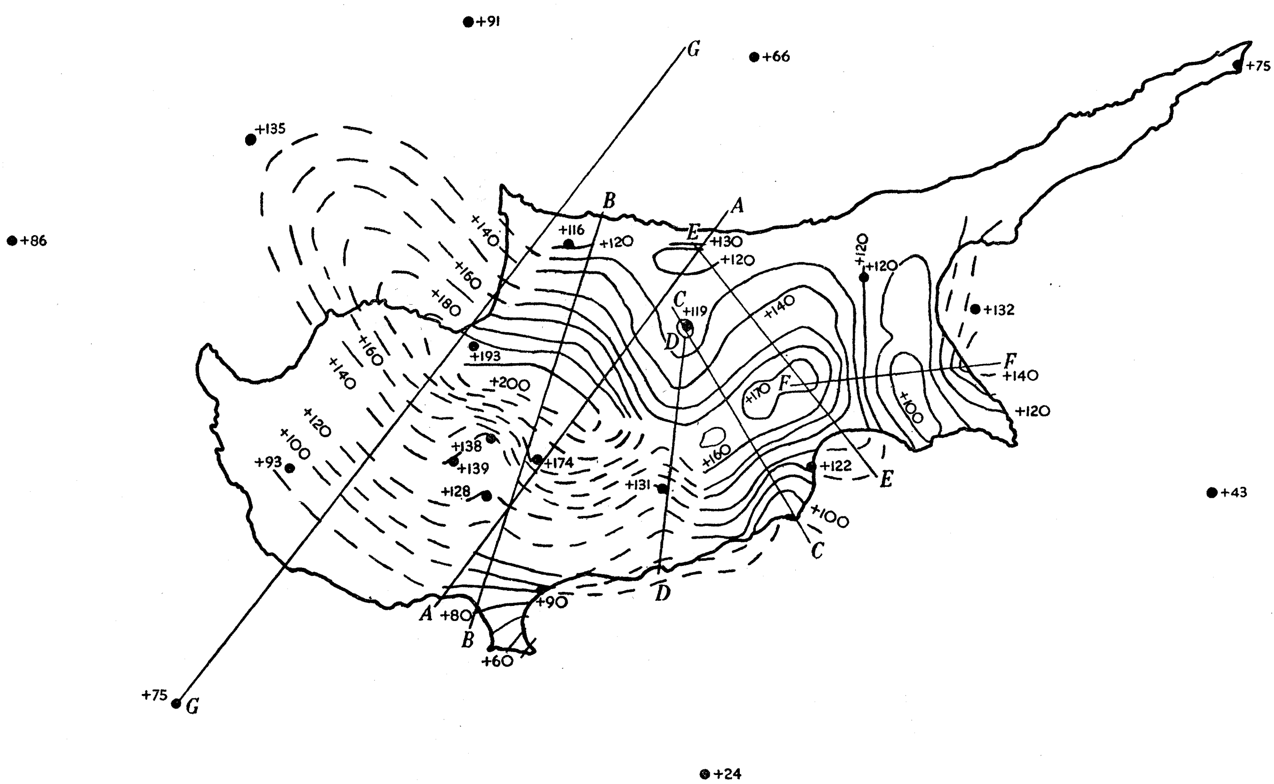


FIGURE 17. Bouguer anomalies on and near Cyprus (mgal). ——, isogams from Iraq Petroleum Company gravimeter survey; ●, pendulum stations; – – –, interpolated isogams.

A map of Bouguer anomalies (figure 17) shows the main feature to be a boomerang-shaped maximum—one arm going out to sea on the western side of Morphou Bay and the other at Famagusta Bay. In both cases there is evidence that the maximum continues out to sea. There is a Bouguer anomaly of +135 mgal at *Talent* station 179, off Morphou Bay, and, at Famagusta, the Bouguer anomaly is increasing seawards. The maximum is crossed by two north-south trends of low anomalies, one through Lefkara and Nicosia and the other about five miles west of Famagusta. A qualitative interpretation of this map suggests a basic mass elongated along an east-west axis, crossed by two north-south troughs of lighter material. A number of sections *AA*, *BB*, … , *GG* have been drawn, all at right angles to the axis of the maximum apart from *FF*, which is parallel to this axis but across the minimum west of Famagusta (figures 18, 19).

The observed gravity field consists of two portions, a regional portion and a local field due to the attraction of the basic mass, and these must be separated before the local field can be matched against computed profiles. The Bouguer anomalies at sea near Cyprus appear to be fairly constant at about +75 mgal except to the east and north-east of the island, where they are considerably less. The position of section *GG* was chosen so that the anomaly is about +75 mgal at each end, and it is assumed that the regional contribution to the anomaly is constant at +75 mgal along the section. The range of anomaly is just over 120 mgal, which is taken to be the maximum attraction of the basic mass at the surface. The regional and local anomalies cannot be separated in the other sections, but

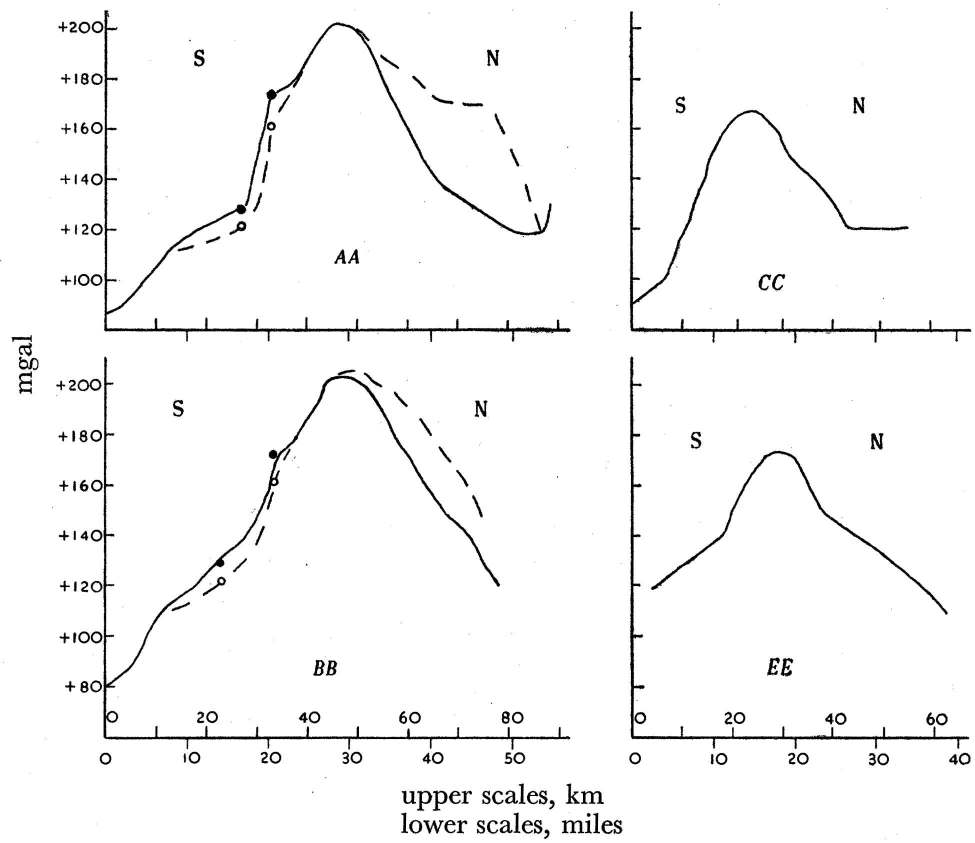


FIGURE 18. Profiles of variation of Bouguer anomaly across Cyprus. – – –, geologically corrected profiles; ●, pendulum valves; ○, pendulum valves corrected for geology.

the shape of the anomaly profiles will be governed by the more rapidly varying local attractions. Geological corrections to the anomalies are of two kinds. For stations on the Troodos massif a density of 3·0 should be used in deducing the Bouguer anomaly, instead of 2·67 as for the anomalies in figure 17. Corrections must also be applied for sediments with densities less than 2·67, in order that the basic mass may be regarded as embedded in material of density 2·67, and the density contrast of 0·33 be correct. The Tertiary sediments surrounding the Troodos massif are very thick in some places and have low densities. The thickness of the Kythrean deposits in the Mesaoria plain has been estimated geologically at over 10000 ft. (Henson *et al.* 1949, p. 22). Seismic work carried out for the Iraq Petroleum Company on the Mesaoria plain confirms thicknesses of this order, but is

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

of little use in determining the sediment distribution. The only other definite information comes from a borehole on the south coast, 9 miles east of Limassol, which struck serpentine after passing through nearly 4000 ft. of limestone (Bishopp 1952*b*). This borehole is hardly more than a mile from pillow lavas of the Troodos igneous massif.

There is no definite information available concerning the densities of these Tertiary formations but a density of 2·35 is probably not much in error. Thus corrections of about 1 mgal for every 250 ft. of sediment should be applied to the Bouguer anomaly. The

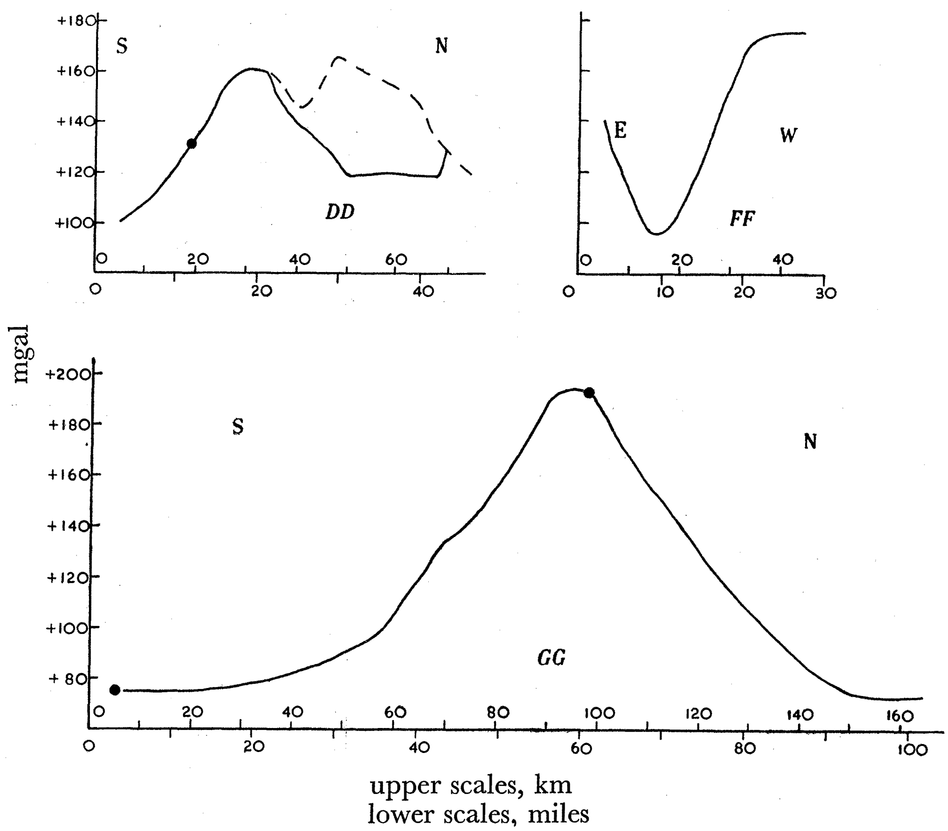


FIGURE 19. Profiles of variation of Bouguer anomaly across Cyprus. – – –, geologically corrected profile; ●, pendulum valves.

geological correction shown in figure 20 was then applied to the anomalies in figure 17, and the geologically corrected anomalies are given in figure 21. Although this correction is based on all available knowledge, it is in fact largely guesswork. Corrections for the dense rocks were applied individually to the pendulum stations on the Troodos. The geological correction was not extended to the low anomalies west of Famagusta, as it is probably better to use the gravity anomalies to determine the sediment thickness from section *FF*. A density of 2·25 was assumed for the Kythrean sediments, and a satisfactory fit can be obtained assuming a north-south sedimentary trough west of Famagusta with a maximum sediment thickness of 10000 ft., thinning to 3300 ft. at Famagusta.

The rapid fall off of Bouguer anomaly on the peninsula south-west of Limassol may be due to a rapid increase in sediment thickness, and the low anomaly at *Talent* station 191 may also be the result of thick sediments. The situation to the north is complicated. The rocks forming the Kyrenia range are dense, and the geological correction has been supposed to die out in this direction. However, these rocks are thrust over the light Tertiary sediments, and it is possible that a large geological correction should have been applied to anomalies over the Kyrenia range, and to the *Talent* stations to the north.

The geologically corrected sections AA', BB' and DD' are given in broken lines in figures 18 and 19. The maximum anomaly remains practically unaltered in magnitude and the axis of the maximum remains orientated east-west, parallel to the Kyrenia range. The maximum is, however, much broader. These main features are independent of the details of the geological corrections. The maximum anomaly occurs on the southern margin of the Troodos igneous rocks, and therefore cannot be much affected by corrections

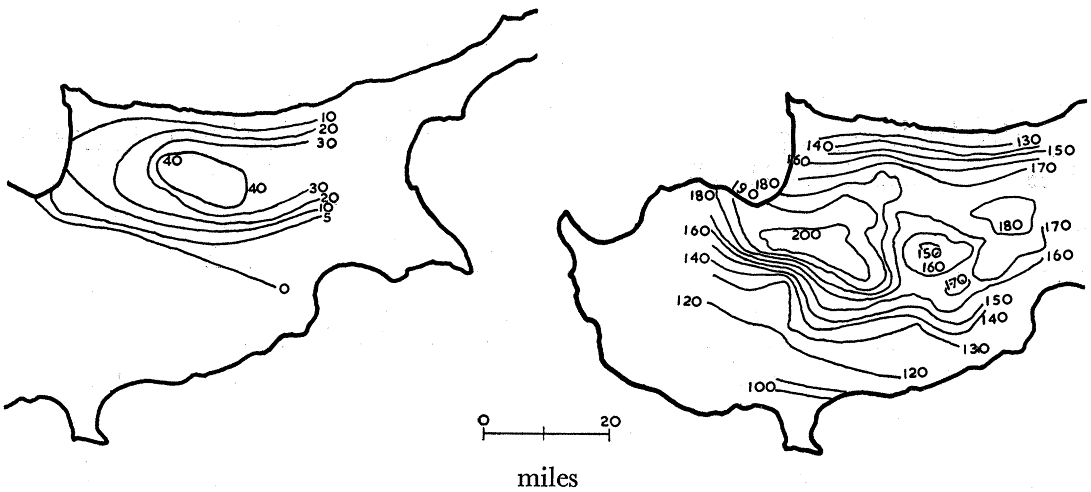


FIGURE 20. Geological corrections applied to anomalies in figure 17 (mgal).

FIGURE 21. Map of geologically corrected anomalies (mgal).

for light sediments. Corrections of the order of 40 mgal over the Mesaoria plain must have the effect of broadening the maximum. The axis of the maximum is still crossed by a subsidiary minimum south of Nicosia, which probably means that the geological correction is too small and that a north-south trough of sediments has not been allowed for.

The geological corrections are too uncertain and the gravity data over the Troodos too sparse to make a detailed analysis of the profiles worth while. However, an approximate idea of the distribution igneous rocks may be obtained by comparing the attractions of certain simple mass distributions with the observed profiles. There is no unique solution to the problem of deducing the mass responsible for a given gravity field, and the examples given are merely possible distributions. The mass is supposed to extend indefinitely along the axis of the gravity maximum and Vening Meinesz's (1934) tables, for the attractions of plane mass distributions extending indefinitely in a direction perpendicular to the section, are used.

Profile 1 (figure 22) gives a reasonable fit with the sections AA', BB' and DD'. The body giving rise to this profile consists of a rectangular core 27 miles (44 km) wide and 33000 ft. (10 km) thick, with wings 6600 ft. (2 km) thick added to bring the total width up to 62 miles (100 km). The density contrast assumed is 0·33 g/cm³, but the general shape of the profile does not vary appreciably if this contrast is increased, and the vertical dimensions decreased in inverse ratio, though the gravity gradients are increased somewhat.

There is considerable uncertainty about the geological correction. Although this correction does not increase the maximum anomaly, it does broaden the maximum considerably and it steepens the gradients at the flanks. Steep gradients must be caused by

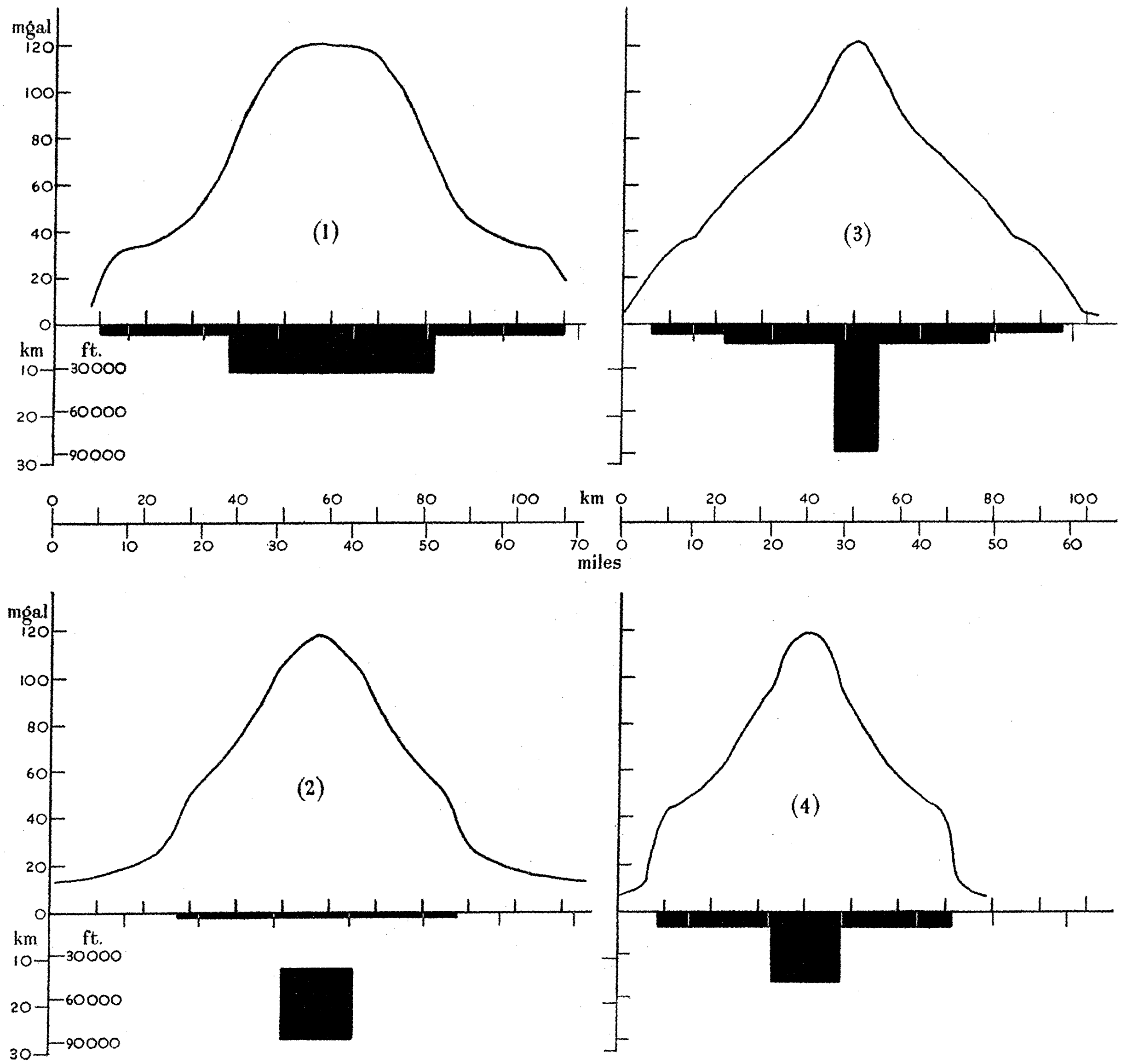


FIGURE 22 FIGURE 23

FIGURES 22 AND 23. Profiles of attractions of trial masses. Density = 0·33 g/cm³.

shallow masses. The gradients in profile 1, in which the mass has its upper surface at zero depth, are in fact slightly less than the gradients in AA' and BB', and it is known that there are at least about 10 000 ft. of sediments above the dense material. Hence the basic or ultrabasic mass is shallow and its upper surface is probably not more than 10 000 to 15 000 ft. deep, the minimum depth allowed by the known geological structure. The steep gravity gradients may have arisen because the geological correction was overestimated. In this case one of the masses in profile 2, figure 22, or profiles 3 and 4, figure 23, which fit the uncorrected gravity sections, may be nearer the truth.

The axis of the Bouguer gravity maximum, whether the anomalies are geologically corrected or not, is oriented parallel to the Tauric strike directions of Alpine age in the Kyrenian range and in southern Turkey. It is, therefore, very probable that the basic rocks producing the gravity anomalies are connected with Alpine events and the diabase is ruled out, because its severe north-south folding shows it to be associated with an earlier orogeny. The maximum anomalies are not centred over the Troodos but are displaced northwards, which again suggests that the exposed diabase is not directly connected with the gravity anomalies. The intrusive gabbro and serpentine are more likely to be directly connected with the rocks responsible for the gravity anomalies, and the plutons are alined along an axis approximately parallel to the Alpine strike directions. But the maximum anomalies do not coincide with the outcrops of the plutonic rocks, and there may be a further group of igneous rocks, which are not exposed at the surface but which are mainly responsible for the gravity anomalies. There is very little evidence of igneous activity in the post-Maestrichtian formations, but there may be Mesozoic greenstones concealed beneath the Tertiary sediments of the Mesaoria plain. If the Troodos plutons are typical of the material causing the gravity anomalies, this material is likely to be ultrabasic, as the gabbro may have been produced by refluxing of the diabase and the serpentine is dunite-serpentine.

The axis of the gravity maximum continues out to sea at Famagusta, and measurements at sea suggest that the positive axis continues across into Syria, though much reduced in magnitude. A *Challenger* seismic profile at 35·2° N, 34·1° E, in Famagusta Bay, located a basement rock with a velocity of 22000 ft./s, 8000 to 9000 ft. below sea-level, which shows that the igneous rocks extend at least as far east as this. Important basic igneous activity has taken place in north-west Syria and the Hatay province. These greenstones have been studied by Dubertret (1953) and may be related to the Cyprus problem. A gravity survey by Yungul (1951) only extends to the edge of their outcrop, but there is a rapid (19mgal/mile) increase of anomaly towards the basic rocks. The actual increase is about 40 mgal, and there is no sign of the gradient decreasing. The succession is from 3000 to 10000 ft. thick and contains, from the bottom upwards, pyroxenitic peridotites and serpentines followed by olivine gabbros and gabbros with no olivine. The gabbros are overlain by fine-grained doleritic gabbros and dolerites and the succession ends with basalts and pillow lavas. The greenstones are autochthonous and are sometimes both underlain and overlain by Maestrichtian sediments, the overlying beds being transgressive. These rocks are, therefore, Maestrichtian in age, though there are also basic rocks of other ages in the area. Some of the magma was injected beneath a cover of the lavas and some of the dolerites.

It is difficult to accommodate a basic mass such as that in figure 22 (1) without supposing large-scale replacement of the upper crustal layers, of which there is no sign. The body can be made smaller, and more manageable, if the density contrast is increased. It could have been a ridge of ultrabasic rocks extruded on to the sea floor, or a shallow laccolithic intrusion, which has since been buried by sediment. The largest reasonable density contrast for such a body is about 1·0, ultrabasic material with density 3·3 contrasted

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

against sediments with a density of 2·3. The thickness would then be 11 000 ft., which is of the same order as the Syrian greenstones. But it is unlikely, judging from the descriptions given by Dubertret, that the mean density of the Syrian greenstones could be much above 3·0. It would, however, be interesting to know whether the anomalies over the Syrian greenstones are comparable in size with those on Cyprus.

On the present evidence, it is not possible to decide whether the rocks responsible for the anomalies on Cyprus are basic or ultrabasic. They form a mass, approximately rectangular in vertical cross-section and some 27 miles (44 km) in width, which extends the whole east-west width of the island between Morphou and Famagusta Bays and is flanked on each side by smaller masses which bring the total width up to about 60 miles (100 km). The possible density contrast for the central portion lies between 0·33 g/cm^3 for basic rocks contrasted against rocks of normal crustal density (2·67) and 1·00 g/cm^3 for ultrabasic rocks of density 3·30 contrasted against sediments of density 2·30. In the former case the mass would be some 33 000 ft. (10 km) in thickness, in the latter 11 000 ft. (3·3 km). The southern margin of the 27 mile wide central portion lies approximately under the centre of the Troodos massif and its northern edge is some 17 miles beyond the outermost outcrop of the pillow lavas surrounding the massif. It is probable that part of this mass reaches the surface as serpentine intrusions into the Folded Diabase, though it may not appear at the surface at all. A Mesozoic age is most probable and a connexion with the Maestrichtian Syrian greenstones is indicated by the trend of the gravity anomalies.

Cyprus, with its large positive anomalies, should be sinking to regain isostatic equilibrium. If the relation between the rate of disappearance of gravity anomaly and the magnitude and lateral extent of the anomalies, as deduced by Vening Meinesz (1937) from his study of the post-glacial uplift of Fennoscandia, is applied to Cyprus, it is found that the island should be sinking at about 0·4 in. per year. There is no evidence for this subsidence: ancient harbour works near Famagusta are in much the same position relative to sea-level as when built; there are raised beaches round the island; the Troodos streams show sign of rejuvenation and Upper Pliocene marine deposits are found up to 1400 ft. above sea-level on the Troodos. However, the Mesaoria plain appears to be a region of Tertiary, and possibly later, subsidence. The indentations of Morphou and Famagusta Bays are connected by a sedimentary trough which contains considerable thicknesses of Tertiary sediments. It is possible that this subsidence was caused by the weight of the igneous rocks.

5. Origin of the dense rocks of Cyprus

The gravity anomalies on Cyprus are caused by dense rocks, which usually only exist deep in the earth's crust, occurring near to the surface in a region where the normal density is lower. These dense rocks must have been raised to their present anomalous position. This section discusses certain physical processes which could have raised them, and possible relations between these processes, the Tauric geosyncline in southern Turkey and the negative anomalies in the eastern Mediterranean.

The dense rocks may have been raised either in a liquid or in a solid state. In the first case the molten rocks would have had a density lower than that of the crust and would have been pushed upwards by hydrostatic forces. In the second, the rocks would have been intruded as an essentially solid, plastic mass of crystals, in which case they would have retained their high density during the intrusion and hydrostatic forces would have been insufficient to raise them through a crust which is in isostatic equilibrium.

Bowen & Tuttle (1949) have shown that a liquid water/olivine magma cannot exist below 1000° C. Thus, if the material were intruded as a liquid it must have had a temperature of over 1000° C, and comparison with Jeffreys's (1952) curves of the normal temperature distribution in the mantle show that this implies a heating of more than 500° C over its original temperature. The problem is thus one of finding a source of heat capable of melting the dense material. A concentration of radioactive material, at first sight the most likely source for the heat, does not seem probable because basic and ultrabasic rocks are normally associated with low radioactivities, though the Cyprian rocks may prove to be an exception.

If the dense material were solid during its upward movement, then it is necessary to postulate forces to push it upwards through the 'granitic' layer of seismology. This layer is generally in approximate floating equilibrium, and even if a hole could be drilled through the upper layers, the pressure at the bottom would be insufficient to bring the dense material to the surface. There are three ways in which the material could be forced up. If the crust is forced downwards into the substratum, then the hydrostatic pressure at the base of the crust is increased and hydrostatic forces alone may be sufficient to raise the dense material. A depression of about 21 000 ft. or 6·5 km is required to raise material of density 3·2 g/cm^3 through a 30 km crust of density 2·7 g/cm^3. The finite viscosity of the substratum means that forces are required to push it aside during a geosynclinal depression, and the consequent increase of pressure at the base of the crust would tend to force material upwards. These two processes suggest a possible explanation of the prevalence of basic and ultrabasic rocks among geosynclinal deposits, particularly their association with radiolarites which may often represent a deep water facies (e.g. Bailey 1936). Cyprus, however, did not lie in the centre of a geosyncline. The main Tauric geosyncline lay to the north, in southern Turkey, and Cyprus lay only in its southern margins. Cyprus lies on the axis of the strip of negative anomalies in the eastern Mediterranean, which represents a geosynclinal depression of the crust. However, geological evidence from Greece and the Aegean area shows that this depression did not start until Miocene times, by which time the igneous activity in Cyprus was over.

Bending of the crust also produces forces which favour the raising of deep material. The curvature is associated with compressive forces on the concave side, and with tensional forces on the convex side, of the bent crust. The crust to the north of Cyprus was depressed during the Upper Palaeozoic and Mesozoic to form the Tauric geosyncline, so that the neighbourhood of Cyprus would have been associated with compression deep in the crust and tension near the surface. The compression would tend to force material from the lower crustal layers upwards, while the tension near the surface would facilitate penetration by the rising material. In the crustal fault hypothesis for geosynclinal depressions discussed in the second half of § 3, the compression at the base of the crust and the tension at the surface equal $\frac{1}{2}Ed\ \mathrm{d}^2y/\mathrm{d}x^2$, which has a maximum when $qx = \frac{1}{4}\pi$, that is at about 75 miles (125 km) from the fault. The maximum throw allowed by the shearing strength of the crust is 8200 ft. (2·5 km) and the fibre stresses corresponding to this throw are $1\cdot 2 \times 10^9$ dyn/cm^2. These forces are superposed on the compression in the crust (3×10^8 dyn/cm^2), giving a total compression at the base of the crust of $1{\cdot}5\times10^9$ dyn/cm^2 and a tension near the surface of $0{\cdot}9\times10^9$ dyn/cm^2. These stresses are probably sufficient to cause fracture. The vertical displacements, for a given reaction at the fault, are increased if the downfaulted area is covered by sediments, or if the elevated area is eroded. The filling of the downfaulted trough by sediments of density 2·3 g/cm^3 would mean that the vertical movements of the crust, and hence the fibre stresses, could be increased by a factor of 2·3 before the limit set by the vertical reaction at the fault is reached.

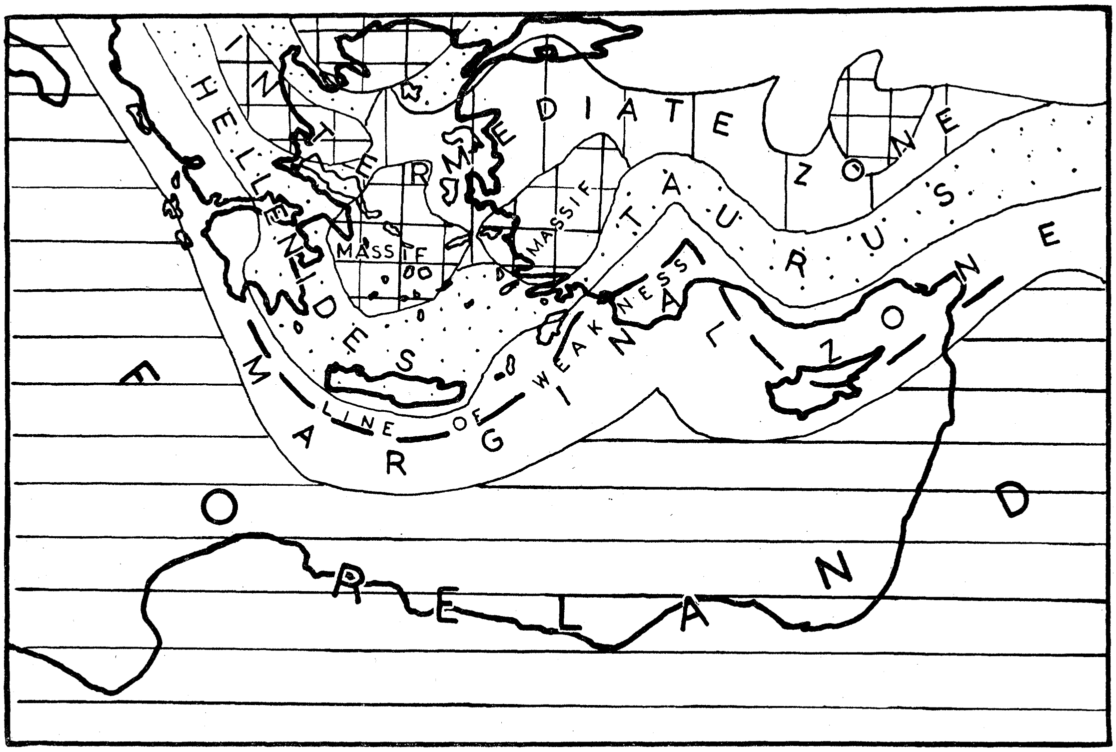


FIGURE 24. Tectonic zones in the eastern Mediterranean.

These forces due to the crustal bending cannot alone account for the Cyprian rocks, because the removal of about 10 km^3 of rock per km width, from the lower layers would remove them entirely while the buried igneous mass beneath Cyprus, even if of density 3·3 g/cm^3, must contain at least 150 km^3 of rock per km width of section. The bending forces may, however, have initiated and determined the position of, the ultrabasic intrusion, which was continued by the first two processes considered.

The southern margin of the Alpo–Himalayan geosyncline is not often characterized by such immense greenstone masses as that underlying Cyprus, and a possible objection to the mechanism just proposed is that it predicts a continuous line of such rocks along the entire length of its southern margins. It is, however, possible for other types of failure to occur along the line of maximum curvature; in particular, a fault may develop as suggested by Bullard (1936) in his theory of the origin of rift valleys. The faults of the Crete island arc may have been formed along the same line of weakness as the Cyprian igneous activity. The position of this supposed line, with the tectonic zones as reconstructed by Egeran (1947), is shown in figure 24.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The nature of the failure along the line of weakness is probably determined by local conditions. Possibly the faulting along the Crete island arc was encouraged by unrelieved compressions after the Alpine orogeny, due to the crust beneath the Aegean resisting deformation, whereas that to the east and west underwent failure to produce the mountains in Greece and Turkey and their roots.

Large greenstone intrusions appear to be associated with the crossing of the Alpo–Himalayan geosyncline by older orogenic belts, as has been pointed out by Henson (in discussion after Dr Hudson's paper at the Geological Society of London on 18 March 1953 (Henson 1954)). The Folded Diabase is strongly folded along north-south axis, which shows that an earlier orogenic belt with a north-south strike direction passed through the position of Cyprus. Two other regions of abnormally large positive anomalies lie in positions relative to the Alpo–Himalayan geosyncline analogous to that of Cyprus. Extensive basic igneous rocks of Mesozoic age in the Oman are associated with a rapid increase in gravity anomaly. The increase is about 200 mgal, and there is no evidence for a decrease in the gradient. The rock types include basic lavas, serpentines, gabbros, diorites and some small granite bosses (Lees 1923). Older north-south strikes are found in the Oman, and there is clear evidence for the intersection of two different strike directions (Henson 1951).

The other example of gravity anomalies, similar to those on Cyprus, occurs in north-eastern India, and is described by Evans & Crompton (1946). After corrections have been made for the known geology, there remains a marked linear maximum near Haflong, just south of the Himalayas, which is convex to the south, being orientated east-west in its western part and NE-SW in its eastern. Evans & Crompton fit a mass distribution to a profile across the maximum, assuming a density 0·3 above normal, and deduce a cross-section about 15 miles (25 km) wide and 50000 ft. (15 km) high. No basic rocks are seen at the surface and there is no information about their age or character. The position of this maximum just south of the Himalayas, at the intersection of the east-west Himalayan strikes with the north-south Burman axes, and its extension generally parallel to the Himalayas are very reminiscent of Cyprus and the Oman. These examples support the hypothesis of a zone immediately to the south of the Alpo–Himalayan geosyncline, in which exceptional basic igneous activity is liable to occur. The curvature forces provide a simple and natural explanation for this zone.

6. Nile delta

Great rivers carry large loads of sediment from the land, depositing them when they flow into the sea, so that great piles of sediment are built up at the river mouths. These sediments increase the mass per unit area of the earth's crust and should, therefore, be associated with positive gravity anomalies. Figure 25 shows that, although the edges of the Nile delta are generally characterized by negative anomalies, the central parts do show the expected positive anomalies.

The gravity measurements in this figure were made by several observers. A number of sea stations on the delta were occupied during the *Talent* survey, and two sea stations and a harbour station had been previously occupied by Vening Meinesz. On land, there are some pendulum measurements on the delta, made by the Survey of Eygpt (Cole 1944), and some gravimeter stations in northern Eygpt, kindly made available by the Shell

Petroleum Company. The Survey of Egypt measurements were based on a value of gravity of 979·295 cm/s^2 at Helwan, but a value of 979·288 cm/s^2 now appears more likely and a corresponding correction has been made to these measurements.

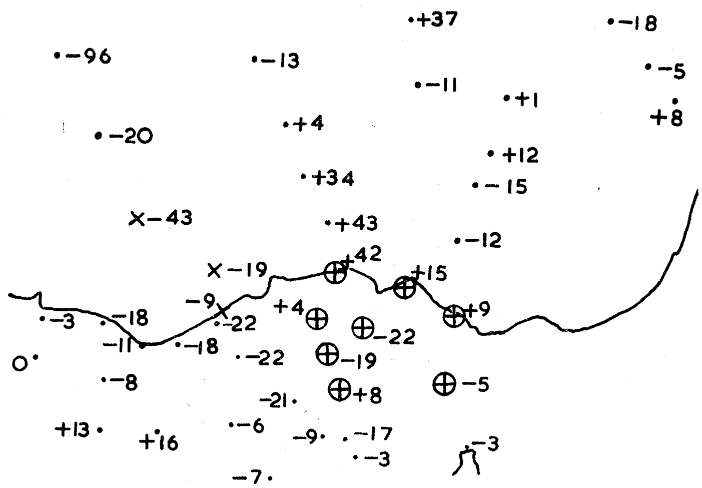


FIGURE 25. Isostatic anomalies (mgal). Airy–Heiskanen hypothesis for $T = 30$ km. • (at sea), Cooper station; • (on land), Shell station; ×, Vening Meinesz station; ⊕, Survey of Egypt station.

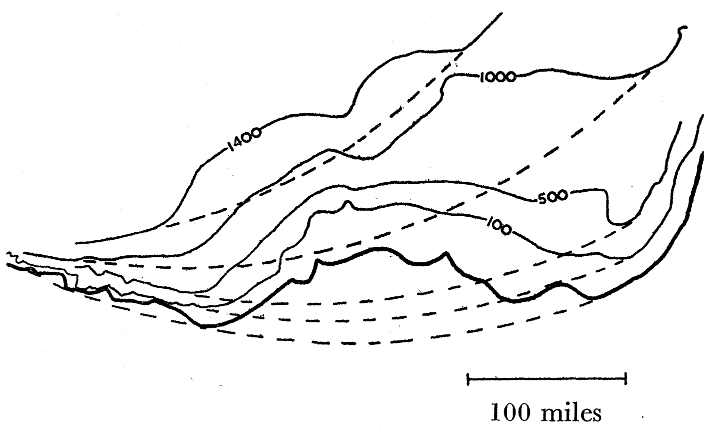


FIGURE 26. Smooth extension of isobaths across Nile delta (depths in fathoms). — Present isobaths; - - - smoothed isobaths.

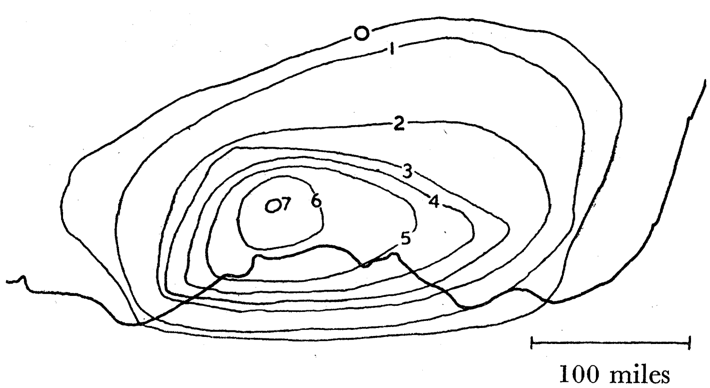


FIGURE 27. Thickness of sediment derived from figure 26 (in thousands of feet).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The apparent size of the pile of sediment can be estimated by continuing the isobaths on either side of the delta smoothly across it, as shown in figure 26. The smooth contours represent the position of the sea bed before the deposition of the sediments, and the volume between this surface and the present sea floor is occupied by sediments. The sediments form a lens-shaped body about 7000 ft. thick at the centre, as shown in figure 27.

If the positive anomalies are solely due to the sediment, it should be possible, making certain density assumptions, to calculate these anomalies from the volume of sediment. The measurements on the delta were reduced isostatically, on Airy's hypothesis for a normal crustal thickness of 30 km, using the topography which existed before the deposition of the sediments. If the isostatic anomalies were zero before the deposition of the sediment, and if the present anomalies are due to the load of sediment, the anomalies calculated above should be equal to the attraction of the sediment. This attraction is

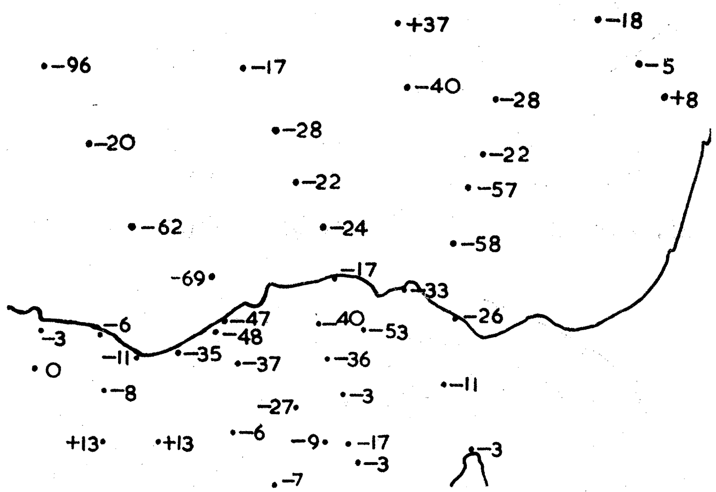


FIGURE 28. Sag anomalies for sediment density of 2·4 g/cm^3 (mgal).

subtracted from the anomalies and a new anomaly obtained, which has been named a 'sag' anomaly. The sag anomaly depends on the density assumed for the sediments, and this might lie anywhere between 2·0 and 2·5. If the sediments are clays, the variation of mean density with thickness, calculated by Cook (1952), suggests a mean density of 2·3 to 2·4. The sag anomalies for densities of 2·0, 2·2, 2·4 and 2·6 are listed in table 3 and those for a density of 2·4 are plotted in figure 28.

The sag anomalies, instead of being small, are consistently negative. This may mean that the earth's crust has been depressed by the weight of sediment, with the displacement of subcrustal material. The effect of this depression, relative to the assumptions made previously, is the displacement of a thickness of subcrustal material and the introduction of an extra thickness of sediment, equal to the distance by which the original sea floor has been depressed. The sag anomalies for a density of 2·4 are converted into depression of the crust, using a density contrast of $(3·3-2·4)=0·9$. Smooth contours of equal depression are drawn (figure 29). There is some uncertainty in these contours because the sag anomalies at four stations (*Talent* 197 and 198, Vening Meinesz 10 and Baltim) do not fit smoothly with the picture given by the others. These stations may be seriously affected by factors other than the sediments and consequent crustal depression.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The calculated distribution of sediments, after including the depression shown in figure 29, is illustrated in figure 30. This calculated distribution is subject to some uncertainty, because of the assumptions made in its derivation, but the broad picture is probably correct and the estimates of thickness are probably accurate to about 2000 ft.

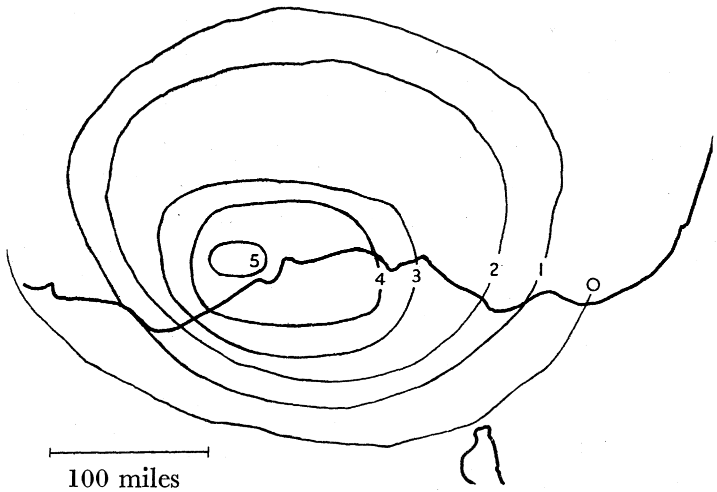


FIGURE 29. Crustal sag deduced from figure 28 (in thousands of feet).

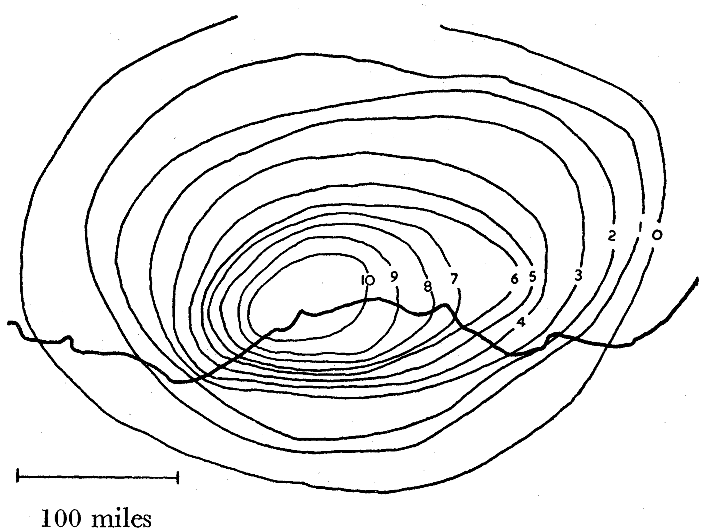


FIGURE 30. Total sediment distribution on Nile delta (in thousands of feet).

No stratigraphical age has been assigned to the sediments in the above discussion. The Nile valley was cut in the Miocene, the cutting being complete in the Pontic (Mio-Pliocene). The valley was flooded by the sea during the Middle and Upper Pliocene to a distance of some 400 miles from its present mouths, and filled in with sediments. Erosion of these sediments began in the Plio–Pleistocene and has, on the whole, been continuing ever since. The re-excavation is not yet complete and the erosion has not been continuous, as evinced by terraces left from periods of deposition (Sandford 1936). Deposits on the present delta are, therefore, probably of two different ages, those laid down during the

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

original excavation of the valley and those laid down during the re-excavation in Plio–Pleistocene and more recent times. It is unlikely that much sediment could have reached the delta during the intervening period.

TABLE 3

station no.	density ... 2·0	2·2	2·4	2·6
	sag anomalies (mgal)			
162	−19	−23	−28	−32
163	−17	−17	−17	−17
173	−29	−34	−40	−46
174	+37	+37	+37	+37
195	−16	−22	−28	−33
196	−9	−16	−22	−28
197	−43	−50	−57	−64
198	−34	−46	−58	−71
199	+9	−8	−24	−40
200	−6	−14	−22	−30
201	−20	−20	−20	−20
202	−96	−96	−96	−96
M. Alex.	−25	−36	−47	−58
M. 8	−54	−58	−62	−66
M. 10	−48	−59	−69	−80
Benha	−3	−3	−3	−3
Tanta	−35	−36	−36	−37
Kafra	−25	−32	−40	−48
Baltim	+10	−4	−17	−30
Pt. Said	−12	−19	−26	−33
Ismaliva	−10	−10	−10	−10
Mansura	−43	−48	−53	−58
Damietta	−11	−22	−33	−44
S. 1	−3	−3	−3	−3
S. 18	−3	−3	−3	−3
S. 19	−17	−17	−17	−17
S. 20	−9	−9	−9	−9
S. 21	−7	−7	−7	−7
S. 22	−27	−27	−27	−27
S. 23	−35	−36	−37	−37
S. 24	−40	−44	−48	−52
S. 25	−33	−34	−35	−35
S. 26	−6	−6	−6	−6
S. 27	+16	+16	+16	+16
S. 28	−11	−11	−11	−11
S. 29	+13	+13	+13	+13
S. 30	−8	−8	−8	−8
S. 31	−6	−6	−6	−6
S. 32	−3	−3	−3	−3
S. 33	0	0	0	0

Station thus: 174 Cooper station.
M. 8 Meinesz station.
Tanta Survey of Egypt station.
S. 22 Shell station.

The deposition of the deltaic sediments in two separate periods would make any deductions about quantities such as sedimentation rates and substratal viscosities very difficult and unreliable.

7. Conclusion

The submarine gravity survey of the eastern Mediterranean has provided much valuable information bearing on its geological structure. Major results of its interpretation are the recognition of an important fault south of Malta and of a very large mass of ultra-basic or basic rock beneath Cyprus, lying slightly to the north of the outcrop of such rocks on the island. It has been possible to make estimates of the thickness of sediment underlying the Nile delta, and the hypothesis, which is strongly suggested by the gravity data, that the topography in the southern Aegean and outside the Crete island arc has been formed by vertical displacements of a uniform crust, is one of great importance. Gravity anomalies alone, however, are capable of being interpreted in many different ways especially as on this survey, when the station spacing is large. In addition, the interpretation has been made more difficult by the absence of gravity data in Greece and Turkey. The *Talent* gravity survey is most valuable as a reconnaissance survey, and its interpretation has defined the main problems in the area and suggested solutions. These solutions have to be tested by other methods which are capable of giving a more detailed and definite answer, and this paper has shown how such future work in the eastern Mediterranean may be most usefully employed.

Acknowledgements

The author is much indebted to Dr R. I. B. Cooper, formerly of the Department of Geodesy and Geophysics, Cambridge, for his very great help and encouragement, to Dr R. W. Hey, of the Sedgwick Museum of Geology, Cambridge, for his assistance with geological problems and to Mr B. C. Browne, head of the Department of Geodesy and Geophysics, for his help and advice. The Royal Dutch Shell Oil Company and the Iraq Petroleum Company very generously allowed the use and publication of geophysical data acquired by them. Much invaluable data was received from the Hydrographic Department, through the courtesy of the Hydrographer, Vice-Admiral A. Day, C.B., C.B.E., D.S.O., R.N., by whose kind permission the charts and profiles in this paper are published. Extra soundings were specially taken in some places of particular interest.

This interpretation was made while the author was a research student at the Department of Geodesy and Geophysics, Cambridge, during which time he received a maintenance grant from the Department of Scientific and Industrial Research. Finally, the author wishes to express his gratitude to the many people who have assisted him by their discussion and by bringing to his attention information and points of view that would otherwise have been overlooked; in particular, to Sir Edward Bullard, F.R.S., for his comments on the manuscript of this paper.

References

Bailey, E. B. 1936 *Bull. Geol. Soc. Amer.* **47**, 1713.

Bellamy, C. V. & Jukes-Brown, A. J. 1905 *The geology of Cyprus.* Plymouth: W. Brendon.

Bemmelen, R. W. Van 1952 *Geol. en Mijnb.* Nr. 8, nw. ser., 14e Jaargang, p. 306.

Beneo, E. 1951 *Boll. Serv. geol. Ital.* **72** (1), Nota II (1950).

Beneo, E. 1952 *Boll. Serv. geol. Ital.* **73** (2) (1951).

Bergeat, A. 1892 *Miner. petrogr. Mitt.* **12**, 263.

Bishopp, D. W. 1952a *Nature, Lond.*, **169**, 489.
Bishopp, D. W. 1952b *C.R. XIXth Int. Geol. Congr.* Sect. xv, 13.
Bowen, N. L. & Tuttle, O. F. 1949 *Bull. Geol. Soc. Amer.* **60**, 439.
Bullard, E. C. 1936 *Phil. Trans.* A, **235**, 445.
Carnera, L. 1915 *Ann. Idrogr.* **9**, Genoa.
Cassinis, G. 1935 *Pubbl. R. Commiss. Geod. Italiana*, Nuova Serie, Genova, no. 9.
Cassinis, G. 1942 *Pubbl. del'Ist. Geod. Top e Fotogr. Milano*, no. 47.
Cizancourt, H. de 1948 *C.R. Acad. Sci. Paris* **226**, 2164.
Cole, J. H. 1944 *Geodesy in Egypt.* Cairo: Government Press.
Cook, A. H. 1952 *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6**, 243.
Cook, A. H. 1953 *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6**, 494.
Cooper, R. I. B., Harrison, J. C. & Willmore, P. L. 1952 *Phil. Trans.* A, **244**, 533.
Coster, H. P. 1945 Doctoral thesis presented to University of Utrecht. Groningen: J. B. Wolters.
Cullis, C. G. & Edge, A. B. 1922 *Report on the cupriferous deposits of Cyprus.* London: Crown Agents for the Colonies.
Dubertret, L. 1953 Géol. des Roches Vertes du N.W. de la Syrie et du Hatay (Turquie). *Notes et Mém. sur le Moyen-Orient.* **6** (Mus. National d'Histoire Naturelle).
Egeran, E. N. 1947 *Tectonique de la Turquie.* Nancy: G. Thomas.
Evans, P. & Crompton, W. 1946 *Quart. J. Geol. Soc. Lond.* **102**, 211.
Fisher, R. A. 1950 *Statistical methods for research workers.* London: Oliver and Boyd.
Gaskell, T. F. & Swallow, J. C. 1953 *Nature, Lond.*, **172**, 535.
Glangeaud, L. 1951 *Bull. Soc. Géol. Franc.* (6e) **1**, 735.
Gunn, R. 1947 *Geophysics*, **12**, 238.
Gutenberg, B. & Richter, C. F. 1949 *Seismicity of the earth.* Princeton University Press.
Harrison, J. C. 1954 *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6**, 604.
Henson, F. R. S., Browne, R. V. & McGinty, J. 1949 *Quart. J. Geol. Soc. Lond.* **105**, 1.
Henson, F. R. S. 1951 *Proc. 3rd World Petroleum Congress*, Sect. I, p. 118.
Henson, F. R. S. 1954 *Quart. J. Geol. Soc. Lond.* **110**, 149.
Hoffman, J. 1952 *Geol. en Mijnb.* nr. 8, nw. ser. 14e Jahrgang, p. 297.
Jeffreys, H. 1929 *The earth*, 2nd ed. Cambridge University Press.
Jeffreys, H. 1932 *Geol. Mag.* **69**, 321.
Jeffreys, H. 1952 *The earth*, 3rd ed. Cambridge University Press.
Lagrula, J. 1951 *Bull. Carte géol. Algér.* 4e Ser. Géophysique, no. 2.
Lees, G. M. 1928 *Quart. J. Geol. Soc. Lond.* **84**, 585.
Mace, C. 1939 *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **4**, 473.
Medi, E. & Morelli, C. 1952 *Ann. Geofis.* **5**, 209.
Reed, F. R. C. 1949 *The geology of the British Empire*, 2nd ed. London: E. Arnold.
Renz, C. 1940 *Prakt. Akad. Athen*, **8**.
Sandford, K. S. 1936 *Geog. Rev.* **26**, 67.
Seidlitz, W. von 1931 *Diskordanz und Orogenese der Gebirge am Mittelmeer.* Berlin: Bornträger.
Staub, R. 1951 *Ecl. geol. Helv.* **44**, 29.
Vening Meinesz, F. A. 1934 *Gravity expeditions at sea*, vol. **2**. Delft: J. Waltman.
Vening Meinesz, F. A. 1937 *Proc. Acad. Sci. Amst.* **40**, 654.
Woolard, G. P., Harding, N. C., Muckenfuss, C., Bonini, W. E. & Black, W. A. 1952 *World wide gravity measurements conducted during the period June* 1949–*January* 1952. Massachusetts, U.S.A.: Woods Hole Oceanographic Inst. (Tech. Report, No. 52–59.)
Yungul, S. 1951 *Bull. Geol. Soc. Turkey*, **3**, 1.