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Record 1973/205

THE GRAVITY ANOMALIES OF CENTRAL AUSTRALIA, AND THEIR SIGNIFICANCE FOR LONG-TERM TECTONIC MOVEMENTS

by

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SUMMARY

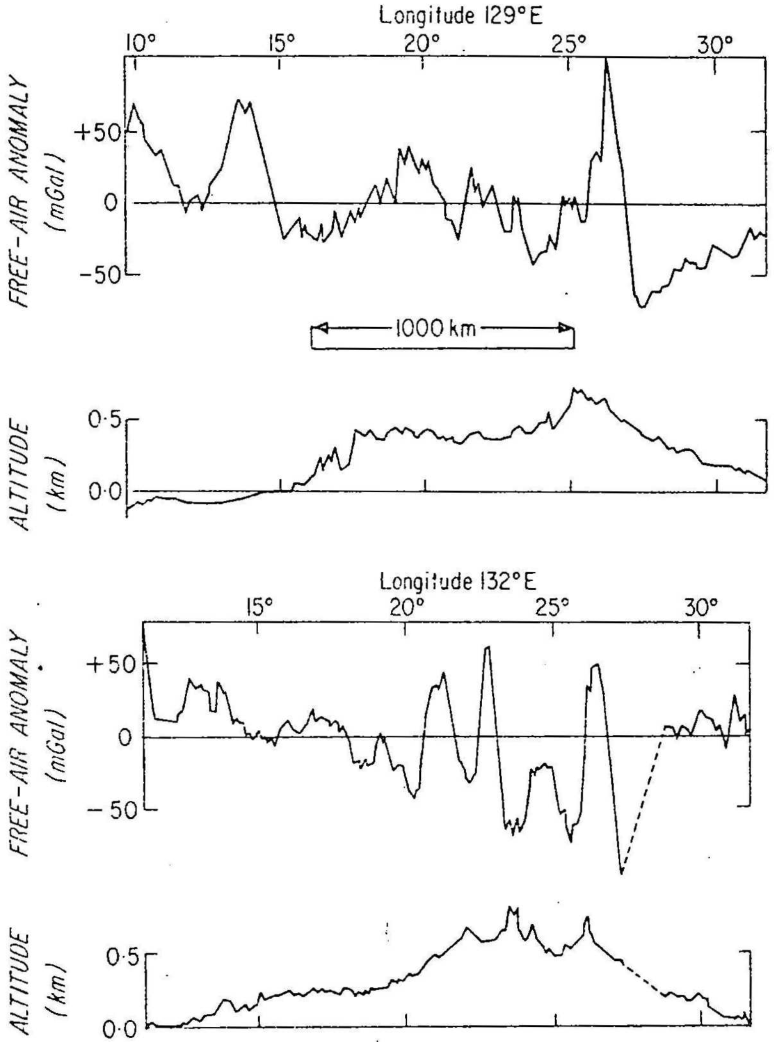
The Bouguer gravity map of Australia shows five prominent elongated negative anomalies striking approximately east-west with peak-to-peak distances of about 80 km and amplitudes up to 160 mGal. These anomalies correlate approximately with the Officer Basin, the southern and northern parts of the Amadeus Basin, the Ngalia Basin, and the Lander Trough in the Wiso Basin. The anomalies are too large to be explained by the sediments in these basins alone, and imply substantial density variations at a depth near the crust/mantle boundary. The absence of any evidence of major tectonic activity since the Carboniferous suggests that these anomalies have existed more or less in their present form for some hundreds of millions of years. This implies that the lithosphere in this region has a long-term strength of about 100 to 200 bar.

Over this area, whose dimensions are about 10° to 15°, the average free-air anomaly is negative with a minimum of about -30 mGal. This could arise from erosion of about 0.3 km of sediments without corresponding isostatic compensation; a time lag of intracratonic isostatic readjustment of the order of 5×10^{7} years, and a lithospheric strength of one or two kbar over this time, would be implied. This anomaly may be partly associated with the deeper mantle structure as revealed by studies of satellite orbits.

On the basis of seismicity evidence, some authors have proposed that the Australian continent is rifting apart. There is a well defined seismic zone running northwards from Spencer Gulf in South Australia to about latitude 30°S, but north of this the available data are far from conclusive. One hypothesis suggests that a 'Fitzroy-Spencer lineament' has been a major zone of shearing displacement since the Precambrian; this must be ruled out as the lineament intersects the gravity anomalies discussed above, and any substantial movement along it would have caused offsets of these anomalies; no such offsets are evident.

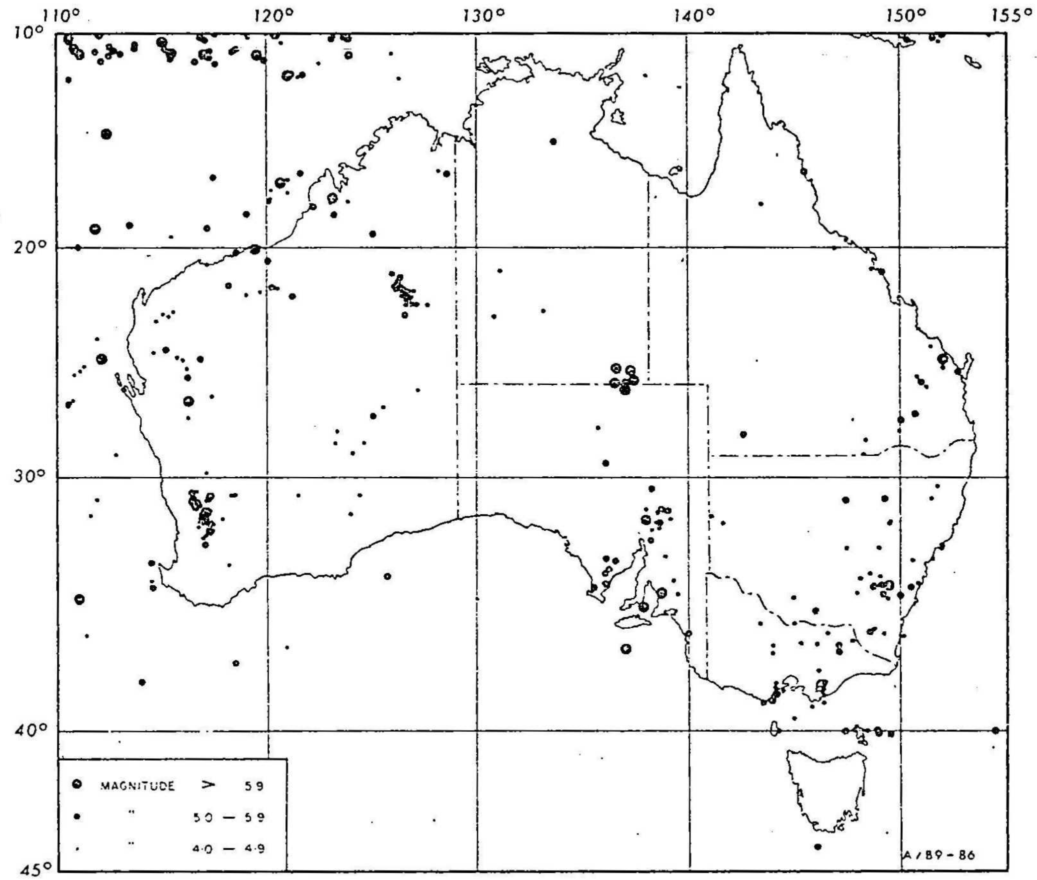
It is suggested that the central block containing the gravity anomalies has been a stable feature at least since the late Palaeozoic, and that stresses are adjusted along zones of weakness shown by minor seismicity around the boundaries. These zones approximately coincide with lineaments truncating the gravity anomalies and the major geological features, and it is probable that movements along them may have persisted for a long time, particularly on the western boundary.

To Accompany Record No 1973 /205



GRAVITY AND ALTITUDE PROFILE ACROSS AUSTRALIA

Fig. 1



AUSTRALIAN SEISMICITY 1900–1972

Fig. 2

A/B2-97A

THE GRAVITY ANOMALIES OF CENTRAL AUSTRALIA AND THEIR SIGNIFICANCE FOR LONG-TERM TECTONIC MOVEMENTS

J.C. DOOLEY

BUREAU OF MINERAL RESOURCES, CANBERRA, AUSTRALIA

This paper is an attempt to see what can be deduced about secular variations in position from the Earth's gravity field in the Australian region, together with some evidence from seismicity.

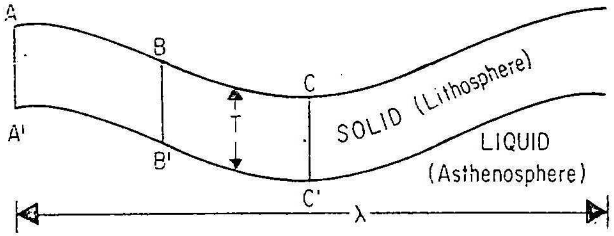
The preliminary Bouguer gravity map of Australia (BMR, 1973; see also Fig. 2 of Anfiloff & Shaw, 1974) shows five prominent negative gravity anomalies in Central Australia between latitudes 20^{o} and 30^{o}S approximately.

These gravity anomalies correlate with five ancient basins - from south to north, the Officer Basin, southern and northern Amadeus Basins, Ngalia Basin, and the Lander Trough in the Wiso Basin. Plumb (1972), and also the Tectonic Map of Australia (G.S.A., 1971; see also Fig. 1 of Anfiloff & Shaw, loc. cit.), described the history of this area in terms of orogenies, transitional periods, cratonization, and platform cover deposition, from the Archaean through to the early Palaeozoic.

The depth of these basins is fairly well known from seismic and aeromagnetic work, but only about half of the gravity anomalies can be accounted for by sediments unless we assume unreasonable density values. Models by Anfiloff & Shaw (1974), Mathur (in prep.), and Forman & Shaw (1973) have all resorted to density changes deep in the crust. The negative gravity anomalies generally overlap the outcropping basement rocks, suggesting major overthrusting. Basement outcrops generally appear as low mountain ranges between comparatively low-lying and flat sediments; thus the correspondence between Bouguer anomalies and elevation is the reverse of that expected for isostasy.

The free-air anomaly profiles along longitudes 129^{o}E and 132^{o}E (Fig. 1, after Wellman, in prep.) show this lack of isostasy. The surface altitudes between basins are not shown to full advantage because they are plotted from gravity station heights, which are generally sited so as to avoid peaks.

No major tectonic activity has occurred in the area since the Carboniferous (Plumb, 1972), nor is there, as far as is known, any present-day seismic activity in the area (Fig. 2, after Denham et al., in prep.). Presumably the anomalies must have originated during a period of intense tectonic activity, with compressive stress and overthrusting, and then have been frozen into the crust or lithosphere and are now supported by its strength.



Maximum stress in bars at AA', BB', or CC'

$\sigma_{max} = \Delta g \; f(\lambda/T)$

$f(\lambda/T)$ as below

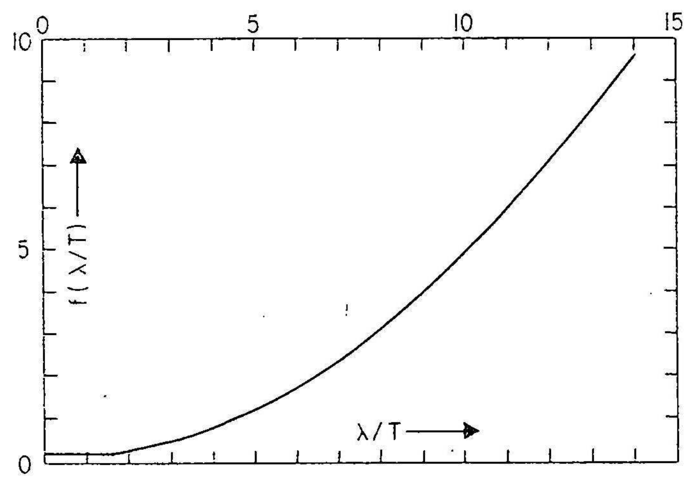


Fig. 3

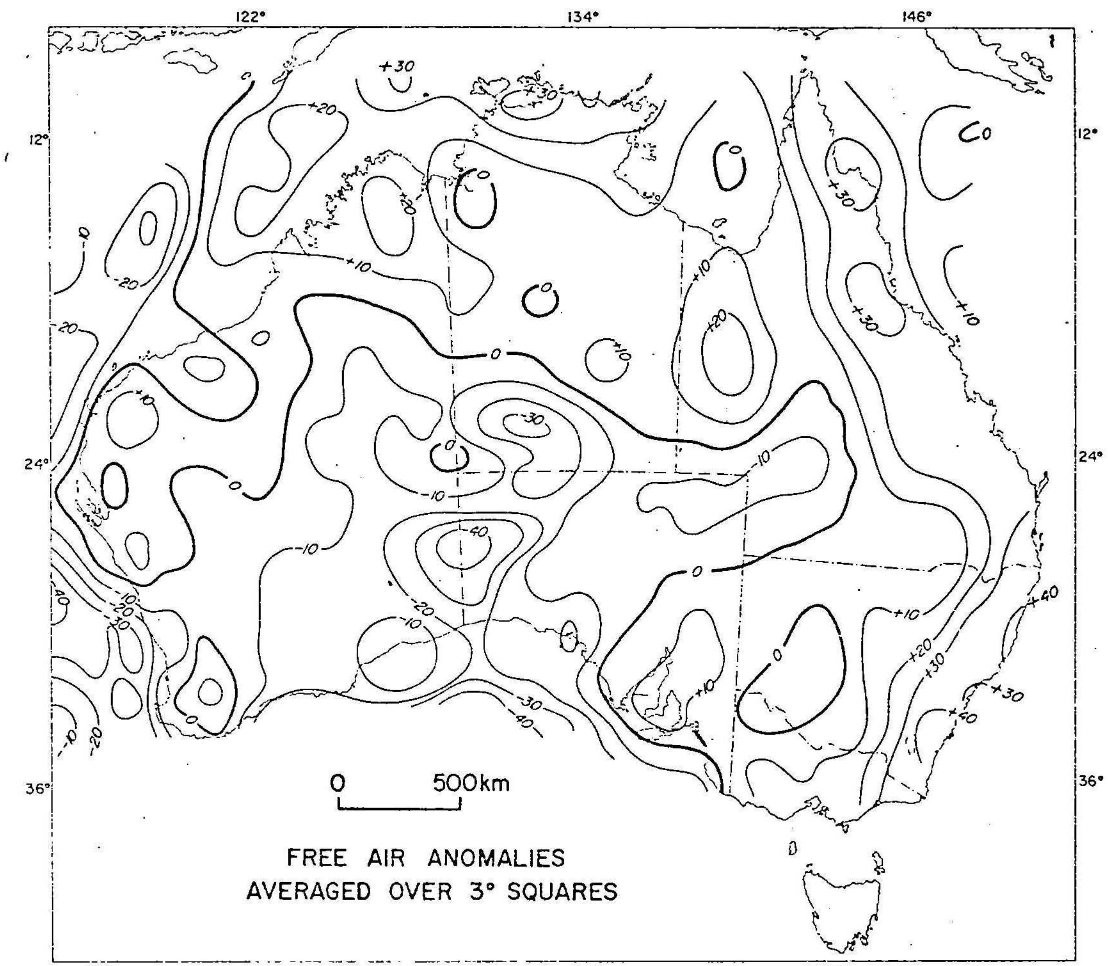


Fig. 4

An estimate of the strength needed to support these anomalies can be obtained from a simple model of McKenzie (1967). In Figure 3, the upper layer is taken as a solid resting on an asthenosphere which is effectively a liquid over the geological periods concerned. An applied load centred at C causes an elastic deformation of the crust (greatly exaggerated in the diagram). Depending on the parameters involved the maximum shear stress σ_{max} will occur either at AA' and CC', or at BB'. The free-air gravity anomaly Δg at C relative to A can also be readily calculated, and thus can be related to the maximum stress by means of the equation:

$$\sigma_{max} = \Delta g \quad f(\lambda/T)$$

where λ is the width of the deflected part of the lithosphere and T is the thickness. $f(\lambda/t)$ follows different laws according to whether σ_{max} occurs at BB' or CC'; the resulting function is plotted in Figure 3.

Estimates of amplitude and wavelength of the anomalies over the five basins are listed in Table 1. The Amadeus Basin was treated firstly as two separate basins, and secondly as one basin with the central gravity high smoothed out. Estimates of the shear strength scaled from Figure 3 are listed for a lithosphere 40, 60, and 100 km thick.

Thus this leads to a minimum strength of the lithosphere of say 100 or 200 bars. Laboratory measurements give somewhere about 4000 bars (Griggs et al., 1960). Naturally it is expected that strength over geological periods is much less, as stress applied for long periods causes deformation without breaking. Carey (1954) had proposed the concept of 'rheidity', or relaxation time beyond which stresses cannot persist without viscous flow becoming important. For igneous rocks he estimates about 10^9 years. Also he defined 'practical strength', which is a function of time and is the stress which can be supported for a given period. Thus we say that the practical strength of the lithosphere in Central Australia is at least 100 or 200 bars for a period of about 2×10^8 years. This is consistent with Carey's estimate of rheidity for igneous rocks.

If we examine the free-air anomaly profiles (Fig. 1), particularly along 132°E, we note that, if local effects of these major anomalies are smoothed out, there is a general negative value in the central portion compared with the southern and northern ends, with a width of 1000 km or more. To study this in more detail a compilation of

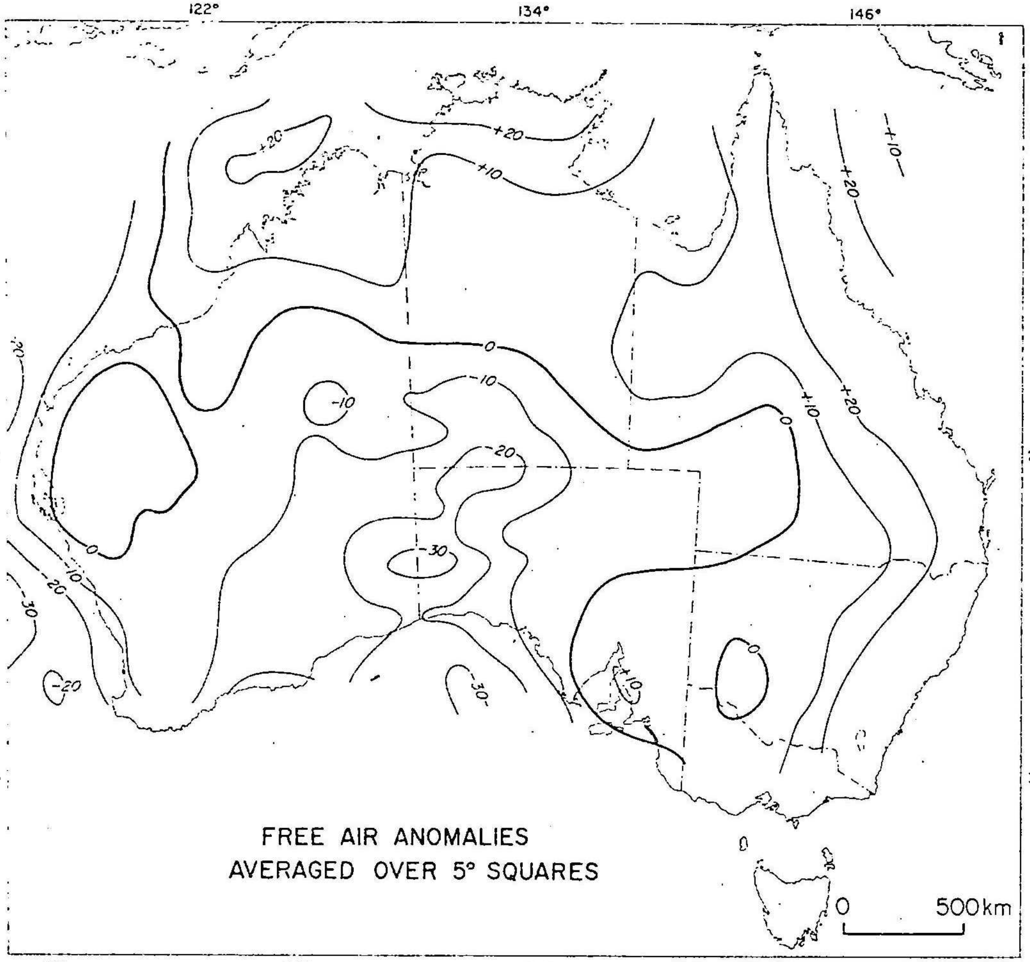

122°
134°
146°
12°
24°
36°
110°
+20
+10
0
-10
-20
-30
FREE AIR ANOMALIES
AVERAGED OVER 5° SQUARES
0 500km

Fig. 5

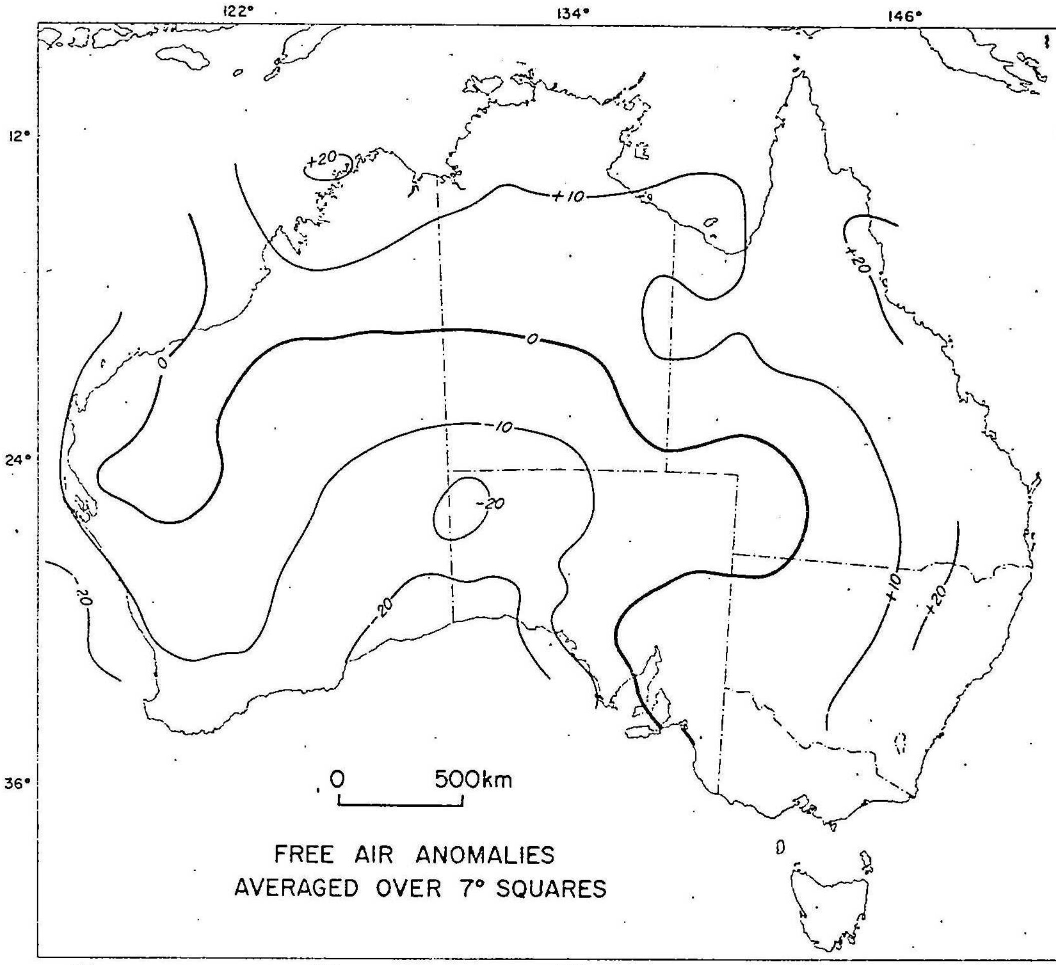

122°
134°
146°
12°
24°
36°
110°
+20
+10
0
-10
-20
0 500km
FREE AIR ANOMALIES
AVERAGED OVER 7° SQUARES

Fig. 6

free-air anomalies of $1^\circ \times 1^\circ$ lat/long 'squares' has been made for the Australian area. This is based largely on Mather's (1969a, 1969b) figures, but includes more data recently available, some from anomalies on tape in BMR national gravity repository, some calculated by Wellman (in prep.) and others estimated from Bouguer anomaly maps and then corrected to the mean elevation of the square for land squares. For more recent BMR marine surveys south and west of the continent the average was estimated directly from preliminary free-air anomaly maps. With coastal squares (i.e. part marine and part land) a combination of these two methods was used.

Some of these data are in a preliminary form and should not be regarded as the best that could be derived from available data for $1^\circ \times 1^\circ$ squares; however, if averaged over larger squares errors become much smaller. The series of maps presented here (Figs. 4, 5, 6, and 7) show contours for means of 3°, 5°, 7°, and 10° squares based on running averages of the 1° square means.

These all show a persistent gravity low in central Australia.

Consider an infinite slab of density anomaly $\Delta\rho$ and thickness T; the gravitational attraction is $\bar{g} = 2\pi k \Delta\rho T$. If the slab has finite width, then by calculating the integrated anomaly of a simple step fault we find that by averaging over a slab of width about 10T we get about $0.9\ \bar{g}$, the remaining $0.1\ \bar{g}$ being in the 'tails' of the anomaly.

Similarly if we consider that the Earth is homogeneous below a depth T, the average excess pressure on a level surface at depth L below this slab is $g_o \Delta\rho T$, where g_o is the surface gravity (actual variation with depth being very small near the surface). The gravity anomaly of such a slab is approximately proportional to the anomalous stress on a level surface beneath it.

Wellman (in prep.) has concluded from Fourier analysis that there is very little lateral density variation beneath about 60 km depth, except for the sources of the very broad anomalies in the low-order spherical harmonics of the Earth's field, as shown for example by satellite orbits. If we neglect these and assume that the whole anomaly is associated with sources in the upper 60 km, then horizontal averages over 600 km, or about 5°, would represent the stress at or just below this depth, and give an indication of strength. This gives a figure of say 1600 bars.

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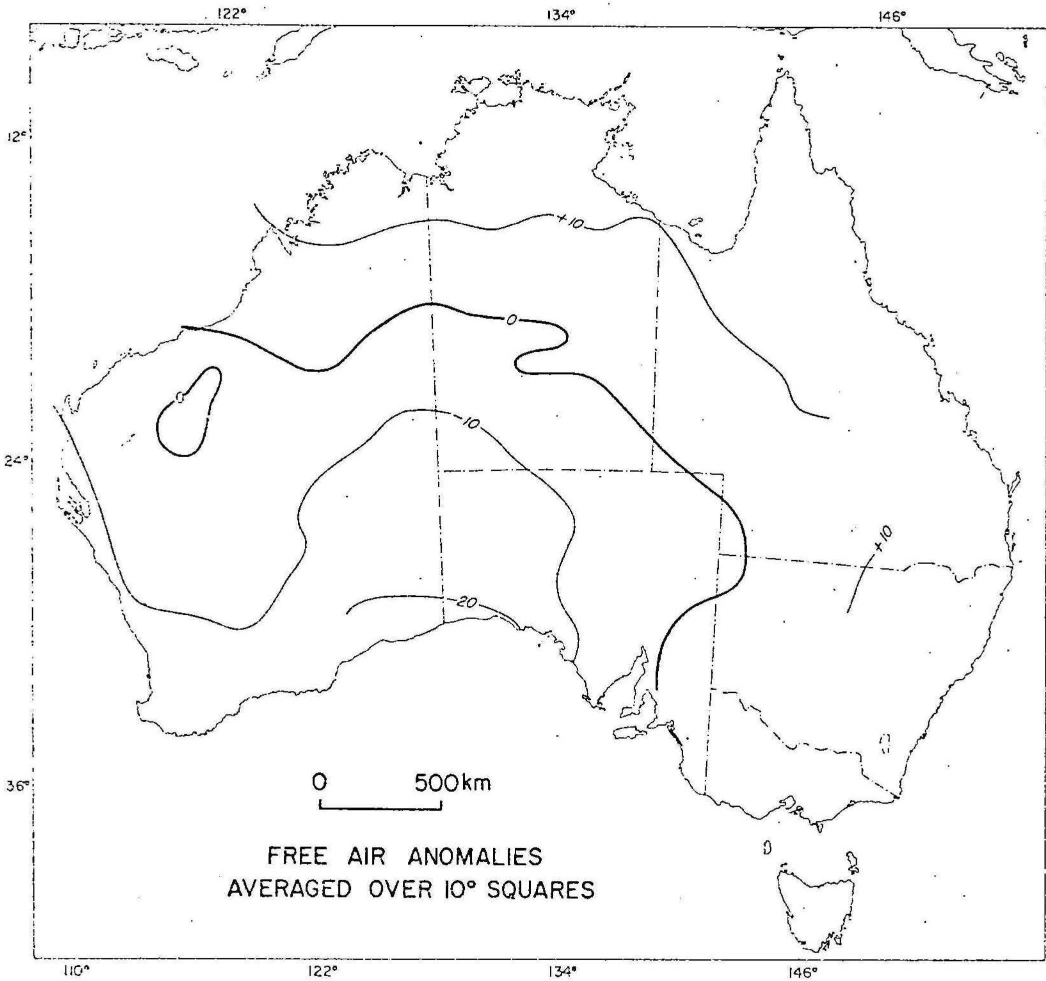
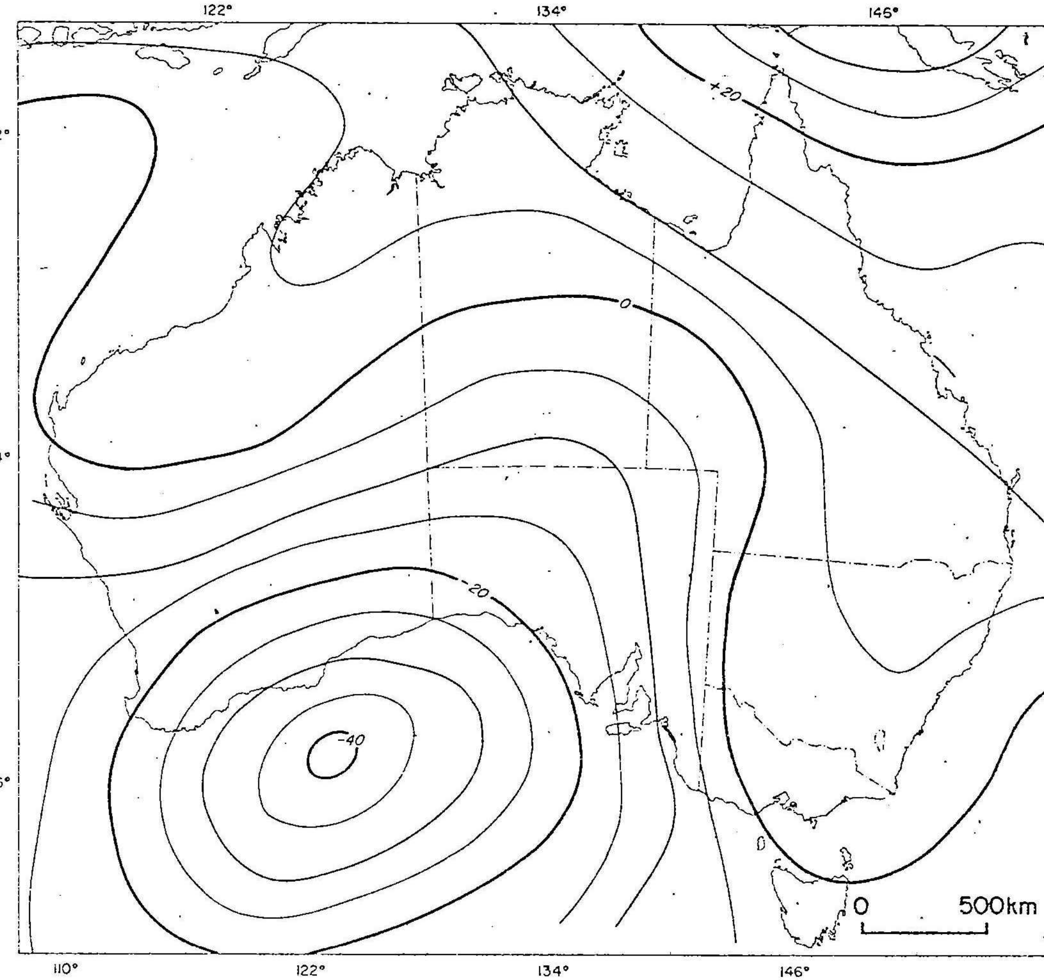


Fig. 7



SATELLITE FREE AIR GRAVITY FIELD / SPHERICAL HARMONICS DEGREES 2-16

Fig. 8

A/B2-100A

If part of the anomaly is due to much deeper sources, then the strength at great depth needs to be of this order. Assume all of the anomaly is caused by density variations below the surface at depth L; then for the slab, ρ and T are constant, and $\Delta(g\rho T)/g\rho T$ is of the order of $\Delta g/g$, or about 1 in 10^4, and can be neglected.

Thus we need to separate anomaly sources above 60 km from deeper - presumably much deeper - sources. This is the old problem of separating residual and regional, and of course there is no unique way of doing this.

As one possible approach to this problem, the satellite harmonic field of 2-16th order was used as a regional (Fig. 8, from fig. 1 of Anderson et al., 1973) based on data of Gaposchkin & Lambeck (1971). This is based purely on satellites - published fields based on combinations of satellite and terrestrial data use part of the Australian data but not all, and hence are likely to introduce bias in different area. The 16th-order harmonics have a wavelength of about $22\frac{1}{2}^{\circ}$; thus this probably represents effects from about 300 km depth or more.

The residual derived from 5° means minus 2-16th order satellite field is shown in Figure 9. We can still see an anomaly of say -20 mGal and about 2000 km wavelength; this gives a strength of, for T = 100 km, 380 bars; for T = 60, 1060 bars.

Elsewhere (Dooley, 1973) I have suggested that this anomaly could be due to slow erosion of the higher parts of the shield, with a long time constant in the process of isostatic compensation. The rate of erosion was estimated at something of the order of 10^{-5} m/yr. Erosion without compensation of 1 km of sediments would produce a negative anomaly of about 100 mGal (41.85 ρ_s, where ρ_s is the density of the material removed), so the anomaly estimated above of 20-30 mGal would imply a time-lag of isostatic compensation of about 20-30 m.y., and the lithospheric strength of the order of 1 kbar estimated above would be the effective strength for this period. Note the great difference in time of isostatic adjustment from that estimated from the Fennoscandian shield post-alluvial rebound of about 15 000 yr. The latter is usually regarded as referring to upper mantle rheidity. If my conclusions are correct and give representative strengths and time constants for shield lithospheres, it may be that the shields move fairly rapidly into a position of isostatic equilibrium as a whole, while maintaining intra-shield stress differences in the lithosphere for much longer periods of time.

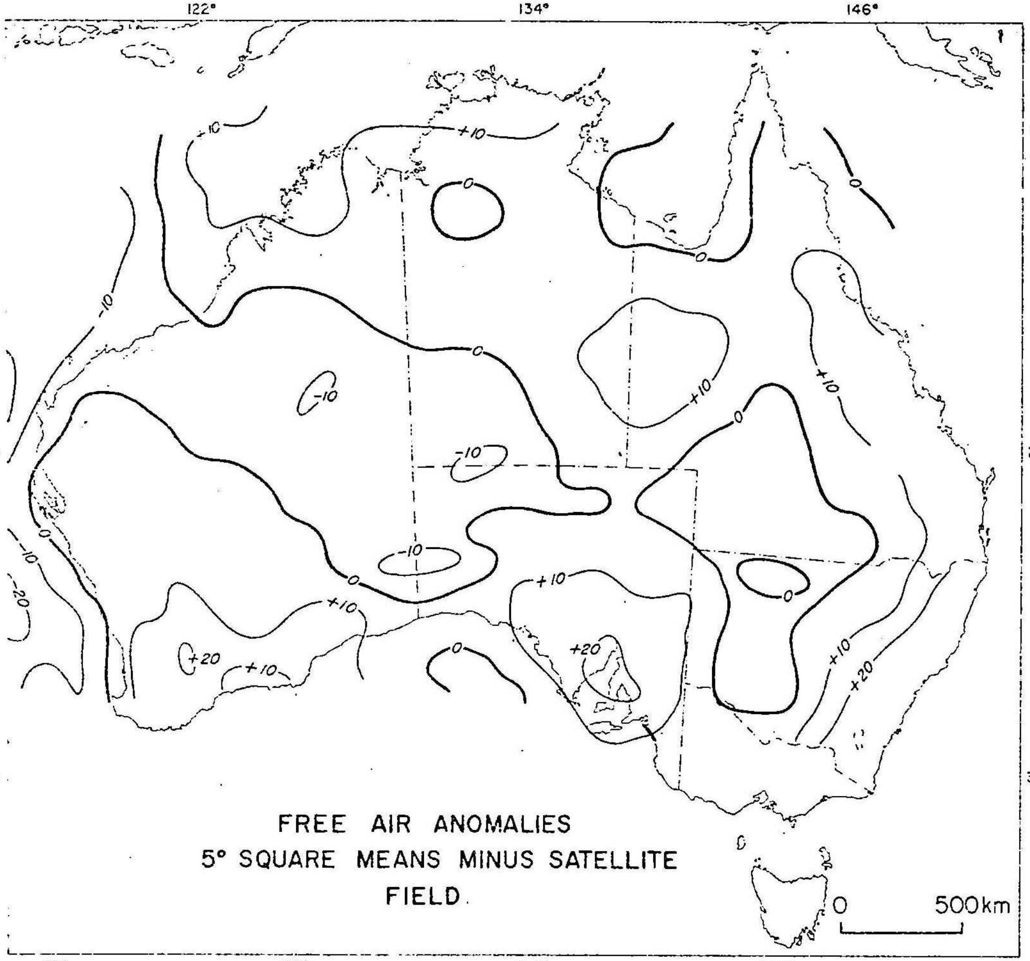

FREE AIR ANOMALIES
5° SQUARE MEANS MINUS SATELLITE
FIELD
0 500km
110°
122°
134°
146°
12°
24°
36°

Fig. 9

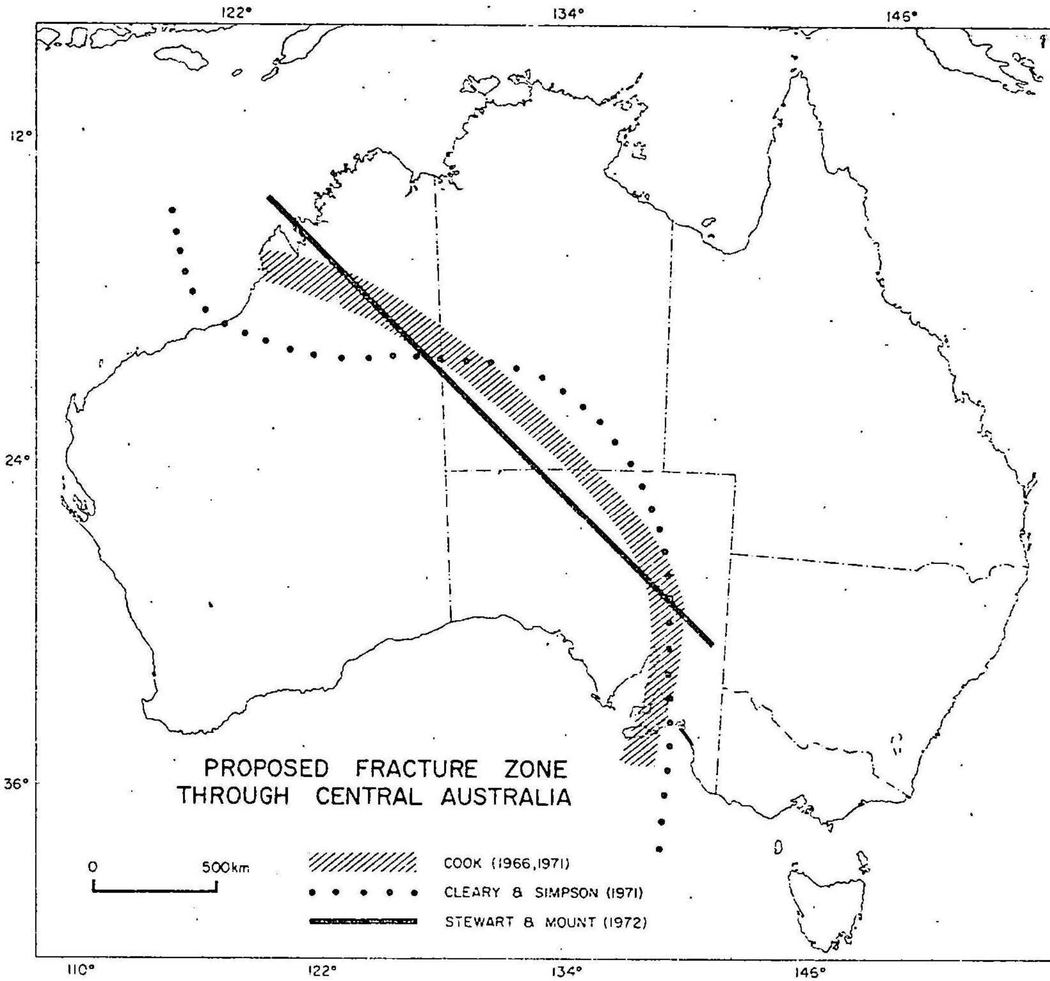

PROPOSED FRACTURE ZONE
THROUGH CENTRAL AUSTRALIA
0 500km
COOK (1966,1971)
CLEARY & SIMPSON (1971)
STEWART & MOUNT (1972)
110°
122°
134°
146°
12°
24°
36°

Fig. 10

We note in passing that Lambeck (1972) has estimated that the harmonics of order as low as 8 or 9 could be supported in the lithosphere with a strength of 1500 bars.

The relation between earthquake magnitude and stress is anything but precise, but the available data suggest that earthquakes of magnitude M_s = 7 or 8 would be associated with stresses of the order of 1000 bar.

The seismicity map of Australia (Denham et al., in prep.) is shown in Figure 4. It must be borne in mind that the distribution of earthquakes shown is affected by density of population and instrumentation; the distribution can probably be regarded as fairly unbiased by these factors for magnitudes greater than 5. As Australian seismicity is low, this does not leave much data for statistical generalization. In fact in several cases one earthquake and its aftershocks have changed the picture entirely.

As regards central Australia, there is a well defined seismic zone running northwards from Adelaide to about 30°S, fairly large recent earthquakes in the Simpson Desert (Stewart & Denham, in press) and Canning Basin (Denham et al., in prep.), and a few minor events.

Several authors have proposed that the Australian continent is rifting or shearing along a plate boundary through the centre. Figure 10 shows three proposed lineaments - that of Cook (1966, 1971), which initially was based partly on gravity evidence, that of Cleary & Simpson (1971) based on seismicity and a proposed relation to a displacement of the Southern Ocean mid-ocean ridge south of Adelaide, and that of Stewart & Mount (1972), who described the 'Fitzroy-Spencer lineament' on the basis mainly of seismicity.

Cook's proposed lineament was based on correlation of widely separated gravity anomalies across areas where few or no observations were available at the time. Subsequent surveys have made these correlations improbable.

Stewart & Mount postulate that the Fitzroy-Spencer lineament has been a zone of shearing relative movement between two blocks of the continent since Precambrian times. However, we note that their lineament intersects at an angle the major gravity anomalies in central Australia. If indeed shearing movement had continued for a prolonged geological period, then we would expect it to show in a large offset displacement of these gravity anomalies, since we have shown that they are some hundreds of millions of years old. Examination of the gravity map shows no indication of such displacement. The same could be said for the major geological boundaries of the associated basins and blocks.

Cleary & Simpson's proposed zone cannot be dismissed on these grounds, as it skirts along the eastern edge of the supposed stable block and then trends westwards along the length of the Ngalia Basin.

However, in view of the low seismicity it seems premature to draw any firm conclusions about trans-continental zones of activity. The central block which we have studied above appears to have shown little or no seismicity for the period for which data are available, but there is a suggestion that earthquakes tend to occur around its edges. In view of the figures for the lithospheric strength inferred above for the central block, it seems that this may be a comparatively strong and stable slab surrounded by weaker material, or zones of weakness, in which stress adjustments are occurring.

Moreover, recent studies of earthquake first motions by Denham (pers. comm.) suggest different stress regimes - north-south compression in southeastern Australia, and N.E.-S.W. compression in the northwestern part of the continent.

Anfiloff and Shaw (loc. cit., fig. 2) have drawn attention to a NNE trending lineament which truncates the major gravity anomalies on the western side, and which also truncates the major geological features - the Arunta and Musgrave blocks, and the Officer, Amadeus, and Ngalia Basins. The zone of seismicity forming the western boundary of the stable block proposed above is approximately linear and coincides approximately with Anfiloff and Shaw's lineament. Thus it appears that movement may still be taking place along or close to this lineament, which is apparently of ancient origin; the time of commencement of these movements is difficult to estimate.

Further, Anfiloff and Shaw postulate a south-east trending lineament truncating the northern gravity anomalies and geological features of the block (loc. cit., fig. 10). The Simpson Desert earthquakes occurred somewhat to the east of this lineament. Examination of the gravity (BMR, 1973) and tectonic (GSA, 1971) maps show that it would be reasonable to move the line of truncation eastwards so as to pass through these earthquakes. The seismicity zone southwards from here shows some agreement with the trend of the eastern boundary of the gravity anomalies and geological features; however both the boundaries and the seismicity zone are irregular in shape, and this boundary cannot be defined clearly.

Conclusions

1. The largest gravity anomalies in the shield area are not associated with evidence of seismicity. This is distinct from the situation in island arcs.

2. These anomalies are very old and imply a significant long-term strength of the shield lithosphere.

3. The lack of noticeable displacement of the anomalies along the proposed Fitzroy-Spencer lineament precludes any significant long-term strike-slip motion along this lineament.

4. Much more seismicity data are required to enable reliable confirmation or rejection of proposed trans-continental rupture zones.

5. Four lines of evidence, i.e. truncation of gravity anomalies, truncation of geological features, the estimated strength of the central block, and the seismicity zones, suggest that the central block has been a stable feature since late Palaeozoic (or possibly earlier) and that stresses in the continental plate have been relieved by movements along the boundaries of this block throughout a considerable period of geological time.

The permission of the Director, Bureau of Mineral Resources, Australia, to publish this paper is acknowledged.

Discussion

W.M. Kaula - Is there any evidence of a low-velocity layer under Australia? If so, what is the depth to the top of this layer?

J.C. Dooley - Denham et al (1972), as the result of refraction recordings from large explosions in the Ord River area, have found indications of a low-velocity layer with a lower boundary of about 160 km depth. The thickness of the zone could not be determined.

B. Purins - To what extent has a study of the Earth's density distribution been carried out in Australia and what are the future plans?

J.C. Dooley - (1) Wellman (in prep.) has modelled the free air gravity field of the Australia in terms of average density and thickness of $2^{o} \times 2^{o}$ crustal blocks on the assumption that each such block is isostatically compensated.

(2) A computer-based file is being established in the Bureau of Mineral Resources for density measurements of bore cores and rock specimens; however no comprehensive analysis has yet been made of these data.

TABLE 1

Basin	Anomaly (mGal)	Width (km)	Maximum Stress T = 40 km	60 km	100 km
Officer	140	225	210	98	42
Amadeus South	105	175	95	42	21
Amadeus North	115	225	173	80	35
Amadeus (whole)	100	400	480	240	80
Ngalia	110	200	132	55	28
Lander Trough	60	250	114	54	21
Regional Anomaly (a)	30	2000	3600	1590	570
(b)	20	2000	2400	1060	380

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