Crustal structure of north Queensland from gravity anomalies

J. E. Shirley[1]

The interpretation of a reconnaissance gravity survey of north Queensland has shown that the area is composed of normal continental crust approximately 40 km thick, and is consistent with relief at the Moho of approximately 7 km. The parameters required for three-dimensional crustal gravity modelling, crustal thickness and density contrast across the Moho, were derived from available crustal seismic refraction experiments, together with analyses of correlations of crustal parameters on a worldwide basis. There are no large departures from isostatic equilibrium in the area. The southeastern part of the area is isostatically compensated and the crustal thickness reaches 43 km. The Mount Isa Block is not isostatically compensated and coincides with an area of thin (38 km) crust. This area is stable and, because of its size, is unlikely to achieve local isostatic equilibrium. The Cape York area has not reached isostatic equilibrium. The gravity anomaly pattern suggests that this area may have approached equilibrium progressively, with those parts of the area farthest from the centre of the Tasman Geosyncline having the smallest departure from isostatic equilibrium. This agrees with the history of development of the northern part of the Tasman Geosyncline, which youngs to the north and east. The Palmerville Fault is a major surface structure, but has no gravity effect originating at Moho depths, and hence may be only an upper crustal feature. The Coen Inlier also has little or no influence on the regional Bouguer anomalies, and is therefore probably a shallow crustal feature, of less significance than its surface outcrop suggests. The Cape York-Oriomo Ridge, however, has little surface expression, but is shown by the gravity data to be a major feature of the crust.

Introduction

A gravity survey was designed to investigate the deep crustal structure of north Queensland. The area is generally recognised as a stable continental block which continues north into southwest Papua New Guinea and is terminated on its eastern margin by the Tasman Geosyncline. The stable block has three major exposures of Precambrian rocks; the subsurface extent of these is unknown.

The gravity data were obtained in 1966 as part of the program for reconnaissance gravity coverage of Australia conducted by the Bureau of Mineral Resources, Geology and Geophysics (BMR). The analysis and interpretation of the gravity and other data were carried out at the University of Tasmania.

This gravity survey of north Queensland (Fig. 1) is the first geophysical survey carried out over the entire area. Earlier gravity data which are suitable, both with regard to survey accuracy and availability of primary data, have been incorporated into the 1966 survey. A review of previous investigations, including drilling and a complete bibliography are detailed in Shirley (1976).

A summary of the geology of the area was published by Hill & Denmead (1960). Since that time most of the area has been mapped in greater detail at 1:250 000 by the BMR and the Queensland Geological Survey.

The geology has recently been summarised by Henderson (1979) and Plumb & others (1979); Bell (1979) has outlined the deformational history. Figure 2 shows the main structural features together with the generalised geology.

Reconnaissance gravity survey

The reconnaissance gravity survey in 1966 was part of a larger program undertaken by the BMR to provide gravity reconnaissance coverage of the Australian continent. The coverage of the Australian continent, including most of the continental shelf, is now complete (Anfiloff & others, 1976). Some of the early geological concepts established and extended as a result of the early parts of the program have been reported by Vale (1965). The gravity survey of Cape York and north Queensland, the 1966 segment of this program, was planned by the author, who also carried out field supervision and quality control of the data.

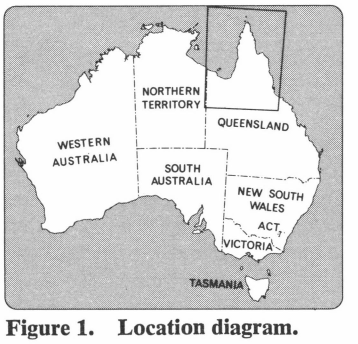

Figure 1. Location diagram.

The technique of helicopter gravity operations used in this survey has been developed by the BMR since 1959; the basic method has been described by Hastie & Walker (1962), and Vale (1962).

Data were reduced using the BMR GRAVHTS programs on a CDC 3600 computer (Bellamy & others 1971). At the time of running these programs utilised the International Gravity Formula, 1930:

$$g_N = 978\,049.0\ (1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)\ \text{mGal}$$

and this has now been altered to

$$g_N = 978\,031.8\ (1 + 0.0053024 \sin^2\phi - 0.0000059 \sin^2 2\phi)\ \text{mGal},$$

the 1967 International Gravity Formula adopted in Australia in 1972.

Had the 1972 Gravity Formula been used for the data reduction it would have resulted in a datum change

1. **Department of Geology, University of Tasmania, G.P.O. Box 252C, Hobart, Tas. 7001.**

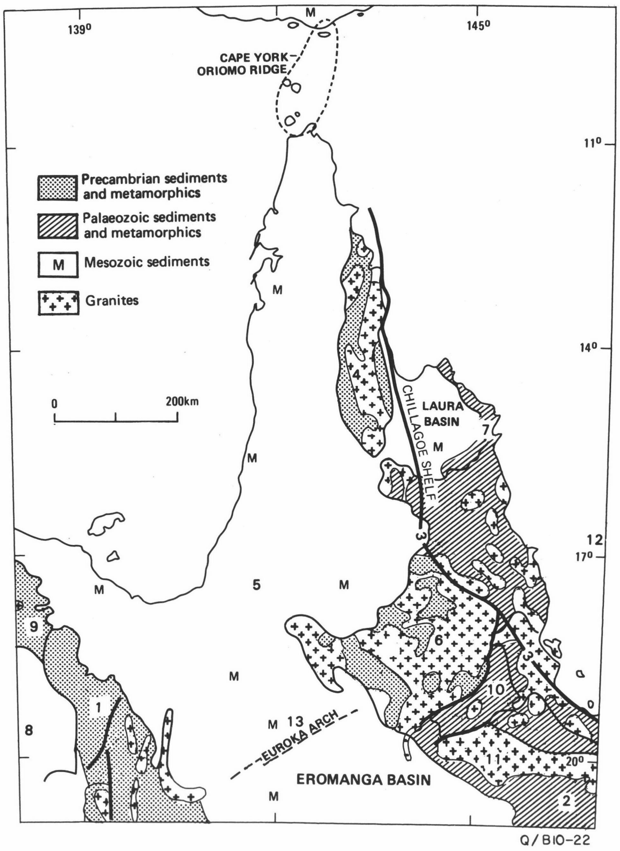

Figure 2. Structural elements and generalised geology.

of 16.8 mGal in the gravity anomalies at latitude 15°S which, if applied over the entire area, would give rise to errors of $\pm$ 0.6 mGal at the northern and southern boundaries of the area due to the $\sin^2\phi$ term of the formula. The variation from +0.6 to −0.6 mGal from north to south is not considered significant when compared to the reconnaissance nature of the survey and its accuracy. All references to average anomaly values in later sections are to data obtained from the literature for which the 1930 Gravity Formula was utilised in the data reductions. The density used in the Bouguer anomaly reductions was 2.2 tm^{-3}; as this was representative of the surface rocks over most of the area. The surface rocks in the Mount Isa area, Coen Inlier, and Georgetown area have densities in the range 2.5-2.6 tm^{-3}; because of the regional nature of the interpretation the use of 2.2 tm^{-3} will cause only small variations in the anomaly size in areas where the elevation is significant, and these anomalies will be removed in the regional-residual separation. Woollard (1969) also notes that the density used in the Bouguer anomaly calculation is not critical for evaluation of isostasy.

Gravity control (Fig. 3) has already been established in the survey area by the Isogal Survey, and the stations used are part of the Australian National Gravity Network (Barlow, 1970). New Isogal stations were also established at Daru and Thursday Island for this survey (Barlow, 1970).

Elevation control was provided by a network of third-order level control traverses (Fig. 3). Mean sea level was also considered the equivalent of a level control traverse and used as elevation control. However, owing to the lack of tide gauges and detailed information on tides in the area, corrections were hard to apply, and, in retrospect, the use of sea level without sufficient control was an error.

Horizontal control was provided by aerial photographs which were available for the entire area, with the exception of part of one 1:250 000 map sheet. In this area dead reckoning was used.

The gravity data were compiled on maps at a scale of 1:250 000, and then reduced to 40 miles to 1 inch. Bouguer anomalies and free-air anomalies are shown on Figures 4 and 5 respectively.

Bouguer anomaly accuracy

The accuracy of the Bouguer anomalies is dependent mainly on the accuracy of the elevation measurements.

It is not possible to assess directly the accuracy of elevation or gravity from this type of survey operation. To obtain an estimate of the accuracy it is necessary to compare the field values statistically with known values before the least-squares adjustment is carried out. Darby (1970) has investigated elevation data from four major surveys (including this one) involving some 25 000 observations. He concluded that the mean error of the field data was approximately 1.8 metres, or approximately twice the standard deviation of the least-squares adjustments. This figure also agrees with the mean observed difference of 1.8 metres found for stations occupied twice (on different survey loops). Darby (1970) also found that the barometers showed differences of up to 3 metres when read simultaneously at field stations, i.e. within the accuracy of the instruments. Consequently I consider that the field data, least-squares adjusted to fixed stations (comprising approximately 20% of the total number of stations) could reliably be expected to have an error of 3-4.5 metres. As the data for this survey had a standard deviation of the elevation adjustments of 0.8 metres, with a maxi-

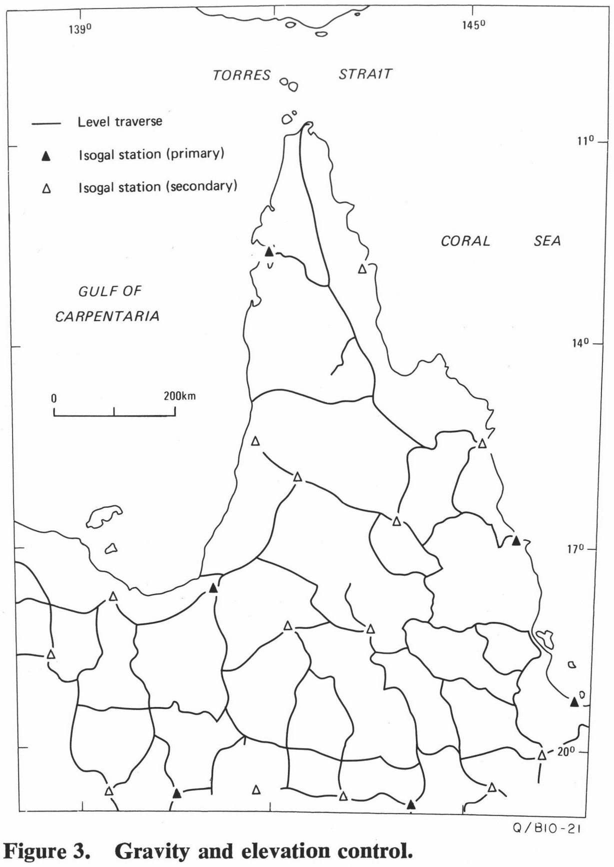

Figure 3. Gravity and elevation control.

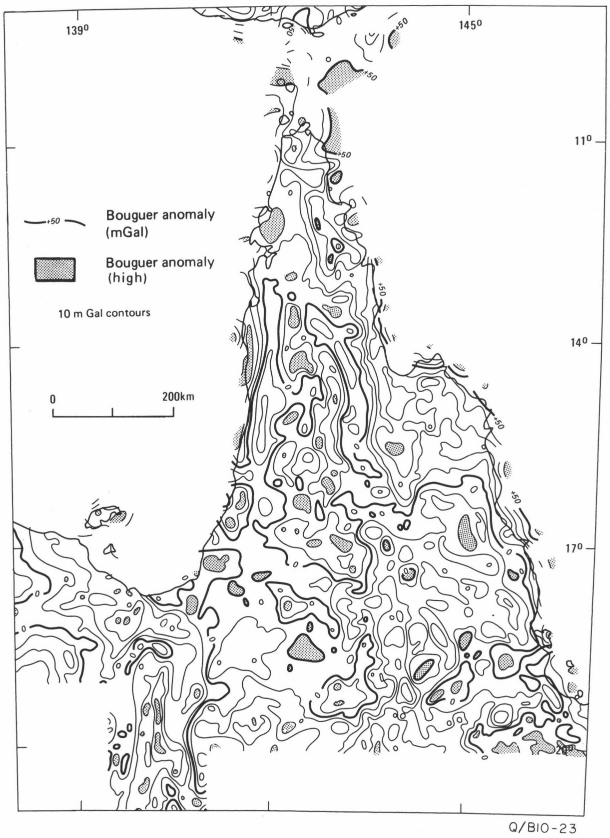

Figure 4. Bouguer anomalies.

mum adjustment of 9.2 metres, it is conservative to assign an error to the elevations equivalent to 2 mGal (approximately 6 metres)—in most cases the error will be less than 1 mGal. Vale (1962) considers that the latitudes are determined to at least better than 300 metres: this is equivalent to $\pm$ 0.25 mGal.

The gravity loops all closed to better than 0.25 mGal and most to better than 0.1 mGal. Tidal gravity corrections (Goguel, 1965) were not applied. The maximum tidal correction in the survey period is 0.135 mGal and this is included in the observed gravity misclosures. The application of tidal gravity corrections (see below) would have been insignificant in terms of the total error. The standard deviation of the gravity adjustments was 0.14 mGal with a maximum of 0.22 mGal. Consequently the error caused by the gravity measurements is less than 0.2 mGal.

The total error in the Bouguer anomalies is then

$$\epsilon_{BA} = [(\epsilon_G)^2 + (\epsilon_L)^2 + (\epsilon_E)^2]^{\frac{1}{2}}$$

when ϵ_G, ϵ_L, ϵ_E are the individual errors assigned to the determinations of gravity, latitude and elevation. Hence $\epsilon_{BA} = 2.03$ mGal.

Using Hammer's (1939) procedure, terrain corrections out to zone 0 were calculated for seven stations in this area where terrain effects were likely to be most marked. The maximum correction calculated was 0.7 mGal, well within the survey accuracy of 2 mGal and consequently terrain corrections were not applied.

Regional Bouguer anomalies

The regional Bouguer anomalies (Fig. 6) were obtained using a four-fold application of a 20-minute band-pass filter. The data obtained from this process (regional gravity anomalies) were subtracted from the

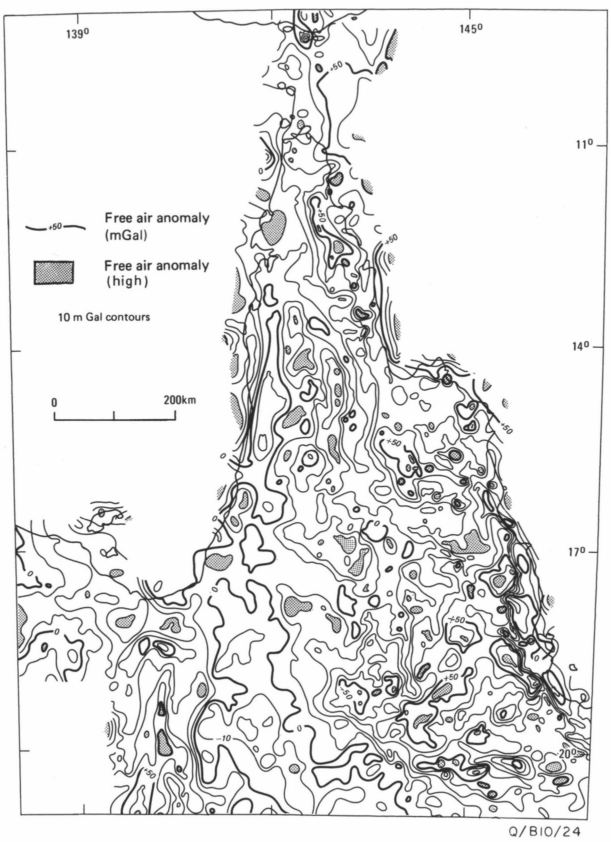

Figure 5. Free air anomalies.

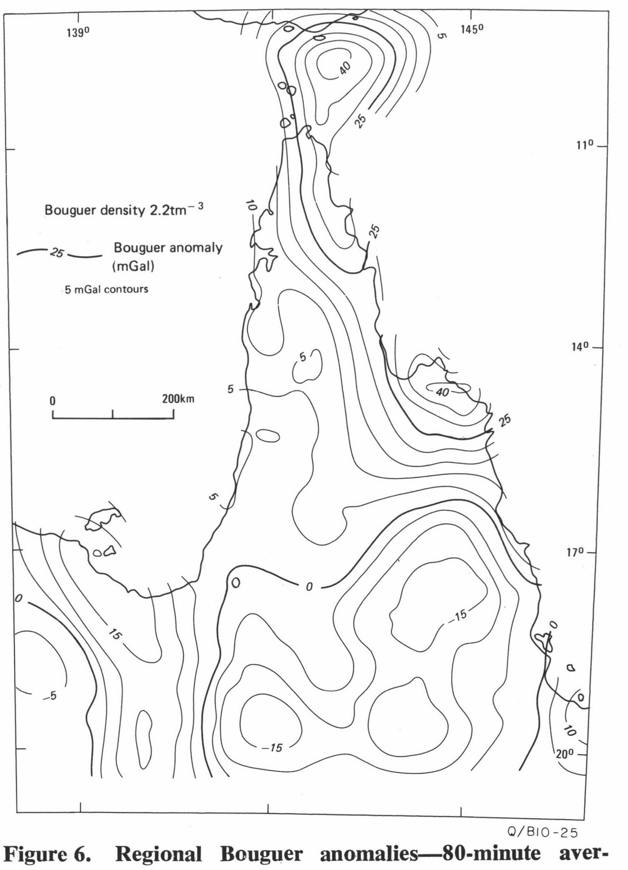

Figure 6. Regional Bouguer anomalies—80-minute averages.

initial data (total gravity anomalies) giving the residual gravity anomalies. Spectral analyses of these three anomalies confirmed that the regional contained all the long wavelengths, the residual all the short wavelengths and that the sum of the regional and residual spectra was identical to the spectrum of the total field, thus confirming that the separation had been performed effectively (Shirley, 1976).

Interpretation

The interpretation has been carried out using crustal models initially derived from seismic surveys. To derive a unique result from indirect gravity interpretation requires more information from other sources than is ever available in practice. Crustal mass deficiencies calculated by Dooley (1976) show that isostatic compensation is not complete at the Moho, and that some compensation must occur in the mantle. Dooley (1977) has also drawn attention to the variations in density in the upper mantle. Using seismic velocity-density relationships he showed that there are variations in crustal mass, and that the small free-air anomalies associated with these areas suggest that there are compensating mass variations in the upper mantle. However, for this regional interpretation, it is assumed that the mantle, except for the upper portion, consists of homogeneous isotropic concentric shells, the actual parameters of which need not be known. The interpretation of the gravity anomalies then consisted of determining the crustal thickness and the crust-mantle density contrast.

In the analysis no correction has been made to the regional field for the global anomalies and they have hence been treated as caused by crustal rather than sub-crustal causes. The global gravity anomalies determined from satellite observations are largely attributed to sub-crustal density variations. Kaula (1972) shows a free-air anomaly gradient across this region which ranges from a high of +30 mGal in the northeast to +5 mGal in the southwest corner; this is partly owing to sub-crustal causes, although part may imply crustal density variations.

To define a crustal model for gravity interpretation it is useful to determine a standard crust for which the Bouguer anomaly will be zero and then, by variation of density contrast and crust size and shape, interpret the regional Bouguer anomalies. However, an infinite number of solutions is permitted, because both density contrast and size can be varied. To constrain the number of possible solutions, a crust-mantle density contrast was derived from consideration of local seismic investigations and world average relationships of density and seismic velocity.

Other investigations

Relevant geophysical and drilling investigations have been outlined elsewhere (Shirley, 1976). The majority of the geophysical surveys were part of oil exploration programs, and hence were concerned with the sedimentary section (Mesozoic or Upper Palaeozoic)—which does not exceed 1 km in the onshore Carpentaria Basin, but is up to 2.5 km thick in the Laura Basin. In the adjoining offshore areas, the Carpentaria Basin reaches a depth of approximately 2.1 km and the deepest sedimentary section is in eastern Torres Strait, where seismic investigations indicate at least 4.2 km of sediment above the basement.

In several reports (e.g. Mid-Eastern, 1963; Marathon, 1963) there was brief mention of deep (sub-basement) reflections. In no cases were velocity-depth relationships available, but estimations showed that the deep reflections were far too shallow to have originated from the intermediate crustal layer, and hence would not provide depth control for this layer. No Moho reflections were recorded. Most of the drilling was shallow, and several of the holes did not penetrate to basement. Consequently only the CRUMP data (Finlayson, 1968), and the crustal seismic data of Cleary (1973), were of use for this interpretation. Near-surface density data is detailed in Shirley (1976).

Isostatic compensation in north Queensland

The regional gravity anomalies in north Queensland are not large (−15 mGal to +40 mGal), and with the global trend removed become still smaller. This suggests that any departures from isostasy in the area are small. If isostatic effects are present, they will mostly be contained in the regional gravity anomaly maps, because any crustal blocks likely to be in isostatic equilibrium will be 250 km across, at least, and will therefore give rise to gravity effects of long wavelength. Geologic features smaller than this are more likely to be supported by the strength of the crust and so not be in local isostatic equilibrium, even though they may well be regionally compensated. The eastern boundary of the survey area approximately parallels the Great Barrier Reef, a short distance to the east, and the crustal thinning at a normal continental margin is reflected in the total Bouguer anomalies, which range up to +70 mGal.

Grushinsky (1963), and Heiskanen & Vening Meinesz (1958) have shown that there is a relationship between free-air and Bouguer anomalies, and isostatic anomalies. A free-air anomaly is equivalent to the isostatic anomaly calculated for a zero depth of compensation, whereas a Bouguer anomaly is equivalent to the isostatic anomaly when the depth of compensation is assumed to be infinite. The free-air anomalies consequently provide a better approximation to the isostatic anomalies than do the Bouguer anomalies. The similarity of both sign and magnitude of free-air and isostatic anomalies for stable areas of low surface relief is well known (Heiskanen & Vening Meinesz, 1958). Lyustikh (1960), and Woollard (1962), have confirmed the equivalence in an analysis of observed free-air and isostatic anomalies. The isostatic anomaly will then be in the range defined by the Bouguer anomaly and the free-air anomaly and, as Grushinsky has noted, positive free-air anomalies and negative Bouguer anomalies imply isostatic compensation. However, if both anomalies are either positive or negative, then some isostatic imbalance is implied.

In areas of significant topographic relief the free-air anomalies are generally positive on the mountains and negative in the valleys, and local free-air and isostatic anomalies can be related principally to local topography and geology. Regional isostatic compensation occurs with structures of the order of 250 km in lateral extent; the more local anomalies result from under or over-compensation of topographic and geologic features which are too small to be individually compensated. Woollard (1962) has shown that if the regional free-air anomalies over distances greater than 250 km are not zero then an isostatic imbalance is implied, the sign of the anomaly indicating the direction of vertical movement necessary for compensation to be achieved. A positive free-air anomaly suggests, in this case, a crust that is thinner than normal (Lyustikh, 1960), and a downward movement of the crust is required for it to be isostatically compensated. The downward crustal

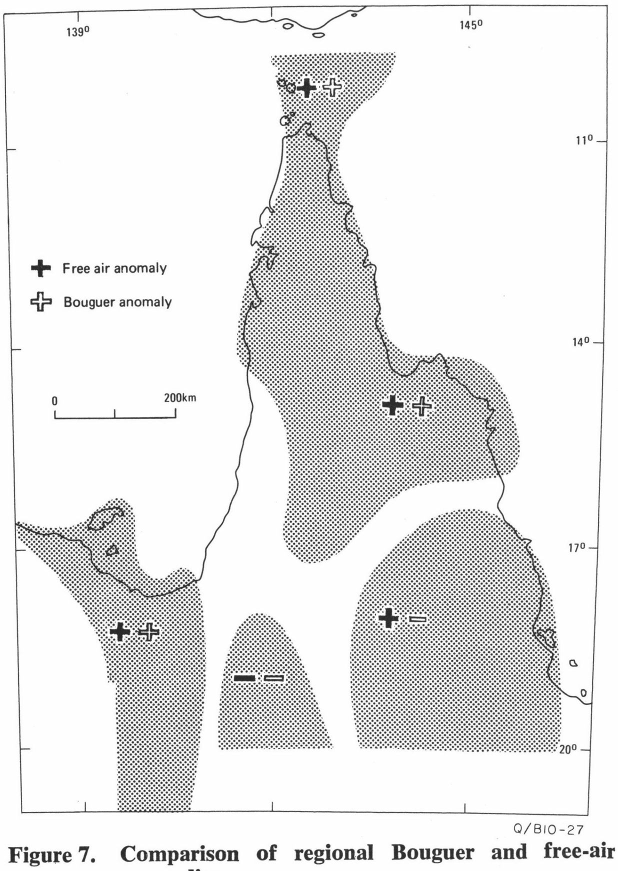

Figure 7. Comparison of regional Bouguer and free-air anomalies.

movement will displace the excess mass at the base of the crust which gives rise to the positive Bouguer and free-air anomalies.

However, as most of the north Queensland area is of low relief and is presently tectonically stable, the free-air anomalies may be regarded as giving a close approximation to the isostatic anomalies.

From this discussion and a comparison of the regional free-air anomalies and the regional Bouguer anomalies (Fig. 7) it can be seen that only part of northern Queensland is isostatically compensated.

Mount Isa Block

In the western part, essentially the Mount Isa Block (Fig. 2), the Bouguer anomalies have a maximum of +20 mGal, and the free-air anomalies are also positive with a maximum of +35 mGal, suggesting a thinner than normal crust which has not quite reached isostatic equilibrium. The area is approximately 250 km in cross-section, and hence is of a marginal size to achieve local equilibrium; it is probably compensated on a larger scale, with the strength of the crust being sufficient to inhibit local compensation by local crustal movement. The southern central part of the area corresponds to the Euroka Arch, a basement high separating the Georgetown Inlier and the Mount Isa Block. The Bouguer anomalies and free-air anomalies are both small and negative, indicating that on a local scale the area is over-compensated.

Cape York

The whole of Cape York (north of 14.5°S latitude) shows much similarity in the form of the Bouguer and free-air anomalies, both of which are positive and of equal magnitude (+40 mGal). This also suggests a thinner than normal crust which has not reached local isostatic compensation. After a detailed study of selected profiles across the coastal-Great Barrier Reef area from latitude 15°S to latitude 19°S Dooley (1965) concluded that this coastal section was not isostatically compensated. His investigations suggested a Moho at a depth of 30 km at the coast line. Along the eastern coastal margin of Cape York the Bouguer anomaly gradient is typical of a fairly well adjusted continental margin, here delineated by the Great Barrier Reef.

Georgetown Inlier

The southeastern sector of the area comprises the Georgetown Inlier, and part of the Tasman Geosyncline. The Bouguer anomaly and free-air anomaly patterns are generally similar, though not as markedly so as in the Cape York area; however, the anomalies are of opposite sign. The Bouguer anomalies reach a minimum of −15 mGal, whereas the free-air anomalies range up to +40 mGal. This area also has significant topographic relief with a maximum elevation of 1600 metres, although on a regional scale, the maximum average elevation for a 20-minute tessera is 840 metres.

The gravity data were reduced using a density of 2.2 tm^{-3} for the Bouguer anomaly computation. As this section of the area has significant relief and the rocks above sea level have a density nearer to 2.5 tm^{-3} than 2.2^{-3} tm, the former value would have been a better density for the Bouguer anomaly calculation in the area. Bouguer anomalies have recently been calculated using a density of 2.67 tm^{-3} by Anfiloff & others (1976), who present regional Bouguer anomalies in this area that have the same form, but reach a minimum of approximately −25 mGal. Thus the Bouguer and free-air anomalies are small and of opposite sign, indicating that the area is generally isostatically compensated. The small anomalies occur over both the Georgetown Inlier and the Tasman Geosyncline, the most recent mobile area in the surveyed region. The geosyncline is up to 300 km wide onshore at these latitudes, and certainly extends eastward for a considerable distance offshore. As the principal tectonism had ceased by the early Mesozoic, and during its active phase moved east from the stable shield, the shelf area of this study would be expected to have gradually approached isostatic equilibrium and stabilized since the Palaeozoic.

The area of the Mesozoic deposition in the onshore section of the Laura Basin, although it is part of the Tasman Geosyncline, appears to be uncompensated. It is generally of low relief and has free-air anomalies up to +40 mGal and Bouguer anomalies of similar magnitude. Consequently, the area is under-compensated and requires a lowering of the crustal rocks to reach local isostatic equilibrium. The area of the Laura Basin is small (250 km x 200 km), situated between the Palaeozoic basement highs of the Chillagoe Shelf and North Coast Structural High (see Fig. 2). This suggests that this small part of the Tasman Geosyncline, although locally under-compensated, may be supported by the strength of the older (Palaeozoic) basement rocks.

Crustal density

A knowledge of the density variation within the crust, and of the density of the upper mantle material beneath the Moho, is necessary for a crustal interpretation of gravity measurements. Surface and near-surface density determinations from boreholes provide density information directly for the near-surface rocks. The density measurements that have been made, apart from having a restricted distribution throughout the area, are representative of only the top kilometre or so of the crust and, as has been pointed out by Woollard (1962), the measured densities always tend to be too low.

Density measurements of subsurface rocks can rarely be obtained directly; even when available (usually from deep drilling associated with oil exploration) the results can only be applied to the upper 5 km or so of the crustal rocks. The deepest stratigraphic hole in the area is 3.6 km (Anchor Cay No. 1—see Tenneco, 1969), and the greatest depth for which density information is available is 901 metres in Mornington No. 2 (Delhi-Santos, 1961).

The measurement of *in situ* density must therefore be carried out indirectly for the deeper rocks, either by high-pressure experimental methods, e.g. Birch, 1960, 1961), or by studies of the propagation velocity of seismic P waves, e.g. Nafe & Drake (1957).

Density and seismic P wave velocity are related by $V_p = [(k + 4\mu/3)/\rho]^{\frac{1}{2}}$. Investigations such as those of Drake (Grant & West, 1965), in which over 500 measurements have been recorded, have been used to determine crustal densities. Woollard (1962) reviewed and synthesised the work of Birch and Nafe & Drake, and his own investigations and the work of Faust (1951), Parasnis (1960), and others.

Woollard's density data are mainly for North American rocks, although the seismic data are worldwide. On a worldwide basis the crustal velocity profile has significant variations. However, the Pn velocity, that of the upper mantle directly below the Moho, is reasonably constant, and usually has a value in the range 8.0 to 8.2 km sec^{-1}. Vogel (1971) and Kosminskaya (1971) both report Pn velocities as high as 8.4 km sec^{-1} in northern Europe and Russia respectively; however, Woollard (1962), using available data from all countries, finds that 8.15 km sec^{-1} is the mean value. Woollard has compiled a velocity-density relationship for sedimentary and crystalline rocks which is generalised, and may be substantially in error in an individual area, but should have general applicability. The relationship between the seismic P wave velocity, V_p, and rock density, ρ, is, to a first approximation, reasonably linear. This result is not suggested by the form of the relationship as given above between V_p and ρ. However, the bulk modulus, k, and the shear modulus, μ, increase rapidly with increasing depth in the crust, whereas ρ increases more slowly resulting in the approximation to a linear relationship for V_p and ρ in the crust. Meissner & Vetter (1976) have compared the velocity-density relationships of Woollard (1962) and of Dortman & Magid (1968). Both relationships coincide for velocities greater than about 6.7 km sec^{-1} (equivalent to 3.05 tm^{-3}); below this the Dortman & Magid relationship gives greater densities for a particular seismic velocity than does Woollard. Woollard's $V_p \sim \rho$ relationship (identical to that of Dortman & Magid (1968) at the depth of interest) with local seismic velocity data has been used to estimate possible densities for the lower crustal rocks in the north Queensland area.

Finlayson (1968) has measured Pn velocities ranging from 7.84 to 8.09 km sec^{-1}, with a mean of 8.0 km sec^{-1}, in northern Queensland, while Underwood (Cleary, 1973) recorded Pn velocities of 8.15 and 8.17 km sec^{-1} in the Northern Territory just west of the area under consideration.

Cleary (1973), in his review of the Australian data, has noted a similar, systematic Pn velocity variation from 7.84 km sec^{-1} on the eastern Australian coast to 8.17 km sec^{-1} in central Australia. Woollard (1962) indicates that the average density contrast at the Moho is 0.4 to 0.5 tm^{-3}, corresponding to a Pn velocity of 8.15 km sec^{-1} and a density of 3.45 tm^{-3} below the Moho. Finlayson (1968) derived P_1 and P_2 velocities within the crust in the ranges 5.9 to 6.0 km sec^{-1}, and 6.5 to 7.0 km sec^{-1}, respectively. On this basis, and using the Woollard relationship between velocity and density, the upper mantle density probably varies from 3.25 to 3.45 tm^{-3} from the east coast to the western margin of the area, with intermediate layers having densities of 2.9 tm^{-3} and 2.7 tm^{-3}, corresponding to the P_2 and P_1 layers respectively, of Finlayson (1968). The crustal density model is shown in Figure 8.

The upper crustal density of 2.7 tm^{-3} is intermediate between the value of 2.74 tm^{-3} suggested by Woollard (1962) and the more generally used value of 2.67 tm^{-3} (see for example Heiskanen & Vening Meinesz, 1958, p. 6).

The density contrast across the Moho then ranges from 0.55 tm^{-3} in the western part of the area to 0.35 tm^{-3} in the southeastern sector and 0.45 tm^{-3} in the Cape York area. If a horizontal (or strictly an equipotential) base is assumed for the upper crustal layer, then any gravity anomaly caused by a density contrast across it will be of infinite wavelength, and hence will not be apparent in the relative anomalies in the survey area. Finlayson (1968), however, has shown in a seismic study the existence of an upper crustal layer with a form similar to the Moho. The entire regional Bouguer anomaly could have been assumed to be related to the density contrast across this interface (0.2 tm^{-3}), the modelling carried out and the shape of the base of the upper crustal layer determined. The result would be the same as an upward continuation from the Moho. As the depth constraints which can be placed

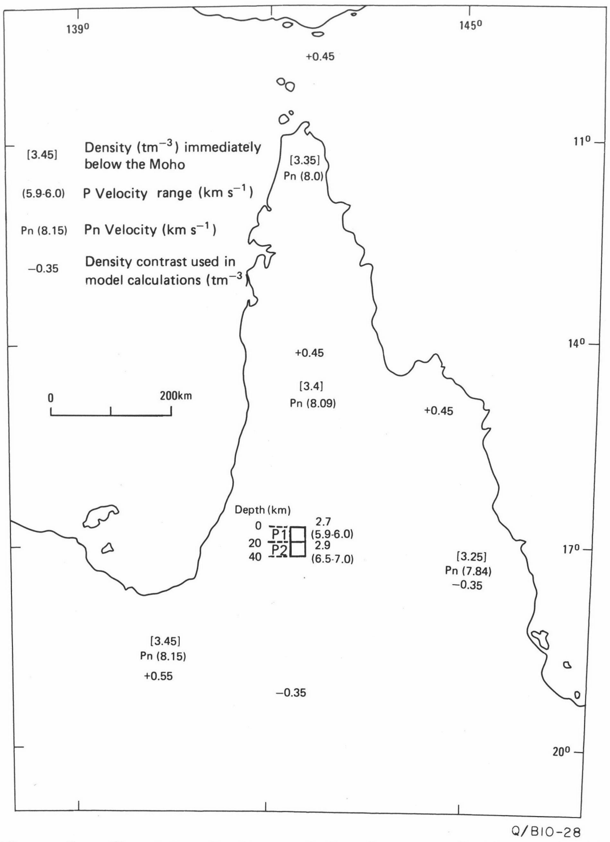

Figure 8. Crustal velocity and density—north Queensland.

on the base of the upper crustal layer are very localised, as indeed they are also for the Moho, it was decided to assume this interface to be horizontal and to assume that the gravity anomalies result from a density variation at Moho depth. As Finlayson (1968) has shown an intermediate layer to exist, the interpretation put forward in the following sections must represent an extreme situation. The Moho relief must actually be smaller than that obtained from the modelling, but may reasonably be assumed to be of similar form.

The standard crust

To provide a basis for interpretation in an area, a 'standard crust' (for which the Bouguer anomaly is zero) can be selected. This concept, while not necessary, is useful, in that it fixes the depth about which anomalous masses may be located to provide a model solution to the potential field. It does not matter whether a standard crustal thickness is selected from the seismic and gravity data, as discussed in this section, or arbitrarily assigned where no geophysical data are available. In either case it has the effect of reducing the number of parameters to be varied while attempting to construct a viable model and hence simplifies the modelling process. If the standard crustal thickness is incorrect, then the general form of the crustal model will still be retained and it requires only upward or downward continuation to meet the correct crustal conditions. As the Moho depth is rarely known precisely, this concept of a standard crust permits the construction of a crustal model with the appropriate form, even though the depths may not be exact. The solution still remains one of an infinite family of solutions, but must be considered to be more probable than the remainder, because it is constructed making use of, and consistent with, other relevant available geophysical data. To refine the model requires accurate depths to the Moho defined by other methods, e.g. deep seismic reflection.

Steinhart & Meyer (1961) concluded from analysis of data from 72 Moho refraction-seismic projects throughout the world that there is no correlation between Pn velocity and crustal thickness. However, after excluding some Russian experiments about which they had reservations, they showed a statistically significant relationship between mean crustal velocity and crustal thickness. As the mean crustal velocity is approximately proportional to density, a crustal section with a higher than 'normal' density will be thicker than a 'normal' crust. After an investigation of the possible correlation between crustal thickness and any, or all, of Pn velocity, mean crustal velocity, elevation, regional isostatic anomalies, Bouguer anomalies, and local isostatic anomalies, Steinhart & Meyer concluded that the only parameters which can be used in a predictor for crustal thickness are Bouguer anomaly and mean crustal velocity. They derived a relationship

$$\text{Crustal Depth (km)} = -61.0 - 0.0390 \times \text{Bouguer anomaly (mGal)} + 15.39 \times \text{mean crustal velocity (km s}^{-1}\text{)}$$

as a 'linear predictor' for the crustal depth from regression calculations using the parameters previously listed. The average Bouguer anomaly in the area of north Queensland is approximately +22 mGal and the mean crustal velocity is 6.33 km s^{-1}, yielding a crustal depth of 36 km.

Woollard (1962), in a study of the relationship of regional Bouguer anomalies and various parameters of the crust, concluded that a linear relationship exists between Bouguer anomaly and crustal thickness. This empirical relationship

$$\text{Crustal thickness (km)} = 33.4 - 0.85 \times \text{Bouguer anomaly (mGal)}$$

exhibits a wide variation in crustal thickness for any Bouguer anomaly and hence can only be applied to indicate the order of the unknown parameter. As Woollard noted, the average relationship may be considerably in error in any area because of geologic conditions. Demenitskaya & Belyaevsky (1969) have summarised the relationships between crustal thickness and Bouguer anomaly, and indicate that they only apply in average conditions, e.g. when no active tectonic forces are operating.

Wellman (1976a) predicted a crustal thickness in this area of 35 km to 40 km, assuming complete isostatic equilibrium. In studies of Rayleigh wave dispersion Thomas (1969) showed that the crust exhibited considerable uniformity; in north Queensland a satisfactory Rayleigh wave-dispersion model had a crustal thickness of 40 ± 1 km. Brooks (1969), from Rayleigh wave-dispersion studies found the probable Moho depth in southern Papua New Guinea (north of this area) to be 33 km ± 1 km.

In the area studied the regional Bouguer anomalies range from −15 mGal to +40 mGal, which would indicate an average crustal thickness of 33 km within a probable range from 25 km to 40 km. The seismic refraction studies in north Queensland indicate a crustal thickness of 35 km near the coastal margins, and 45 km in the central part of the area. A thickness of 40 km has been selected as the standard crustal thickness for the gravity modelling. This value is the upper limit of the range predicted by Woollard (1962) from his worldwide gravity analysis, is only 11 percent greater than the value given by the linear predictor derived from gravity and seismic data of Steinhart & Meyer (1961), and is in the mid range of the thicknesses measured by Finlayson (1968).

Kosminskaya (1971) also suggests from deep seismic sounding that 40 km is an average depth for continental crust. The value chosen is thus consistent both with worldwide studies, seismic refraction profiles carried out in the actual area, and Rayleigh wave dispersion studies.

Modelling method

There are few anomalies in north Queensland which meet the accepted criteria for modelling in two dimensions without the application of significant corrections for end effects; three-dimensional models have therefore been used. Three-dimensional models may be calculated by various methods, such as comparison to standard curves for simple geometric bodies, summation of the attraction of vertical prisms, e.g. Nagy (1966), or a mass line approximation. In this study the body was approximated by a series of polygonal laminae and the effects of these were summed. The method has been described by Talwani & Ewing (1960), and Talwani (1965), and a computer program, in Elliott 503 Algol, utilising this method has been written in the Geophysics Division of the Department of Scientific and Industrial Research, New Zealand. This three-dimensional body-attraction program (Woodward, pers. comm., 1970) was modified to run on the University of Tasmania Elliott 503 computer.

The closeness of fit between the observed and calculated gravity anomalies can be evaluated in two ways. In this analysis both methods of evaluation were used.

Firstly a subjective, but rapid, assessment of the fit of the anomalies was used during the modelling process. It becomes readily apparent when small changes in body parameters produce changes in the computed anomalies such that the computed anomaly contours oscillate about the Bouguer anomaly contours for successive models. At this stage, body changes are of the order of 0.1 km in contour depth, and of 1 km to 2 km in contour position. Changes of these magnitudes at the Moho are insignificant having regard to the values of depth, and the precision of lateral position, of the anomalous masses.

The second method of assessment of the fit of the anomalies is objective, and was used in the final selection of the model. Because the accuracy of the Bouguer anomalies and their gradient is known, the horizontal variation in position of each observed contour could be assigned a range within which the calculated contour must lie. Once within this range it becomes pointless to adjust the body parameters, as the fit is within the accuracy of the observed data. This would be an extremely tedious process to perform manually, and is performed by a digital computer with sufficient storage. For the volume of data under consideration, it is outside the capability of the Elliott 503 available. However, this range may be assessed in another way. The Bouguer anomaly accuracy is $\pm$ 2 mGal, hence, as the contour interval is 5 mGal, the fit required is to within 40 percent of the horizontal contour separation. This assumes that the gravity gradient between adjacent contours is linear, which it rarely is. However, for these purposes, the assumption of linearity is considered reasonable. The accuracy of the fit can then be assessed visually.

The crustal model

The Moho structure contours determined seismically by Finlayson (1968) were used to define the first crustal model. The -35 km, -40 km and -45 km structure contours were digitised, and the gravitational attraction of the body thus defined was computed, using a density contrast of -0.4 tm^{-3}.

Following this preliminary computation the basic crustal model was defined in three segments to simplify the computations. The first segment, A, corresponds to a zone of positive regional Bouguer anomalies west of longitude 141°E. The area of negative regional Bouguer anomalies from longitude 141°E to 146°E and generally south of latitude 16°S, is designated segment B, while segment C includes the positive regional Bouguer anomalies north of latitude 16°S. These three basic segments are subdivided, both for computational purposes and for discussion (Fig. 9). The density contrasts used for all computations were $+0.55$ tm^{-3} for segment A, -0.35 tm^{-3} for segment B, and $+0.45$ tm^{-3} for segment C. After a series of model adjustments a final crustal model was adopted and its gravitational attraction was obtained (Figs. 9, 10 respectively).

The Moho has been structure-contoured as three separate segments with respect to mean sea level (Fig. 11), using the model of Figure 9. The contour interval of the structure contours within each segment is 1 km. Broken form lines have been added at smaller intervals, where necessary, to show the Moho form and relief adequately. Areas of 40 km thick crust between the structure-contoured segments are stippled.

The relief shown by the Moho across the area is 6.5 km, with the crustal thickness varying from 36 km to a maximum of 42.5 km. The structure of the Moho

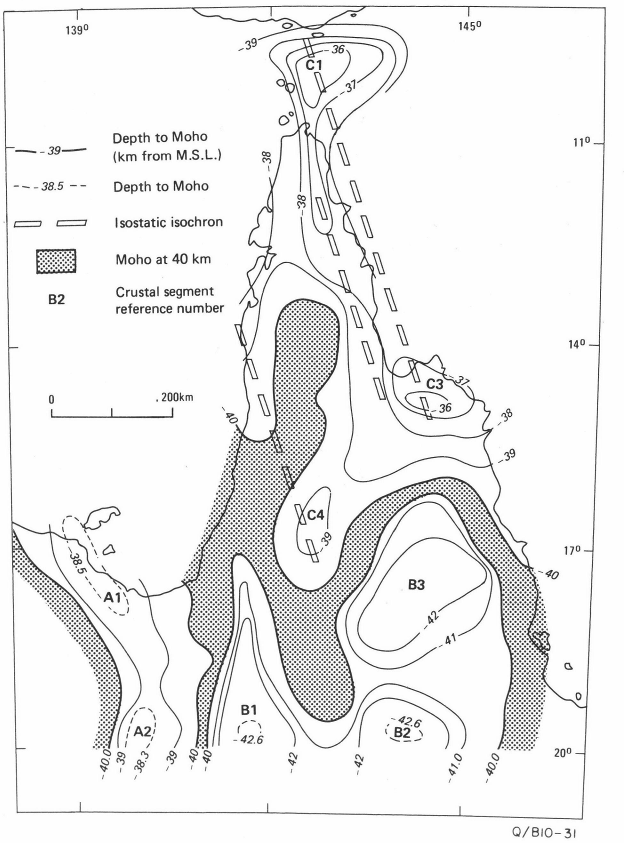

Figure 9. Crustal model—north Queensland.

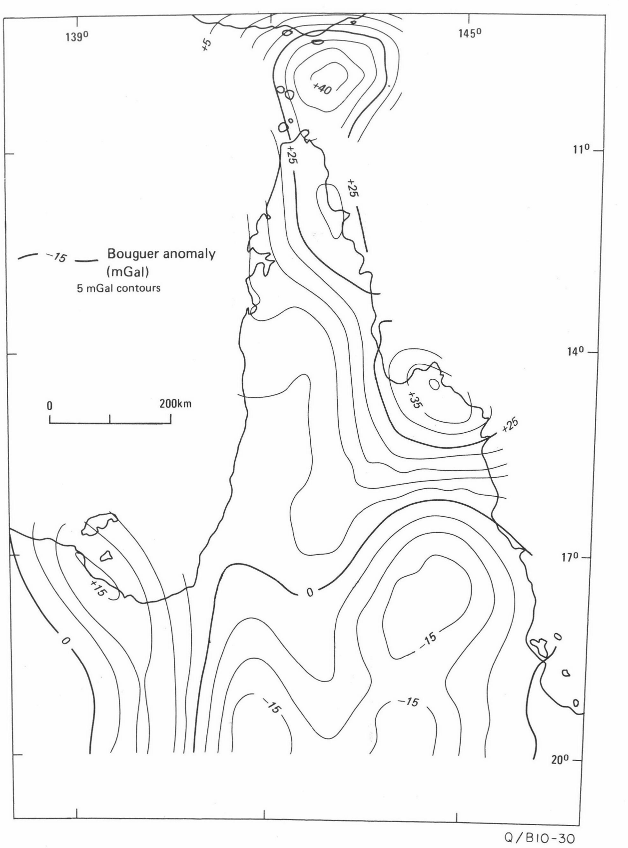

Figure 10. Gravitational attraction of the crustal model.

reveals a close correlation with major surface structures in some areas, and little or none, in others.

A number of the residual gravity anomalies were modelled; they all appear consistent with the known surface geology and can be attributed to local variations of basement depth or to near-surface rocks. A more detailed discussion of this aspect is given in Shirley (1976).

Crustal Segment A

The segment A2 corresponds closely with the outcrop of the Mount Isa Block. This is a major crustal upwarp, which was part of the final orogeny at the end of the Lower Proterozoic. The Mount Isa Block has since been a structurally high area and forms the divide between the Palaeozoic sediments to the east, and the Cambrian and Ordovician sediments of the Georgina Basin to the west. The north-northwest extension of A2 (segment A1) is clearly a continuation of the Block beneath the Mesozoic cover into the Gulf of Carpentaria. Pinchin (1973) suggested that this zone of positive anomalies extends across the southern part of the Gulf of Carpentaria into Arnhem Land, but the recently published Gravity Map of Australia (Anfiloff & others, 1976) shows this positive anomaly zone to terminate west of Mornington Island. This extension of the present Mount Isa Block was probably the eastern margin of the Proterozoic deposition in the McArthur Basin. The existence of Mesozoic outliers on parts of the Mount Isa Block (Doutch & others, 1972) shows that the block has been uplifted since the early Mesozoic, but this movement seems to have been small. The Mesozoic and younger sedimentation in the Carpentaria Basin has been mainly controlled by the sagging of the basement which left local highs, e.g. the Fort Bowen Ridge.

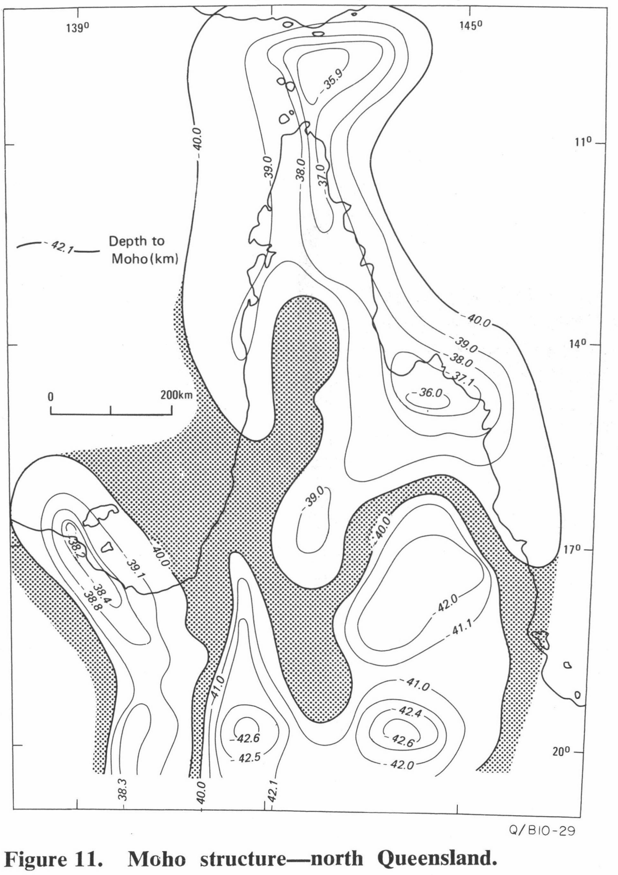

Figure 11. Moho structure—north Queensland.

The A segment is thus an elongate zone of thin crust, varying in thickness from 38 to 38.5 km, occupied by metamorphosed Proterozoic sediments and intrusive rocks, and which stabilised at the end of the Lower Palaeozoic. It has not yet reached local isostatic equilibrium and owing to its narrow width, it is unlikely to do so. The surface expression of this crustal unit is the Mount Isa Block, the northern end of which is concealed by a thin Mesozoic sedimentary cover and the waters of the Gulf of Carpentaria.

Crustal Segment B

The B segment defined by the gravity model consists of three discrete sections. Segment B1 coincides with the uplifted basement area of the Euroka Arch. Segments B2 and B3 are in isostatic equilibrium and B1 is slightly overcompensated. Local compensation for an area as small as B1 is unlikely. On a broad scale, segments A and B1 together appear regionally compensated but locally they are under-compensated, and over-compensated respectively, by small amounts.

The north-tapering crustal segment B1 does not close to the south, and represents a depressed section of crust that reaches its maximum depth of 42.6 km at the southern boundary of the area. Here the basement rocks are folded and eroded Palaeozoic sediments, which appear as small outcrops through thin Mesozoic cover on the Fort Bowen Ridge, a north-trending line in the central section of the Euroka Arch. The Euroka Arch has been rising owing to isostatic adjustment, at least since the Mesozoic, when it first formed the depositional barrier between the Carpentaria Basin to the north, and the Eromanga Basin to the south. Doutch & others (1972) consider that this barrier moved south during the Mesozoic into its present position, implying that the uplift was more extensive in the southern part of segment B1 than in the northern end. At present the thickest part of the crust in this segment is at 20°S, and it now appears to be in regional isostatic equilibrium. The gradual emergence of other basement areas of the Carpentaria Basin, north of the Euroka Arch, is also suggested by the structures in the Mesozoic sediments. These movements appear to have been minor compared with that of the Euroka Arch, and only the lobate area C4 is reflected by the regional gravity field. The Euroka Arch is, then, the basement expression of the crustal feature B1.

The segments B2 and B3 correspond to the general surface expression of the Georgetown Inlier and the southern part, in this area, of the western portion of the Tasman Geosyncline. No expression of the Palmerville Fault or the Broken River Embayment is apparent. The Lolworth Block, an extensive Middle Ordovician and lower Devonian granite mass emplaced across the Tasman Geosyncline, is also not evident in the regional gravity interpretation. The thick crust of segments B2 and B3 is isostatically compensated and reaches its maximum thickness of 42.6 km in segment B2. The area covered by segments B2 and B3 corresponds with the maximum topographic relief; the apparent crustal high between B2 and B3 corresponds to a relative topographic low in which the relief is approximately 250 metres. If the data in this area were corrected for terrain it would result in a partial coalescence of segments B2 and B3. Hence, these two segments are regarded as the crustal expression of the Georgetown Inlier, and the area of thick crust in isostatic equilibrium corresponds to the area of significant topographic relief. After a history of Proterozoic and early Palaeozoic sedimentation it emerged and stabilised by the Mid- to Late Devonian. The eastern margin has been faulted and would have undoubtedly been affected isostatically by the orogenic movements in the Tasman Geosyncline. However, the Georgetown Inlier appears to have stabilised rapidly, with the Tasman Geosyncline, by the Mesozoic, with only small movement since. Voluminous intrusive and extrusive rocks of the area (other than the granites) do not appear to be directly related to the regional gravity anomalies and major crustal structures.

Crustal Segment C

Segment C forms an elongate meridional zone of thin crust with a minimum thickness of 36 km. Segment C1 corresponds with the Cape York-Oriomo Ridge, evident on the surface as granite outcrops from the northern extremity of Cape York to Mabaduan in southwest Papua New Guinea. If the gravity anomaly of this crustal segment corresponds solely to a granite body, or bodies, it is the only one in the area to exhibit this correlation on a crustal scale. It is, however, noted that two of the wells in southwest Papua New Guinea (Iamara No. 1 and Wuroi No. 1) bottomed in acid volcanics on the northerly extension of the Oriomo Ridge; Mutare No. 1, however, bottomed in granite. Possibly the crustal feature C1 reflects uplifted basement rocks in which granite is intruded, rather than being an enormous mass deficiency solely related to a granite body. It is evident that this crustal feature is much more extensive than suggested by the actual granite outcrops in the Torres Strait area.

The C2 segment coincides with a Moho gradient with the crust thinning to the east. This is the area of the Coen Inlier. In contrast with the Cape York-Oriomo Ridge, there is extensive surface outcrop of upwarped Precambrian metamorphics and granites, but the Inlier does not correspond with a closed crustal thickness anomaly. This suggests that vertical displacement may have been less than in the northern C1 area, and that the extensive Precambrian outcrop does not imply major vertical movement. Indeed, the basement relief across Cape York in this area, say along the parallel of 14°S latitude, is small, with shallow Mesozoic cover in the western part. The lobate areas C4 and C5 show small variations in crustal thickness, of the order of 1 km. The area covered by segments C4 and C5 is near to isostatic adjustment, whereas segment C2, although its location at the edge of the survey area causes it to be poorly defined, requires more downward movement to become isostatically adjusted. This is consistent with the concept of the younging, to the north and east, of the tectonic activity associated with the Tasman Geosyncline. The process of isostatic adjustment would be expected to respond to this progressive stabilisation of the Tasman Geosyncline. Figure 11 illustrates the areas (marked by broken lines) for which contemporaneous isostatic adjustment is proposed. In an analysis of gravity trends in Australia Wellman (1976b) shows a general correlation of gravity trends, the trends being younger to the east in north Queensland; but he could not define the relative ages of the Mount Isa and Georgetown areas because of an intervening area of complex gravity trends.

Eastern continental margin

The eastern border of the area, essentially the eastern Queensland coast, cannot be reliably interpreted from this study owing to its proximity to the edge of the continental shelf and to the lack of data in the shelf area. [These data have recently become available (Anfiloff & others, 1976) but are not used in this investigation.] As mentioned earlier, the strong positive gradient, normally exhibited by gravity anomalies near isostatically-compensated continental margins, is readily apparent on the plotted data for this area. Here the continental slope is, in general, at least 50 km east of the coastline. Its closest approach to the coast is 30 km northeast of Cape Melville; it reaches 140 km from the coast near Torres Strait.

East of the continental margin in the southern part of the area is a downfaulted block of continental rock, the submerged Queensland Plateau (Ewing & others, 1970), separated from the continental margin by the Queensland Trough. The seismic-refraction profiles over the Queensland Plateau suggest a depth of at least 15 km to a layer with a velocity of 7.3-7.6 km sec^{-1}. The Moho, although not recorded under the Plateau, was detected further east and had a velocity of 8.3 km sec^{-1}. Ewing & others (1970) consider the Queensland Plateau to be downfaulted continental crust rather than uplifted oceanic crust. Pinchin & Hudspeth (1975) estimate from marine gravity observations that its crustal thickness is approximately 25 km.

The critical problem in the interpretation of the near-coastal information is the lack of knowledge concerning the crustal thinning from continental crust of 40 km to oceanic crust of 10 km. Flavelle & Yoshimura (1974) have shown that significant crustal thinning generally commences approximately 50-70 km towards the continent from the edge of the continental slope. Because the extensive continental block of the Queensland Plateau is submerged adjacent to the continental slope in the southern part of the area, where the continental slope is narrowest, it is reasonable to assume that the crustal thinning here will be less than if oceanic crust had been adjacent to the area. Consequently the model data are considered valid for the area to within 20 km or 30 km of the coast, because the continental shelf is wide in the north of the area; and where it is narrower in the southern part, the crustal thinning is probably minimised by the presence of the Queensland Plateau.

East of segments B2 and B3 the southern part of the coastal area appears to be a normal isostatically adjusted continental margin. North of this (from 15.5°S) the continental margin exhibits positive Bouguer anomalies, but is not compensated. It is therefore suggested that, regionally, this area still needs to sink to reach isostatic equilibrium. Isotopic dating (Richards & others, 1966; Cooper & others, 1975) indicates that the Tasman Geosyncline is younger to the east and the north, and this is consistent with the development of the Geosyncline as determined from a study of the mineral deposits (Solomon & others, 1972). Consequently it is suggested that the northern region, downwarped and overlain by up to 3.7 km of Mesozoic to recent sediments, still needs to sink to reach isostatic equilibrium. Mutter (1973) has calculated that the Queensland Plateau, with regional free-air anomalies up to +50 mGal, needs to sink 450 metres to reach isostatic equilibrium. Because the Tasman Geosyncline becomes younger to the east and north it is suggested that the Queensland Plateau and the northern section of Cape York (segments C1, C2, and C3) are at a similar stage of isostatic development.

This suggestion that there is a correlation between the degrees of isostatic compensation of the various areas (see Fig. 11) does not imply that the areas are still undergoing active adjustment. Rather it is thought that the areas have stabilised at similar stages of compensation, apparently paralleling the growth of the Tasman Geosyncline. Earthquakes would be expected if isostatic adjustment were currently progressing at a significant rate, but the area appears aseismic. Although the only stations near the area are those of the World Wide Seismic System at Charters Towers (CTA) and Port Moresby (PMG), together with some portable stations operated from time to time in Papua New Guinea, these stations could be expected to detect events of magnitude 3.5 or greater over the area of this study (*cf.* Denham, 1976). In the period 1960-1972 only four earthquakes with a magnitude (M) greater than three were recorded in the area (McEwin & others, 1976) and since 1900 only 8 earthquakes with $M>4.5$ have been recorded (data supplied from BMR earthquake data file, 1976) with four more events nearby, in the Gulf of Carpentaria. This low seismicity indicates that the area is relatively stable. Falvey & Taylor (1974) have shown from seismic studies over the Queensland Plateau that basement (Palaeozoic?) faults were still active in the Eocene, but the Late Oligocene to recent sediments are not faulted. It seems then that this area was stable by the Late Oligocene, although as noted earlier, Mutter (1973) has calculated that the Queensland Plateau should sink 450 metres to reach local isostatic equilibrium.

Segment C3 coincides with the Laura Basin. The Mesozoic sediments in this basin are thin (<1.5 km) and rest unconformably on Palaeozoic basement which outcrops as the basin edge to the east (North Coast Structural High). This area is of marginal size for isostatic adjustment, and consequently will lag behind the larger area crustal units in which isostatic compensation will be approached more quickly. The stage of adjustment appears consistent with the concept of the isostatic adjustment following the pattern of the orogeny, i.e. younger to the north and east, because segment C3 appears to have reached a similar isostatic state to that of segment C1.

Conclusions

The departures from isostatic equilibrium that occur are not large. The western part of the area, the Mount Isa Block and its inferred northern continuation, is an area of thin crust which has not quite reached isostatic equilibrium and, because of its dimensions, will probably not do so. The southern part of the Carpentaria Basin across the Euroka Arch south into the northern Eromanga Basin is near isostatic adjustment. This area, with the Mount Isa Block, appears to be regionally compensated with local isostatic anomalies over each area but in the opposite sense (Fig. 8). East of this, the Georgetown Inlier and the Tasman Geosyncline are isostatically adjusted. The northern part of the Tasman Geosyncline, northern Carpentaria Basin, Coen Inlier and the Cape York-Oriomo Ridge still need to sink to reach isostatic equilibrium, but now appear to have achieved a stable condition. The isochrons of the isostatic movement (Fig. 12) parallel the stages of development of the Tasman Geosyncline in this area, i.e. they are younger to the north and east.

The deep crustal structure is not generally amenable to two-dimensional analysis; a three-dimensional crustal model has been computed, assuming that the regional Bouguer anomalies are due to density variations at Moho depth. Having regard to the restrictions imposed in the interpretation, the crust appears to vary in thickness from 35.9 km to 42.6 km with the thickest crust being in the isostatically adjusted region in the south-east part of the survey area. The structure contours of the Moho show a good correlation between deep crustal structure and surface structure in some areas, e.g. Mount Isa Block, Euroka ridge, but little correlation in others, e.g. Coen Inlier. As may be expected, the smaller surface geological features, e.g. Broken River Embayment, have no deep crustal structural expression in terms of density variation. The Palmerville Fault has no expression in the regional gravity field, and is probably an upper crustal feature.

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