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The British Submarine Gravity Surveys of 1938 and 1946

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THE BRITISH SUBMARINE GRAVITY SURVEYS OF 1938 AND 1946

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CONTENTS

PAGE

PART I. INTRODUCTION

PART II. APPARATUS AND TECHNIQUE

PART III. MEASUREMENTS AND RESULTS

PART IV. INTERPRETATION OF RESULTS

PART I. INTRODUCTION

1·1. Objects of the expeditions

The structure of the ocean basins is one of the most outstanding problems of geology. The fact that the rocks which form the floor of the ocean are not directly accessible for investigation renders its solution a matter of considerable difficulty. Until recently, almost the only data available were derived from soundings and bottom samples, but the development of geophysical methods now provides means by which additional information can be obtained. One of the most notable advances was the development, by Professor F. A. Vening Meinesz, of the submarine pendulum apparatus which enables accurate measurements of gravity to be made at sea. More recently, the application of the seismic technique has provided another powerful means of investigation. In 1935, Professor M. Ewing (Ewing, Cary & Rutherford 1937) used this method to study the structure of the continental shelf on the Atlantic seaboard of the United States. His results indicated that although the depth of the water only increased very gradually out to the 100-fathom line, the underlying basement rock, as it may be called, shelved more steeply, and near the edge of the shelf was overlaid by many thousands of feet of less compacted sediments. This work was soon followed by similar investigations carried out by Dr E. C. Bullard (Bullard & Gaskell 1941) at the mouth of the English Channel, where the same type of structure was found. These two regions differ in that the main structural lines in the eastern United States run roughly parallel to the coast, while at the mouth of the English Channel they are more nearly at right angles to the edge of the continental shelf. It appears probable, therefore, that the presence of large thicknesses of sediment may well be a general feature of the edge of the continental shelf.

To explain this structure, it has been suggested that, owing to the action of tides and waves, the sediment which is continually being brought down by the rivers is unable to remain permanently in the shallow parts of the sea and is gradually carried farther offshore until it eventually comes to rest in the deeper and quieter waters beyond the 100-fathom line. On this theory, the edge of the continental shelf is an area of deposition, and the question at once arises as to how the crust of the earth behaves under such a gradually increasing load. Some measurements of the gravitational field at the mouth of the English Channel had already been made by Vening Meinesz and had shown that, although in the main the area was in isostatic equilibrium, there was a tendency for the isostatic anomalies, as usually calculated, to become more positive as the depth of the sea increased. Such a result might well arise if the density of the sediments were less than 2·67, the value assumed when making the isostatic reductions. The theoretical value of gravity would therefore have been overestimated near the edge of the shelf, and so the anomalies would appear more negative than they should. To confirm this hypothesis, accurate gravity measurements were required over the region where the depth of sediment was already known from Bullard's observations. Meinesz had also found that the increase in isostatic anomalies on crossing the edge of the shelf was not confined to the mouth of the English Channel. If the above explanation should prove correct, gravity measurements might be used to infer the presence of sediment in other areas. These considerations made it evident that important results were likely to be obtained from a gravity survey at the mouth of the English Channel, and that their value could be greatly extended if further profiles across other parts of the continental shelf were also made.

Besides the primary object, the work of Nörgaard (1933) and one of the authors (Browne 1937) had shown that second-order effects, due to accelerations of the submarine, might introduce errors into measurements of gravity made at sea. This possibility had already been investigated by Meinesz (1938), who carried out some preliminary experiments in the North Sea, which tended to confirm these ideas, but further work was clearly desirable.

1·2. ORGANIZATION

The Department of Geodesy and Geophysics at Cambridge University approached the Royal Society with the proposal that a submarine gravity survey on the lines indicated above should be undertaken. This request was given full support, and the Society agreed to make the necessary funds available.

Bullard's seismic experiments had also been carried out under the auspices of the Royal Society, who had appointed a small committee, under the chairmanship of Admiral Sir John Edgell, at that time Hydrographer of the Navy, to supervise and direct the work. This committee undertook the supervision of the submarine gravity survey. The Board of Admiralty were approached and agreed to make H.M. Submarine *Narwhal* available, during the summer of 1938. One of the authors (B.C.B.) was in charge of the technical arrangements for the expedition and was ably assisted by Mr L. H. Flavill, who accompanied him on the cruise. Unfortunately, the international situation became so tense that the programme had to be cancelled only 36 hr. after sailing, and it was evident that there was little hope of being able to renew the work for some time. After the war the project was revived and again received the active support of the Royal Society. On this occasion the matter was referred to the Naval Research Facilities Committee under the chairmanship of Sir Geoffrey Taylor. The Board of Admiralty allocated H.M. Submarine *Tudor* for the work which was successfully carried out during the summer of 1946. Both the authors took part and were accompanied by Dr W. Nieuwenkamp of the Royal Dutch Geodetic Commission.

1·3. NARRATIVE: H.M.S. *NARWHAL* (1938)

Much of the apparatus for this expedition was borrowed from several sources. Thanks largely to the help of Professor Vening Meinesz, the Royal Dutch Geodetic Commission agreed to lend their pendulum apparatus, and one of the authors (B.C.B.) visited Holland for a week early in 1938 to learn how to use the instrument. Through the good offices of Professor R. M. Field, the Bell Telephone Laboratories of New York agreed to make available the special 'crystal chronometer' which had previously been used by Ewing (1937). Henry Hughes Ltd. not only generously provided deep-sea echo-sounding equipment but also allowed a member of their staff, the late Mr J. Hutchins, to take part in the expedition.

During the spring of 1938, the main parts of the apparatus were assembled and tested at Cambridge. On 21 August base-station swings were made at the Pendulum House. The apparatus was then taken to Devonport, and installed in the submarine, the pendulum apparatus being mounted in the middle of the control room. This work, especially the fitting of the echo-sounding equipment which was secured to the keel by wire ropes, called for considerable assistance from the Dockyard. On 4 September two observations were made while the submarine lay alongside in one of the basins. The water was extremely calm and no trouble was experienced from movements of the boat.

A short trial trip was made on 7 September to test the instruments at sea and to find the best conditions for making observations. A speed of approximately 2 knots was found to be sufficient to ensure that the submarine was well under control and yet free from vibration. This speed was then accurately measured by making runs, while submerged, over a measured mile, thus calibrating the log, and it was subsequently used during all observations. The next day two gravity measurements were made a few miles south-west of Plymouth, but the results were not satisfactory, as the phonic motor driven from the crystal chronometer stopped several times owing to electrical interference from the wireless transmitter.

Despite the serious international situation, H.M.S. *Narwhal* sailed from Plymouth on 12 September, and that morning two observations were made, one 8 miles south-east of the Lizard and the other 20 miles south of Land's End. On surfacing, fog was encountered, which made it unsafe to dive until it lifted the following evening. After crossing the 100-fathom line speed was slackened to allow a clear echo-sounding record to be made. This revealed the very complex submarine topography which is found on the edge of the continental shelf. A dive was made at a position 48° 09′ N, 10° 06′ W, where a satisfactory gravity measurement was obtained. Soon after surfacing a signal was received from the Admiralty cancelling the cruise and giving orders to return at once to Portsmouth. Fort Blockhouse was reached on the morning of 15 September, and the apparatus was immediately dismantled and taken ashore. After returning to Cambridge, the pendulums were swung at Pendulum House on 26 September. The periods were in good agreement with the previous observations, showing that the pendulums had not changed in length during the voyage. Some weeks later, the pendulum apparatus and crystal chronometer were sent to Holland, as it was clear that there was little hope of our being able to resume the gravity survey for a considerable time.

1·4. NARRATIVE: H.M.S. *TUDOR* (1946)

As soon as the end of the war made it possible to resume the plan for a submarine gravity survey, steps were taken to collect the necessary apparatus. The Royal Dutch Geodetic Commission kindly renewed the loan of their pendulum apparatus and, thanks to a grant from the Royal Society, two portable quartz-crystal controlled frequency standards were specially constructed by Standard Telephones and Cables Ltd. The Admiralty agreed to fit special echo-sounding equipment, which was designed by the Underwater Detection Establishment, Portland. By June 1946, all the necessary apparatus had been assembled at the Pendulum House and on the 27th and 29th base-station swings were made. The instruments were installed in the 'fore-ends' of the submarine at Portland, where the authorities at the Underwater Detection Establishment kindly arranged for workshop and dark-room facilities. The pendulums were first swung in H.M.S. *Tudor* on 28 July while the vessel was lying alongside. The results obtained were satisfactory. Tests carried out in the submarine before reaching Portland had, however, shown that neither the shallow-water nor the special deep-sea echo sounder was working satisfactorily. Representatives from the Underwater Detection Establishment examined the equipment and were able to repair the former. To repair the latter the submarine had to be docked. Arrangements were made to sail to Fort Blockhouse on 29 July where a dock was available. While on passage, a preliminary gravity measurement was made and the log calibrated by running over the measured mile near St Albans Head. The repairs were completed in time to sail for Devonport on 2 August, and two further gravity observations were made, one south of the Isle of Wight and the other off Portland Bill. Some trouble was experienced due to the armature of a motor generator burning out, but a spare was available at Devonport and was fitted within a few hours.

The week-end was spent developing the photographic records and computing the results, which were quite satisfactory. It was therefore with some confidence that the first week's programme was begun on 5 August.

A track chart, showing the positions of the various stations, is given in chart 1.* These are numbered chronologically. After the three preliminary dives in the Channel the next thirteen stations lie on a line from the Lizard to a position 47° N, 16° W. These measurements were carried out successfully. The only trouble experienced was a minor breakdown in the echo-sounder recorder which was temporarily repaired at sea and subsequently replaced on return to Devonport. 9 to 13 August were spent in developing and examining records.

The second week's programme consisted of nine stations on a line running south from Ushant to Gijon on the north coast of Spain. Some rough weather was experienced while crossing the Channel, and this caused a small trimming condenser in one of the frequency standards to break loose. This was found and repaired within a few hours, and the use of a mechanical chronometer prevented the loss of any observations. Later, trouble was again experienced with the frequency standards. This was eventually traced to corrosion of the contacts in the high-tension accumulators. 15 to 18 August were spent at Falmouth, where records were developed and examined. An attempt was made to make a gravity measurement while lying alongside, but this proved very difficult owing to the rapid increase in amplitude of the pendulums, caused by small waves bumping the submarine against the jetty. Eventually two swings were made, but it was found necessary to bring the centre pendulum to rest half-way through each observation by gently pushing the apparatus.

On 20 August, H.M.S. *Tudor* sailed for the third and longest lap of the expedition. After steaming west to 50° N, 13° W, the submarine turned north over the Porcupine Bank and then altered course to the north-west to a position 57° 45′ N, 17° 26′ W. From there observations were made on a straight line passing a few miles north of Rockall to St Kilda. A final dive in the Sea of the Hebrides was made before reaching Oban on the morning of 25 August. In all, eighteen observations were made during the week, but two were not properly recorded owing to failure of the clockwork mechanism which drives the camera in the pendulum apparatus. This trouble was overcome by fitting an auxiliary drive in the form of an air-driven wheel which was blown round by compressed air. At Oban, observations were made while lying alongside, but difficulty was again experienced and the procedure used at Falmouth had to be adopted.

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* The charts are printed at the end of the paper.

We sailed from Oban on Tuesday, 27 August, and in the Sound of Jura it was so calm that an observation on the surface was attempted. Although there was no swell and only a very slight sea, it proved impossible to prevent the pendulums from building up to an excessive amplitude. A record was obtained by bringing the centre pendulum to rest every 4 min., but it was not felt that much reliance could be placed on an observation made under these conditions. A second observation was therefore made immediately afterwards while submerged. Even then, at a depth of 80 ft., there was still quite marked disturbance, and some trouble was experienced in keeping the boat at a steady depth. The only explanation appears to be that there was considerable vertical movement of the water in the Sound.

During the next two days, five more observations were made between the Mull of Kintyre and Land's End. The weather was not good, but satisfactory records were obtained. After rounding Land's End the last observation of the voyage was made a few miles south of the Eddystone. Portland was reached early on the morning of 30 August. In case the pendulum periods had changed, it was most important to make accurate observations before removing the apparatus from the boat. The wind had moderated considerably, but there was still too much disturbance to make measurements while lying alongside the jetty. An attempt was therefore made to make the observations at anchor in the harbour. The results, however, were little better than those obtained in the Sound of Jura. Finally, it was decided to make a special dive just outside the harbour the following morning. Particular care was taken to determine both the position and Eötvös correction during the dive, and the observations were accordingly made at periscope depth. Although a certain amount of disturbance due to wave movements was experienced, the results appear to be quite reliable. The apparatus was accordingly dismantled, and on 3 September it was brought back to Cambridge by road where it was at once set up and base-station swings made on 5 September. These showed that the periods of the pendulums had changed by less than one part in a million during the voyage.

1·5. Acknowledgements and thanks

From what has already been written, it will be clear that the gravity surveys described in this paper could never have been undertaken but for the assistance which was received from numerous sources. It is impossible to give detailed acknowledgement to all who so kindly helped us, but it is hoped that the short list given in this section will serve to show something of the help received. To those not specifically mentioned the authors offer their apologies, and assure them that their kindness and assistance were very much appreciated.

Our thanks are primarily due to the Royal Society under whose auspices the expeditions were carried out and who provided the necessary funds; and to the Lords Commissioners of the Admiralty, for allocating H.M. Submarines *Narwhal* and *Tudor* to undertake the work. Special mention must also be made of The Hydrographer of the Navy, The Flag Officer Submarines and the Captains in Charge of Devonport and Portland Dockyards, together with the members of their staffs. On the civilian side, the Director of Naval Construction and the Chief of the Royal Naval Scientific Service and all those working in their Departments must be mentioned, especially the members of the Admiralty Research Laboratory, the Admiralty Gunnery Establishment and the Underwater Detection Establishment. Very special thanks are also due to Captain R. Conway, D.S.O., R.N., who was in command of

H.M.S. *Narwhal*, to the late Lieutenant A. Hobson, R.N., the captain of H.M.S. *Tudor*, and to all their officers and men, who contributed so much to the success of the expeditions by their hospitality, cheerfulness and help. To the Royal Dutch Geodetic Commission, especially to Professor F. A. Vening Meinesz and Dr W. Nieuwenkamp, we are greatly indebted not only for the loan of equipment but also for their personal kindness and assistance. To Professor R. M. Field and the Bell Telephone Laboratories for arranging for us to use the 'crystal chronometer' and to Henry Hughes and Sons Ltd. for lending the deep-sea sounding apparatus we are most grateful. Our thanks are also due to the Director of the Ordnance Survey and to Thomas Mercer and Sons for the loan of aneroid barometers and a chronometer. At Plymouth, the Director of the Marine Biological Station kindly provided dark-room facilities, and the Falmouth Photographic Society also allowed us to use their dark-room. One of the authors (R.I.B.C.) wishes to express his thanks to the Department of Scientific and Industrial Research for a grant, without which he would not have been able to take part in the work. Finally, the continued guidance and help given by Sir Gerald Lenox-Conyngham and the encouragement and assistance of Professor E. C. Bullard are most gratefully acknowledged.

PART II. APPARATUS AND TECHNIQUE

2·1. Pendulum apparatus

The pendulum apparatus used throughout both expeditions was the original instrument designed by Meinesz and used by him so extensively in the past. A very complete description has already been published (Meinesz 1929), but since then some important improvements have been made. The first of these is the addition of two long-period pendulums mounted in a case between the main body of the pendulum apparatus and the camera. The movement of these pendulums is recorded photographically on the same record as the main pendulums, and enables the two components of horizontal acceleration to be obtained with sufficient accuracy to give a satisfactory measure of the second-order corrections under normal working conditions. In *Narwhal* these long-period pendulums were undamped, but they were later modified in Holland by the addition of air-damping vanes. Details of their construction and use have now been published (Meinesz 1941 *a*). The other important modification was the inclusion of a small phonic motor in place of one of the original shutter arms used for putting time marks on the records. As this is a part of the timing system it is described in the next section.

During both expeditions remarkably little trouble was experienced, and the whole apparatus worked extremely well. The only failure which occurred was when the clockwork motor, used to drive the paper through the camera, became worn and the spring proved inadequate to run it for long enough to make a complete half-hour record.

2·2. Chronometers

The accuracy required for timing the pendulum in a submarine gravity survey is not quite so high as that needed for the most accurate land surveys. Nevertheless, it is desirable to know the rate of the chronometer to at least 1 in 2×10^6 (approximately $\frac{1}{20}$ sec./day). By comparison with the rhythmic time signals transmitted by the Post Office Wireless Station at Rugby (G.B.R.), the mean rate can easily be determined with this accuracy, but it requires an exceptionally good chronometer to ensure that the rate shall remain constant throughout the interval between time signals. In the past mechanical chronometers have been used, but the fact that these must operate electrical contacts, and the unfavourable conditions on board a submarine, make it difficult to ensure the necessary constancy of rate. Matters may be improved by using two or more chronometers, but it is quite possible that the conditions experienced during a dive, such as the change in temperature and pressure and the cessation of violent motion, may introduce systematic changes in the rates.

A great advance in the accuracy of timing was made by the American submarine gravity survey of 1936–1937 on board the U.S.S. *Barracuda*, by using the 'crystal chronometer' designed and constructed by the Bell Telephone Laboratories in New York (Ewing 1938). This proved extremely accurate even under the most exacting conditions. It consisted of a 100 kc./sec. valve-maintained oscillator controlled by a quartz crystal, the output from which was demultiplied to 1000 c./sec. and supplied the power required to run a small phonic motor mounted in the pendulum apparatus. The whole instrument, with the exception of the motor, was contained in a metal box measuring only 10 × 14 × 28 in. It was operated from batteries, the current consumption being 2 A at 12 V and 50 mA at 120 V. On board the submarine two sets of accumulators were used which were kept continuously charged from the ship's mains. The temperature coefficient of the G.T. cut crystal was so small that no thermostat was required. Other possible sources of error, such as variation in supply voltage and the effect of tilting, were found by experiment to be negligible.

The 'crystal chronometer' proved so successful that it was decided that a similar instrument should be used on the *Tudor* expedition. Thanks to a grant from the Royal Society Parliamentary Grants Committee, two quartz-crystal controlled frequency standards were specially constructed by Standard Telephones and Cables Ltd. These were somewhat similar to the Bell Telephone Laboratory's design, but provision was made for obtaining outputs at 100 and 10 kc./sec. as well as at 1000 c./sec. They could be operated from either batteries (h.t. and l.t.), a.c. mains or a single 12 V supply. Their construction and performance during this voyage have been described by Cooper (1948).

2·3. Timing systems

In *Narwhal*, the pendulums were timed by interrupting four times per second the light beam by which their movements were recorded, by an arm rotated by a phonic motor. This method was very similar to that devised by Ewing and his collaborators and has considerable advantages. The marks appear on the record as sine waves of period equal to the coincidence interval between the pendulums and the crystal chronometer. Measurements are made where the sets of marks cross each other in the middle of the record. This obviates the necessity of estimating the centre of the record by measurements from the edges, which are sometimes slightly blurred. Alternate marks are made by the same end of the rotating arm, and the gear wheels are therefore in the same relative positions when these occur. The other sets of alternate marks occur almost midway between these. Besides allowing twice as many sets of coincidences to be observed in a given time, this makes it possible to follow the fluctuations of the chronometer marks throughout the whole of the beginning and end part of the record, and so increases the accuracy with which the vertical accelerations of the apparatus can be estimated. Unfortunately, in *Narwhal* it was found that the period of the pendulums in the Channel was so nearly equal to one mean second that it was only possible to observe one coincidence between them and the crystal chronometer at the beginning and end of the record. The accuracy given by these was hardly sufficient, and so a sidereal chronometer operating one of the standard shutters was also used. Several coincidences between this chronometer and the pendulums and between the two chronometers could thus be measured during each observation. This considerably increased the accuracy with which the pendulum period could be obtained. The sidereal chronometer was also used to put minute marks on the record and to obscure the light beam for alternate half-seconds during the middle part of the record when the paper was run at half-speed. Two spare chronometers, one mean and one sidereal, were also taken, but it was not found necessary to use them.

In *Tudor*, the timing system was somewhat modified to overcome this difficulty. The rotating arm of the phonic motor was arranged to make approximately four revolutions a second, and the gear ratio was altered to give a coincidence interval of about 200 sec. As the light beam was interrupted twice each revolution, a coincidence could be observed every 25 sec. The mechanical shutter was used as before. It was operated from the second frequency standard by contacts fitted to the electric clocks described in the next section. This system proved most satisfactory. On only two occasions was any difficulty experienced, and it was then possible to operate the shutter from a mechanical chronometer, so that no records were lost.

2·4. Apparatus for rating chronometers

For rating the chronometers certain additional apparatus was required. On the *Narwhal* expedition a stroboscopic method was originally employed. The rotating arm of the phonic motor was illuminated intermittently by flashes of light from a special type of neon discharge tube manufactured in the U.S.A. under the name of 'Strobotron.' The discharge could be triggered either from the submarine's wireless receiver which was used for the reception of the time signals, or from the contacts of the sidereal chronometer. The flashes of the Strobotron occurred at intervals slightly less than the time taken for the arm of the phonic motor to make two complete revolutions. The arm therefore appeared to rotate slowly backwards, and the times at which it appeared to pass a fiducial mark could be estimated to within the nearest quarter of a second. In this way coincidences between the crystal chronometer and the time signals or sidereal chronometer were observed and hence their rates obtained.

For comparing the mechanical chronometers with the time signals, the usual method of connecting a pair of telephones in series with the chronometer contacts and the output of the wireless receiver was used. The times at which the signal appeared and disappeared were observed aurally. For intercomparison of the mechanical chronometers a similar method was adopted, a small buzzer being connected to the telephones through the contacts of the two chronometers in series. These various comparisons necessitated a considerable number of different circuit combinations which could be selected by multi-position switches. Some slight trouble was experienced from vibration which caused the chronometer contacts to make irregularly, but this was overcome by packing the chronometer with cotton waste in place of sponge rubber. A more serious difficulty arose from electrical interference which made the Strobotron flash spasmodically when receiving time signals. To avoid this, the sidereal chronometer was rated aurally from the time signals and the rate of the crystal chronometer obtained by observing coincidences with it. Although this gave the necessary accuracy, it was found that the conditions on board made the observations very difficult and tedious, and even the best observers were liable to make gross errors on occasions.

In *Tudor* a different system was adopted. Each of the two frequency standards was arranged to drive an electric clock. These were fitted with second and minute contacts which were used either to operate the shutter in the pendulum apparatus or a small moving-coil oscillograph. The rectified output from the wireless receiver was also applied to the oscillograph and arranged to deflect the coil an equal amount in the opposite direction. When time signals were being received a series of square-topped waves was produced, the upward movements being produced by the clock contacts and the downward ones by the time signals. If the two coincided, there was no displacement. The deflexions were recorded photographically, giving a permanent record from which the coincidences could be measured accurately. The oscillograph was fitted with three separate coils, so that both frequency standards, and the sidereal chronometer, could be rated simultaneously. Though this system provided an excellent check it had the drawback that it was necessary to develop and measure up the records before the rate could be determined. As it was most desirable to have a rapid means of checking the rates before and after each dive, the following auxiliary scheme was also provided.

The 100 kc. output from the frequency standard was doubled electronically and then mixed with the carrier frequency from the 200 kc. B.B.C. transmitter at Droitwich. The resulting output fluctuated at the beat frequency which was of the order of one cycle and was used to operate a Post Office-type counter. An auxiliary contact on one of the electric clocks automatically connected the counter in circuit for 50 sec. The number of beats between the two 200 kc. frequencies in this time gave the frequency difference directly in parts in 10^7. Although the B.B.C. only claim to keep their frequency constant to 1 in 10^6, it was seldom found that the relative rates differed by more than ± 2 in 10^7 from their mean value. It took only a few minutes to check the rate of both frequency standards. Except at one or two of the most remote stations, where the signal strength was insufficient to operate the counter, the system worked most satisfactorily throughout the entire voyage.

2·5. Accelerometers

When a Vening Meinesz pendulum apparatus is used the quantity which is directly determined is the mean phase velocity of the fictitious pendulum. Since the period of a pendulum depends on the inverse square root of the resultant acceleration acting on it, the mean phase velocity observed when the resultant acceleration fluctuates will in general differ from the value that would have been observed had the acceleration remained constant at its mean value. It has been shown (Browne 1937) that if the period of the fluctuations is long compared with the pendulum period, a correction must be subtracted from the value of gravity calculated from the observed mean phase velocity given by

$$\delta g = (\overline{\ddot{y}^2} + \overline{\ddot{z}^2} - \tfrac{1}{2}\overline{\ddot{x}^2})/2g,$$

where $\ddot{x}$, $\ddot{y}$ and $\ddot{z}$ represent respectively the vertical and two horizontal components of acceleration and the bar indicates the time average throughout the duration of the observation. To evaluate this correction term, one must know the mean square horizontal and vertical accelerations. Inside a submerged submarine it is not possible, without making observations of external phenomena, to distinguish between a constant acceleration and a change in g, but it is theoretically possible to determine small fluctuations of the resultant acceleration about its mean value. For example, the vertical accelerations may be estimated from the fluctuations of the chronometer marks on the pendulum records. Small horizontal accelerations can be measured if the angle between the direction of the resultant acceleration and its mean direction is known. These principles have been applied by Meinesz in the design of the long-period pendulums mentioned in § 2·1 above.

2·51. *Apparatus used in H.M.S.* Narwhal

In *Narwhal*, an attempt was made to use a more ambitious acceleration recorder, so as to get accurate records of fluctuations with periods as short as 1 sec. Vertical accelerations were measured by recording the deflexion of a horizontal cantilever spring loaded at one end and damped by a vane moving in oil. Horizontal accelerations were measured by recording the difference in angular deflexion between two damped pendulums with periods 0·3 and 30 sec. respectively. Two pairs were used with their axes at right angles so as to record the fore-and-aft and athwart-ship components. The angles of pitch and roll were also recorded by measuring the deflexion of the long-period damped pendulums relative to the framework of the apparatus. These instruments were all mounted on one base-plate and recorded on the same moving strip of photographic paper, 4 in. wide. A paper speed of 1 mm./sec. was used, and time marks were put on at 5 sec. intervals with wider marks every minute. The method of damping the pendulums had to be such that rotations of the apparatus would not cause any appreciable displacement. This was done by mounting the pendulums inside cylindrical containers full of water with their knife edges coincident with the axes of the containers. If the container performs angular oscillations about its axis, the water in contact with the surface suffers a viscous drag. The movement dies away rapidly as the distance from the surface increases. It can be shown that in a semi-infinite medium, bounded by the x, y plane, the velocity at a distance z from the boundary is given by the expression $v = v_0 e^{-\alpha z} \cos(\omega t - \alpha z)$, where $v_0 \cos \omega t$ is the velocity at the boundary and $\alpha = (\omega/2\nu)^{\frac{1}{2}}$, ν = kinematic viscosity. Putting $\nu = 0{\cdot}01$ for water one finds that the wave-length is approximately 1 cm. for normal wave periods (6 to 12 sec.), and hence a few centimetres from the surface the disturbance due to rotations of the container is negligible. The general construction of the long-period pendulums is shown diagrammatically in figure 1*a*. They were made of disks of duralumin 20 cm. in diameter supported by knife edges at their centre. The water in the containers not only reduced their effective weight but also added considerably to their moment of inertia. In this way a very long period (30 to 40 sec.) could easily be secured. The damping was such that the amplitude was reduced to half-value in

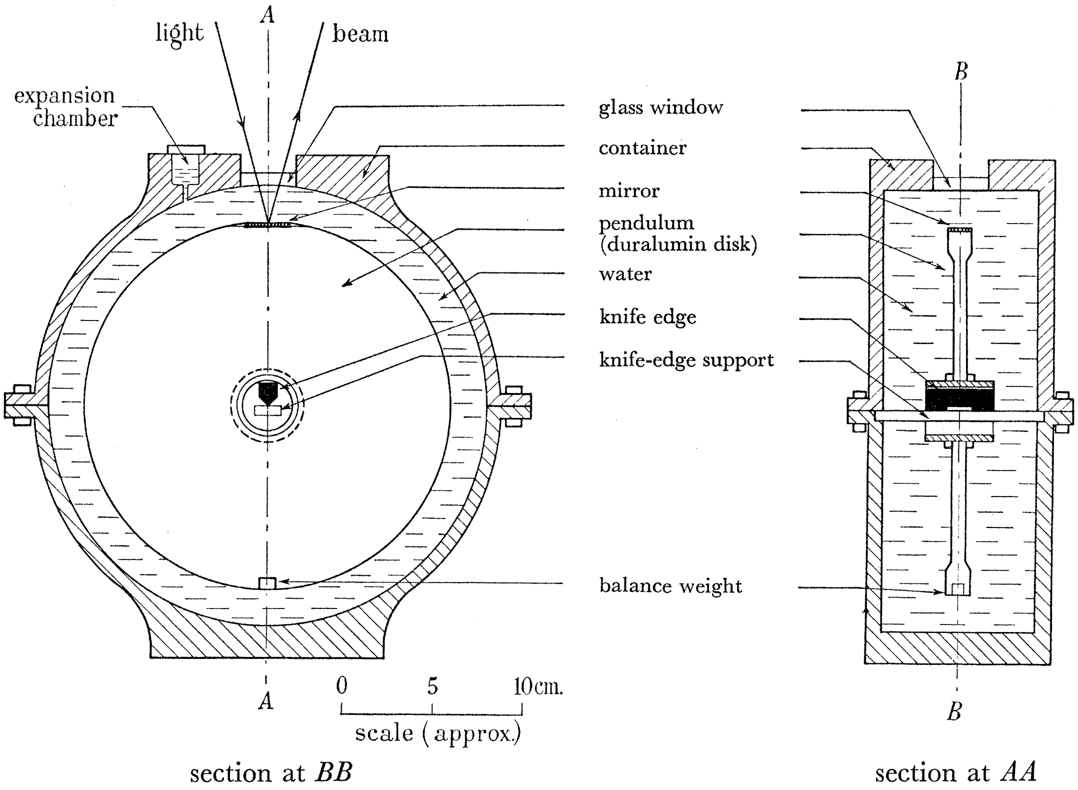

FIGURE 1*a*. Long-period damped pendulum used in H.M.S. *Narwhal*.

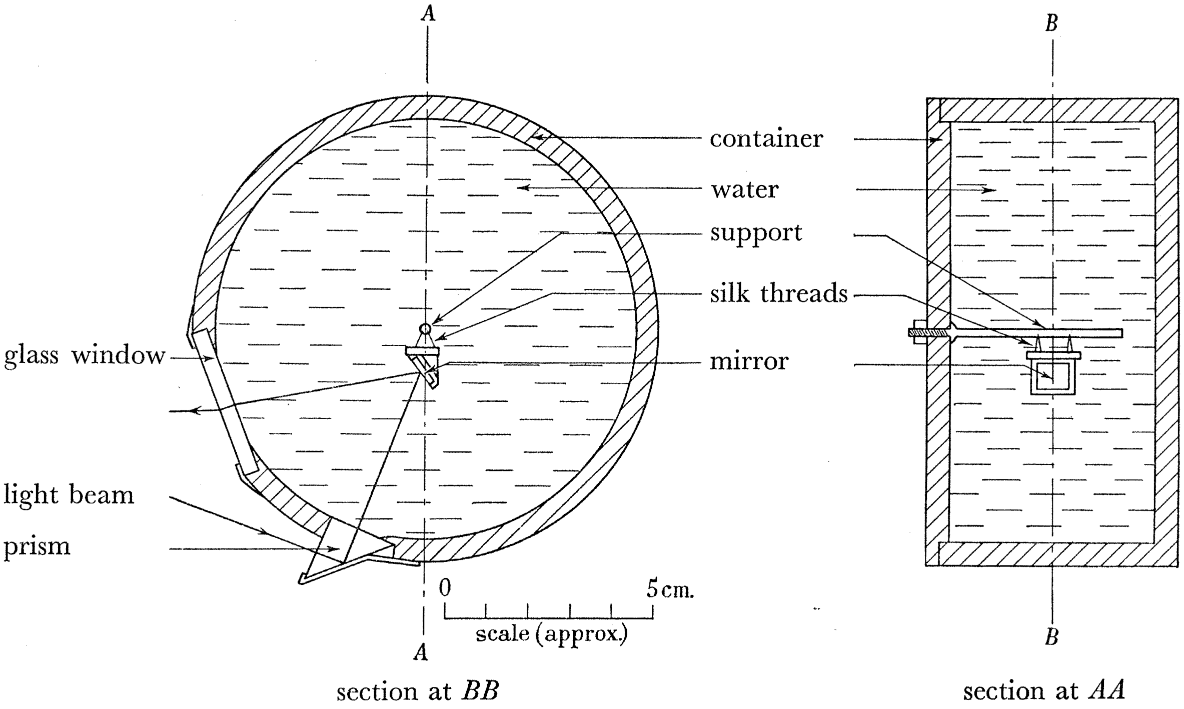

FIGURE 1*b*. Short-period damped pendulum used in H.M.S. *Narwhal*.

approximately one cycle. The short-period pendulums consisted of small, back-silvered mirrors supported by silk threads from a spindle coincident with the axis of the container. Their construction is shown diagrammatically in figure 1*b*. Their period was about $\frac{1}{3}$ sec. and the damping nearly critical. To prevent unwanted modes of oscillation, which were apt to be troublesome on account of their small damping, it was found necessary to use four threads. Although the short duration of the *Narwhal* expedition did not allow a thorough trial, it was clear even from the few results obtained that the apparatus was far from satisfactory. The long-period pendulums gave considerable trouble due to wandering of the zero and poor light intensity.

2·52. *Apparatus used in H.M.S.* Tudor

For the *Tudor* expedition the acceleration recorder was redesigned and a gyroscope was used instead of long-period pendulums to indicate the direction of the vertical. After consultation with the Admiralty Gunnery Establishment a suitable gyroscope was made available on loan. This had a 4 in. diameter steel rotor which was driven by a three-phase induction motor. The whole assembly was mounted in gimbals and balanced so that it was in neutral equilibrium. The axis of the gyroscope was kept vertical by a system of mercury switches mounted so that if the axis became displaced one of the switches made and allowed a current to flow in a solenoid which attracted a soft-iron armature and so applied a couple which caused the axis to precess towards the vertical. It was found that adequate stability could be maintained when the rate of precession was only 25′/min. In addition to indicating the direction of the vertical, the gyroscope was also used to stabilize the mountings of the short-period pendulums; the danger of the forced oscillations due to rotations of the apparatus was therefore eliminated. The short-period pendulums were made as shown in figure 2. Each consisted of a brass rod 2 mm. in diameter and 6 mm. long mounted in jewelled pivots and carrying a mirror 4 mm. square. To give stability a piece of wire 7 mm. long weighted at its lower end was fastened below the mirror, and damping was provided by allowing the weight to move in a dash-pot filled with phenolphthalate. A period of $\frac{1}{3}$ sec. and damping slightly less than critical were attained. Horizontal accelerations were recorded by a light beam reflected from a mirror attached to an arm maintained vertical by the gyroscope and the mirror of the short-period pendulum. The deflexion was therefore proportional to the angle between the vertical and the direction of the resultant acceleration. Part of the beam from the gyroscope mirror was also reflected from a mirror fixed to the framework of the apparatus. Its deflexion was proportional to the rotation of the instrument, and records of both pitch and roll were thus obtained. It is worth noting that by placing the short-period pendulum mirror half-way between the gyroscope mirror and the pivot of the arm to which these were attached, the whole apparatus could be tilted through quite a large angle before the light beam was deflected off the mirrors. This made it possible to dispense with gimbals and obviated the use of large mirrors. The vertical accelerations were recorded by the same damped cantilever spring system which had been used in *Narwhal* and the optical system and camera were similar. The three-unit oscillograph used for recording the time signals (§ 2·4 above) was also incorporated in the apparatus, and an alternative optical system made it possible to photograph the light beams from this in place of the other beams. The whole apparatus worked most satisfactorily, except for the vertical acceleration recorder, which developed play in the pivots supporting the mirror and so gave unreliable readings. When first assembled it was found that the gyroscope gave out a considerable current of air which caused a deflexion of the short-period pendulums. However, by placing draught shields in suitable positions the difficulty was overcome. Careful balancing and the use of massive supports reduced the vibration considerably, but as an additional precaution, the acceleration recorder was mounted independently of the main pendulum apparatus. The short-period pendulums were at the same height as the knife edges and about 40 cm. forward of the swinging plane of the pendulums. The accelerations recorded were therefore almost identical with those experienced by the pendulum apparatus except for very short periods, when it is possible that the two mountings did not respond similarly.

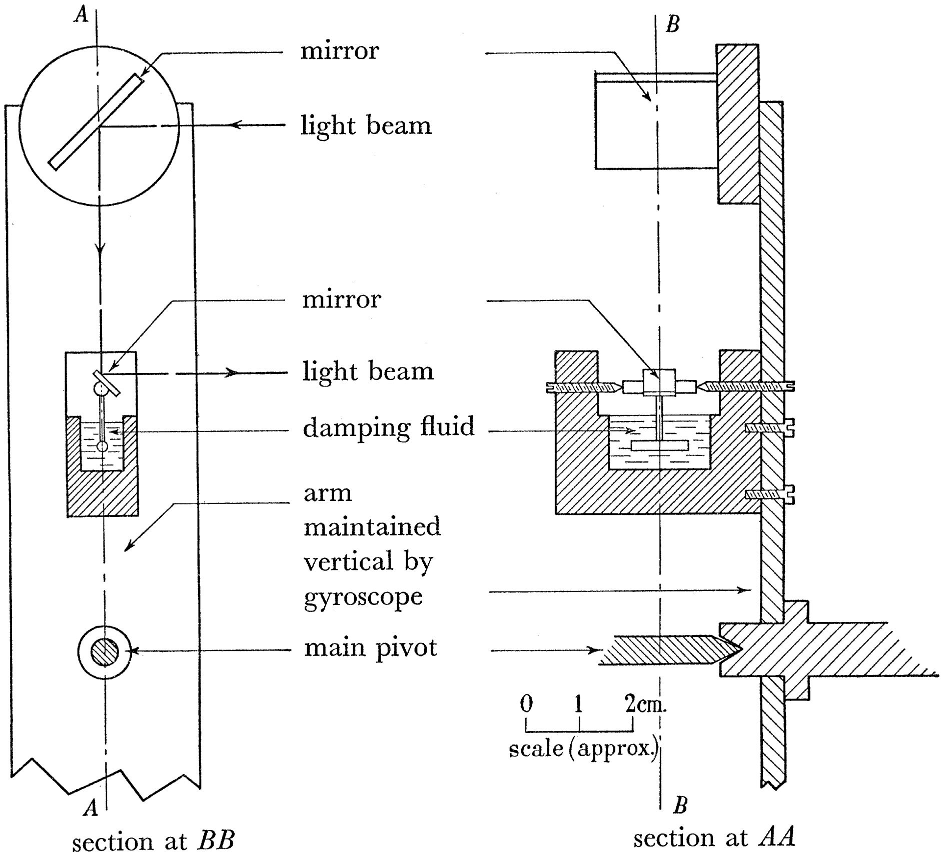

FIGURE 2. Short-period damped pendulum used in H.M.S. *Tudor*.

2·6. ECHO SOUNDERS

To calculate the attraction of the topography, it is necessary to know the heights of the zones surrounding the station. The inner zones contribute most to this attraction, and the depth of the sea at each station where a gravity measurement is made must therefore be accurately known. The difference between the attraction of an infinite slab of sea water (density 1·03) and rock (density 2·67) is 0·06867 d mgal, where d is the thickness of the slab in metres. If an error of 14·7 m. is made in the depth the calculated attraction due to topography will therefore be incorrect by approximately 1 mgal. To attain such accuracy in shallow water is easy, but in the oceans this calls for measurements to better than 1%.

Charts cannot be relied upon, and it is essential to make special soundings. Submarines are not normally equipped with the necessary echo-sounding apparatus, and a special deep-sea set had therefore to be fitted.

On the *Narwhal* expedition, a suitable instrument was generously made available on loan by Henry Hughes and Sons Ltd. To fit this in the keel would have required docking the submarine for which neither the time nor the necessary funds were available. It was therefore decided to mount the transmitting and receiving oscillators inside pressure-tight containers fixed to a cradle lashed under the keel by wire ropes. Although excellent soundings were obtained down to 800 fathoms, this method of mounting cannot be regarded as satisfactory. The wire ropes are subject to great strain when steaming on the surface, and even during the few days that the trials lasted two of the six wires parted.

As a result of this experience, *Tudor* was fitted with a special deep-water echo sounder, the oscillator of which was installed face down in the keel while the submarine was in dock for refitting, prior to the cruise. This was arranged to operate in conjunction with the existing Asdic installation, the same transmitter, receiver and recorder being used for both; a change-over switch made it possible to use either the Asdic oscillator or the echo-sounding oscillator. The effective beam width was about 25° and the power during transmission some 50 W, giving an axial pressure of 5×10^4 dyne-cm.$^{-2}$ yards. Measurements of echo strength received from a depth of 2600 fathoms gave a mean pressure of 0·28 dyne/cm.^{2} Assuming that the bottom was a perfect reflector, and that no other losses were present, the echo strength should have been 4·8 dynes/cm.^{2} The difference can be accounted for by an attenuation loss of about 2 db./kiloyard.

The figures quoted above represent good conditions in the Atlantic. On the edge of the continental shelf, where gradients of up to 1 in 5 are experienced and the bottom is extremely irregular, it was sometimes difficult to record echoes at all. This was attributed to the fact that the echoes were very much drawn out. Although it is estimated that under these conditions the maximum pressure did not exceed 0·02 dynes/cm.^{2}, it was always possible to get a sounding, and at the majority of stations excellent records were obtained.

2·7. NAVIGATION

It is clearly desirable to know the positions of stations as accurately as possible, but for gravity measurement the latitude and the east-west velocity during each dive are the important quantities. At latitude 50° gravity increases by 1·5 mgals/mile north. The latitude of each station is therefore required to within about 1 min. of arc. Under good conditions, this can be obtained by star sights or from observations of the sun near local noon. The conning tower of a submarine only gives a height of eye of some 20 ft., so that it is seldom that the sea is calm enough to give a good horizon. Weather conditions are frequently poor, with the result that navigation presents a difficult problem calling for skill and perseverance. In *Narwhal*, one of the ship's officers was given a special course in navigation before the cruise, but during the *Tudor* expedition a specialist navigator, Lieut. J. Noble, accompanied us. 'Loran' was also fitted, and though the results in the Channel area were not satisfactory owing to the unfavourable positions of the shore stations, some very good fixes were obtained north of Ireland and during the run from Rockall to St Kilda. The agreement between these and the sextant observations was usually within half a mile.

TABLE 1. SEA STATIONS: H.M.S. *NARWHAL*

station no.	lat. N	depth of dive (ft.)	E. comp. velocity (knots)	pressure (mm.Hg)	temp. (° C)	T_{88} (sec.)	T_{90} (sec.)	diff. (10^{-7} sec.)	mean T (sec.)	g (cm./sec.^{2})	corrections to g (0·001 cm./sec.^{2}) depth	Eötvös	acc.	g_0 (cm./sec.^{2})	γ_0 (cm./sec.^{2})	$g_0-\gamma_0$ (mgals)
						0·501,	0·501,		0·501,							
Devonport	50° 23′	0	0	769·2	22·78	4363,3	4304,7	58,6	4334,0	981·126	−0·2	0	0	981·125	981·113	+12
1	49° 56′	35	−3·56	775·8	21·37	4383,0	4317,6	65,4	4350,3	981·119	−2·4	−17·2	0	981·099	981·073	+26
2	49° 45′	35	−3·44	778·5	20·65	4468,2	4408,6	59,6	4438,4	981·085	−2·4	−16·6	0	981·066	981·057	+ 9
3	48° 09′	115	−1·76	777·6	21·24	4991,5	4930,1	61,4	4960,8	980·881	−7·8	− 8·8	0	980·864	980·914	−50

TABLE 2. SEA STATIONS: H.M.S. *TUDOR*

station no.	lat. N	depth of dive (ft.)	E. comp. velocity (knots)	pressure (mm.Hg)	temp. (° C)	T_{88} (sec.)	T_{89} (sec.)	diff. (10^{-7} sec.)	mean T (sec.)	g (cm./sec.^{2})	corrections to g (0·001 cm./sec.^{2}) depth	Eötvös	acc.	g_0 (cm./sec.^{2})	γ_0 (cm./sec.^{2})	$g-\gamma_0$ (mgals)
				7		0·501,	0·501,		0·501,							
1*a*	50° 32′	27	+1·0	68·4	19·80	4376,6	4326,1	50,5	4351,3	981·115	− 1·8	+ 4·8	−11·5	981·107	981·126	−19
1*b*	50° 31′	60	+0·3	72·5	19·96	4381,7	4325,5	56,2	4353,6	981·114	− 4·1	+ 1·4	− 1·8	981·110	981·125	−15
2	50° 12′	89	−1·1	64·6	21·03	4491,7	4426,0	65,7	4458,8	981·073	− 6·1	− 5·1	0	981·062	981·096	−34
3*a*	50° 10′	69	+1·4	66·0	20·66	4469,1	4400,6	68,5	4434,9	981·083	− 4·7	+ 6·7	− 0·2	981·085	981·094	− 9
3*b*	50° 10′	136	+1·9	69·0	20·58	4466,2	4407,8	58,4	4437,0	981·082	− 9·2	+ 9·2	0	981·082	981·094	−12
4*a*	49° 54′	68	−2·8	59·6	19·96	4372,1	4311,8	60,3	4341,2	981·119	− 4·6	−13·5	− 0·4	981·100	981·069	+31
4*b*	49° 53′	30	−2·5	65·5	20·08	4392,4	4327,7	64,7	4360,0	981·112	− 2·0	−12·1	− 2·0	981·096	981·067	+29
5	49° 39′	176	−2·4	63·2	20·43	4425,2	4386,9	38,3	4406,0	981·093	−12·0	−11·6	0	981·069	981·048	+21
6	48° 57′	200	−2·3	60·9	20·04	4660,3	4599,6	60,7	4629,9	981·006	−13·6	−11·1	0	980·981	980·985	− 4
7	48° 40′	159	−1·4	63·9	19·98	4592,4	4535,1	57,3	4563,7	981·031	−10·8	− 6·7	0	981·014	980·960	+54
8	48° 27′	199	−2·3	64·0	20·17	4740,2	4678,3	61,9	4709,2	980·975	−13·5	−11·1	− 0·4	980·950	980·940	+10
9	47° 24′	199	−1·6	64·1	20·48	4989,7	4923,8	65,9	4956,8	980·878	−13·5	− 7·7	0	980·856	980·846	+10
10*a*	47° 07′	80	−1·7	65·6	20·56	5059,6	5005,0	54,6	5032,3	980·848	− 5·4	− 8·2	−10·7	980·824	980·821	+ 3
10*b*	47° 07′	155	−1·7	67·6	20·67	5058,5	5002,0	56,5	5030,2	980·849	−10·5	− 8·2	− 1·8	980·829	980·821	+ 8
11	46° 59′	143	+2·2	66·3	21·25	5081,2	5022,6	58,6	5051,9	980·840	− 9·7	+10·6	0	980·841	980·808	+33
12	47° 45′	154	+2·3	62·6	20·67	4968,8	4904,3	64,5	4936,5	980·886	−10·5	+11·1	+ 0·2	980·886	980·877	+ 9
13*a*	48° 02′	60	+1·9	67·1	20·51	4987,6	4928,1	59,5	4957,8	980·877	− 4·1	+ 9·2	− 9·7	980·872	980·903	−31
13*b*	48° 03′	165	+1·9	68·9	20·56	4982,6	4924,4	58,2	4953,5	980·879	−11·2	+ 9·2	− 0·5	980·876	980·904	−28
14	48° 12′	146	+2·3	60·2	20·80	4942,0	4889,1	52,9	4905,6	980·898	− 9·9	+11·1	0	980·899	980·918	−19
15	49° 08′	80	+1·7	57·5	20·09	4609,5	4547,3	62,2	4578,4	981·026	− 5·4	+ 8·2	0	981·028	981·002	+26

16*a*	49° 22′	80	+2·1	53·6	20·30	4569,4	4518,3	51,1	4543,9	981·039	−5·4	+10·1	−4·2	981·040	981·022	+18
16*b*	49° 23′	116	+2·2	54·9	20·44	4558,0	4498,8	59,2	4528,4	981·045	−7·9	+10·6	−1·8	981·046	981·024	+22
17	46° 30′	201	−0·2	78·4	19·13	5382,0	—	(60,1)	5352,0	980·723	−13·6	−1·0	−0·8	980·708	980·766	−58
18	45° 57′	185	−0·2	71·6	19·56	5456,9	5389,2	67,7	5423,0	980·695	−12·5	−1·0	0	980·682	980·715	−33
19	45° 23′	168	−0·4	65·9	20·07	5482,6	5421,1	61,5	5451,8	980·684	−11·4	−2·0	0	980·671	980·664	+7
20	43° 39′	78	−0·1	68·3	21·20	5760,3	5696,0	64,3	5728,2	980·576	−5·3	−0·5	0	980·570	980·508	+62
21*a*	44° 13′	81	0	70·0	22·00	6098,6	6039,7	58,9	6069,1	980·443	−5·5	0	−2·7	980·434	980·559	−125
21*b*	44° 15′	144	0	74·8	22·12	6057,9	5999,3	58,6	6028,6	980·459	−9·8	0	−0·4	980·448	980·562	−114
22	44° 49′	147	−0·1	67·5	22·58	5821,7	5764,3	57,4	5793,0	980·551	−10·0	−0·5	0	980·540	980·613	−73
23	47° 11′	79	+0·1	65·3	21·81	4945,4	4886,6	58,8	4916,0	980·894	−5·4	+0·5	0	980·889	980·827	+62
24*a*	47° 45′	80	+0·1	66·9	21·41	4919,2	4862,0	57,2	4888,6	980·904	−5·4	+0·5	−5·5	980·894	980·878	+16
24*b*	47° 47′	150	+0·1	76·8	21·40	4884,0	4826,1	57,9	4855,0	980·917	−10·2	+0·5	−1·0	980·907	980·881	+26
25	48° 21′	79	+1·3	66·0	21·10	4803,0	4745,2	57,8	4774,1	980·949	−5·4	+6·6	0	980·950	980·932	+18
26	49° 49′	116	−2·1	69·8	18·67	4390,0	4333,8	56,2	4361,9	981·110	−7·9	−10·0	0	981·092	981·063	+29
27	49° 52′	116	−2·1	71·4	18·95	4331,1	4264,5	66,6	4297,8	981·135	−7·9	−10·0	0	981·118	981·067	+51
28	49° 54′	115	−2·1	68·1	18·94	4447,7	4388,8	58,9	4418,2	981·088	−7·8	−10·0	0	981·070	981·070	0
30	51° 33′	81	0	64·3	19·08	4039,2	3978,7	60,5	4009,0	981·249	−5·5	0	0	981·243	981·216	+27
32	53° 22′	117	−0·3	64·0	19·50	3561,2	3502,2	59,0	3531,7	981·435	−7·9	−1·4	0	981·426	981·374	+52
33	54° 43′	118	−0·3	67·9	18·64	3452,2	3586,3	65,9	3419,3	981·479	−8·0	−1·4	0	981·470	981·490	−20
34	55° 41′	115	−1·2	68·0	18·06	3166,9	3101,3	65,6	3134,1	981·591	−7·8	−5·0	0	981·578	981·572	+6
35*a*	56° 25′	112	−1·2	67·4	17·93	2912,4	2854,5	57,9	2883,4	981·689	−7·6	−5·0	−1·3	981·675	981·633	+42
35*b*	56° 26′	80	−1·2	74·6	17·94	2962,6	2898,2	64,4	2930,4	981·671	−5·4	−5·0	−7·0	981·653	981·636	+17
36	57° 05′	117	−1·2	65·6	17·71	2811,6	2750,6	61,0	2781,1	981·729	−7·9	−5·0	−4·8	981·712	981·689	+23
37	57° 45′	198	+0·8	60·5	17·38	2705,9	2644,2	61,7	2675,0	981·771	−13·4	+3·4	0	981·761	981·744	+17
38	57° 45′	116	+2·3	54·6	17·13	2713,5	2657,9	55,6	2685,7	981·767	−7·9	+9·2	−3·0	981·766	981·744	+22
39*a*	57° 44′	145	+2·2	54·9	17·13	2613,3	2552,4	60,9	2582,8	981·807	−9·8	+9·2	−0·5	981·806	981·743	+63
39*b*	57° 44′	78	+2·2	59·8	17·19	2625,0	2557,3	67,7	2591,1	981·804	−5·3	+9·2	−4·0	981·804	981·742	+62
40	57° 45′	115	+2·4	54·5	17·38	2798,0	2739,2	58,8	2768,6	981·734	−7·8	+10·1	0	981·737	981·745	−8
41	57° 42′	116	+2·4	59·1	17·33	2867,5	2804,1	63,4	2835,8	981·708	−7·9	+10·1	0	981·710	981·740	−30
42	57° 43′	118	0	64·8	17·23	2593,9	2504,4	53,5	2567,1	981·813	−8·0	0	−3·5	981·802	981·742	+60
43	56° 49′	80	−1·3	60·1	16·72	2928,8	2873,9	54,9	2901,4	981·682	−5·4	−5·4	0	981·671	981·666	+5
44*b*	55° 27′	80	+0·1	60·0	16·02	3217,9	3148,9	69,0	3183,4	981·572	−5·4	+0·5	0	981·567	981·553	+14
45	55° 01′	80	+2·3	53·9	17·06	3365,3	3297,2	68,1	3331,3	981·514	−5·4	+10·3	−0·4	981·518	981·516	+2
46	53° 43′	114	+0·6	44·0	17·03	3543,6	3490,5	53,1	3517,0	981·441	−7·7	+2·6	−0·4	981·435	981·405	+30
47	53° 05′	215	−0·2	42·7	17·33	3711,0	3659,0	52,0	3685,0	981·375	−14·6	−0·9	−1·2	981·358	981·350	+8
48	52° 28′	177	−0·7	38·8	17·61	3960,1	3909,1	51,0	3934,6	981·278	−12·0	−3·2	−2·6	981·260	981·296	−36
49	50° 26′	146	−0·7	54·6	18·03	4242,7	4194,8	47,9	4218,8	981·172	−9·9	−3·2	−4·7	981·155	981·117	+38
50	50° 01′	114	+3·4	56·5	17·92	4449,4	4395,0	54,4	4422,2	981·087	−7·7	+15·4	0	981·095	981·080	+15
51*a*	50° 33′	30	−0·8	63·5	16·84	4351,5	4308,9	42,6	4330,2	981·123	−2·0	−4·0	−2·2	981·115	981·128	−13
51*b*	50° 33′	30	−0·8	67·2	16·98	4354,6	4299,1	55,5	4326,9	981·124	−2·0	−4·0	−2·5	981·116	981·128	−12

An even more difficult problem is presented by the Eötvös effect. Owing to the rotation of the earth, the apparent value of gravity depends on the east-west component of velocity of the observer. In these latitudes the increase amounts to 4·8 mgals/knot steaming west. To determine the speed of a submerged submarine relative to the earth with an accuracy of $\frac{1}{5}$ knot is far from easy. In *Narwhal*, but not in *Tudor*, taut-wire gear was available, but this could be used only in shallow water. Under these conditions, however, it gave the speed within 0·05 knot, which was more than adequate. In deep water, or where taut-wire gear is not fitted, the best that can be done is to ensure that the log is accurately calibrated by making preliminary runs over a measured mile and to use any data that are available concerning the currents. Although measurements of the variation of current with depth have often been made, the results are not very consistent. Not only the velocity but also the direction may vary, and often results may be in doubt by as much as half a knot. This represents one of the most serious sources of uncertainty in the observations.

PART III. MEASUREMENTS AND RESULTS

3·1. Gravity measurements

During the *Narwhal* expedition three measurements were made at sea and one while lying alongside in the North Yard at Devonport. The results are given in table 1. In *Tudor*, observations were made at fifty-one sea stations and also at Portland, Falmouth and Oban.

Table 3. Base-station observations

Pendulum House, Cambridge, $g = 981{\cdot}265$ cm./sec.^{2}.
latitude 52° 13′ N; longitude 0° 06′ W; height 82 ft.

date	T_{88} (sec.)	T_{90} (sec.)	diff. (10^{-7} sec.)	$\frac{1}{2}(T_{88}+T_{90})$ (sec.)
21. viii. 38	0·501,4009,0	0·501,3946,6	62,4	
	4008,0	3948,2	59,8	
	4005,8	3949,6	56,2	
mean	0·501,4007,6	0·501,3948,1	59,5	0·501,3977,85
26. ix. 38	0·501,4003,9	0·501,3956,5	47,4	
	4006,5	3951,6	54,9	
	4007,7	3950,8	56,9	
mean	0·501,4006,0	0·501,3952,9	53,1	0·501,3979,45
change	−1,6	+4,8	+6,4	+1,6

H.M.S. Narwhal. *Mean value assumed for computing results* 0·501,3978,6

date	T_{88} (sec.)	T_{89} (sec.)	diff. (10^{-7} sec.)	$\frac{1}{2}(T_{88}+T_{89})$ (sec.)
23. vi. 46	0·501,3994,6	0·501,3939,3	55,3	
	3995,1	3941,7	53,4	
	3997,8	3944,1	53,7	
29. vi. 46	3998,2	3946,1	52,1	
	3995,4	3941,9	53,8	
mean	0·501,3996,2	0·501,3942,6	53,6	0·501,3969,4
5. ix. 46	0·501,3992,6	0·501,3934,8	57,8	
	3994,6	3936,9	57,7	
	3989,2	3940,0	49,2	
mean	0·501,3992,1	0·501,3937,2	54,9	0·501,3964,6
change	−4,1	+5,4	+1,3	−4,8

H.M.S. Tudor. *Mean value assumed for computing results* 0·501,3967,0

Results for the sea stations will be found in table 2. The measurements made while lying alongside in harbour will be discussed later (see § 3·4 (*b*) below). The periods of the pendulums at the Pendulum House, Cambridge, before and after each cruise will be found in table 3. It will be seen that the mean period only changed by $+1{\cdot}6\times10^{-7}$ and $-4{\cdot}8\times10^{-7}$ sec. during the two expeditions. On each occasion the mean of the values observed before and after the voyage was used to compute the results, using the value of $g=981{\cdot}265$ cm./sec.^{2} adopted for the Pendulum House, Cambridge, relative to Potsdam (Bullard & Jolly 1936).

3·2. Base-station observations

The base-station observations were carried out under conditions as similar as possible to those experienced on board the submarine, with the apparatus hanging freely in its gimbals. The pendulum period was calculated from the record by the graphical method described by Meinesz (1929). Each record lasted for 30 min.; observations of the coincidences between the pendulums and chronometer were made between the beginnings of the 2nd and 6th minutes and again between the beginnings of the 26th and 30th minutes. It is estimated that the error in the measurement of the period of the fictitious pendulum due to inaccuracy of reading of the records was only 1×10^{-7} sec. Corrections were applied as follows:

(i) *Temperature.* The temperature of the pendulums was measured by the thermometer mounted in the dummy pendulum. A small correction was applied to allow for the scale error found when the thermometer was standardized in Holland. The pendulum periods were then reduced to 0° C, using the following temperature coefficients:

pendulum number	88	89	90
temp. coeff. $\left(\dfrac{\text{change in period }\times10^7\text{ sec.}}{\text{change in temp. in }^\circ\text{ C}}\right)$	45·88	47·07	46·91

This correction was accurate to 2×10^{-7} sec.

(ii) *Density.* The pendulum period was assumed to vary linearly with the density, D, of the surrounding air as calculated from the relation $D=\dfrac{p-\frac{3}{8}\epsilon}{760+2{\cdot}79\theta}$, where p = pressure in mm. of Hg, θ = temperature in ° C and ϵ is the partial pressure of atmospheric water vapour. The atmospheric pressure was measured by a pair of aneroid barometers, the temperature of the air was assumed the same as that of the pendulum, and a hygrometer mounted inside the pendulum apparatus was used to determine the humidity. Both barometer and hygrometer were calibrated against standard instruments. The pendulum periods were reduced to a standard value $D=1{\cdot}000$, using the following density coefficients:

pendulum number	88	89	90
density coeff. $\left(\dfrac{\text{change in period }\times10^7\text{ sec.}}{\text{change in density}}\right)$	665·9	673·2	673·2

At the base station, where the barometers and hygrometer were accurately calibrated, the error of this correction did not exceed 2×10^{-7} sec.

(iii) *Arc, deviation from isochronism and tilt.* These were obtained from the records by the method already described by Meinesz (1929). The accuracy depends on the regularity of the middle pendulum record, and on land it is estimated that the error did not exceed 1×10^{-7}.

(iv) *Chronometer rate*. The method of rating the chronometers differed somewhat on the two expeditions (see § 2·4 above). In both cases, however, the accuracy achieved at the base station was certainly as good as 1×10^{-7} sec.

For a discussion of the overall accuracy of the base-station results see § 3·4 below.

3·3. Sea-station observations

The records made during a dive differ from the base-station records mainly on account of the irregular motion of the middle pendulum record and the fluctuations of the chronometer marks. During most of the observations care was taken to dive sufficiently deep to avoid any serious errors. It was found that, using the graphical method of averaging out the fluctuations, the self-consistency of the eight determinations of the coincidence interval (approximately 200 sec.) gave a probable error of only $\pm 0{\cdot}015$ sec. This indicates that the period of one of the fictitious pendulums could be measured to within $\pm 2 \times 10^{-7}$ sec. The estimated accuracy of the other corrections is as follows:

(i) *Temperature* as for base station: $\pm 2 \times 10^{-7}$ sec.

(ii) *Density*. Owing to small changes in calibration the pressure and humidity could not be so accurately determined at sea as on land. At most stations the error is not likely to exceed $\pm 3 \times 10^{-7}$ sec.

(iii) *Arc, deviation from isochronism and tilt*. These corrections all depend on the magnitude of the perturbations caused by horizontal accelerations. Except at those stations where observations were purposely made at shallow depths, the accuracy with which these corrections can be measured is $\pm 4 \times 10^{-7}$ sec.

(iv) *Chronometer rate*. During the *Narwhal* expedition the crystal chronometer was rated from the time signals sent out at 1000 and 1800 hr. from the Post Office transmitter at Rugby. Assuming that this rate remained constant between signals, the probable error at the time of the pendulum observation is $\pm 1{\cdot}5 \times 10^{-7}$. On the *Tudor* expedition, checks made before and after each dive showed that the rates of the two frequency standards were consistent to within 1×10^{-7}, after allowance for a small temperature coefficient had been made to one of the instruments (Cooper 1948).

The above corrections enable the pendulum periods to be reduced to standard conditions which make them directly comparable with the base-station results. However, the value of g calculated from these depends on the conditions under which the observation was made, and it is therefore necessary to apply corrections to obtain the value of g which would have been observed at a point at rest at sea level. These corrections will now be considered.

Depth correction. To allow for the variation of gravity with depth a correction of 0·069 mgal/ft. must be applied. During each dive, depth was read from the gauges in the boat at the beginning, middle and end of each observation. The mean of these is almost certainly within ±5 ft. of the true mean depth and the error in the correction is therefore probably less than ±0·3 mgal. Besides the normal depth correction an additional first-order effect may arise owing to variations in vertical velocity. If v_0 and v_1 are the vertical velocities at the beginning and end of the observation, then the mean acceleration during the time, t, will be $(v_0 - v_1)/t$ gals. It would have been quite possible for a vertical velocity as great as 1 cm./sec. to have persisted for some minutes before the change in depth became so noticeable on the depth gauges that the hydroplane operators would have corrected it. If we assume $v_0 = v_1 = 0 \pm 1$ cm./sec. and the duration of the observation 1400 sec., we might expect errors up to ±1 mgal.

It can be seen from the records of pitch (figure 3*a*) that there tends to be a marked component with a period of about 100 sec. This arises because the forward and after hydroplanes are worked by different operators. Assuming a speed of 2 knots, the pitch records suggest that the actual vertical displacement of the fore-ends of the submarine might well be of the order of 1 m. This would lead to vertical velocities as great as ±6 cm./sec. If this were so, the coincidence interval between the pendulums and chronometer marks should vary by amounts up to ±0·4 sec. The actual observed scatter is only about one-tenth of this, and we may therefore assume that the source of error is not so serious as might at first be supposed. It is well to bear in mind, however, the possibility of this type of error, which in the absence of an actual record of the depth cannot definitely be assumed to be negligible.

Eötvös correction. The determination of the east-west velocity of the boat during the time of observation has already been discussed in § 2·7 above. On the *Narwhal* expedition, taut-wire gear was available and was used whenever the water was sufficiently shallow. In *Tudor* attempts were made to measure the east-west velocity by using the 'Asdic' and observing the rate of approach or recession of objects on the sea bed from which echoes could be heard. The results, however, were not satisfactory because often no echoes could be obtained, and on other occasions several echoes gave inconsistent values of velocity. It is believed that some of these echoes were reflected from waves, while others appear to have come from material moving with the water. At most stations the speed of the submarine through the water was measured by the log to the nearest tenth of a knot. The speed of the current was taken from tidal data given on charts or, where this was not available, estimated from the difference in positions found by dead reckoning and by navigational fixes. The accuracy is therefore rather uncertain, but it is believed to be about ±2 mgals at the majority of stations.

Second-order corrections. These will be dealt with in the next section of the paper. The corrections at the majority of stations are small and their accuracy better than $\pm\frac{1}{2}$ mgal.

The above corrections suffice to give the value of gravity which would have been observed at a point at rest on the surface above the mid-point of the dive. This position is not exactly known, since it depends on the accuracy of the navigation. The free-air anomalies, which are the difference between the observed values of gravity and the values calculated from the international gravity formula, are therefore subject to an additional uncertainty. The positions of most of the stations are known to within 1 min. of latitude, and the probable error arising from the uncertainty is therefore ±1·0 mgal.

The accuracy of the observations will be further discussed in the next section.

3·4. ACCURACY OF RESULTS

(*a*) *Base station*

For the observations made at the Pendulum House, Cambridge, the accuracy of the determination of the mean period of the pendulums before and after each cruise was $\pm 1{\cdot}5 \times 10^{-7}$ sec. (root mean square error) as calculated by allowing for the individual errors given in § 3·2 above. The internal consistency of the observations themselves, indicates an accuracy of $\pm 1{\cdot}0\times10^{-7}$ sec. (r.m.s. error), so it appears that the errors introduced by such effects as the uncertainty in the temperature measurements have been rather overestimated. During the *Narwhal* expedition the pendulum periods changed by $-1{\cdot}6\times10^{-7}$ and $+4{\cdot}8\times10^{-7}$ sec., a change in mean value of only $+1{\cdot}6\times10^{-7}$ sec. If we base the results on the mean of initial and final values and assume no excursions meanwhile outside these limits, we get a final figure of $\pm1{\cdot}4\times10^{-7}$ as the error introduced due to uncertainty of the pendulum period at the base station. This is equivalent to $\pm0{\cdot}56$ mgal. In the case of *Tudor*, the pendulum periods changed by $-4{\cdot}1\times10^{-7}$ and $-5{\cdot}4\times10^{-7}$ sec., equivalent to an error of nearly $\pm1{\cdot}0$ mgal. If values relative to Potsdam are required, the uncertainty of the value of g at Cambridge must also be included; Bullard & Jolly (1936) have estimated this at $\pm0{\cdot}5$ mgal. (p.e.), but see § 4·2.

(*b*) *Sea stations*

At sea stations, all the errors due to such causes as inaccuracy of measuring up the records, etc., naturally arise, but besides these there are additional errors of which uncertainty in the magnitude of the Eötvös correction is the most serious. The estimate of the overall accuracy of a sea station is given in table 4. In the case of the free-air anomalies, uncertainty in the position of the station will introduce an additional error of $\pm0{\cdot}5$ mgal, but this will hardly affect the result. We therefore conclude that the accuracy of a sea station, relative to Potsdam, is $\pm3\frac{1}{2}$ mgals r.m.s. or $\pm2\frac{1}{2}$ mgals (p.e.).

TABLE 4. R.M.S. ERRORS IN SEA-STATION OBSERVATION

uncertainty	mgal	mgal^2
in g at base	±0·7	0·5
in period at base	±1·4	2·0
in computing period	±2·0	4·0
in Eötvös correction	±2·0	4·0
in depth correction	±0·3	0·1
in first-order correction	±0·6	0·4
in second-order correction	±0·5	0·2
sum of squares of errors		11·2
total r.m.s. error	±3·4	

The relative accuracy between two sea stations will be higher, since uncertainties in the base-station results will not be introduced. In these circumstances the accuracy may be taken as 2·0 mgals for a deep and $2\frac{1}{2}$ mgals for a shallow dive. The figures just quoted depend very much on the accuracy assumed for the Eötvös correction, which naturally varies considerably, depending on the accuracy of the tidal data etc.

Some check on the above results can be obtained from comparison of measurements made on board the submarine in harbour with those made on land at Portland, Falmouth and Oban. At four sea stations, nos. 4, 16, 20 and 25, previous observations made at sea afford additional evidence. The results are shown in table 5. The first four columns give the place, position and elevation of the *Tudor* stations. Where the observations were close to the comparison station, the fifth column gives the actual value of g. Where the comparison station is some distance away, it has been thought best to compare the modified Bouguer anomalies.* Results for the check stations are shown in columns 6 to 10. The values of g

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* A definition of this anomaly is given in § 4·21 below.

TABLE 5. COMPARISON OF RESULTS

Tudor station					check station					diff.	
place	lat. N	long. W	height (ft.)	g_0 or mod. Boug.[1]	place	lat. N	long. W	height (ft.)	g_0 or mod. Boug.[1]	g_0 or mod. Boug.[1]	reference
Portland Harbour	50° 34′	2° 26′	0	981·126	Portland Royal Ho.	50° 35′	2° 28′	16	981·127	− 1	Anglo-Amer.[2]
stn. 4 *a*	49° 53′	5° 07′	− 30	+22	*Narwhal* no. 1	49° 56′	5° 00′	−35	+19	+ 3	see table 1
stn. 4 *b*	49° 54′	5° 11′	− 68								
stn. 16 *a*	49° 22′	6° 56′	− 80	+ 8	V. Meinesz no. 839	48° 56′	7° 36′	—	+11	− 3	V. Meinesz[3]
stn. 16 *b*	49° 23′	6° 53′	−116								
stn. 20	43° 40′	5° 42′	− 78	+42	Cape Peñas	43° 40′	5° 51′	351	+39	+ 3	Galbis (1902)[4]
stn. 25	48° 22′	5° 25′	− 79	+ 4	V. Meinesz no. 726	48° 29½′	5° 27½′	—	+16	−12	V. Meinesz[3]
Falmouth Harbour	50° 09′	5° 03′	0	981·099	St Mawes	50° 09′	5° 02′	85	981·104	− 5	Bond (1933)[5]
Oban Harbour	56° 25′	5° 28′	0	981·641	Oban Light House	56° 25′	5° 29′	20	981·642	− 1	Jolly (1932)[6]
stn. 51 *a*	50° 33′	2° 20′	− 30	−15	extrapolation from Anglo-Amer.[2] gravimeter survey of Dorset coast	—	—	—	−14	− 1	Anglo-Amer.[2]
stn. 51 *b*	50° 33′	2° 21′	− 30								

Notes: 1. Mod. Boug.: modified Bouguer anomaly.
2. Anglo-Amer.: gravimeter survey made by Anglo-American Oil Co. Ltd. (not published).
3. V. Meinesz: see *Gravity expeditions at sea*, vol. 3, Publ. Netherlands Geod. Com. (1941).
4. Galbis (1930): see Ackerl, *Die Schwerkraft am Geoid*, Vienna, 1932.
5. Bond (1935)
6. Jolly (1939) } see Bullard and Jolly (1936).

given in column 10 are the values which would be expected at the position and elevation of the *Tudor* stations; the difference between this and the observed value is shown in column 11. The last column gives the authorities from which the check-station data have been obtained.

At Portland Harbour, the value of g was calculated from a gravimeter station observed by the Anglo-American Oil Co. Ltd., at the Royal Hotel. This is based on a survey which is connected to Potsdam through an observation made by Kater at Clifton, as corrected by Helmert. The observation at Cape Peñas (north Spain) was taken from Ackerl (1932) and corrected to the Potsdam standard by adding 16 mgals as shown by Jeffreys (1941). Bond's observation at St Mawes, Falmouth, is less accurate, since his pendulums suffered an anomalous change in length during his survey of Devon and Cornwall. Jolly's observation at Oban Light House is, however, quite reliable (Bullard & Jolly 1936). The other check stations are based on previous submarine observations (Meinesz 1934, 1941 *b*). In two cases, nos. 4 and 16, the agreement is well within the experimental error. At station no. 25, there is, however, a discrepancy of 12 mgals between the *Tudor* observation and Vening Meinesz Station no. 726, which is only 8 miles away. The r.m.s. difference between the *Tudor* observations and the check stations is only ±5 mgals, which is in good agreement with the figure of $\pm 3\frac{1}{2}$ mgals as the r.m.s. error of a single observation. Although this appears satisfactory, analysis of the results obtained at double stations throws some doubt on these figures. These results will now be discussed in some detail.

3·5. Second-order corrections

In 1938, one of the authors (Browne 1937) pointed out that the horizontal and vertical accelerations of the submarine would produce systematic errors in the value of gravity as measured at sea. This has also been discussed at some length by Meinesz (1941 *a*), who made an experimental investigation during a special voyage in 1938. To apply these second-order corrections, it is necessary to know the mean-square accelerations during each observation. To obtain further confirmation a number of double observations was made, each pair at approximately the same position but at two different depths. At the deeper, the wave movement was small and the corrections were unimportant. At the shallower, the greater accelerations produced an appreciable second-order effect. A comparison of the gravity values under these conditions should give a measure of the effect which the wave movement had on the period of the pendulums. The results obtained will be described in the next section; before doing so the methods of measuring the accelerations and the results obtained will be discussed.

On both expeditions, two independent systems were available for measuring the accelerations. First, they could be calculated from the fluctuations of the chronometer marks and the records of the long-period pendulums in the Vening Meinesz apparatus, and secondly, from the acceleration recorder. In *Narwhal* the cancellation of the expedition made it impossible to make any double observations. The second-order corrections at the three stations occupied were estimated from the Vening Meinesz apparatus, as the results obtained with the first model of the acceleration recorder were not reliable. In *Tudor*, the best estimates were obtained from the redesigned acceleration recorder. These records contain much information concerning the movements of a submerged submarine, but owing to limitations of time and facilities a full analysis has not been made. The broad outline of the results will now be given.

On inspection the records appear as a fairly smooth sinusoidal train of waves of varying amplitude. Figure 3*a* shows a copy of the record. It was taken at a depth of 200 ft., on a course of 020°, wind at the time being south, force 4 as estimated on the Beaufort scale. Thanks to the assistance of the Admiralty Research Laboratory at Teddington a frequency analysis of the roll record has been made on the harmonic analyzer developed by Barber (1946). This is shown in figure 3*b*. It will be seen that, while the main part of the energy lies in a band between 7 and 10 sec. period, appreciable energy is present with periods as long as 15 sec. and as short as 5 sec. The records from the long-period pendulums in the Vening Meinesz apparatus are very similar in appearance. The mean-square amplitude was measured by drawing an arbitrary zero line on the records and measuring the size of the

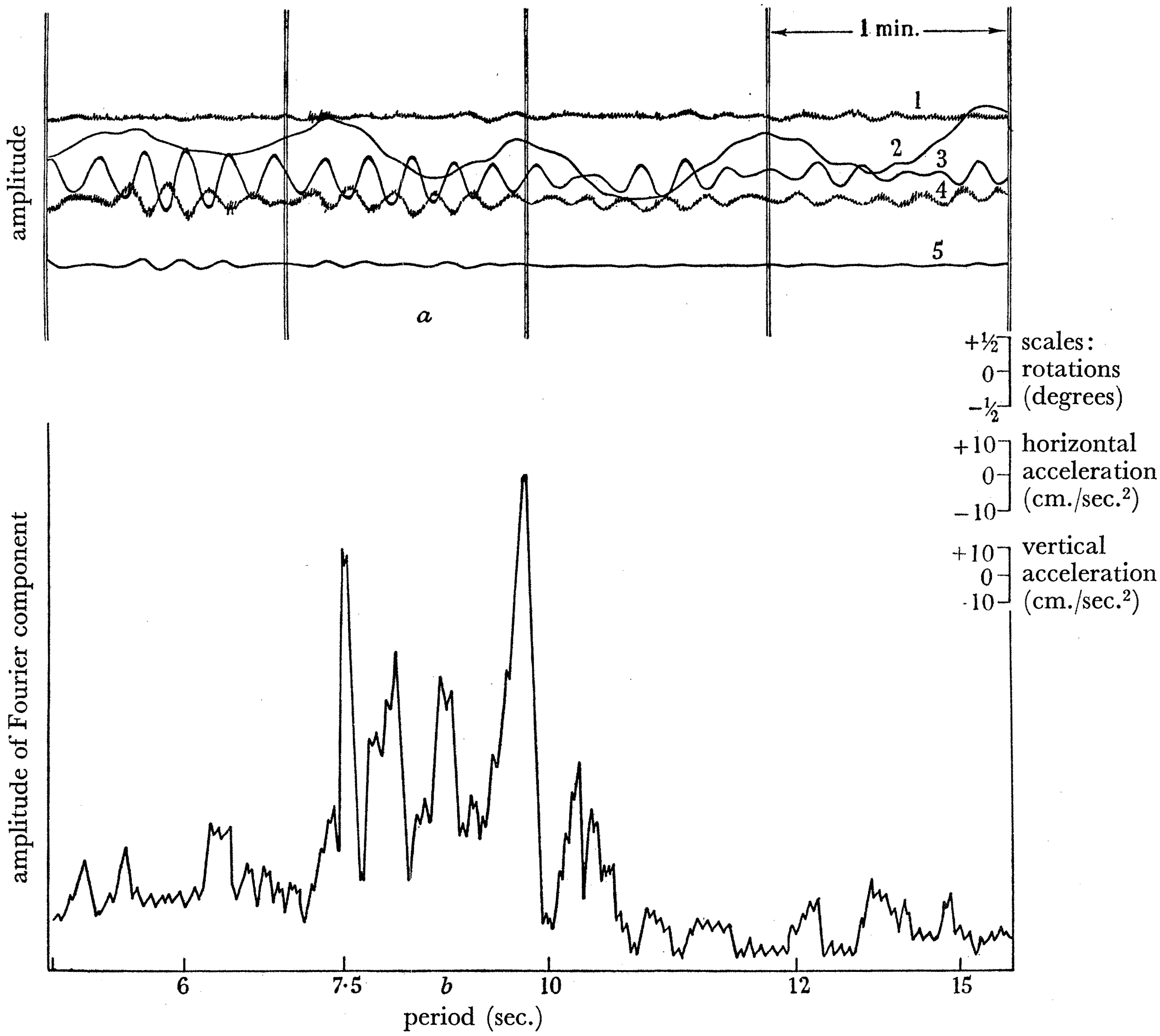

FIGURE 3. *a*, record of accelerations and rotations: 1, fore and aft acceleration; 2, pitch; 3, roll; 4, athwart-ship acceleration; 5, vertical acceleration; the double lines are time marks (one minute interval). *b*, Fourier analysis of roll record.

peaks on both sides with a millimetre scale. Assuming the peaks are sinusoidal in form and all of equal duration, the mean-square value is equal to half the sum of the squares of the peak amplitudes divided by the number of peaks. A small correction must be applied if the zero line has not been accurately drawn. The mean wave period was taken as equal to the duration of the record divided by half the total number of peaks measured.*

The sources of error in calculating the corrections will next be considered. They may be divided into two parts: (i) errors in reading and measuring the records, and (ii) errors owing to limitations in the instruments.

3·51. *Errors in reading and measuring the records*

The error arising from measuring up the record may be estimated as follows. If a cm. is the amplitude and we assume that the maximum values a_{m_1}, a_{m_2}, etc., can be measured to within $\pm\epsilon$, independent of their magnitude, it can be shown that $\Delta(\overline{a_m^2}) = 2\epsilon(\overline{a_m^2}/N)^{\frac{1}{2}}$ is a good estimate of the error in the mean-square peak value, where N is the total number of peaks measured. If $\ddot{y}$ is the horizontal component of acceleration, $\ddot{y} = ka$, where k gal/cm. is a constant of the apparatus, and the second-order correction δg is $\overline{\ddot{y}^2}/2g$. Assuming that each peak is sinusoidal, $\overline{a^2} = \frac{1}{2}\overline{a_m^2}$ and $\delta g = k^2\frac{1}{2}\overline{a_m^2}/2g$; hence

$$\Delta(\delta g) = k^2\Delta(\overline{a_m^2})/4g = k^2\epsilon(\overline{a_m^2}/N)^{\frac{1}{2}}/2g.$$

For a typical acceleration recorder record, $N = 360$, $k = 9{\cdot}81$, $(\overline{a_m^2})^{\frac{1}{2}} = 0{\cdot}4$ and ϵ may be taken as ± 0.1 cm., to allow not only for errors in measuring the amplitude but also for the fact that individual peaks are neither truly sinusoidal in form nor of equal duration. This gives $\delta g = 7{\cdot}8$ mgals and $\Delta(\delta g) = 0{\cdot}146$ mgal. If we assume that the two horizontal components are independent, then the error in the resultant will be the square root of the sum of the squares of the errors in the individual components. If the mean-square values of both components are equal, the total correction will be 15·6 mgals and the error only ±0·21 mgal. The accuracy with which the records can be measured is therefore quite adequate. In the case of the long-period pendulum records the scale factor $k = 19{\cdot}6$. The accuracy is therefore slightly inferior but still quite adequate. For the fluctuations of the chronometer marks the situation is somewhat different. Details of the method of measuring have been given by Meinesz (1941 *a*).

3·52. *Errors owing to limitations in the instruments*

Besides errors arising from measurements of the records, there are certain sources of systematic errors which must also be taken into account. As these vary with the different instruments they will be discussed separately. Only the apparatus used in *Tudor* will be considered, as no double observations were made in *Narwhal*.

(*a*) *Acceleration recorder*

(1) *Horizontal accelerations*. The construction of the instrument for measuring these has already been described in § 2·5 above. The period of the short-period pendulums was approximately $\frac{1}{3}$ sec. and their damping almost critical. Even for wave periods as short as 1 sec. an error of only some 6% will occur due to resonance, and at the periods normally

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* Owing to the movement of the submarine, this is not quite the same as the mean period of the waves as recorded by an instrument at rest with respect to the water.

experienced (between 5 and 15 sec.) this effect will be negligible. The effect of the finite rate of erection of the gyroscope is for the axis to try and follow the direction of the resultant acceleration, which gives rise to a systematic underestimate. During the *Tudor* expedition, the measured rate of erection was 40′/min. about one axis and 25′/min. about the other. To these must be added the effect of rotation of the earth which produces an apparent angular velocity of some 10′/min. about a horizontal axis in the north-south plane in these latitudes. This may either increase or decrease the apparent rate of erection. The maximum rate could therefore not have exceeded 50′/min., and if the mean wave period was 10 sec. this rate could only last for half a period, so that the total deflexion would be slightly more than 4′, corresponding to an acceleration of approximately 1 gal. During the next half-period, the acceleration would be in the reverse direction and the rotation of the earth would decrease the apparent rate of erection, so that the axis of the gyroscope would move back $2\frac{1}{2}'$. The axis thus becomes deflected until it has taken up a mean position such that equilibrium is established, and it will then oscillate about this position with an amplitude of some $3\frac{1}{4}'$. This, however, will have only a very small effect on the mean-square value of acceleration as calculated by the method described earlier in § 3·51. The deflexion of mean position is eliminated, since amplitude of the peaks is measured relative to a centre line so chosen that the average value of the peak amplitude is zero. The maxima occur at times which are nearly half-way between the instants when the acceleration changes sign. The axis of the gyroscope is therefore very near to its mean position when a reading is made and, although individual peaks may be slightly over- or underestimated, the systematic error is quite negligible.

It was found in practice that tilting the apparatus caused some deflexion of the light beams. The exact cause is not known, but it is probably due to friction in the bearings of the gyroscope gimbal system or to the reaction caused by the stream of air which is sucked through the gyroscope for cooling. The magnitude of the effect was such that a rotation sufficient to displace the pitch or roll records by 1 cm. caused a deflexion of approximately 1 mm. on the acceleration record. If the rotations are considered to be independent of the accelerations, the random error produced will be similar to the error arising from measuring up the records if the mean amplitude of the roll record is 1 cm. Only at a few of the shallow stations was this figure exceeded, so under these circumstances the error is unimportant. Some correlation between rotation and acceleration is, however, to be expected and was evident on the records. This arises because the apparatus was not mounted at the centre of rotation of the boat. Its actual position was 20 m. forward, 1 m. to starboard and 1 m. up from the metacentre. It can easily be shown that the linear accelerations associated with these rotations will be negligible except for the effect of pitching on vertical acceleration. The most marked correlations observed on the records were between:

(*a*) pitch and fore-and-aft acceleration (as the bows come up the boat accelerates astern), and

(*b*) vertical and fore-and-aft acceleration (the vertical leading or lagging by nearly 90°).

These relations are just what would be expected on a simple wave theory in which the orbit of a water particle is circular, assuming that the inclination of the boat is always tangential to the surface of constant pressure through the metacentre. Although correlation does exist between acceleration and rotation the error introduced is not serious.

The conclusion is that random errors are unimportant but that small systematic effects tend to make the calculated value of the mean-square acceleration too great. For a second-order correction of 10 mgals they may possibly be as great as $\frac{1}{2}$ mgal. If we assume that the error for all corrections below 10 mgals is $\frac{1}{2}$ mgal and for all corrections above this figure 1 mgal, there is certainly little danger that they have been underestimated.

(2) *Vertical accelerations.* The construction of the instrument for recording these has been described in § 2·5 above. For calibration a small known weight was added to the mass on the end of the cantilever spring. It was found that the sensitivity was such that a vertical acceleration of 16·0 gals gave a deflexion of 1 cm. on the record. The natural period was 0·5 sec. and the damping approximately half-critical. The readings should therefore have been accurate to within 1 % at periods greater than 5 sec. Unfortunately, early in the voyage, play developed in the pivots supporting the mirror, which made it possible for the mass to move a small distance without deflecting the mirror. This was not detected until the records were measured after the cruise, when it was noticed that the peaks were rather square. Measurements showed that the mean-square vertical acceleration as recorded was considerably less than half the mean-square horizontal acceleration. The theory of sea waves indicates that at a point in deep water these two quantities should be equal. It was concluded that little or no reliance could be placed on these records, and the results obtained from them have not been used in estimating the second-order corrections.

(*b*) *Vening Meinesz apparatus*

(1) *Horizontal accelerations.* Details of the arrangement of the long-period pendulums and the method of computing the second-order corrections from their records have already been published (Meinesz 1941 *a*). At several stations the results obtained by this method were compared with the measurements of the acceleration recorder, and it was found that in general the values given by the Vening Meinesz apparatus were significantly greater. The possibility of systematic errors must therefore be considered. The frequency spectrum of the wave motion shows clearly that a considerable band of frequencies is present. This will readily be appreciated when it is remembered that the record shown in figure 3 is taken at a depth of 200 ft., and that at shallower depths effects of the shorter period waves will predominate. This is confirmed by the fact that the damped pendulum record which is used to estimate the correction for tilting of the swinging plane of the main pendulums shows marked oscillations, indicating that the natural period of the gimbal system (approximately 2·3 sec.) is being excited. When computing the second-order corrections, a factor is introduced to allow for the effect of resonance of both the gimbal system and long-period pendulums. This factor is almost independent of frequency for a considerable band in the region of 8 to 9 sec., but if wave periods widely different from this value are present the magnification factor estimated from the 'mean wave period' will certainly be too small. An estimate of the magnitude indicates, however, that this error can hardly exceed 10 % even under the most severe conditions encountered. The damping of the long-period pendulums and the fact that their knife edges are above the axis of the gimbals will also tend to cause a slight overestimate of the acceleration, but their combined effects cannot exceed a few per cent. These errors account for part of the observed discrepancy but not all of it.

(2) *Vertical accelerations.* The fluctuations of the chronometer marks provide a method by which the vertical accelerations may be estimated. The results obtained are not entirely satisfactory because the fluctuations could only be measured during the beginning and end-parts of the record and at those places during the middle part near where a coincidence with the sidereal chronometer occurred. Thus only three or four samples, each of a few minutes' duration, were available during the 30 min. record. It was noticeable that the intensity of the wave movement varied considerably throughout the record, and the sampling errors introduced may have reached values as high as 30 % on some occasions. The second-order corrections derived by this method are therefore subject to considerable uncertainty. It must be pointed out, however, that the case considered here is for very disturbed conditions when the second-order corrections may be as great as 20 mgals. For normal operating conditions, when the total correction is only a few milligals, the fluctuations of the chronometer marks provide a most valuable check that the second-order terms are small, and in these circumstances their magnitude may be estimated with sufficient accuracy.

TABLE 6. ACCELERATION MEASUREMENTS

station no.	depth of dive (ft.)	ship's course (°)	swell direction	B.S. mag.	corrections by accel. meter				corrections by L.P.P. chron.				total corr.
					ath.	f. & a.	hor.	vert.	ath.	f. & a.	hor.	vert.	
1*a*	27	085	WSW	2	18·8	4·2	23·0	12·0	26·5	5·2	31·7	14·3	11·5
1*b*	60	085	WSW	2	2·6	1·0	3·6	1·0	3·3	1·0	4·3	2·6	1·8
2	90	270	WSW	3	—	—	—	—	—	—	—	—	0*e*
3*a*	70	080	W×S	2	—	—	—	—	—	—	—	—	0·2*e*
3*b*	136	080	W×S	2	—	—	—	—	—	—	—	—	0*e*
4*a*	68	248	SW	1	0·4	0·4	0·8	0·2	—	—	—	—	0·4
4*b*	30	248	SW	1	1·9	2·2	4·1	2·5	—	—	—	—	2·0
8	199	250	SW	4	0·5	0·2	0·7	—	—	—	—	—	0·4
10*a*	80	260	W	3	17·8	3·6	21·4	6·0	—	—	—	—	10·7
10*b*	155	260	W	3	2·8	0·8	3·6	0·3	—	—	—	—	1·8
13*a*	60	074	W	2	15·6	3·8	19·4	5·6	—	—	—	—	9·7
13*b*	165	074	W	2	—	—	—	—	—	—	—	—	0·5*e*
16*a*	80	068	W	2	5·7	2·7	8·4	1·7	—	—	—	—	4·2
16*b*	116	068	W	2	2·5	1·2	3·7	0·2	—	—	—	—	1·8
17	201	180	NW	3	—	—	—	—	—	—	—	—	0·8*e*
21*a*	81	003	N	1	4·6	0·8	5·4	0·7	5·0	1·0	6·0	2·0	2·7
21*b*	144	003	N	1	0·6	0·1	0·7	0·1	0·5	0·2	0·7	—	0·4
24*a*	80	003	—	0	—	—	—	—	—	—	—	—	5·5*e*
24*b*	150	003	—	0	—	—	—	—	—	—	—	—	1·0*e*
35*a*	112	325	WSW	4	—	—	—	—	2·9	2·9	5·8	4·5	1·3
35*b*	80	325	WSW	4	7·6	6·7	14·3	7·3	9·3	11·7	21·0	14·2	7·1
36	117	325	WSW	3	—	—	—	—	4·3	4·2	8·5	3·7	4·8
39*a*	145	095	SSW	2	—	—	—	—	—	—	—	—	0·5*e*
39*b*	78	095	SSW	2	—	—	—	—	—	—	—	—	4·0*e*
42	118	180	SW	1	6·2	0·7	6·9	1·1	—	—	—	—	3·5
45	80	146	—	0	—	—	—	—	—	—	—	—	0·4*e*
46	114	170	S	5	—	—	—	—	—	—	—	—	0·4*e*
47	215	180	S	3	0·8	1·5	2·3	0·3	—	—	—	—	1·2
48	177	204	SW	3	1·4	3·9	5·3	1·8	2·7	5·8	8·5	3·1	2·6
49	146	185	SW	3	9·0	0·5	9·5	2·2	—	—	—	—	4·7
51*a*	30	225	—	—	—	—	—	—	—	—	—	—	2·2*e*
51*b*	30	225	—	—	—	—	—	—	—	—	—	—	2·5*e*

e, correction estimated only. B.S. mag., magnitude on Beaufort scale. ath., athwart-ship. f. & a., fore and aft. L.P.P., long-period pendulums.

3·53. *Results of acceleration measurements*

Details of the acceleration measurements are given in table 6, together with the conditions at the time when the observations were made. The depth of dive, ship's course, direction and strength of swell as measured on the Beaufort scale are shown. At the majority of the stations the results from the acceleration recorder are given in detail, and at several the results of the records from the long-period pendulums and from the fluctuations of the chronometer marks are available for comparison. Where the correction was very small, it was found that sufficient accuracy could be obtained simply by estimating the correction by eye. Such figures are denoted by *e*. At those stations not shown in table 6 the second-order corrections are negligible.

An examination of the acceleration recorder results shows that after station 8 the defect mentioned above in the vertical acceleration recorder became serious. These results have not therefore been used in computing the final correction. A comparison of the mean-square values of horizontal acceleration, as measured by the Vening Meinesz apparatus and the acceleration recorder, shows that the discrepancy is greater than can be accounted for by the known causes of systematic error which have been considered above. Since the acceleration recorder is believed to be the more accurate, its results have been used for calculating the final corrections, except in the case of stations 35*a* and 36, for which records are not available. To estimate the effect of vertical accelerations, the fluctuations of the chronometer marks could be used, but, as stated above, these suffer from serious sampling errors. It has been considered wisest, therefore, to estimate the correction by assuming that the horizontal and vertical accelerations have the same mean-square value. The final figures used for the total second-order corrections are therefore half the correction due to horizontal acceleration as derived from the acceleration recorder.

3·6. OBSERVATIONS AT DOUBLE STATIONS

To find the effect of the accelerations on the mean period of the pendulums, the results obtained at those stations where observations were made at two different depths must be considered. Since the two observations were usually made at positions a mile or two apart, it is best to compare the free-air anomalies. These differences ΔFA (shallow–deep) are given in table 7, together with the depths at which the observations were made, the wind direction and force (as measured on the Beaufort scale), and depth of sea. In all cases except one a smaller anomaly is obtained at the shallower depth. The mean difference is $-6{\cdot}2$ mgals but there is a considerable scatter from $+3$ to -25 mgals. The r.m.s. difference from the mean value is $\pm 7{\cdot}0$ mgals. The error of a single observation will depend to a large extent on the accuracy with which the Eötvös correction can be measured. At double stations it was assumed that the east-west component of the velocity was the same at each depth. In these circumstances, errors arising from other causes might be expected to introduce an uncertainty of $\pm 2{\cdot}0$ mgals in the deeper and $\pm 2{\cdot}5$ mgals in the shallower observation. Thus $\pm 3{\cdot}3$ mgals might be expected in the difference, but this figure is still well below the observed value of $\pm 7{\cdot}0$ mgals. If the whole discrepancy is to be accounted for by the Eötvös correction, we should have to assume that the east-west component of velocity was $1{\cdot}2 \pm 1{\cdot}1$ knots greater at the shallower position. As this seems improbable other possibilities will first be considered.

TABLE 7. DOUBLE-STATION OBSERVATIONS

stations	depths of dives (ft.)		wind		depth of sea (ft.)	differences in milligals		
			direction	force		ΔFA	ΔS	$\Delta FA - \Delta S$
1*a*–1*b*	27	60	WSW	2	108	− 4	−10·0	+ 6·0
3*a*–3*b*	69	136	W × S	2	196	+ 3	− 0·2	+ 2·8
4*b*–4*a*	30	68	SW	1	270	− 2	− 1·6	− 0·4
10*a*–10*b*	80	155	W	3	16,010	− 5	− 8·9	+ 3·9
13*a*–13*b*	60	165	W	2	13,940	− 3	− 9·2	+ 6·2
16*a*–16*b*	80	116	W	2	380	− 4	− 2·4	− 1·6
21*a*–21*b*	81	144	N	1	15,380	−11	− 2·3	− 8·7
24*a*–24*b*	80	150	—	0	422	−10	− 4·5	− 5·5
35*b*–35*a*	80	112	WSW	4	1,670	−25	− 5·7	−19·3
39*b*–39*a*	78	145	SSW	2	434	− 1	− 3·5	+ 2·5
					mean	− 6·2	− 4·8	− 1·4

ΔFA = difference in free-air anomaly. ΔS = difference in second-order correction. $\Delta FA - \Delta S$ = difference between ΔFA and ΔS.

It is natural to inquire how much of the observed difference arises from the second-order corrections. Table 7 gives the difference, ΔS, between the corrections at the two depths, and also the difference between ΔFA and ΔS, which is the difference in the free-air anomalies as computed from the two observations before second-order corrections have been applied. The mean value is −1·4 mgals, the r.m.s. scatter about this mean remaining ±7·0 mgals as before. The omission of the second-order corrections has then reduced the mean difference to a value which does not differ significantly from zero but still leaves the scatter much greater than can be accounted for by the known uncertainties in the observations. One concludes that either the second-order corrections should not be applied or that some unknown systematic error is present of approximately the same magnitude but of opposite sign. In either case the r.m.s. difference is ±7·0 mgals; this may indicate an uncertainty of ±5·0 mgals in each observation or greater accuracy at the deeper, with a corresponding reduction in accuracy at the shallower and more perturbed position. It is hard to see how long-period horizontal and vertical accelerations can fail to affect the mean period of the pendulums, and one is therefore forced to consider the other possible causes of systematic error.

(*a*) *Sway correction*

The shallower stations show greater perturbations of the centre pendulum record which indicates that sway of the support is taking place. However, the fictitious pendulums are in antiphase, and hence the changes in their periods should show opposite signs. Reference to column 9 of table 2 shows that the observed differences at the shallow stations are not abnormal, and one concludes that sway cannot be the cause. This is confirmed by the observations made while lying alongside at Oban, where the perturbation of the centre pendulum was very marked and yet the values of gravity obtained were in good agreement with those previously observed on land (see § 3·4).

(*b*) *Vibration of support*

It is quite probable that some vibration of the support did occur during the observations, and it is possible that accelerations so developed, whose period would be short compared with the pendulum period, might give rise to second-order effects tending to make the observed pendulum period too long. The horizontal acceleration records do show that such vibration took place, and vertical vibration may also have been present and yet escaped detection owing to play in the pivots of the mirror. But there is no obvious reason why the vibration should have been worse at the shallow depth, and an examination of the acceleration records confirms this. Although vibration might possibly account for some of the large uncertainty it cannot explain the systematic error.

(*c*) *Eötvös correction*

There is a possibility of a systematic change in the direction and strength of the current with depth. Ekman (1902) has shown* that wind-driven currents in the northern hemisphere tend to veer and decrease exponentially in velocity as the depth increases. Since in our latitudes the prevailing wind is south-west to westerly, the wind-driven currents will be directed easterly to south-easterly at the surface. At greater depth the current will become more southerly and weaker, and both changes would tend to reduce the Eötvös correction and so make the apparent value of gravity greater. This effect is therefore of the correct sign, but an estimate of the magnitude shows that it is too small to be of any great significance. The maximum wind encountered during a double observation was some 15 knots, and this would only give rise to a surface current of about $\frac{1}{4}$ knot. Such a current would reverse its direction and be reduced to e^{-1} of its surface value at a depth of 175 ft., but this could only make a difference of a fraction of a milligal as between the deeper and shallower observations. Some modification would be introduced if temperature layers existed, but even so it is considered improbable that this could be the real explanation of the systematic effect.

It is perhaps fortunate that this is so because otherwise all submarine gravity measurements made in waters where the prevailing wind was westerly would give values systematically too large, if the Eötvös correction were calculated on the assumption that the surface currents persisted unaltered down to the depth at which the observation was made.

Further experimental work is required, but until this can be done there is little to be gained from speculation. As far as the present results are concerned it is considered wisest to rely on the gravity values deduced from the deeper observations where the perturbations are small, but to bear in mind that these may possibly have a systematic error of a few milligals, and that the uncertainty in these values may well be greater than that estimated in § 3·4.

PART IV. INTERPRETATION OF RESULTS

4·1. Echo soundings

Before discussing the gravity results, the echo soundings made during the expedition will be briefly described. The primary object was to find the depth of the sea at each station. This is necessary in order to calculate the attraction of the topography (see § 2·6 above). If the error is not to exceed 1 mgal, soundings are required to within about 8 fathoms. In many places, such as the English Channel, good charts are available and the depths can be read directly from these. In the deep ocean, however, special soundings become essential, as those shown on the charts are neither sufficiently frequent nor accurate. To obtain measurements within ±8 fathoms in depths of 2400 fathoms is not easy, but the results

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* For a short account see Sverdrup, H. U., Johnson, M. W. & Fleming, R. H. (1942). *The Oceans*, pp. 492 to 498. New York: Prentice-Hall.

given in this paper have a random error of approximately that magnitude though some systematic error is also present. The results are given in table 8. These soundings were made while submerged and are average values during the time for which the pendulums were swung. The conditions of observation were very good, since the boat was steady, and at a speed of only 2 knots the background noise was negligible. Excellent records were obtained in *Narwhal* down to 800 fathoms and in *Tudor* to a depth of 2700 fathoms.

In shallow water, the standard Admiralty-pattern echo sounder normally fitted in H.M. submarines was used. The results from this are certainly accurate to within 1 fathom. In deep water, however, special equipment was necessary. As already described in § 2·6 above, *Narwhal* was fitted with an echo-sounding equipment designed and manufactured by Messrs Henry Hughes and Sons Ltd. which incorporated one of their 'Veslakari' recorders giving a record 6 in. wide. The full scale represented 200 fathoms, and it is estimated that the beginning of the echo could be read to within $\frac{1}{2}$ mm. The instant of transmission was known with approximately the same accuracy, and the error in reading the record was therefore about $\pm 1{\cdot}0$ fathom. In deep water a switching arrangement made it possible to introduce a known time lag corresponding to any desired multiple of 100 fathoms between the instant of transmission and moment when the stylus crossed the zero mark. This lag was controlled by a cam operated from the motor that drove the stylus, and its speed was checked by stop-watch to within 1 part in 10^3. Even in a depth of 2400 fathoms the error due to this cause would therefore be less than $2\frac{1}{2}$ fathoms. In *Tudor* an Admiralty-pattern recorder with scales of 6 in. = 1250 fathoms and 6 in. = 2500 fathoms was used. The accuracy of reading these records was similar to that obtained with the 'Veslakari' recorder, but owing to the difference in scales the corresponding errors were ± 6 and ± 12 fathoms. Careful checking of the motor speed made errors arising from this negligible. Shrinkage of the records was eliminated by making all measurements while the records were still wet. In both sets of measurements, however, some uncertainty arises due to variations in the velocity of sound with temperature and pressure. The recorder scales were calibrated on the assumption that the velocity of sound in sea water was 820 fathoms/sec. The Admiralty *Tables of the velocity of sound in pure water and sea water* (1939) give convenient tables from which the systematic errors arising from the variation of velocity with depth can be readily obtained. These show that in the areas where our soundings were made errors greater than 8 fathoms can occur only at a few stations in the Atlantic and Bay of Biscay. The largest discrepancy is at station no. 10, where a correction of 120 ft. should be added to the observed sounding of 16,160 ft.

Besides the depth measurements made at the gravity stations, some profiles were recorded by running the echo sounder while steaming on the surface. The results are shown in figure 4. *a* and *b* were made on the outward and homeward run west-south-west from the Lizard, while crossing the edge of the continental shelf. It should be noticed that the vertical scale is exaggerated approximately four times.

In some places where the echoes were doubtful the profile has been dotted. These weak echoes are probably due to considerable variations in depth within the area of the bottom *illuminated* by the sound beam. They usually occur near the bottom of a *valley*. The fact that many of these appear to be V-shaped is because echoes are received from both sides of such a depression. For instance, if soundings were made while steaming over a valley of the cross-section shown in figure 5*a*, a record as shown in figure 5*b* would be obtained. It is

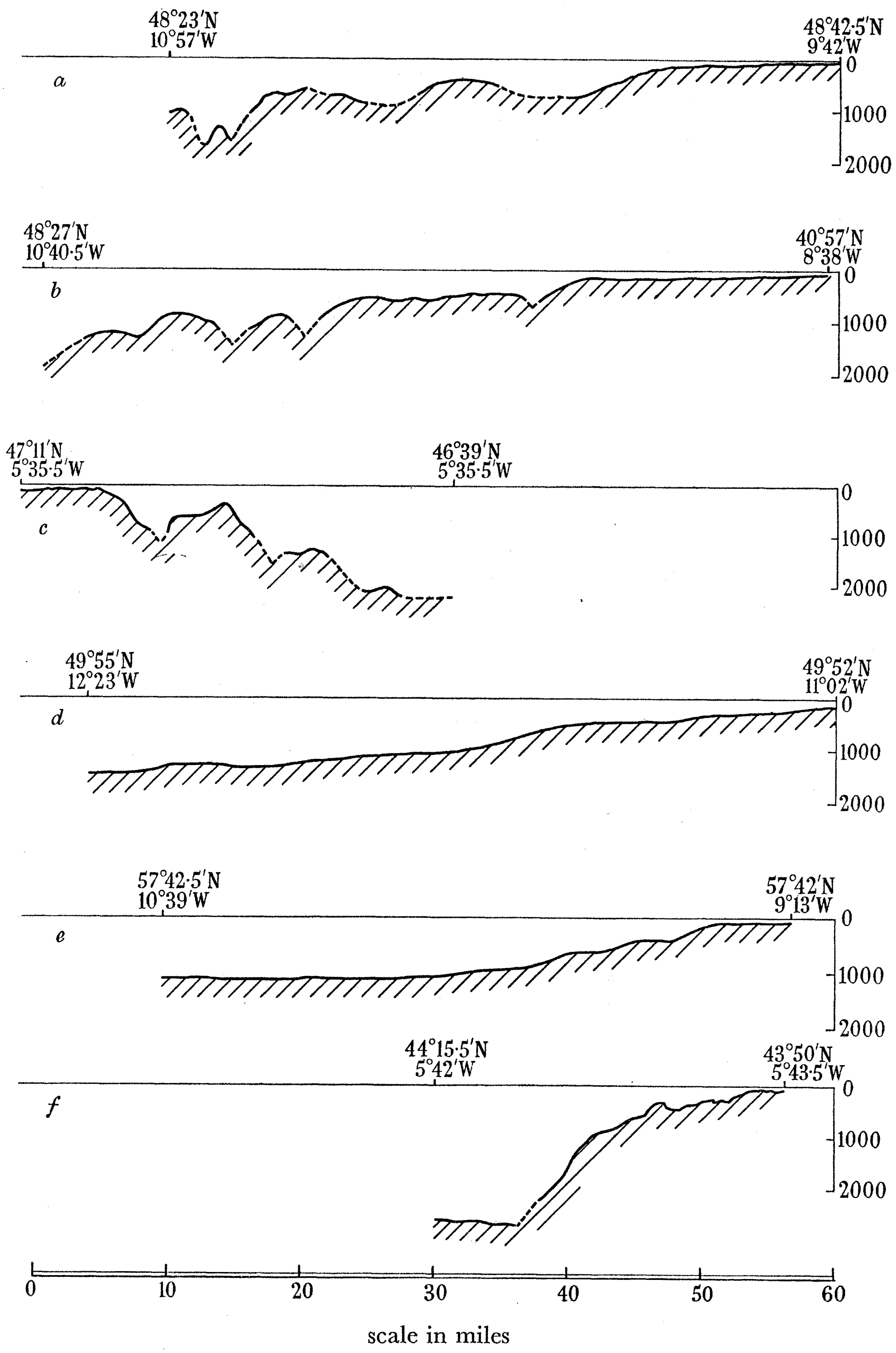

FIGURE 4. Echo-sounding profiles (depths in fathoms) *a*, *b*, and *d*, Atlantic; *c*, Bay of Biscay (north); *e*, St Kilda; *f*, Bay of Biscay (south).

easy to see how this arises by considering the echoes received by a ship at S_1. These return from all points *illuminated* by the sound beam, but are only of large intensity from regions such as A_1 and B_1 where the normal to the bottom passes through S_1. The record, therefore, shows two main echoes at depths corresponding to S_1A_1 and S_1B_1. As the ship moves forward to S_2 and S_3 the first echo will get deeper and the second shallower, and they may be observed to cross one another. Over the centre of such a channel a third set of echoes corresponding to the path S_2C is sometimes observed, which may arrive either before or after S_2A_2 and S_2B_2. Considerable discretion is therefore needed in the interpretation of such echo-sounding records. The first echo comes from that part of the bottom which is nearest the ship and still within the sound beam, but strong echoes are obtained only from areas which are normal to the direction of the incident sound. If the direction of the slope is known a correction can be applied, but this is seldom possible in the case of a single profile. In the present instance no such correction has been made. The profiles shown therefore overemphasize the V-shape of the valleys.

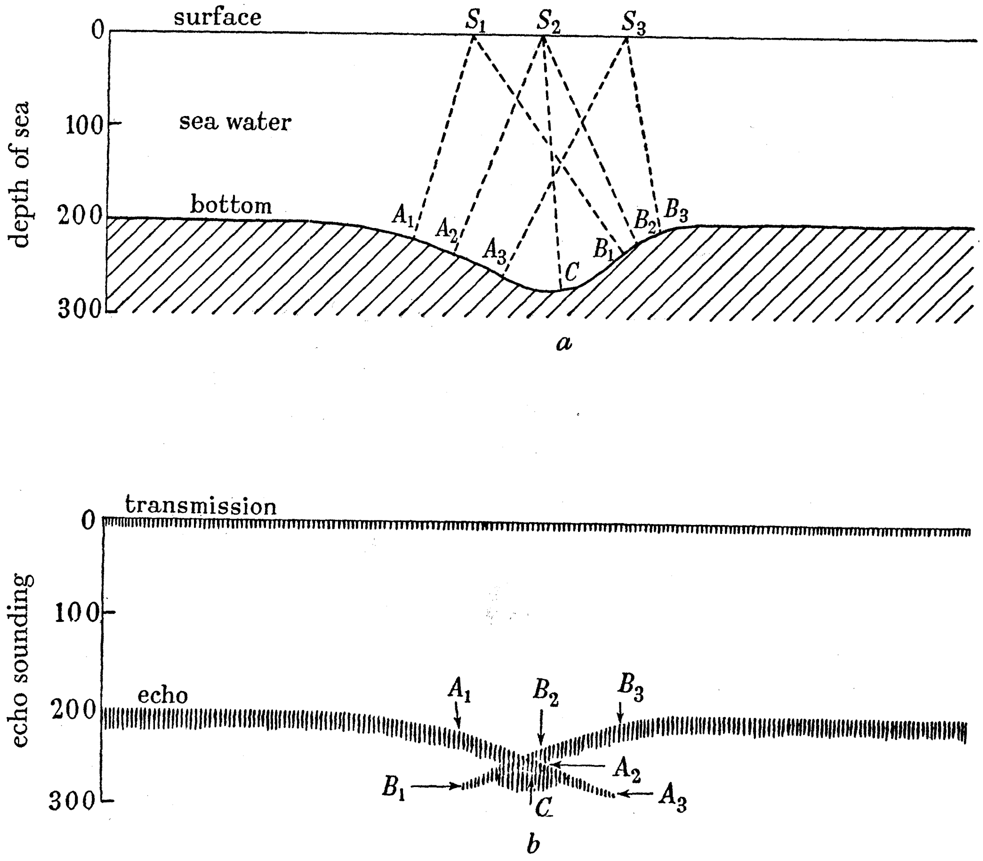

FIGURE 5. *a*, section of submarine valley; *b*, echo-sounding record.

A detailed study of the charts available for the area in which profiles (figure 4*a*, *b*) were observed shows that the soundings are very irregular. The obvious conclusion is that this part of the continental shelf is crossed by submarine canyons. Ewing (Ewing, Woollard, Vine and Worzel, 1946, plate 6) has used the explanation to account for very similar profiles observed by him.

Profile *c* of figure 4 was made while crossing the edge of the continental shelf south of Ushant. Though considerably steeper than profiles *a* and *b* it shows much the same general features. Profile *d*, on the other hand, which was made due west of the Lizard, does not. Apart from a slight flattening near 500 fathoms the slope here is quite smooth and gradual. The difference may be explained if we assume that submarine canyons, to which the irregularities in the first three profiles are most probably due, develop only where there is sediment and that little is present in the region of profile *d*. This is not unreasonable if, as we believe, most of the sediment now forming the shallow part of the continental shelf in this region was carried down the English Channel. The change in general direction of the 100-fathom line at about 11° W, 49° N may indicate the northern limit of the area of deposition. Profile *e* is also smooth, probably again because little sediment is to be expected to the west of St Kilda, where this record was obtained.

Finally, profile *f* shows the very steep slope found off the north coast of Spain. The average gradient between the 100- and 2000-fathom line is 1 in 8, but the lower parts are as steep as 1 in 3. The bottom of the slope is sharply defined, and from there northward the floor of the Bay of Biscay is remarkably flat. One might explain this by assuming that the slope was made up of sediment which had been piled up on a relatively flat floor of ancient rock. More careful consideration, however, shows that this is improbable. In the first place, the gradient of the lower part of the slope is too steep for unconsolidated sediment to come to rest there. Also the floor of the southern part of the Bay of Biscay appears to be so unusually level that its surface is unlikely to be rock. The depth at stations nos. 21 and 22 which are 33 miles apart are identical within the limits of experimental error and, at both, the sounding remained constant throughout the whole of each dive, during which a distance of over a mile was covered. Unfortunately, intermediate soundings are not available, but it seems most probable that the bottom here is really level to within a few fathoms over distances of several miles. It is most unlikely that such a very flat surface should be found in close proximity to the violent topography immediately to the south, where the crust of the earth is far from being in isostatic equilibrium (see § 4·33), unless some gravity-controlled process were responsible. The simplest explanation appears to be that the detrital mud is so finely divided that it can be carried in suspension for a very long time and gradually spread by bottom currents so as to fill in the hollows in the original topography. This suggestion has already been put forward to account for the transport of bottom sediments, but so far little experimental evidence is available.* It is possible, therefore, that the basement rock in this region may be covered by a considerable thickness of mud. Such an accumulation of material of low density might go some way towards explaining the low values of gravity found here but discussion of these will be postponed until § 4·33 below.

4·2. REDUCTION OF OBSERVATIONS

Base station values. The measured values of gravity reduced to sea-level (g_0) have already been given in tables 1 and 2. The value $g = 981{\cdot}265$ cm./sec.^{2} at the Pendulum House, Cambridge, has been adopted because almost all the other pendulum observations in the

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* For a discussion of this see Sverdrup, H. U., Johnson, M. W. & Fleming, R. H. (1942). *The Oceans*, pp. 962 to 966. New York: Prentice-Hall.

British Isles are based on this value (Bullard & Jolly 1936). Meinesz bases his submarine observations on a value of 981·268 cm./sec.^{2} at the Meteorological Institute at de Bilt. Jeffreys (1948) has reanalyzed the available data and concludes that

$$g \text{ (Pendulum House)} = 981{\cdot}2642 \pm 0{\cdot}0010 \text{ cm./sec.}^2,$$
$$g \text{ (de Bilt)} = 981{\cdot}2677 \pm 0{\cdot}0009 \text{ cm./sec.}^2,$$

are the most probable values on the Potsdam standard. On this basis, our results are 0·8 mgal, and Meinesz's results 0·3 mgal, too large. Both are within the probable error.

4·21. *Free-air and Bouguer anomalies*

The free-air anomalies are obtained from the observed values, reduced to sea-level, by subtracting the value given by the international gravity formula (γ_0). These results for the "Tudor" expedition are given in Table 8*a*, and those for six other land stations in Table 8*b*. Both are plotted on chart 2. Examination of this chart shows that there is a well-marked correlation between the free-air anomalies and the main topographic features. The effect of these can be calculated if their density is known. We have made the usual assumption that the densities of rock and of sea water are 2·67 and 1·03. The former is a good approximation to the mean density of the upper layers of the earth's crust, but is generally greater than the density of sedimentary rocks exposed at the earth's surface. Subtracting the calculated attraction of the topography from the free-air anomaly gives the anomaly as originally suggested by Bouguer. This represents the attraction of the mass distribution within the earth which together with the attraction of the known topography would produce the free-air anomalies. They show a marked correlation with the depth of the sea, having large positive values over the ocean. This has been found by other expeditions to be almost universally true. This well-known result is in general agreement with the theory of isostasy. Although there are many instances where the observed values of gravity cannot be wholly accounted for by any form of the theory it is clear that additional matter must be present under the oceans whose attraction very nearly compensates for the lower density of the sea water. This is also true for most of the earth's major topographic features, and consequently, when estimating the attraction of the unknown mass anomaly at a given point, it is desirable to take into account, not only the attraction of the topography but also the attraction of the compensation, except in the region immediately surrounding the station. To do this we subtract from the free-air anomalies the attraction of topography only out to a radius of 167 km. (zones A to O of Hayford's scheme), and for the rest of the earth assume isostatic equilibrium on Hayford's hypothesis for a depth of compensation of 113·7 km. The anomaly so obtained is sometimes called the 'Modified Bouguer' anomaly, but throughout this paper it will be referred to simply as the Bouguer anomaly. The results are given in table 8 and shown plotted in chart 3.

4·22. *Isostatic anomalies*

The isostatic anomalies are obtained by subtracting from the free-air anomalies the attractions of topography and compensation for all zones according to the various assumptions. Nine different anomalies have been calculated for each of the stations and the results are tabulated in tables 8*a* & *b*. The choice was based on the following considerations.

Pratt's hypothesis, as interpreted by Hayford, has already been used by many other

TABLE 8*a*. GRAVITY ANOMALIES: H.M.S. *TUDOR*

station no.	lat. N	long. W	sea depth	free air	mod. Boug.	Hayford 113·7	Heisk. $T=20$ $R=0$	regional		Heisk. $T=30$ $R=0$	regional			Heisk. $T=40$ $R=0$	Heisk. $T=60$ $R=0$	I.E.
								$T=20$ $R=58$	$T=20$ $R=174$		$T=30$ $R=58$	$T=30$ $R=174$	$T=30$ $R=232$			
1	50° 32′	1° 58′	108	−17	−19	−16	−14	−14	−11	−15	−15	−13	—	−15	−71	−2
2	50° 12′	1° 13′	227	−34	−33	−34	−32	−32	−28	−32	−32	−28	—	−32	−33	−2
3	50° 10′	2° 23′	196	−11	−14	−14	−10	−10	−7	−11	−10	−9	—	−12	−13	−2
4	49° 54′	5° 07′	270	+30	+22	+20	+29	+28	+29	+27	+26	+26	—	+25	+20	−2
5	49° 39′	6° 05′	326	+21	+10	+6	+17	+16	+16	+14	+14	+13	—	+11	+5	−2
6	48° 57′	8° 38′	494	−4	−30	−42	−17	−18	−31	−24	−25	−38	—	−32	−45	−1
7	48° 40′	9° 37′	603	+54	+26	−9	+25	+18	−12	+12	+7	−18	—	+2	−16	−1
8	48° 27′	10° 40′	7,550	+10	+117	+19	+23	+28	+22	+25	+27	+19	—	+24	+20	+1
9	47° 24′	14° 11′	16,160	+10	+274	+61	+16	+23	+31	+29	+32	+38	—	+36	+49	+2
10	47° 07′	15° 05′	16,010	+8	+269	+49	+11	+14	+28	+20	+24	+34	—	+28	+41	+3
11	46° 59′	15° 59′	14,000	+33	+245	+42	+29	+32	+25	+33	+33	+27	—	+36	+38	+3
12	47° 45′	13° 21′	14,310	+9	+243	+38	+11	+11	+17	+16	+15	+20	—	+20	+31	+2
13	48° 02′	12° 29′	13,940	−28	+203	+21	−19	−10	+10	−6	+1	+16	—	+4	+18	+2
14	48° 12′	11° 33′	11,570	−19	+169	+19	−11	−6	+12	−1	+5	+12	—	+6	+17	+1
15	49° 08′	7° 54′	455	+26	+5	−2	+17	+16	+11	+12	+12	+6	—	+7	−3	−2
16	49° 22′	6° 56′	380	+22	+8	+2	+15	+15	+14	+12	+11	+10	—	+8	−2	−2
17	46° 30′	5° 35′	11,300	−58	+149	+13	−37	−29	+5	−21	−13	+13	—	−8	+14	+1
18	45° 57′	5° 35′	15,260	−33	+253	+68	−15	−5	+42	+9	+19	+57	—	+29	+62	+2
19	45° 23′	5° 38′	14,990	+7	+298	+94	+23	+21	+53	+39	+41	+71	—	+55	+85	+2
20	43° 39′	5° 42′	225	+62	+42	+23	+47	+44	+16	+38	+35	+12	—	+30	+13	−2
21	44° 13′	5° 42′	15,380	−114	+129	+2	−72	−37	+1	−36	−10	+8	—	−16	+6	0
22	44° 49′	5° 37′	15,390	−73	+221	+34	−54	−50	+14	−30	−21	+29	—	−8	+28	+1
23	47° 11′	5° 31′	540	+62	+47	−4	+16	+4	−18	+4	−2	−21	—	−3	−11	−1
24	47° 46′	5° 29′	422	+26	+8	−8	+13	+11	−9	+6	+4	−14	—	+1	−9	−2
25	48° 21′	5° 25′	385	+18	+4	−2	+12	+11	+7	+8	+7	+4	—	+4	−3	−2
26	49° 49′	10° 01′	528	+29	+7	+4	+20	+18	+7	+13	+11	0	—	+7	−5	−2
27	49° 52′	11° 00′	866	+51	+31	+4	+29	+16	+9	+21	+18	+3	—	+13	0	−1
28	49° 54′	12° 02′	5,700	0	+72	+4	+13	+16	+13	+13	+14	+9	—	+11	+5	0
30	51° 33′	13° 23′	2,910	+27	+46	−3	+17	+16	+7	+12	+11	+1	—	+6	−4	−1
32	53° 22′	13° 29′	522	+52	+26	−1	+29	+14	−4	+17	+14	−9	−19	+8	−7	−1
33	54° 43′	13° 52′	9,510	−20	+136	−12	−20	−18	+7	−10	−7	+14	+26	−2	+12	+1
34	55° 41′	14° 58′	4,150	+6	+60	−6	+2	−2	−3	−1	0	−6	−13	−3	−7	0
35	56° 25′	15° 50′	1,670	+42	+41	+11	+32	+32	+17	+23	+15	+12	+4	+20	+10	−1
36	57° 05′	16° 41′	3,915	+23	+71	+19	+24	+26	+32	+25	+26	+29	+21	+24	+21	−1
37	57° 45′	17° 26′	3,860	+17	+66	+9	+14	+14	+14	+14	+14	+14	+13	+12	+9	−1
38	57° 45′	15° 12′	2,220	+22	+37	+3	+15	+14	+11	+12	+11	+7	+2	+9	+1	−1
39	57° 44′	13° 40′	434	+63	+43	+21	+45	+41	+19	+36	+33	+14	+6	+29	+17	−1
40	57° 45′	11° 53′	6,350	−8	+94	+10	−3	−2	+12	+3	+5	+13	+17	+7	+10	0
41	57° 42′	10° 11′	6,810	−30	+87	+11	−8	0	+17	+1	0	−3	+18	+7	+14	0
42	57° 43′	8° 28′	490	+60	+53	+40	+53	+51	+41	+49	+49	+39	+35	+45	+38	−2
43	56° 49′	6° 45′	530	+5	+5	+10	+13	+15	+25	+14	+16	+22	+15	+14	+12	−2
44	55° 27′	5° 57′	290	+14	+11	+15	+19	+21	+25	+19	+20	+23	—	+18	+16	−2
45	55° 01′	5° 33′	422	+2	+4	+6	+10	+12	+15	+10	+11	+13	—	+9	+7	−2
46	53° 43′	5° 07′	225	+30	+29	+29	+32	+32	+8	+31	+32	+38	—	+31	+30	−2
47	53° 05′	5° 05′	395	+8	+10	+11	+13	+15	+21	+14	+15	+20	—	+14	+13	−2
48	52° 28′	5° 14′	267	−36	−37	−36	−34	−33	−28	−34	−33	−29	—	−34	−35	−2
49	50° 26′	5° 52′	416	+38	+30	+28	+36	+35	+36	+34	+33	+34	—	+32	+28	−2
50	50° 01′	4° 25′	354	+14	+10	+8	+15	+15	+16	+14	+14	+13	—	+13	+17	−2
51	50° 33′	2° 20′	138	−12	−7	—	—	—	—	—	—	—	—	—	—	—
Portland	50° 34′	2° 26′	0	−4	−10	−7	−2	−2	0	−3	−2	−1	—	−4	−6	−2
Falmouth	50° 09′	5° 03′	0	+7	−5	−4	+5	+3	+2	+2	+1	+0	—	−1	−7	−2

I.E. = indirect (Bowie) effect.

TABLE 8*b*. LAND-STATION ANOMALIES (ALL UNITS MGALS)

station	lat. N	long. W	height (ft.)	free air	mod. Boug.	Hay. 113·7	Heisk. $T=20$ $R=0$	regional		Heisk. $T=30$ $R=0$	regional		Heisk. $T=40$	Heisk. $T=60$	observer
								$T=20$ $R=58$	$T=20$ $R=174$		$T=30$ $R=58$	$T=30$ $R=174$			
Lochmaddy	57° 36′	7° 09′	10	+47	+34	+33	+41	+41	+40	+39	+39	+38	+37	+32	Jolly
Oban	56° 25′	5° 28′	20	+10	+1	+9	+19	+20	+18	+17	+17	+17	+15	+11	Jolly
Southampton	50° 55′	1° 24′	79	−30	−33	−32	−27	−27	−28	−28	−28	−29	−29	−31	Bond
Devonport	50° 03′	4° 11′	0	+13	+3	+7	+18	+16	+13	+15	+14	+12	+12	+7	Browne
Arbas	43° 01′	5° 45′	4360	+92	−79	−27	+14	+5	−38	−4	−11	−47	−20	−44	Galbis
Benavente	42° 01′	5° 41′	2370	+40	−57	+9	+33	+34	+36	+28	+28	+26	+21	+7	Sans
Salamanca	40° 58′	5° 39′	2641	+38	−54	+16	+37	+41	+39	+32	+34	+30	+26	+13	Sans

workers, and although it is doubtful if the physical basis of this method is now generally acceptable, it provides a useful standard of comparison. Our results have been calculated for a depth of compensation of 113·7 km. Airy's hypothesis, for which Heiskanen has prepared the necessary tables, has also been extensively used, and accumulated results show that a crustal thickness T of about 30 km. usually gives the best results. These anomalies have therefore been calculated assuming $T=20$, 30, 40 and 60 km. Here again doubt has been cast on the physical basis of the method. Although it would be possible for material with the strength of the rocks as seen at the surface to support the 'roots of mountains' required by the theory, it is doubtful whether at the base of the crust, where the temperature is considerably greater, the strength would still be sufficient. The roots, even if formed, would soon flow out sideways. Bucher's (1931) remarks on the melting-points of acid and basic rocks are very pertinent. Joly (1925) has also pointed out that the extra radioactive heating in a large mass of granite, such as would be required to support the Tibetan plateau, would be sufficient to raise the temperature of the base of the crust to above the melting-point of quartz (1700° C).

The regional isostatic hypothesis of Meinesz (1931, 1940), by which the compensation is distributed as if the earth's crust behaved as a slightly compressible elastic plate floating on a denser substratum, probably accords more accurately with the actual conditions. Theoretically, if the elastic constants of the crust are known, a definite relationship should exist between the crustal thickness, T, and the radius of regionality, R. If E and m are Young's modulus and Poisson's ratio for the crust, and if $\Delta\rho$ is the density difference between it and the fluid substratum,

$$\frac{R}{T}=\left\{\left(\frac{m^2}{m^2-1}\right)\left(\frac{E}{12T\Delta\rho}\right)\right\}^{\frac{1}{4}}.$$

This ratio is not very sensitive to variations in the values of the quantities on the right-hand side. Values of E and m can be deduced with sufficient accuracy from seismic data, and using these a value of $R/T=6$ approximately is obtained for T between 20 and 40 km. In practice, however, it is usual to calculate the anomalies for various values of T and R to find which combination gives the best agreement with observation. The value of R/T obtained then affords a check on the validity of the assumptions on which the above theory is based. Meinesz (1941 *c*) himself finds that the gravity field over the continental shelves agrees best with the assumption of a rather small radius of regionality. He concludes that $T=30$, $R=58$ km. are most suitable in this case. The anomalies for $T=20$ and 30 km. and $R=58$ and 174 km. have accordingly been calculated for our results. Over regions such as volcanic islands, values of R of the order of 200 km. give results in better agreement with the theoretical value of R/T. For those stations near the Rockall Bank (nos. 32 to 43) the anomalies for $T=30$, $R=232$ km. have therefore also been computed. The values of the regional anomalies for $T=30$, $R=58$ km., as given in tables 8*a* & *b*, are plotted in chart 4. Comparison with charts 2 and 3 shows that although the mean anomaly is still positive, the isostatic reduction has considerably reduced the fluctuations.

The type of isostatic reduction which agrees most closely with the observations is usually taken as that in which the anomalies show the least correlation with topography. In the case of our measurements, however, the depths of the sea at the various stations fall into two well-defined groups, one around 100 fathoms and the other about 2500 fathoms. We have therefore adopted as our criterion the minimum r.m.s. residual anomaly. The mean values and the r.m.s. residuals for the various sections and for the region as a whole are given in table 9. From the latter, it will be seen that $T=40$, $R=0$; $T=30$, $R=58$ and $T=20$, $R=174$ km. are all equally satisfactory.

TABLE 9. MEAN AND ROOT MEAN SQUARE RESIDUAL ANOMALIES

	stations	Hayford 113·7	$T=20$ $R=0$	$T=20$ $R=58$	$T=20$ $R=174$	$T=30$ $R=0$	$T=30$ $R=58$	$T=30$ $R=174$	$T=30$ $R=232$	$T=40$ $R=0$	$T=60$ $R=0$
mean anomaly (mgals)	4 to 16, 50	16	12	13	13	13	14	13	—	13	14
	17 to 19, 23 to 25	27	2	2	13	8	9	18	—	13	23
	19 to 22, ABS	22	4	9	17	10	14	18	—	13	15
	30 to 40	8	16	13	11	13	12	9	11	6	6
	41 to 43, L	21	24	25	28	24	22	23	—	24	21
	1 to 50	12	8	9	12	10	11	12	—	10	11
root mean square residual anomaly (mgals)	4 to 16, 50	27	15	14	16	15	15	19	—	17	24
	17 to 19, 23 to 25	40	21	16	28	17	17	34	—	22	37
	19 to 22, ABS	35	44	36	28	30	24	33	—	26	35
	30 to 40	9	18	17	10	13	11	11	10	9	14
	41 to 43, L	13	22	18	10	17	15	14	—	15	11
	1 to 50	25	25	22	15	20	15	21	—	15	23

ABS = Arbas, Benavente, Salamanca. L = Lochmaddy.

The 'indirect' or Bowie effect has been calculated using Lambert & Darling's (1936) tables which are based on Hayford's hypothesis. For other forms of isostatic reduction slightly different values would be found, but the difference is small and it has not been considered necessary to undertake this additional work. The results are given in the last column of table 8 but have not been included in the figures given for the isostatic anomalies, because the whole question of the method of calculating the indirect effect has recently been reopened by Meinesz (1942). He concludes that the Lambert & Darling (1936) tables require modification leading, in general, to rather larger values, but as yet there is no general agreement on this point. For the present, therefore, it seems wisest not to include the indirect effect with the anomalies.

4·23. *Sediment corrections*

A further correction has been applied at those stations (nos. 6 to 8 and 13 to 15) which lie on the line where Bullard & Gaskell (1941) measured the thickness of the sediment by the seismic method. There is little doubt that the density of the upper layers, where velocities in the region of 6000 to 12,000 ft./sec. were found, will be considerably less than 2·67, and it is desirable to make some allowance for this. The method employed was to estimate the thickness of the sediments and so prepare the chart (figure 6) showing the depth of the upper surface of the basement rock. Subsequent consideration of the isostatic anomalies at stations 26 to 28 indicated that there is probably no appreciable thickness of sediment here. This will not seriously affect the correction for sediments at stations 6 to 8 and 13 to 15. A density of 2·27 was assumed for the material above this level, and the correction to be applied to the attraction of the topography was then found. A similar correction to the attraction of the compensation was also computed. The results are given in table 10.

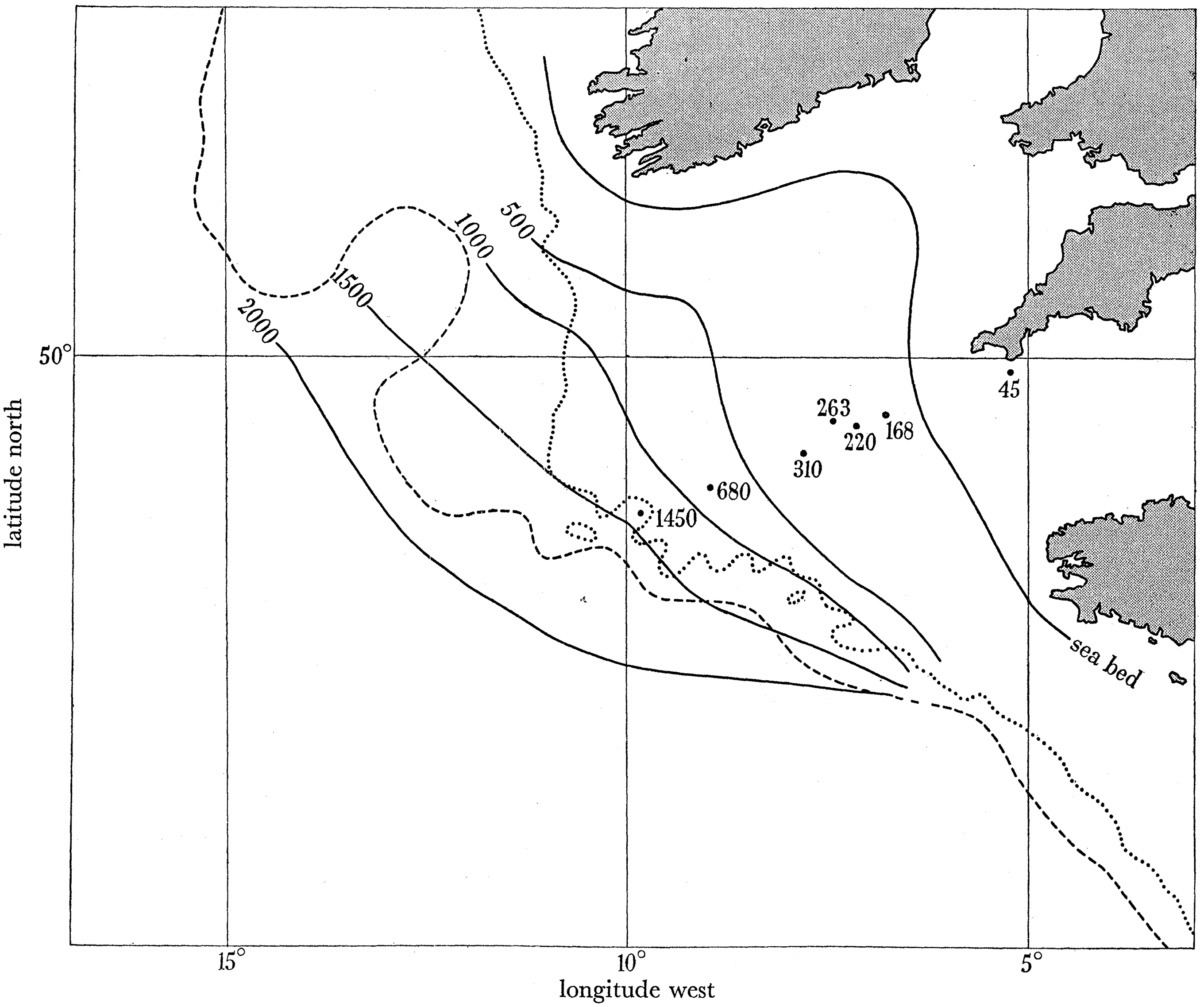

Figure 6. Assumed depth of basement rock at mouth of English Channel.

............100 fathoms }depth of sea
---------1000 fathoms }depth of sea
———— contours of surface of basement rock: fathoms below M.S.L.
• seismic observation.
310 depth of basement (fathoms)

Table 10. Corrections in milligals to be applied to the gravity anomalies assuming the density of the sediments forming the continental shelf to be 2·27 instead of 2·67

station no.	distance WSW from 100-fathom line (miles)	attraction of sediments (mgals)	corrections to the gravity anomalies, to allow for the attraction of sediments and compensation (mgals)									
			Bouguer	Hayford 113·7	$T=20$ $R=0$	$T=20$ $R=58$	$T=20$ $R=174$	$T=30$ $R=0$	$T=30$ $R=58$	$T=30$ $R=174$	$T=40$ $R=0$	$T=60$ $R=0$
15	− 63	+ 29	+ 9	+1	0	0	0	0	0	0	0	+ 1
6	− 31	+ 55	+18	+4	+ 1	+ 3	+ 7	+ 1	+ 4	+ 9	+ 3	+ 5
7	0	+131	+42	+8	+11	+14	+24	+16	+19	+26	+20	+25
8	+ 47	+ 41	+13	+2	− 3	− 3	− 3	− 3	− 2	− 1	− 2	+ 1
14	+ 79	+ 3	+ 1	−5	− 1	− 3	− 7	− 3	− 4	− 8	− 4	− 5
13	+109	+ 1	0	−2	0	− 1	− 4	− 1	− 2	− 4	− 2	− 2

4·24. *Calculated mass distributions*

The object of making isostatic reductions is to try to obtain information about the disposition of anomalous masses within the earth by comparing the calculated attraction of an assumed distribution with the observed results. It would clearly be more direct if the mass distribution could be calculated from the gravity anomalies, but, as is well known, this problem has no unique solution. If, however, the depth of the mass distribution is given, a solution becomes possible, but still not one which is unique, since it is always possible to find a mass distribution whose space variations are so rapid that its gravitational attraction at the surface will be everywhere less than the uncertainties in the observations.

A method of solution has been given by Tsuboi (1938) who carried out an harmonic analysis of the surface field in the U.S.A. and from this was able to infer the mass distribution at any given depth. More recently, new methods of arriving at the result have been published in two papers (Bullard & Cooper 1948; Kreisel 1949). These calculations have been made in two cases in the present work. The methods are most powerful when applied to a two-dimensional case, where it is assumed that the mass distribution does not vary in the direction normal to the vertical plane through the gravity profile. Our observations in the Atlantic and the Bay of Biscay have accordingly been treated in this way.

It is interesting to compare the results with the compensation assumed when making isostatic reductions. On Airy's hypothesis this can easily be done, given the difference in density between the crust and the substratum, because the shape which the lower surface of the crust would have is an inverted mirror image of the topography on an appropriate scale. However, if the mass distribution has been computed from the Bouguer anomalies by the Bullard or Kreisel method, the results are not directly comparable since the topography beyond 167 km. has been assumed compensated. For any given crustal thickness, however, the effect can be estimated and an allowance made for it.

4·3. Discussion of gravity anomalies

4·31. *General distribution*

Chart 4, which shows the regional isostatic anomalies for $T=30$, $R=58$ km., gives the best general idea of the distribution of anomalies. It will be seen at once that most of the values are positive. Nearly all the negative anomalies occur near the edge of the continental shelf or in the central part of the English Channel. Their significance will be discussed in the later sections of this paper, but first we shall consider the mean positive anomaly of the whole area.

The mean free-air anomaly for all our stations is +8 mgals. The mean isostatic anomalies, given in table 9, differ slightly according to the different hypotheses used. As the stations are not distributed uniformly throughout the area, these figures do not give an accurate estimate of the mean anomaly. Land observations in the British Isles show that in Devon and Cornwall, Wales and western Scotland positive values are also found, but, as no measurements have yet been made in Ireland, the data are still too meagre to judge whether or not these represent the eastern margin of a widespread field of positive anomalies stretching out into the Atlantic. Jeffreys (1941, 1943*a*) has written two papers on the analysis of the gravitational field of the whole earth including harmonics up to the order three, and finds that the departure from the international gravity formula at a position 50° N, 10° W is +18 mgals. The observational data, on which this result is based, show clearly that the areas covered by these fields of positive anomalies are often large, extending over several adjacent 10° squares. Meinesz has also emphasized this point, and both authors have put forward theories to account for them.

Jeffreys (1943*b*) has discussed the strength required to support such an additional load on the assumption that the earth has a fluid core surrounded by a crust capable of plastic flow once a certain stress difference has been reached. Assuming that the radius of the fluid core is 0·545 of the radius of the earth, he finds that a strength of some 150×10^6 dynes/cm.^{2} is required at the earth's surface, falling to about half this value at the bottom of the crust. If it is assumed that the earth is fluid out to 0·9 of its radius, a strength of about 330×10^6 dynes/cm.^{2} is necessary in the crust. Such values are by no means excessive compared with values of the order of 10^9 dynes/cm.^{2} required in the upper layers to explain the support of mountain ranges of the size of the Himalaya. Experiments show that under laboratory conditions the crushing strength of basalt is $1{\cdot}5\times10^9$ dynes/cm.^{2} Jeffreys also considers that the occurrence of earthquakes with foci as deep as 600 to 700 km. indicates that considerable strength must exist at such depths. On the other hand, it seems difficult to reconcile these results with the observed fact that areas where sediment has accumulated, such as the edge of the continental shelf, appear to be in isostatic equilibrium. The uplift in Fennoscandia as a result of the recession of the ice cap also indicates that in such areas readjustment can take place comparatively quickly. It is also doubtful whether the required strength could be maintained at the high temperatures found at great depths. Certainly, in parts of the earth where volcanoes are active, it is evident that under suitable conditions plastic flow can occur near the surface.

Meinesz's convection-current theory (1934) goes a long way towards overcoming these difficulties. He supposes that owing to differential heating, density differences are set up in the semi-fluid substratum which in turn lead to convection currents. Downward movement will occur in the denser parts and will give rise to positive gravity anomalies and a tendency for the surface to sink over these regions. In the later development of the theory, Meinesz (1947) assumes that the substratum is not perfectly fluid but has a small limiting strength of the order of 5×10^7 dynes/cm.^{2} With this assumption a reasonable explanation of the time scale of the various geological orogeneses has been given. The theory is attractive, as it goes some considerable way towards explaining the relation between gravity anomalies and vertical earth movements. It is also possible to give a qualitative explanation of the evolution of a geosyncline and the distribution of deep-focus earthquakes (Meinesz 1946). However, the evidence for convection currents is still indirect and further work is needed. Theoretically, the horizontal extent of each convecting 'cell' is of the same order of magnitude as its depth. It seems well established that in certain parts of the earth, especially near Japan, the travel-time curves for earthquakes show a definite discontinuity near 20°, which implies a change of density within the earth at a depth of about 400 km. In such regions it is probable that convection currents with linear dimensions of this order would be most easily generated. Adjacent cells might coalesce to form an extension in one horizontal direction, but it is unlikely that areas of positive anomalies of more than a few square degrees could be accounted for without assuming convection down to depths below the density discontinuity. Whether or not such currents are possible depends on the nature of the discontinuity. If, as Bernal has suggested, the density change arises from a rearrangement of the crystal structure, it is possible that such convection could take place, but the liberation and absorption of heat during this process would disturb the temperature distribution and so change the form of the convection. At present, therefore, there is no theory which accounts satisfactorily for the observed facts. The widespread fields of positive anomalies indicate excess mass, but whether this is supported by the static strength of the crust or by a dynamical process, such as convection currents, is still an open question. The latter hypothesis appears to be the more attractive, since the assumption of a semi-plastic substratum provides a simple explanation of the fact that the sediments which form the outer margin of the continental shelf are very nearly in isostatic equilibrium. The evidence for this will be considered in the next section.

4·32. *Atlantic section* (*stations* 4 *to* 16 and 50)

This profile comprises stations nos. 4 to 16 and 50 and extends a distance of some 500 miles west-south-west from the Lizard. The results are shown diagrammatically in figure 7. Profile *a* gives the free air, Bouguer and Hayford anomalies. It is clear from these that the large positive Bouguer anomalies over the oceanic part can be mainly accounted for by assuming that the area is in isostatic equilibrium. The Hayford anomalies are generally positive, the effect being larger towards the west. Superposed on this are several fluctuations, the most pronounced of which is the dip near the edge of the continental shelf due largely to the negative anomaly at station no. 6. This tendency for the isostatic anomalies to increase algebraically on crossing the edge of the shelf from shallower to deeper water has already been found by Meinesz (1934) and appears to be a common feature of the gravitational field in such regions. It is natural to inquire how far the presence of the low-velocity layers found by Bullard's seismic experiment can account for this. The method of allowing for the lower density of these layers has already been described in § 4·23. Figure 8 shows diagrammatically the effect of applying these corrections and also of assuming that the sediments are not compensated. The full curve shows the Hayford anomalies as in figure 7*a* but on a larger scale. The dashed line indicates the corrected curve after assuming that the density of the low-velocity layers is 2·27 and that they are fully compensated. The curve is slightly flatter, but the difference is not great. In contrast, the dotted curve shows the anomalies on the assumption that the low-density layers are uncompensated. They therefore appear as a load on the crust, and the calculated value of gravity is increased by nearly 100 mgals locally. Since no such anomalies are observed the region must be very nearly in isostatic equilibrium. This agrees well with the known facts concerning the Fennoscandian uplift. Niskanen (1939, 1943) and Meinesz (1937) have reviewed the available data, and the latter concludes that for a linear structure such as the continental shelf, τ, the time taken to return half-way to the equilibrium position, and l, the linear dimensions perpendicular to the axis, are connected by the relation $l\tau = 15\times10^6$ km. years. Taking $l=100$ km., this gives $\tau = 1{\cdot}5\times10^5$ years. There is still much uncertainty as to the age of the sediments forming the continental shelf, but the main bulk of them must certainly be much more than 10^5 years old. They should therefore have had ample time to attain isostatic equilibrium.

The anomalies calculated on Airy's hypothesis for $T=20$, 40 and 60 km. are shown in figure 7*b*. From inspection of the curves $T=20$ km. appears least satisfactory while, apart from the drop at station no. 6, $T=40$ and 60 km. show reasonably small fluctuations. The values of the r.m.s. residuals given in table 9 appear to show that $T=20$ and 30 km. give the best fit, $T=60$ km. having a considerably greater residual. This is due to the tendency for

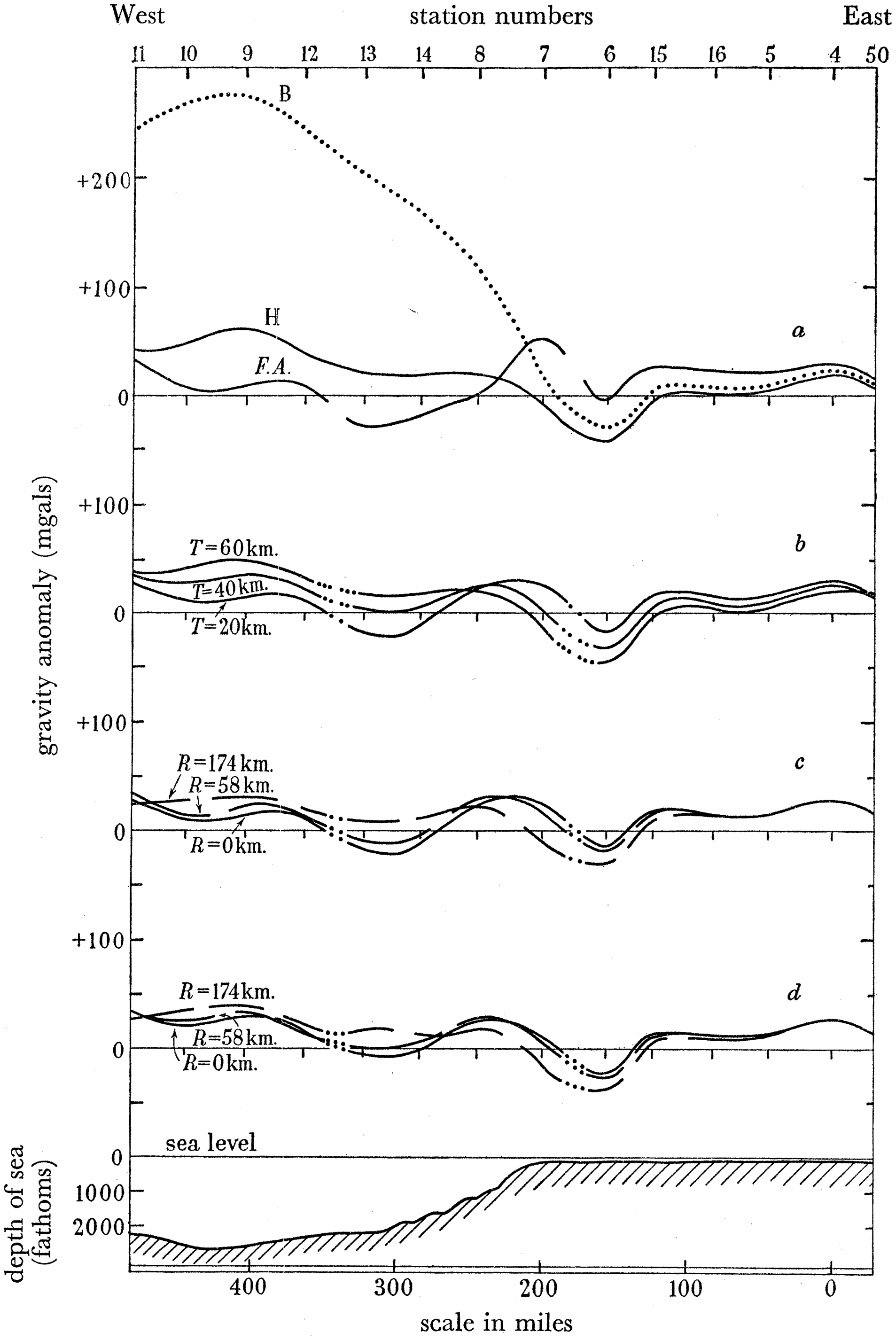

FIGURE 7. Gravity anomaly profile, Atlantic section. *a*, B, Bouguer; H, Hayford; *F.A.*, free air. *b*, Heiskanen. *c*, regional $T=20$ km. *d*, regional $T=30$ km.

the anomalies to become increasingly positive over the ocean and to the large negative value at station no. 6 biasing the result in favour of small values of T.

In the case of the regional anomalies shown in figure 7*c* for $T=20$ km. and in figure 7*d* for $T=30$ km., a somewhat similar result is obtained. Table 9 shows that $T=20$, $R=58$ km. gives the smallest residual, in good agreement with Meinesz (1941*c*). Nevertheless, inspection of the curves leads one to believe that a smoother transition is obtained with a arger radius of regionality. Here, again, the negative anomaly at station no. 6 is biasing he results

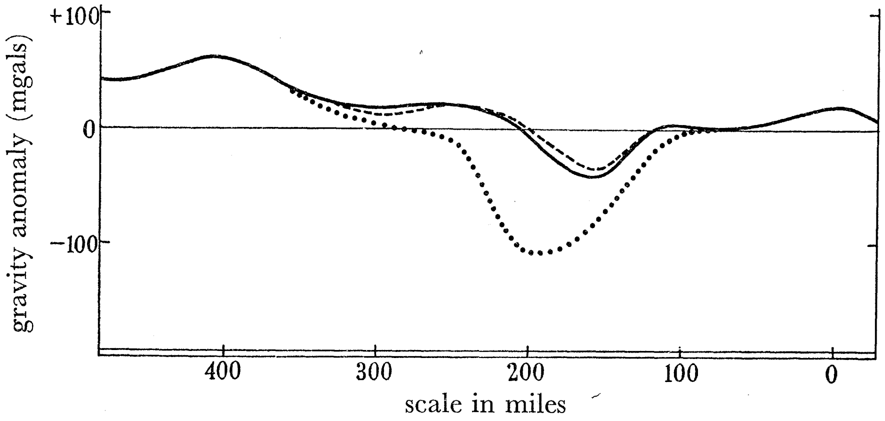

FIGURE 8. Gravity anomaly profile, Atlantic section. Effect of density deficiency and compensation of sediments.

——— Hayford anomalies.
………… corrected for density deficiency of sediments (uncompensated).
--------- corrected for density deficiency of sediments (compensated).

We must therefore consider whether or not the result at this station ought to be included when trying to determine which form of isostatic reduction to adopt. It is most unlikely that such a large anomaly should be due to random errors, because the value at station no. 6 is 35 mgals, or nearly ten times the probable error, below the mean of the stations on either side. The possibility of an error of observation cannot be overlooked, as it is by no means easy to avoid mistakes. On the other hand, Meinesz has made several observations in this area and finds similar negative anomalies further to the east-south-east. There is thus some corroboration from other measurements, and we are therefore inclined to accept the result as reliable and assume that there is a large local mass deficit in this region.

Perhaps the simplest assumption is that there is a greater thickness of low-density sediment here than had previously been thought likely. Such a feature would have to be of small extent in the direction at right angles to the edge of the continental shelf if its presence were not to have an effect on the stations on either side, which are only 90 miles apart. A thickness of some 7000 ft. of sediment of density 0·4 less than that of the underlying basement rock would account for the observed anomaly. This is not inconsistent with the results of Bullard & Gaskell's (1941) seismic experiments, for their nearest observation, some 25 miles west of the gravity station, showed that the thickness of the low-velocity layers exceeded 3570 ft., while 32 miles farther west the basement rock was found at a depth of 8110 ft. If it is assumed that somewhere between our stations nos. 6 and 15 the depth of sediment increases rapidly to about 8000 ft. we can explain the gravity observations without any contradiction of the seismic evidence. The exact thickness depends on whether or not it is compensated. As the rest of the shelf area is nearly in isostatic equilibrium, we conclude that this additional thickness is also compensated. For a large radius of regionality the effect on the calculated thickness is not large, but if small values of T or R are assumed it will be necessary to increase the estimated depth accordingly.

On the other hand, Meinesz has already suggested that the anomaly may be produced by a local thickening of the earth's crust, possibly due to the remnants of the root of a former chain of Armorican mountains. If further seismic experiment does not confirm the presence of a large thickness of low-velocity material, we should have to adopt this theory, but until then we prefer the earlier assumption because it will explain the observed effects without supposing a local departure from isostatic equilibrium.

Returning now to the question of what form of isostatic compensation agrees best with the gravity observations, we shall assume that the depth of sediment has been so chosen that the anomaly at station no. 6 has been reduced to the mean of those at the stations on either side. The effect of this on the r.m.s. residuals is shown in the top row of figures in table 11. The lower row shows the result of also applying the correction found on the assumption that the sediments have a density of 2·27 and are fully compensated. Comparing these with one another, the uncorrected residuals show a minimum r.m.s. value of 10 mgals for $T=30$, $R=58$ km. with a standard deviation of $\pm 1{\cdot}2$. For the same crustal thickness and radius of regionality, the r.m.s. residual and the standard deviation remain the same after the sediment correction has been applied, but we now find that the minimum occurs for $T=20$, $R=174$ km. giving an r.m.s. residual of $7{\cdot}5 \pm 1{\cdot}5$ mgals. The probability that two samples of fourteen observations will have r.m.s. residuals differing by 1·7 times their standard deviation is 0·12, and hence the difference cannot be regarded as significant. It follows that, although the evidence points towards a lower density for the sediments and a thinner crust, neither can be regarded as definitely proved by the results at present available. However, sediment is known to be present from the seismic experiments, and the value $T=20$, $R=174$ km. agree better with the ratio of R/T derived from results of gravity surveys in other areas. One is, therefore, strongly inclined to believe that the sediment has in fact a lower density, and that the crustal thickness is small. The reason why these results cannot be conclusively proved at present is because the structure of the continental shelf in this region is complicated by the presence of the local mass deficiency, indicated by the negative anomaly at station no. 6, and the seismic and gravitational observations are not sufficiently detailed.

TABLE 11. ROOT MEAN SQUARE RESIDUAL ISOSTATIC ANOMALIES FOR STATIONS ON ATLANTIC PROFILE (NOS. 4 TO 16 AND 50) AFTER ALLOWING FOR A LOCAL MASS DEFICIENCY BELOW STATION NO. 6 BY ASSUMING THE ANOMALY THERE EQUAL TO THE MEAN OF THE ANOMALIES AT THE ADJACENT STATIONS NOS. 7 AND 15

assumed density of sediments	root mean square residual anomalies (mgals)								
	Hayford 113·7	$T=20$ $R=0$	$T=20$ $R=58$	$T=20$ $R=174$	$T=30$ $R=0$	$T=30$ $R=58$	$T=30$ $R=174$	$T=40$ $R=0$	$T=60$ $R=0$
2·67	20	14	12	12	11	10 (±1·2)	13	11	17
2·27	19	15	12	7·5 (±1·5)	11	10 (±1·2)	10	11	17

As mentioned above (§ 4·24) the Bullard-Kreisel two-dimensional method has been used to calculate the mass distribution at various depths necessary to produce the observed gravity field along the profile. In making the calculation the Bouguer anomalies have been used. A correction for the lower density of the sediments has been applied, and the anomaly at station no. 6 has been increased by 50 mgals to allow for the local mass deficiency. The actual values used, together with the calculated mass distributions at

Table 12. Atlantic-calculated mass distributions

distance (miles)	mod. Boug.	calculated mass distributions			
		18 km.	36 km.	54 km.	72 km.
0	220	—	—	—	—
	180	150	—	—	—
	151	111	67	—	—
	126	76	26	−12	—
	104	41	−27	−109	−232
50	88	16	−66	−165	−303
	81	3	−82	−182	−337
	79	0	−87	−184	−276
	81	−2	−92	−191	−293
	90	4	−91	−195	−306
100	110	22	−79	−192	−324
	140	50	−55	−170	−289
	179	88	−18	−144	−267
	232	141	34	−121	−302
	299	204	93	−72	−281
150	379	280	165	19	−164
	473	376	263	147	14
	573	493	394	292	168
	688	623	547	459	346
	816	768	711	651	582
200	949	918	885	852	839
	1080	1065	1048	1033	1025
	1213	1209	1210	1207	1182
	1348	1365	1383	1403	1413
	1479	1509	1551	1609	1694
250	1602	1643	1704	1788	1904
	1708	1761	1831	1935	2093
	1803	1857	1929	2028	2182
	1885	1934	1992	2066	2168
	1962	1999	2039	2076	2096
300	2033	2063	2093	2103	2044
	2107	2134	2160	2199	2199
	2180	2204	2221	2234	2257
	2243	2271	2280	2259	2183
	2329	2356	2369	2339	2200
350	2421	2474	2513	2528	2491
	2531	2605	2686	2779	2908
	2632	2722	2840	2994	3223
	2702	2811	2952	3134	3358
	2740	2863	3025	3232	3477
400	2748	2884	3060	3292	3596
	2731	2862	3035	3280	3608
	2690	2795	2938	3187	—
	2630	2690	2765	—	—
	2550	2570	—	—	—
450	2450	—	—	—	—

Units are 0·0001 cm./sec.^{2}. To convert to gm./cm.^{2}, multiply by 238. Distances are measured along line of stations west-south-west of Lizard Head.

depths of 18, 36, 54 and 72 km., are given in table 12. Figure 9 shows a comparison of the calculated shape of the lower surface of the crust with that required on Airy's hypothesis. Here the corrected Bouguer anomalies, the topography and the lower surface of the crust, assuming local compensation and a thickness of 40 km., are plotted. The shape of the lower surface of the crust necessary to produce the field of Bouguer anomalies has been calculated by multiplying the figures given in table 12 for a depth of 36 km. by the factor

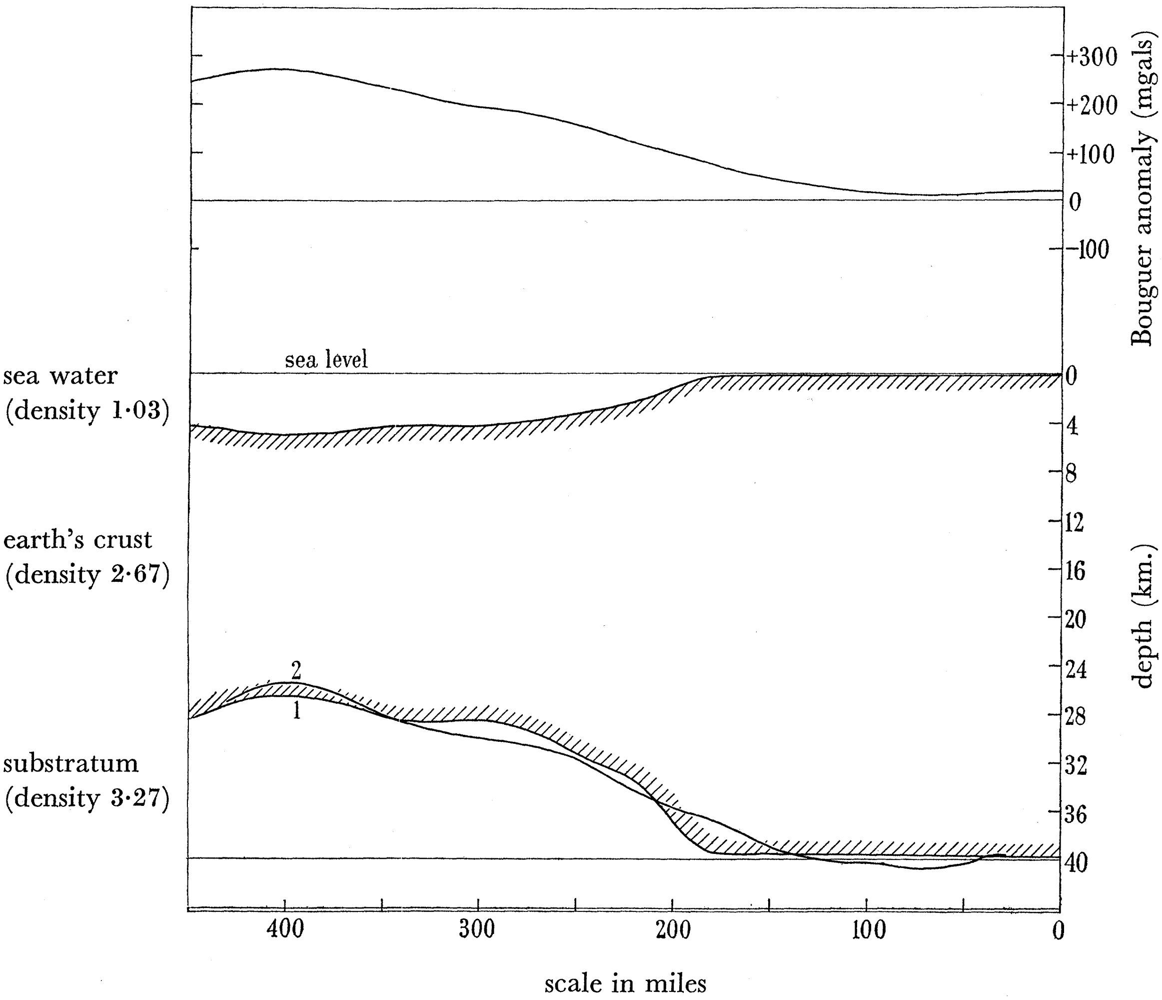

FIGURE 9. Calculated mass distribution, Atlantic section. Lower surface of crust 1, on Airy's hypothesis; 2, calculated.

1·18 to allow for the fact that the topography has been assumed compensated outside zone O. These figures represent the mass-distribution condensed on a plane at this depth and it can be seen that the centre of gravity of the compensation for the Airy hypothesis with $T = 40$ km. is not far from 36 km. In both cases the density of the crust has been taken as 2·67 and that of the substratum as 3·27. We see that the calculated thickness of the crust is less below the shallow water and greater below the sloping edge of the shelf than would be found if the compensation were local. A thinner crust is also found at the western end of the section, as would be expected in view of the positive isostatic anomaly found here.

These results strongly suggest that the compensation of the sediments has a regional character, though part of the effect is probably due to the gravity section not being exactly at right angles to the edge of the shelf.

It is also of interest that, in spite of the Bouguer anomalies being everywhere positive, there is a region at the eastern end of the section which is overcompensated. That is to say, if the crust were free to move vertically it would tend to rise. This is because the local anomaly is produced by the excess mass below neighbouring regions and not by material directly below the station. The calculated mass distribution here reveals something which isostatic reductions are unable to demonstrate. It is evident that when considering the equilibrium of any particular area, full account must be taken of the effect of the mass distribution in the surrounding regions.

4·33. *Bay of Biscay* (*stations* 17 *to* 25)

This section consists of nine stations (nos. 17 to 25) which lie on a line running south from a point some 30 miles west of Ushant to Gijon on the north coast of Spain. In conjunction with these, observations made on land at Arbas, Benavente and Salamanca will also be considered so as to continue the gravity profile south across the Cantabrian mountains. The values of g at these land stations have been taken from Ackerl (1932) corrected to the Potsdam standard. Isostatic anomalies have been computed and the results will be found in table 14. Profiles showing the free-air, Bouguer and various isostatic anomalies are shown in figure 10. The values at station no. 4 have been included at the extreme left of these diagrams in order to secure one station in common with the profiles of figure 7. The free-air anomalies show considerable fluctuations over the Bay of Biscay. Both to the north and south, positive values are found near the 100-fathom line with negative values over the adjacent deep water. In the centre, a small positive anomaly occurs at station no. 19. The fluctuations over the southern part are greater than over the shelf area to the north. Evidently much of the variation is the direct result of topography. The Bouguer anomalies, however, show large positive values in the centre of the Bay and become negative over Spain. This correlation with topography indicates that isostatic compensation is playing a part, and this is well borne out by the Hayford anomalies which, except for the rather large positive value at station no. 19, are in general much smaller than either the free-air or Bouguer anomalies.

The mean and r.m.s. residual anomalies for the northern and southern parts of the section have been treated separately in table 9. Over the shelf area to the north (stations 17 to 19 and 23 to 25) $T=20$, $R=58$ km. shows the smallest residual, but it must be remembered that no allowance has been made for the density deficiency of the sediments which are almost certainly present. If this had been done, a larger value of R would have given better agreement. Over the southern part (stations 19 to 22 and Arbas, Benavente and Salamanca) $T=30$, $R=58$ km. is best, but even this assumption shows a large residual indicating considerable local departures from isostatic equilibrium. This is clearly a case where the finite difference method of calculating the mass distribution can profitably be applied. The solutions for depths of 18, 36 and 54 km., calculated from the observed Bouguer anomalies, are given in table 13. We see at once that the anomalous masses cannot be very deep; the results for 54 km. already show large density fluctuations. This implies that if the gravity anomalies are to be accounted for by variations in thickness of the crust, the crust itself cannot be more than some 40 km. thick. The results for 36 km. are shown diagrammatically in figure 11, in which are also plotted the Bouguer anomalies, the height of the

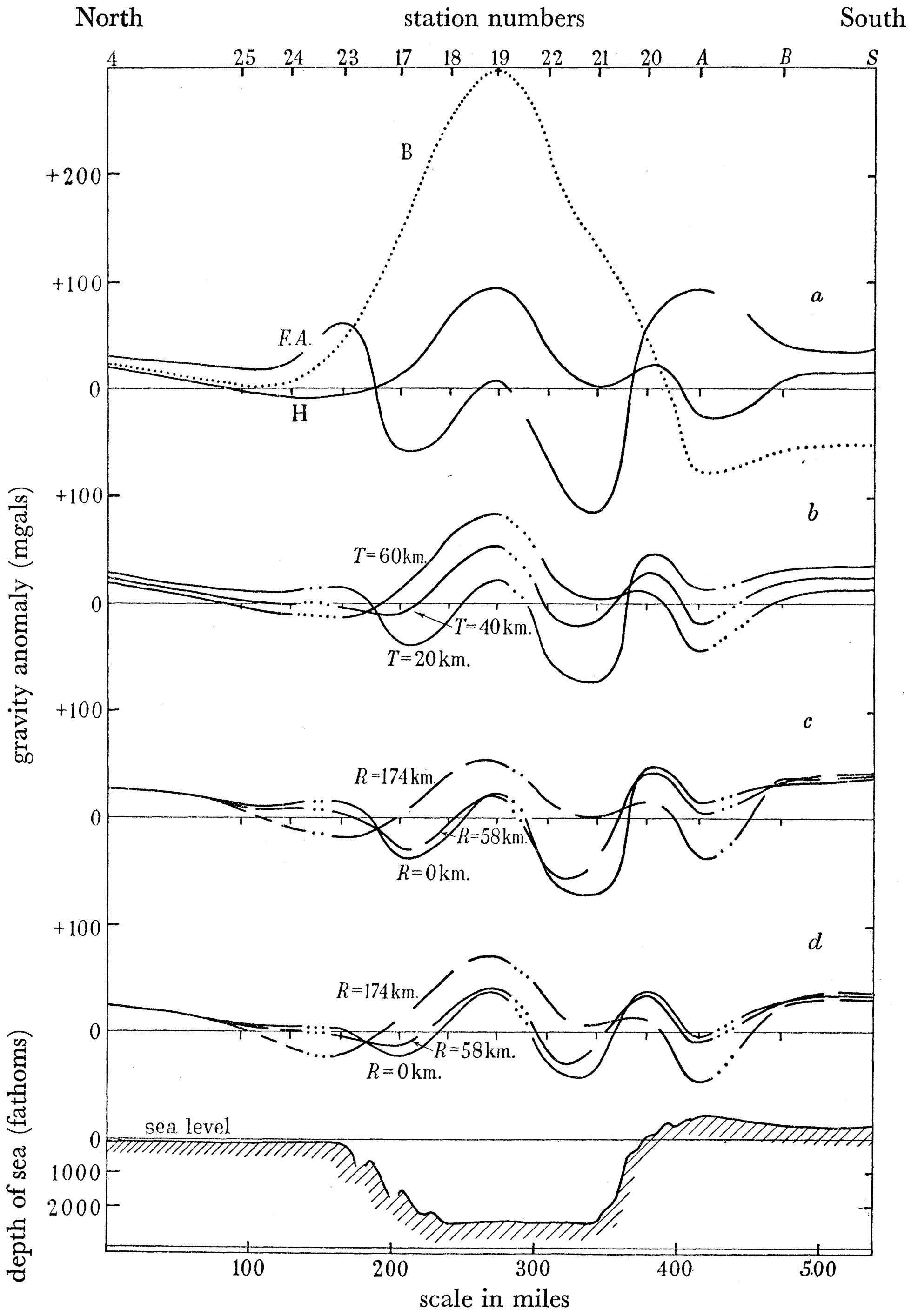

FIGURE 10. Gravity anomaly profile, Bay of Biscay section. *a*, B, Bouguer; *F.A.*, free air; H, Hayford. *b*, Heiskanen. *c*, regional $T = 20$ km. *d*, regional $T = 30$ km.

A = Arbas; *B* = Benavente; *S* = Salamanca.

topography and the shape of the under-surface of the crust according to Airy's hypothesis. The latter differs considerably from the shape necessary to account for the calculated mass distribution.

To explain the anomalies over the edge of the shelf at the northern end of the section, one is naturally influenced by the conclusions already reached in the previous section of this paper. The trend of the anomalies is very similar, and it is highly probable that the explanation in both cases is the same. A wedge-shaped deposit of sediments, reaching a maximum thickness of 4000 to 8000 ft., would account for the observed results provided either that

TABLE 13. BISCAY-CALCULATED MASS DISTRIBUTIONS

lat. °N	mod. Boug.	calculated mass distributions at depths 18 km.	36 km.	54 km.
41	−540	—	—	—
	−530	—	—	—
	−507	−552	—	—
	−488	−509	−496	—
	−487	−500	−468	−365
	−518	−536	−511	−405
42	−578	−620	−635	−589
	−661	−741	−820	−887
	−740	−862	−1017	−1264
	−794	−949	−1122	−1583
	−814	−997	−1189	−1314
	−814	−1053	−1323	−1495
43	−811	−1106	−1555	−2237
	−722	−1039	−1554	−2554
	−462	−707	−1068	−1788
	−38	−105	−223	−244
	367	394	505	1951
	662	779	898	1225
44	885	990	1083	1171
	1130	1206	1273	1284
	1401	1477	1519	1525
	1669	1760	1801	1775
	1942	2069	2150	2073
	2245	2456	2657	2734
45	2580	2897	3288	3791
	2849	3257	3807	4647
	2978	3422	4036	4949
	2968	3400	3966	4677
	2875	3262	3751	4324
	2707	3040	3452	3963
46	2462	2730	3054	3467
	2162	2351	2567	2810
	1840	1947	2053	1727
	1518	1559	1571	1539
	1214	1196	1133	1016
	938	871	749	547
47	703	604	445	172
	509	406	255	65
	352	246	104	−31
	222	111	−54	−173
	124	8	−172	−512
	65	−31	−130	—
48	42	−67	—	—
	40	—	—	—
	40	—	—	—

Units are 0·0001 cm./sec.^{2}. To convert to gm./cm.^{2}, multiply by 238.

a thick crust or regional compensation with $R > 100$ km. is assumed. Here again there is no evidence that the sediments are not in isostatic equilibrium.

Farther south even larger anomalies are found. The calculated mass distribution (figure 11) shows that these irregularities arise mainly from the mass excess below the central part of the Bay of Biscay and a mass deficit off the north coast of Spain. The crust below the Cantabrian mountains seems rather thicker than is required for isostatic compensation. It is hardly likely that these anomalies could be produced by local density variations near the surface. The regional isostatic anomalies for $T = 30$, $R = 58$ amount to $+41$ mgals at station no. 19 and about -25 mgals between stations nos. 20 and 21. If we assume that the density of the rocks beneath the former is 3·0 and below the latter 2·3, we should require thicknesses of 10,000 and 7000 ft. to explain the anomalies. The idea that a tongue of rock as dense as basalt and nearly 2 miles thick should be found beneath the

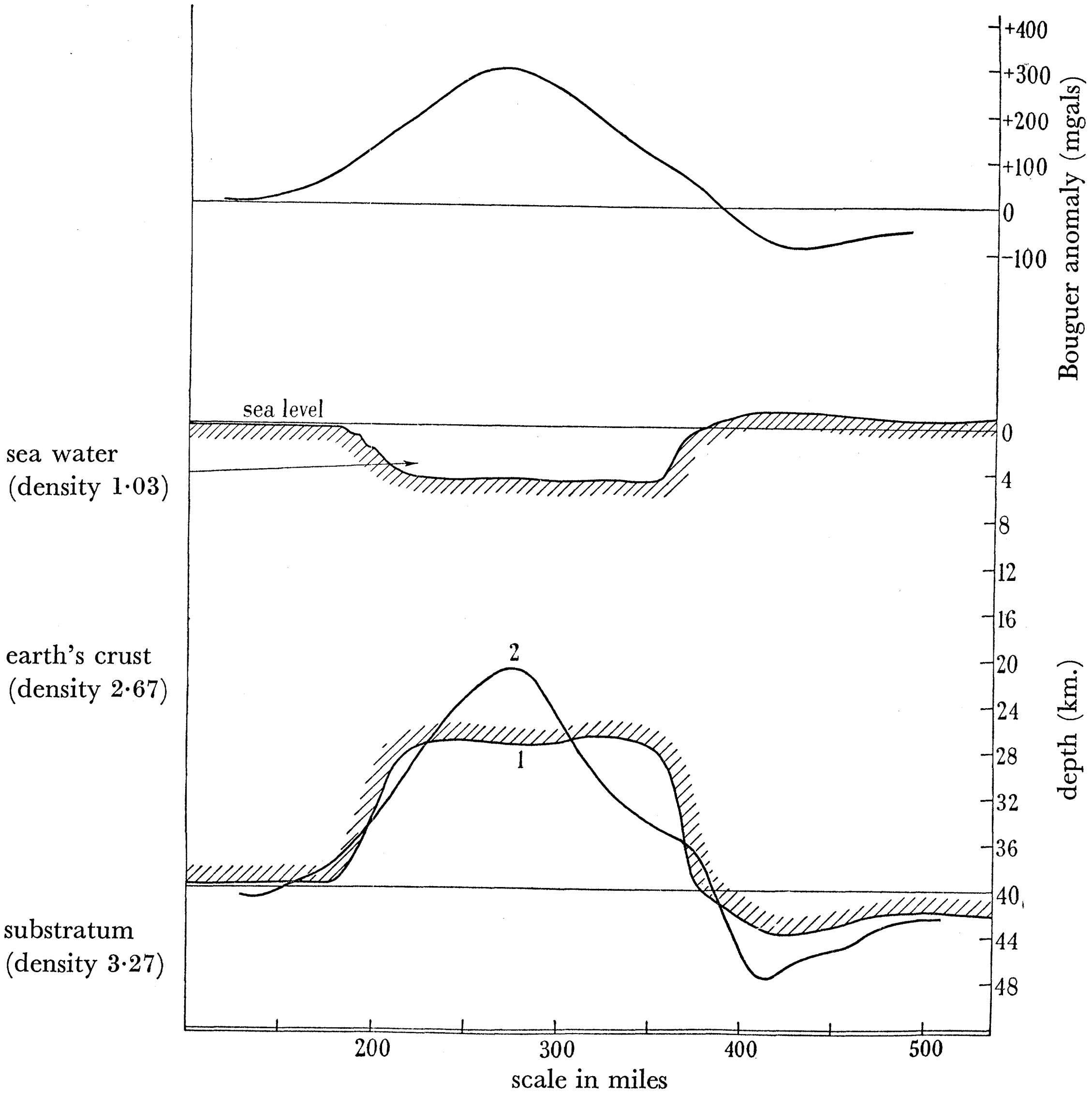

FIGURE 11. Calculated mass distribution, Bay of Biscay section. Lower surface of crust 1, on Airy's hypothesis; 2, calculated.

centre of the Bay is most improbable. The possibility of a trough of sediment off the north coast of Spain has already been suggested in § 4·1 above to explain why the bottom here is so extraordinarily level. Possibly such a trough might be as much as 7000 ft. deep. We shall see later in § 4·41 that a similar suggestion is put forward as a possible way of accounting for the large scatter of the isostatic anomalies found over the deep water farther west.

The above depth estimates have been made on the assumption that the anomalous masses are uncompensated. If they are compensated, even greater density differences or depths must be assumed. Nevertheless, the horizontal extent of the anomalies is small enough to make it possible to account for the observed fluctuations in the gravity field without abandoning the idea of local or regional compensation. The region as a whole shows a positive isostatic anomaly just as is found farther to the north and west, but since the sediments forming the continental shelf appear to be nearly compensated, there are good grounds for believing that other topographic features should also tend towards a similar equilibrium. However, such general considerations are of little help in deciding the particular distribution of mass, and we must therefore see what information can be obtained from the geological structure of northern Spain.

Unfortunately, no extensive survey has been made in this region. It is generally accepted that the Cantabrian mountains were formed as the result of the same series of earth movements which formed the Pyrenees at about the time of the lower Oligocene (Rupelian). Simultaneously the Betic cordillera was being raised by compression in southern Spain. The intervening Meseta is crossed by a number of small folds and thrusts with a tendency towards a preferential east-west direction. It is therefore reasonable to suppose that the forces which caused the formation of the Alps may also have been in part responsible for the formation of the Cantabrian mountains. The geological evidence therefore points to the conclusion that compressional forces have caused the earth's crust in this region to buckle into a series of parallel east-west folds.

Such a structure would provide a reasonable basis for interpreting the gravity anomalies. The crust below the northern coastal regions may be abnormally thick, and the buckling process may also have produced an accumulation of light material below the southern part of the Bay of Biscay. Both these features are clearly shown in figure 11. The excess of mass below the central part of the Bay is not so easy to explain. It must be noticed, however, that compared with other observations farther west in the Atlantic, the anomaly here is not unduly large. The exact value is strongly influenced by the particular type of isostatic compensation assumed because there is a rather sudden change in the mean heights at about zone O, which contains the 100-fathom line to the north and the Cantabrian mountains in the south.

4·34. *Latitude* 50° *N* (*stations* 26 *to* 28)

This line of three stations is not long enough to give a clear indication of the gravitational field over the edge of the continental shelf at latitude 50° N. Certain restrictions prevented the submarine from diving east of longitude 10° W, and a failure of the clockwork mechanism in the recorder of the Vening Meinesz apparatus spoilt the record at station no. 29, at a position of approximately 50° N, $13\frac{1}{2}$° W. Examination of the soundings along the line shows that the slope of the edge of the continental shelf (see figure 4*d*) is here much less steep than farther to the south-east. This might be due to the absence of any great thickness of sediment, and it was hoped that gravity measurements would be able to give information on this point. The results given in table 8 show that no striking isostatic anomalies are found. There is a tendency towards positive values, but this is probably due to the general positive field found farther south and not to any special feature of this particular part of the continental shelf. The mean values of the isostatic anomalies for stations nos. 4 to 16 and 50 given in table 9 show that a value of about +15 mgals is to be expected. If we accept this, then the anomalies found for $T=20$, $R=58$ km. are remarkably uniform and only slightly greater than the expected mean value. Even this small difference is almost entirely explained by the indirect effect. Other types of isostatic assumption change the mean value considerably and the relative values to a smaller extent, but none of them shows any marked tendency for the anomalies to increase over the deeper water. This confirms the view that no great thickness of sediment is present but without further evidence it is not possible to be certain of this point. On the other hand, the free-air and Bouguer anomalies show much larger fluctuations than the isostatic anomalies, and it is clear that, apart from the general mass excess which extends over a wide region, the local variations can be accurately accounted for on the assumptions of isostasy. A thin crust ($T=20$ or 30 km.) and a moderate radius of regionality ($R=58$ km.) give the best agreement.

4·35. *Porcupine and Rockall Banks* (*stations* 30 *to* 40)

Unfortunately, there are only two observations over the Porcupine Bank, the photographic recording mechanism having failed at station no. 31. Over the Rockall Bank, however, stations nos. 34 to 40 give a fair representation of the gravitational field. Reference to table 8 and charts 2 and 3 show that both the free-air and Bouguer anomalies are strongly correlated with topography. The latter are all highly positive, the maximum values being found over the deepest water. As might be expected, the regional isostatic anomalies for $T=30$, $R=58$ km. (chart 4) show smaller fluctuations though the influence of the topography is still clearly present. Table 9 indicates that the smallest r.m.s. residuals are found for the Hayford system and for Airy's hypothesis, assuming a crustal thickness of 60 km. However, Heiskanen $T=40$ km. and regional $T=20$, $R=174$ km. and $T=30$, $R=174$ km. are not significantly worse. This tendency towards a rather large radius of regionality made it worth while to investigate the results for $T=30$, $R=232$ km., and these anomalies were therefore also calculated for this particular section. Examination of the profiles in figure 12 shows that there is a general tendency for the anomalies to increase towards the east. This will be further discussed in the next section, but it should be noticed that, if we assume a regional trend, the curves for $T=20$, $R=174$ km. and $T=30$, $R=232$ km. are certainly as smooth as the curve for Heiskanen $T=60$ km. and distinctly smoother than the curve for Heiskanen $T=40$.* The mean anomalies are all positive, but there is a strong tendency for the mean values to be less for those hypotheses which give the smallest residuals. The only definite conclusion we can draw is that the gravitational evidence indicates an excess of mass in this region with a general trend towards larger values in the east.

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* We are dealing here with a region in which the topography is only gently undulating and it is not surprising that there should be little to choose between the various hypotheses.

Geological evidence suggests that Rockall Bank is a tertiary basalt plateau, originally erupted subaerially and later submerged. This conclusion is based mainly on the dredgings of the Irish Academy expedition of 1896 (Green 1896, pp. 58 to 64) and the analysis by Lacroix (1923) of the specimens taken in this and in Charcot's subsequent expedition in the *Pourquoi Pas*. Geikie (1896) considers that the Porcupine and Rockall Banks form part of the Thulean Tertiary igneous province comprising Iceland, the Hebrides and Northern Ireland. The uniformity of the composition of these tertiary basalts (Washington 1922, p. 789) suggests a common origin, but it also makes it impossible to say where a particular flow

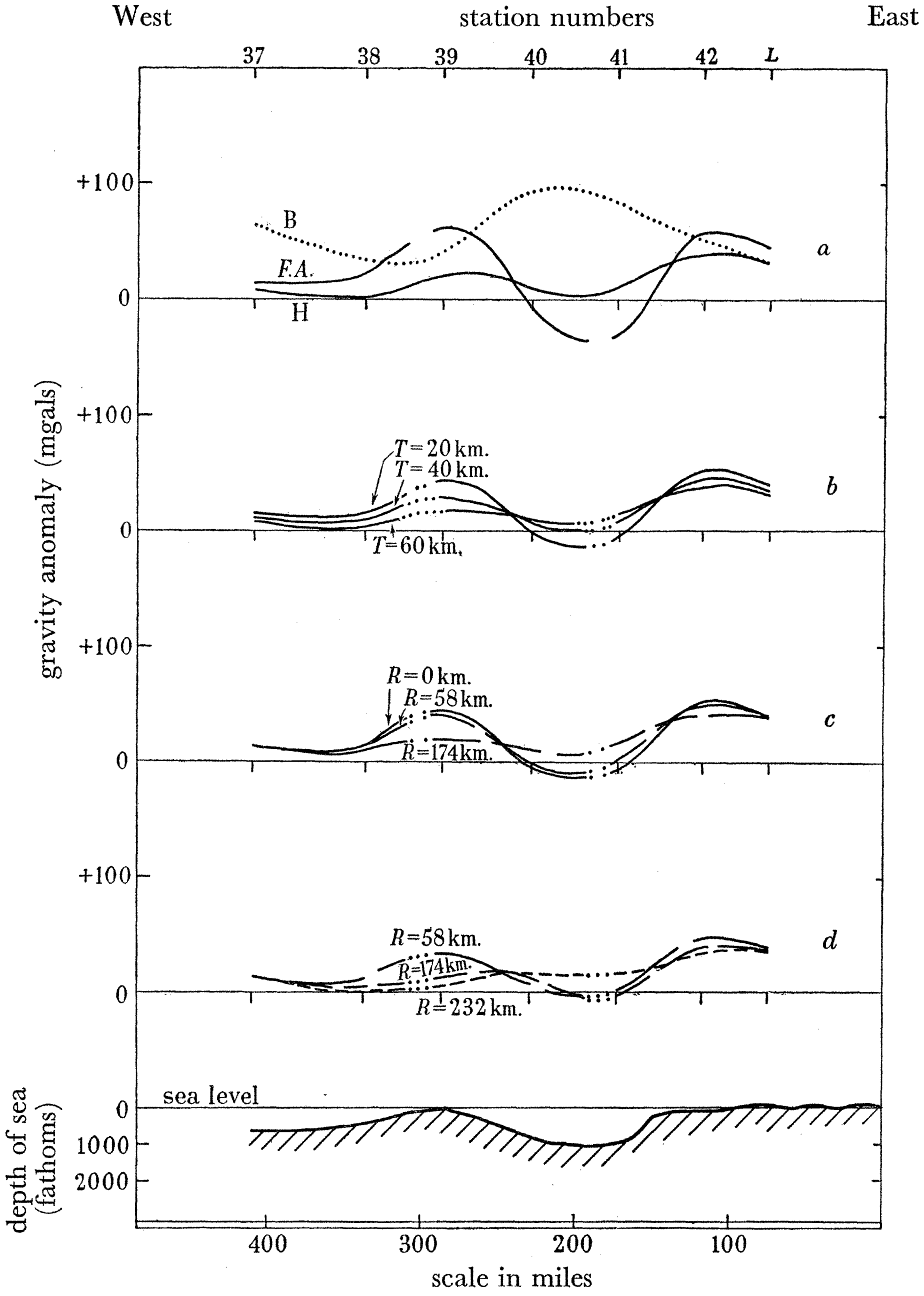

FIGURE 12. Gravity anomaly profile, Rockall-Hebrides section. *a*, B, Bouguer; *F.A.*, free air; H, Hayford. *b*, Heiskanen. *c*, regional $T = 20$ km. *d*, regional $T = 30$ km. L = Lochmaddy.

originated. Unless a flow transgressed across the crust for a distance of the order of hundreds of miles, it is unlikely that any great isostatic disturbance would occur, and subsequent sinking of the area could not be accounted for as a return towards equilibrium. Yet Geikie suggests that Rockall Bank and the Hebrides should have sunk 3000 to 4000 ft. Lacroix does not regard the basalt dredgings as having been formed under water, but this does not necessarily mean that the whole thickness of the flow was formed subaerially. A local sinking of 100 to 150 fathoms could be ascribed to isostatic adjustment of a regional kind, but one would expect a basalt flow to represent a return towards, rather than a departure from, isostatic equilibrium. Lacroix has suggested that Rockall itself, which is the only part of the bank still above sea-level, is part of an intrusive dyke. Commenting on the isolated dredging of granite from immediately north of the rock, he expresses the belief that the whole of the bank may be riddled with such dykes intruded during a later acid igneous phase like the dykes in the Skye gabbros. Echo soundings in this area reveal a small-scale ruggedness which suggests the absence of sediment.

There seems, therefore, to be no notable conflict between the geological and gravitational evidence, though there is a definite indication of excess matter in the region whose presence cannot be adequately explained. If the bank is formed of basalt, we should expect the isostatic anomalies to show a correlation with the topography because the density of 2·67 assumed when making the isostatic reductions will have been less than the actual density of the rock, which may well be as high as 2·9. This might also explain why Hayford's hypothesis gives such good results, since such a high surface value would lead to a rather gradual increase of density with depth. It is evident that the major topographic features are isostatically compensated, though the residual positive anomaly shows that some further sinking is to be expected before they attain equilibrium.

4·36. *Hebrides and west Scotland* (*stations* 41 *to* 45 *and Lochmaddy*)

The eastern end of the profiles in figure 12 should be considered in conjunction with chart 6, which shows the regional isostatic anomalies for $T=30$, $R=58$ km. A representative selection of Jolly's (Bullard & Jolly 1936) observations on land have also been included, and isostatic anomalies for these have been computed on the nine different hypotheses used throughout this paper. As the anomalies do not vary greatly from one system to another chart 6 gives a good idea of the general trend over the area. With one exception, the values are all positive and the land stations show a marked increase to the west, reaching +55 mgals in the Outer Hebrides. The submarine observations indicate that this trend does not extend much beyond St Kilda.

It is not easy to account for the positive field found in this area. The only relevant geological fact is that the islands have apparently undergone continuous submergence since the ice age. This indicates a return towards isostatic equilibrium but does nothing to explain why the original uplift occurred. A possible explanation would be that at one time an upward convection current existed below this region. Cooling, owing to convection or a diminution in the source of supply of heat, possibly because of erosion of the areas raised by the current, has now brought the circulation to a standstill or even reversed the current. We are left with an excess of matter and a tendency for the crust to sink. The tertiary igneous activity found in the Inner Hebrides is possibly connected with the increase in temperature associated with the rising convection current. The fact that no such activity is found in the Outer Hebrides may indicate that the original current did not extend as far west as the present field of positive anomalies. To try to account for the anomalies by assuming the rocks in this region are abnormally dense is not satisfactory. Even if we take the density to be 3·0, a thickness of at least 10,000 ft. would be required. To produce any appreciable effect over such an extensive region they cannot be compensated. For a limited area, the strength of the earth's crust might be sufficient to support the additional mass now present but it does not explain its origin.

4·37. *English Channel and Irish Sea* (*stations* 1 *to* 3 *and* 46 *to* 51)

The observations in the English Channel (nos. 1, 2 and 3) are too few to enable any detailed conclusion to be reached, but the negative anomalies in this area fit in with the known facts concerning the geology of the region. The positions of the stations and the free-air, Bouguer and isostatic anomalies are given in table 8 and are plotted on charts 2, 3 and 4. As the topography is slight, these do not differ greatly from one another. At Southampton a Bouguer anomaly of −31 mgals is found (Bullard & Jolly 1936); 12 miles south-east of this, the Portsdown borehole penetrates to a depth of about 6000 ft. and just reaches the Trias. Assuming that the mean density down to this depth is 2·2, we can account for the observed anomaly provided there is no isostatic compensation. The geological evidence concerning the eastern part of the Channel indicates that there is probably a basin filled with Mesozoic sediments. The evidence has recently been reviewed by King (1949), who confirms this general structure and shows that in mid-Channel the depth of sediment may well be 4000 to 6000 ft. This would more than suffice to account for the observed anomalies. The fact that even larger anomalies are not found indicates that either the density of the sedimentary rocks is greater than 2·2 or that some degree of isostatic compensation has taken place. Both are quite probable. A gravity survey of this area has now been carried out in H.M. Submarine *Talent*, and until the results of these measurements are available it is not profitable to pursue this question further.

With the exception of station no. 48, the observations in the Irish Sea all give positive anomalies. Were it not for this observation, one would tentatively conclude that the general field of positive anomalies found in west Scotland extended south, through Wales and south-west England to Ushant. Recent gravimeter work in Wales shows that here, as in west Scotland, positive anomalies are found which increase westward, reaching a value of +50 mgals at Aberystwyth (Cook & Thirlaway 1948). The result at station no. 48, which only lies some 40 miles farther west and has a Bouguer anomaly of −37 mgals is, therefore, most surprising. The possibility of some error in the observation cannot be overlooked, and it would be most unwise to place too much confidence in a single measurement, especially as we experienced some bad weather at the time that it was made. On the other hand, it is interesting to note that in 1923, Duffield (1924), using a barometric gravimeter on board S.S. *Nestor*, observed a free-air anomaly of −25 mgals in the Irish Sea at a latitude of approximately 53° N. This result cannot be regarded as very accurate, as observations on a surface ship are liable to large errors. Nevertheless, it was made under good conditions and very shortly before reaching the base station at Liverpool.

If we assume that our observation is correct, it indicates a very considerable mass deficiency; the probable explanation is that here, as in the English Channel, there is a trough filled with light sediments, some 10,000 ft. thick. The only geological evidence is that Silurian and Ordovician rocks are found on either side of St George's Channel, and our station lies near the centre of the Caledonian geosyncline which runs north-north-west—south-south-east. It seems doubtful if such an ancient feature could exert much influence on the present gravitational field. A more probable, but purely hypothetical, suggestion is that here we have a deep Triassic basin. Unfortunately, there are as yet no gravity observations in Ireland which might throw light on this matter.

4·38. *Oceanic and continental shelf area*

To obtain the best general picture of the area between the lines of stations running west-south-west of the Lizard and south from Ushant, we shall include all the submarine observations made between these lines and latitude 45° N and longitude 15° W. Meinesz (1934, 1941 *b*) has made twenty-two measurements in this area, for which results have already been published. The authors are much indebted to him for advance information of the isostatic reductions for those stations given in volume 3 of *Gravity expeditions at sea*. The positions of the stations and the regional isostatic anomalies for $T=30$, $R=174$ km. are shown in chart 5. The mean anomaly for the sixteen stations lying to the landward side of the 100-fathom line is $+7\pm2$ mgals, while, for the twenty-four observations made where the depth of the sea exceeds 1000 fathoms, the mean value is $+11\pm3$ mgals. The difference between these two means can be attributed to the indirect effect, which will be seen from the figures given in table 8 to change by some 5 mgals across this region. There is therefore no evidence that the isostatic anomalies are greater over the oceanic parts of the area.

The next point of interest is that the scatter of the individual observations about the mean is very much less in shallow water than over the ocean, the mean residuals without regard to sign being 10 and 19 mgals respectively. It has already been estimated that the probable error of a single observation is $\pm2\frac{1}{2}$ mgals, equivalent to a mean error of ±3 mgals. There is always the possibility that this error is an underestimate and that, for some unknown reason, large errors occur in observations made in deep water, owing to causes such as the uncertainty in the Eötvös correction. It will be seen that where two or more observations have been made near one another considerable differences are found. For example, the three stations near 45½° N, 13° W and the pair near 47½° N, 9° W show differences of 21 and 48 mgals in distances of less than 20 miles. These gradients, if real, are certainly larger than one would have expected, but this does not necessarily imply that the observations are very inaccurate, as the topography, especially in the vicinity of the edge of the continental shelf, is not well known and uncertainty may arise in the calculation of the isostatic reduction. For instance, over a canyon 1000 ft. deep, the value of gravity would be reduced by some 20 mgals. If its presence were unknown when the observation was made, the calculated anomaly would therefore be too negative by this amount. This might go some way to explain the discrepancy between the two stations near 47½° N, 9° W. It is unlikely, however, that for the three stations near 45½° N, 13° W, such errors would occur. The floor of the ocean in this region is not very irregular, and the error in estimating the mean depth in each zone probably does not exceed ±100 fathoms. This would give an uncertainty in the calculated value of gravity of ±5 mgals. To account for the whole of the observed scatter, we should have to assume a mean error of ±15 mgals at each deep-sea station. Even allowing ±5 mgals due to uncertainty in the Eötvös correction, ±5 mgals for errors in the isostatic anomalies and an error of ±3 mgals in the gravity measurement, we get an overall mean error of only ±7·5 mgals. It appears, therefore, that most of the observed scatter is really due to variations in gravity.

The results of pendulum observations in Devonshire and Cornwall show that changes of the order of 10 mgals may often occur over distances of a few tens of miles. This is confirmed by gravimeter observations in south-west England. The scatter in the submarine measurements in the shallow parts of the area therefore seems quite normal. The fact that almost twice as great a scatter should be found over the oceanic part is surprising, particularly when it is remembered that these observations are made at a height of some 5 km. above the sea bed. One must conclude that the earth's crust under this part of the Atlantic Ocean is even less homogeneous than below the mouth of the English Channel.

These changes in gravity occur within distances which are certainly not greater than 100 km. and probably considerably less. Their cause must therefore be near the upper surface of the crust. Assuming that the inhomogeneity arises from a complex structure in which rocks of different density are present, an idea of the order of magnitude can be obtained from the fact that two semi-infinite horizontal layers of rock 3 km. thick separated by a vertical interface and differing in density by 0·2, would give a gravitational field at a level 5 km. above their upper surface, having a maximum gradient of 1 mgal/km. directly over the interface and an overall difference of 25 mgals. A structure in which blocks of granite a few kilometres thick were embedded in a matrix of basalt would therefore account for the observed scatter in the gravity anomalies. Alternatively, large variations in thickness of the deep-sea sediments as suggested in §§ 4·1 and 4·33 would produce a similar effect. If the density difference between the sediments and the basement rock is taken to be 0·4, as assumed for the continental shelf, variations in thickness of 1 or 2 km. would be required, but if we assume that the basement is basalt, density differences as great as 1·0 might exist which would reduce the thickness to less than 1 km. It has recently been reported by Hersey (1948) that the Woods Hole Oceanographic Institution have carried out seismic reflexion experiments between Bermuda, the Greater Antilles and the east coast of the United States. They report obtaining reflexions from a few hundredths of a second up to 0·6 sec. after the first bottom echo. These are attributed to reflexions from layers below the upper surface of the deep-sea sediments. If we assume that they are reflexions from the top of the basement rock we can estimate the minimum thickness of sediment. If the velocity of sound in the sediments is taken to be 8000 ft./sec., this gives a depth of 0·8 km. Although this is much less than the variations in thickness required to account for the scatter in the gravity anomalies, it nevertheless shows that changes in thickness of the bottom sediment could play a very important part.

Returning once again to the main distribution of the anomalies over the whole area, the question arises whether there is any systematic trend on crossing the edge of the continental shelf. The results have been treated by dividing them into groups according to their distance from the 100-fathom line and investigating the variations in the mean values in these groups.

For this purpose, the 100-fathom line is taken as coinciding with a straight line passing through positions 49° N, 10° W and 47° N, 5° W. The size of the groups was selected so that each contained sufficient observations to provide an estimate of the probable error of the mean. One degree (60 nautical miles), giving an average of $6\frac{1}{2}$ observations per group, was chosen. The mean regional isostatic anomaly for $T=30$, $R=174$ km. and its probable error were found for the observations made between 0° and 1°, 1° and 2°, 2° and 3°, etc., on either side of the line. These means were then corrected for the indirect effect; the results are shown in table 14 and are plotted in figure 13 (full circles). It was found that the actual distribution of the means was considerably affected by the positions chosen for the boundaries of the groups. The results of an intermediate set of groups from $-\frac{1}{2}°$ to $+\frac{1}{2}°$, $\frac{1}{2}°$ to $1\frac{1}{2}°$, $1\frac{1}{2}°$ to $2\frac{1}{2}°$, etc., were accordingly calculated. These figures have also been tabulated in table 14 and plotted in figure 13 (open circles). A smooth curve has been drawn through the points to indicate the general trend of the mean anomalies. It cannot be claimed that this gives an accurate estimate of the mean gravitational field, but the dip occurring over the edge of the shelf is considered significant, since it falls some 30 mgals below the average level on either side, while the probable error of each mean in this region is only ± 13 mgals.

It is evident that this can be largely accounted for by the presence of low-density sediments. The corrections due to such a layer and its compensation can be estimated from the figures given in table 10. These have been used to calculate the sediment corrections given in table 14. Applying these to the full curve in figure 13 we obtain the dashed curve. It is seen that the negative anomalies found near the edge of the shelf have been largely eliminated, and the positive values found between 60 and 100 miles to the west-south-west have also been reduced. There is, however, still a tendency for the anomalies some 30 miles to the landward side of the 100-fathom line to be negative.

In § 4·32 above, it has already been pointed out that, to account for the observations made along the profile running west-south-west from the Lizard, it is reasonable to assume that the thickness of the low-density sediments remains at approximately 8000 ft. for some 40 miles to the landward side of the 100-fathom line. The anomalies found by Meinesz suggest that this feature extends some 200 miles east-south-east along the edge of the shelf, and it is this feature which causes the dip in the dashed curve in figure 13. The alternative possibility that the dip arises from a more deeply seated cause, as Meinesz has himself suggested, is quite possible. This hypothesis, that the roots of ancient mountain ranges can persist long after the mountains themselves have been eroded away, has also recently been proposed by Garland (1948) to account for the anomalies observed in the Canadian shield area. He finds instances of granite outcrops associated with regions of negative anomalies. Possibly the same explanation may apply to the low values of gravity found by Bond (Bullard & Jolly 1936) to the north and north-west of Dartmoor. However, until further seismic work near the edge of the continental shelf has provided evidence of the thickness of the low-velocity layers, no definite decision can be reached.

The fluctuations in the mean anomalies over the deep water are small compared with the probable errors of the mean values and hence cannot be considered significant. This in no way contradicts the argument advanced earlier in this section, that the large scatter in the observations indicates that the structure of the earth's crust below this area must be less homogeneous than below the mouth of the Channel. Inspection of chart 5 shows that, apart from the negative anomalies in the vicinity of the 100-fathom line, no other systematic trend is obvious. The two stations about 50 and 90 miles south-west of the Lizard each have anomalies of −4 mgals, which are surprisingly low compared with the mean of about +10 mgals found for the other observations a similar distance to the north-east of the

Table 14. Mean regional isostatic anomalies ($T=30$, $R=174$ km.)

limits of group (degrees)	mean anomaly (mgals)	probable error	correction for sediments	corrected mean
−2 to −3	+19	± 4	0	+19
−1½ to −2½	+13	± 5	0	+13
−1 to −2	+11	± 5	0	+11
−½ to −1½	+ 8	± 9	+ 1	+ 9
0 to −1	−12	±13	+ 9	− 3
½ to −½	−26	±13	+26	0
1 to 0	+ 2	±13	+11	+13
1½ to ½	+17	±13	− 7	+10
2 to 1	+30	±13	− 6	+24
2½ to 1½	+21	±11	− 2	+19
3 to 2	+ 7	± 9	0	+ 7
3½ to 2½	+22	±10	0	+22
4 to 3	+30	±10	0	+30

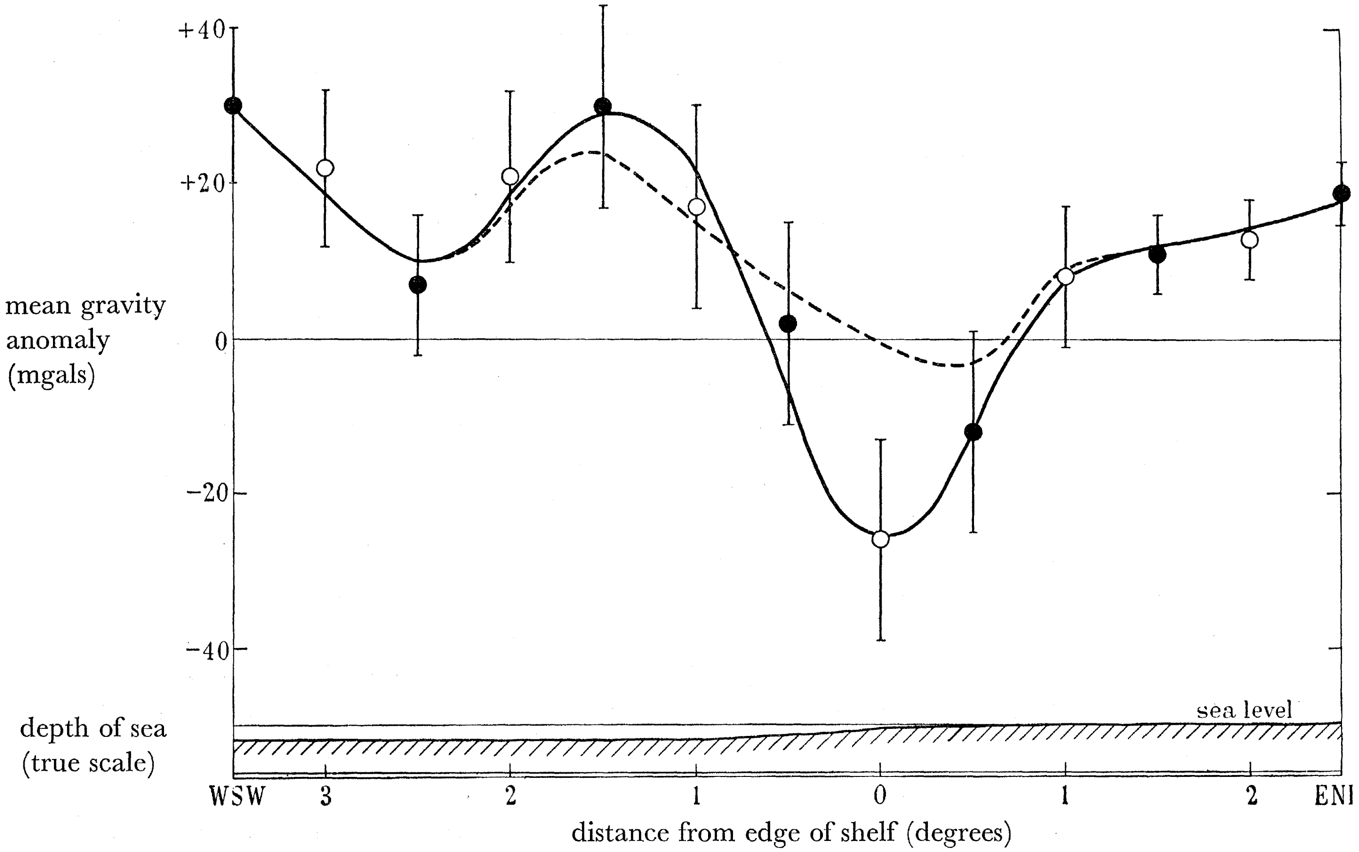

Figure 13. Mean gravity anomalies between Atlantic and Bay of Biscay sections.
——— trend of group mean gravity anomalies.
-------- as above, corrected for low density of sediments and their compensation.
Vertical lines indicate probable errors.

100-fathom line. This may indicate a thickening of the sediments, possibly in a trough forming a westward continuation of the main axis of the Channel.

4·4. Conclusions

We shall conclude with a summary of the main results. These are divided into two groups: the advances made in the technique of measuring gravity at sea, and the information gained concerning the structure of the area surveyed.

4·41. *Summary of technical results*

The Vening Meinesz pendulum apparatus has again proved a most satisfactory instrument for making gravity measurements in a submarine. Crystal-controlled frequency standards provide a very precise means of timing the pendulums, but the accuracy attainable in the final value of gravity at sea-level is still only about ±3 mgals (p.e.). This is largely due to uncertainty in the Eötvös correction. Experiments made to confirm the existence of the second-order corrections arising from the accelerations of the submarine were inconclusive. It is believed, however, that provided the perturbations have a period long compared with that of the pendulums the effect is as predicted by theory. The presence of vibration, or of components with periods comparable with the pendulum period, may introduce serious errors. Careful attention must be paid to this point if accurate results are to be obtained.

4·42. *Summary of geophysical results*

Echo-sounding records made while crossing the edge of the continental shelf off the mouth of the English Channel reveal very rugged submarine topography, probably due to the presence of canyons.

The results of the gravity measurements show that the area has a mean positive anomaly. Whether the excess mass which must therefore be present is supported by the static strength of the crust or by a dynamic process such as convection currents is still uncertain. Observations to the south and west of Cornwall show considerable scatter. Over the shallow water at the mouth of the English Channel, the variations are of about the same magnitude as those observed in south-west England. Over the deep water, the scatter is nearly twice as great, showing that there must be variations in density below the floor of this part of the ocean which greatly exceed those found in Devon and Cornwall. Whether this indicates a complex structure of the basement rocks or variations of several thousands of feet in the thickness of the deep-sea sediments cannot be decided without further experiment.

The increase in isostatic anomaly on crossing the edge of the continental shelf from shallow to deep water is again confirmed. The presence of a wedge-shaped layer of sediment as indicated by the results of seismic experiments would go far towards explaining this provided that its density was about 2·3 and that it was very nearly in isostatic equilibrium. To account fully for the anomalies on the landward side of the 100-fathom line, it is necessary to assume that the thickness of the sediments remains constant at about 8000 ft. for some 30 miles north-east of the edge of the shelf, or that there is a down-warping of the crust below the eastern part of this area.

Gravitational and geological evidence points to a series of east-west folds as the probable structure in northern Spain. The isostatic anomalies here and over the southern part of the Bay of Biscay are large, indicating that compensation is not complete. Calculations of the mass distribution confirm this and show that the depth of the anomalous masses cannot exceed some 40 km.

Rockall Bank, and probably the Porcupine Bank, are nearly in isostatic equilibrium. The best results are obtained by assuming a rather large radius of regionality ($R = 174$ km.). The gravity observations do not conflict with the accepted geological evidence that the Banks are part of a basaltic plateau. The positive anomalies found in western Scotland do not extend farther west than St Kilda. There is geological evidence that the Outer Hebrides have sunk since the ice age. This represents a return towards isostatic equilibrium but gives no indication as to the cause of the original excess mass.

Three observations in the centre of the English Channel and one isolated station in St George's Channel west of Aberystwyth show negative anomalies. This information is too scanty to allow any definite conclusion to be drawn, but may indicate considerable thicknesses of sediment in these areas.

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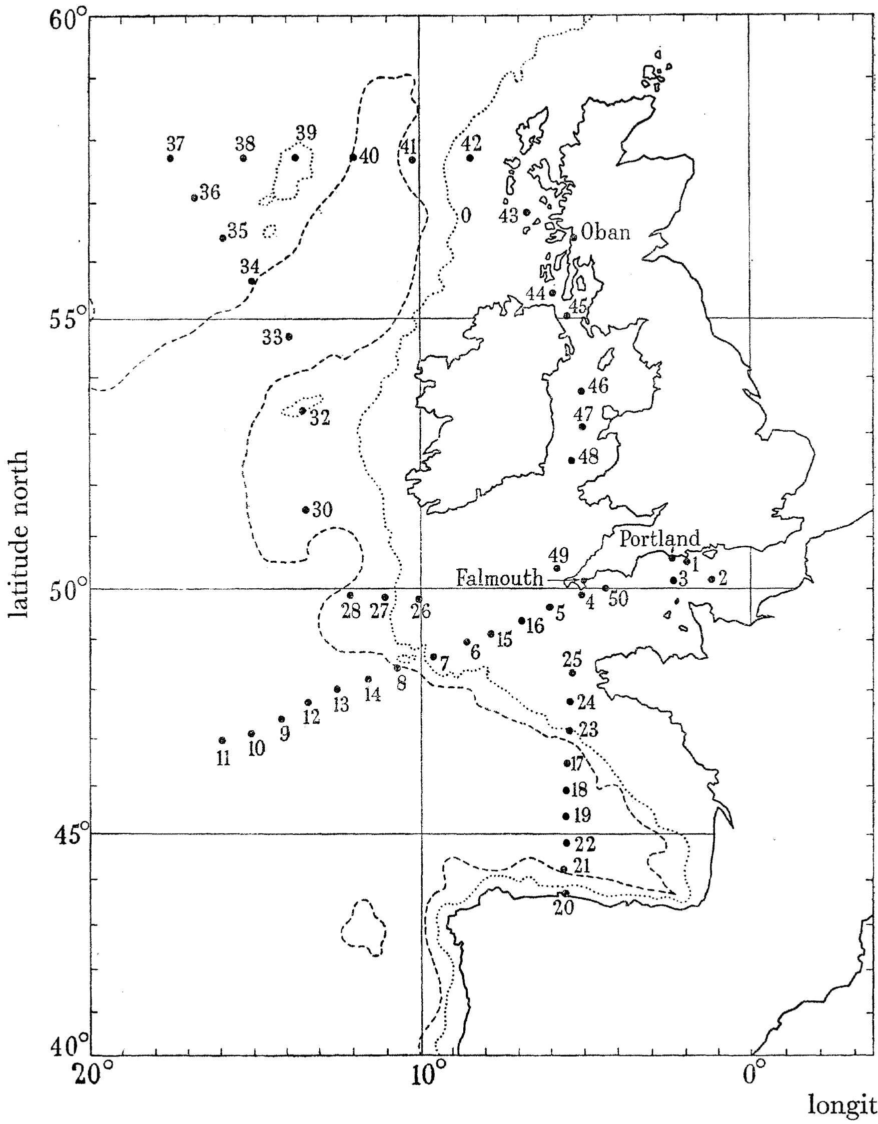


CHART 1. Positions of observations and station numbers.

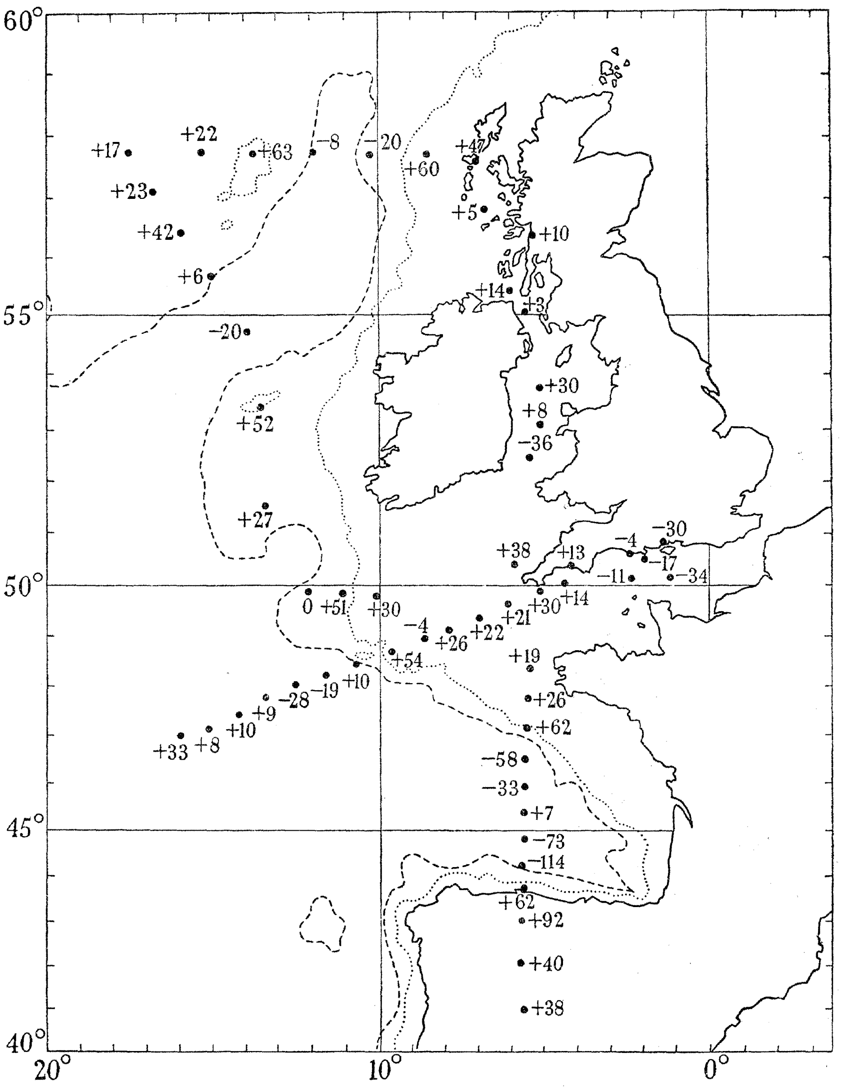
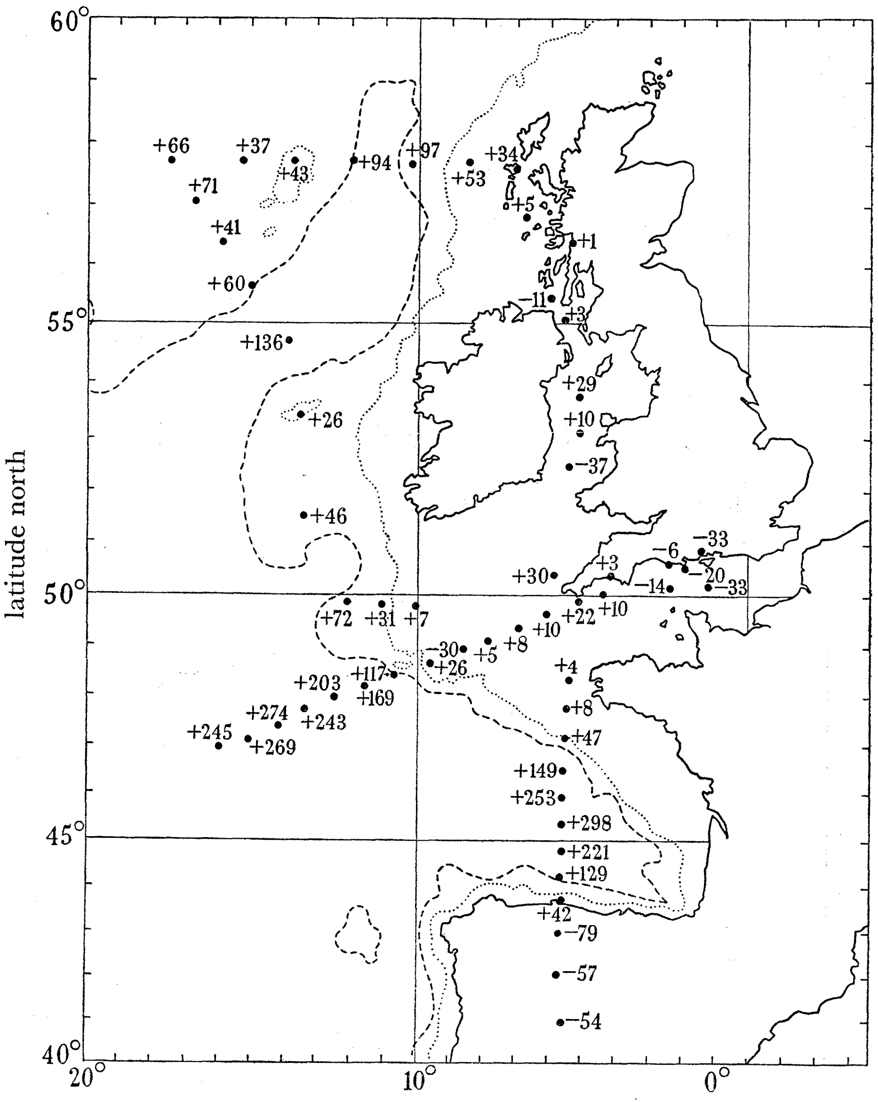
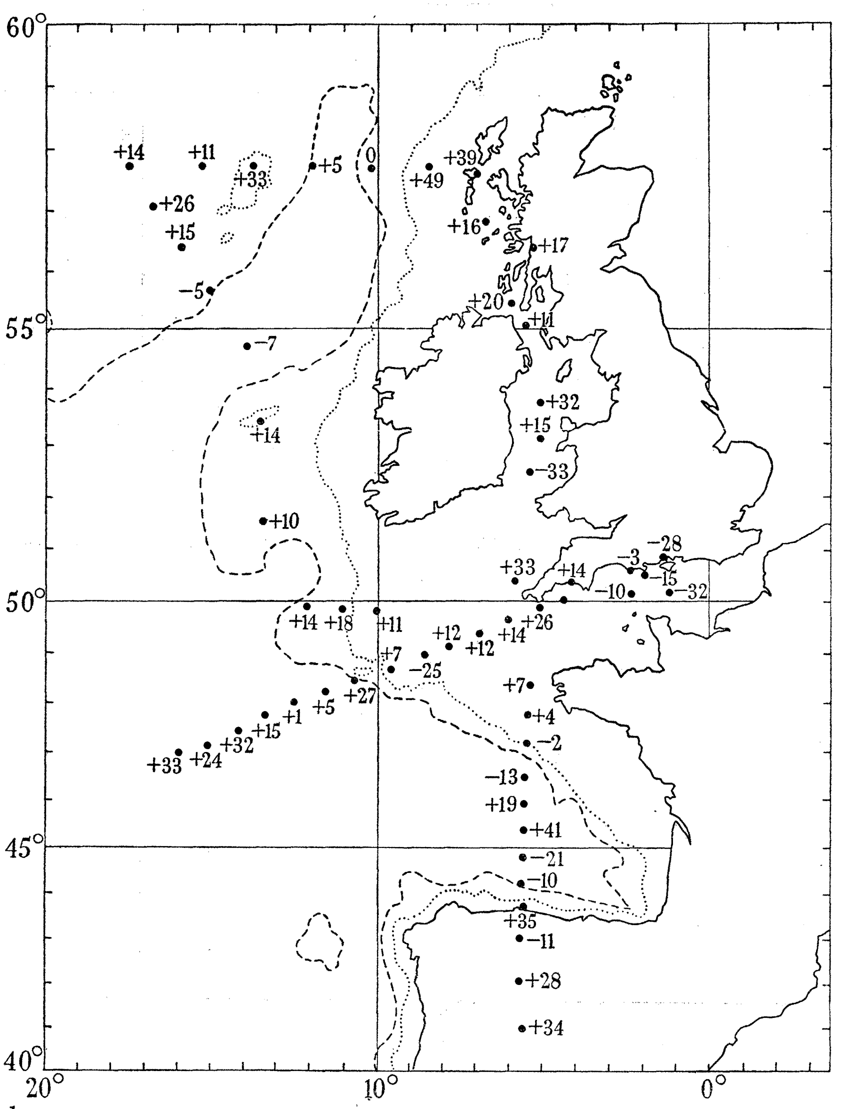


CHART 2. Free-air anomalies (mgals).

in both charts { ....100 fathoms
--------1000 fathoms





longitude west

CHART 3. Bouguer anomalies (mgals).

CHART 4. Regional isostatic anomalies (mgals). $T = 30$, $R = 58$ km.

in both charts ………… 100 fathoms
in both charts - - - - - - - - - 1000 fathoms

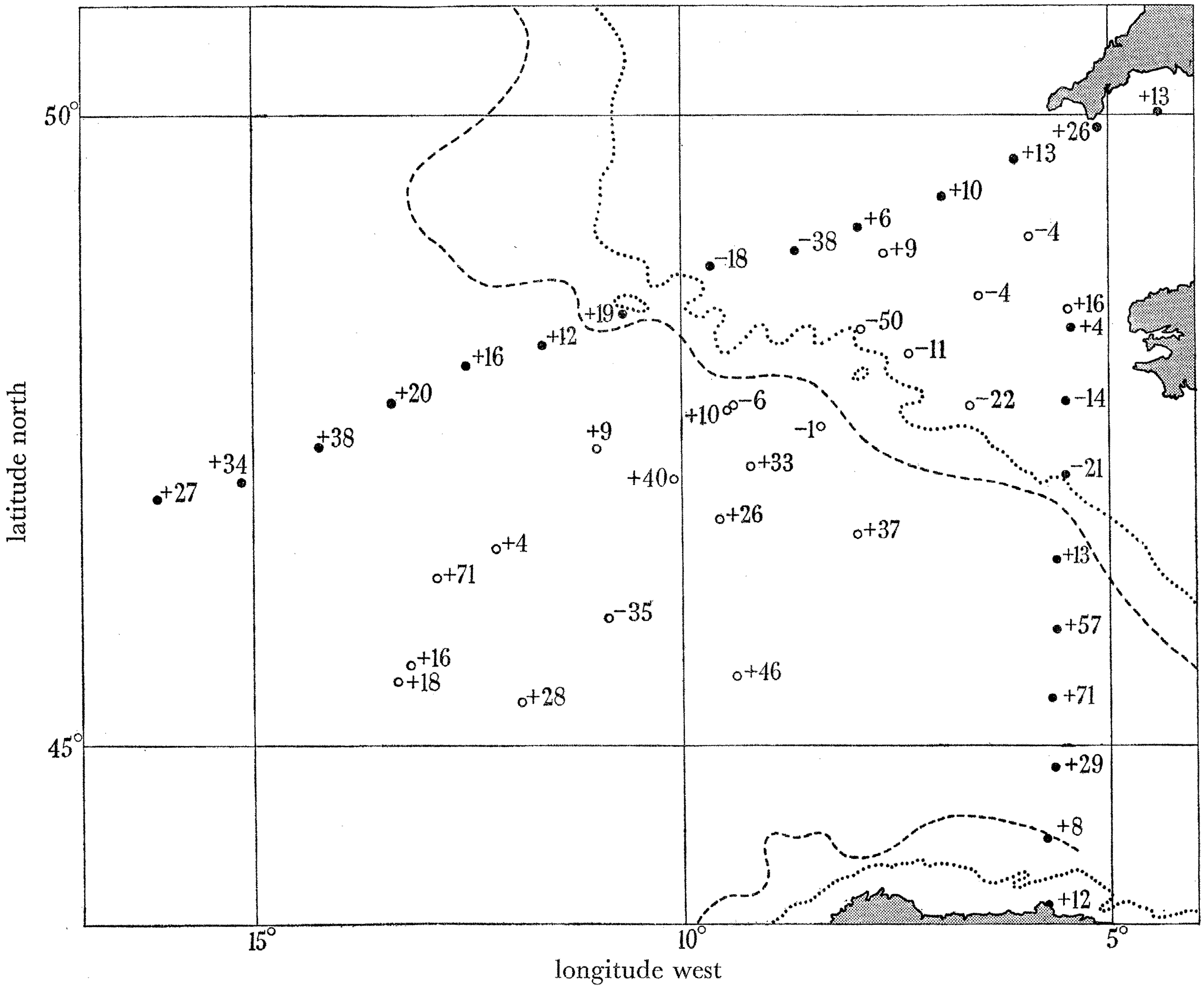


Chart 5. Regional isostatic anomalies (mgals). $T=30$, $R=174$ km.

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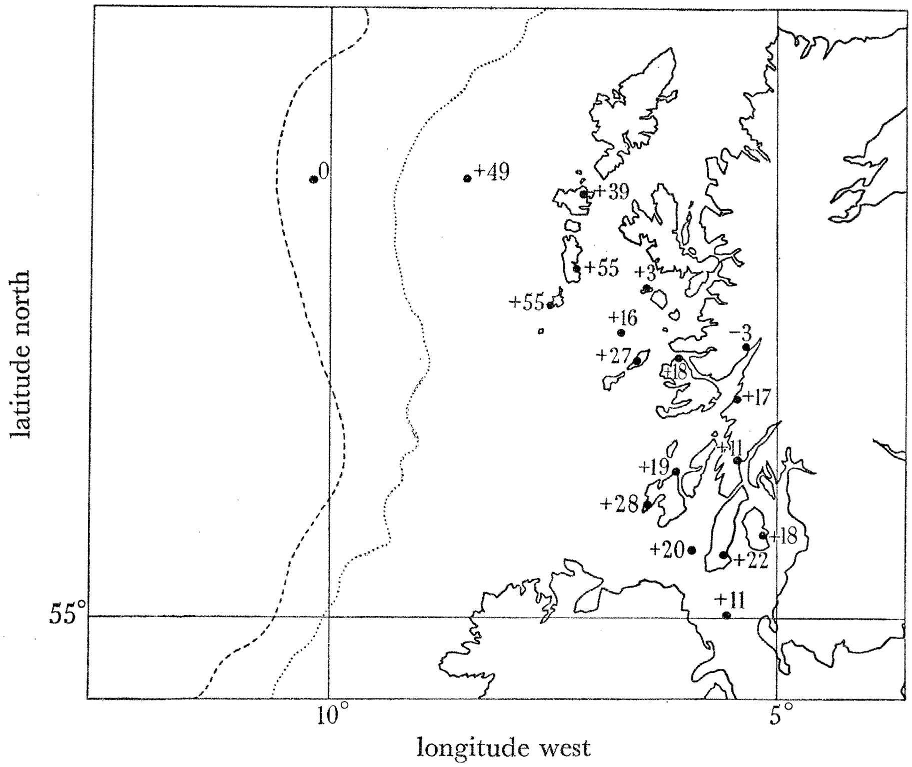

Chart 6. Regional isostatic anomalies (mgals). $T=30$, $R=58$ km.

In both charts{ .... 100 fathoms
--------- 1000 fathoms