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THE GRAVITY EFFECTS OF THREE LARGE UPLIFTED GRANULITE BLOCKS IN SEPARATE AUSTRALIAN SHIELD AREAS

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ABSTRACT

The three linear gravity features on the Australian continent have a common form, and are an order of magnitude larger than any anomalies of comparable origin with the possible exception of the Perth Basin in Australia. They correspond with three belts of Proterozoic deformation involving narrow zones of crustal uplift, coupled with downwarping and the formation of large granite batholiths on both sides. The development of all three belts appears to have been controlled by two major crustal dislocations.

Model studies of the gravity anomaly at the Fraser Range, south-western Australia, suggest that the Fraser Range mafic granulite has been thrust upwards at least 4 km through granitic cover, with no corresponding displacement in the Conrad and Mohorovicic Discontinuities below the granulite. Two major granites on either side of the granulite are both interpreted as terminating at about 12 km.

Model studies of the anomalies in central Australia aid in delineating the southern Arunta and Musgrave upthrust granulite blocks and suggest the possible presence of four large bodies of granite and metasediment which terminate at a common depth horizon, possibly the Conrad Discontinuity. The horizon is interpreted as relatively flat. Because no gravity interpretation is unique, other models of the central Australian region which explain the gravity anomalies in terms of crustal warping or thrusting are equally plausible. The models presented here are acceptable alternatives because they are consistent with the observation by Cleary of a Conrad Discontinuity at an average depth of about 20 km in many parts of Australia, and a crustal thickness which does not vary more than 5 km from an average value of about 40 km. The termination of the gravity features associated with the southern Arunta granulite abruptly eastwards against a pronounced gravity lineament is taken to imply that a N-S compression was the cause of deformation, and that stress was released across a major crustal dislocation.

There is geological evidence of compressive events in the central Australian region at approximately 1700, 1000, 600, and 300 m.y., all consistent with stresses resulting from a primary N-S compression vector acting through central Australia. The permanence of a principal compression direction would be a limiting factor for theories of continental drift involving the rotation of the Precambrian Australian plate relative to its surroundings.

INTRODUCTION

This paper deals with the gravity anomalies associated with the Fraser Range, Musgrave, and southern Arunta mafic granulitic belts located in southwest and central Australia (Fig. 1). In terms of amplitude and length, these are three of the biggest linear gravity features in Australia, and are prominent on the gravity map of Australia (Fig. 2).

The systematic reconnaissance gravity coverage of most of Australia has enabled the anomalies to be compared with other gravity features, and their common characteristics to be assessed. Three belts of gravity anomalies are recognized. Each consists of a gravity ridge flanked by gravity troughs and each corresponds to a deformed belt consisting of an upthrust mafic granulite block flanked by combinations of granite and sediment. These are referred to as the Fraser Range, Musgrave, and southern Arunta Gravity Belts and Deformed Belts respectively. A model is suggested for the 3 structural belts which explains their present structure, and has some far-reaching, though speculative, implications.

Gravity profiles across the Fraser Range Gravity Belt along sections F1-F5 are shown in Figure 3, and profiles across the Musgrave and southern Arunta Gravity Belts along sections C0-C5 in Figure 4. The profiles of all three belts have a similar form, maintained over large distances. The maximum peak to trough amplitude is 170 mgal and gradients reach 4 mgal/km. In relation to the gravity levels in surrounding areas, the anomalies reach 60 mgal above and 110 mgal below surrounding levels.

Whereas the gravity ridges can be directly attributed to narrow zones of crustal uplift resulting in the exposure of belts of mafic granulite at the surface (Marshall & Narain, 1954), the adjacent gravity lows have been interpreted in various ways. Everingham (1966) attributes the low west of Fraser Range to a granite 10 km thick; Flavelle (1965) explains the major low associated with the Ngalia Basin, N.T., mainly in terms of granite; Milton & Parker (1973) attribute the major low in the eastern part of the Officer Basin, S.A., mainly to a sediment in a basement trough with a

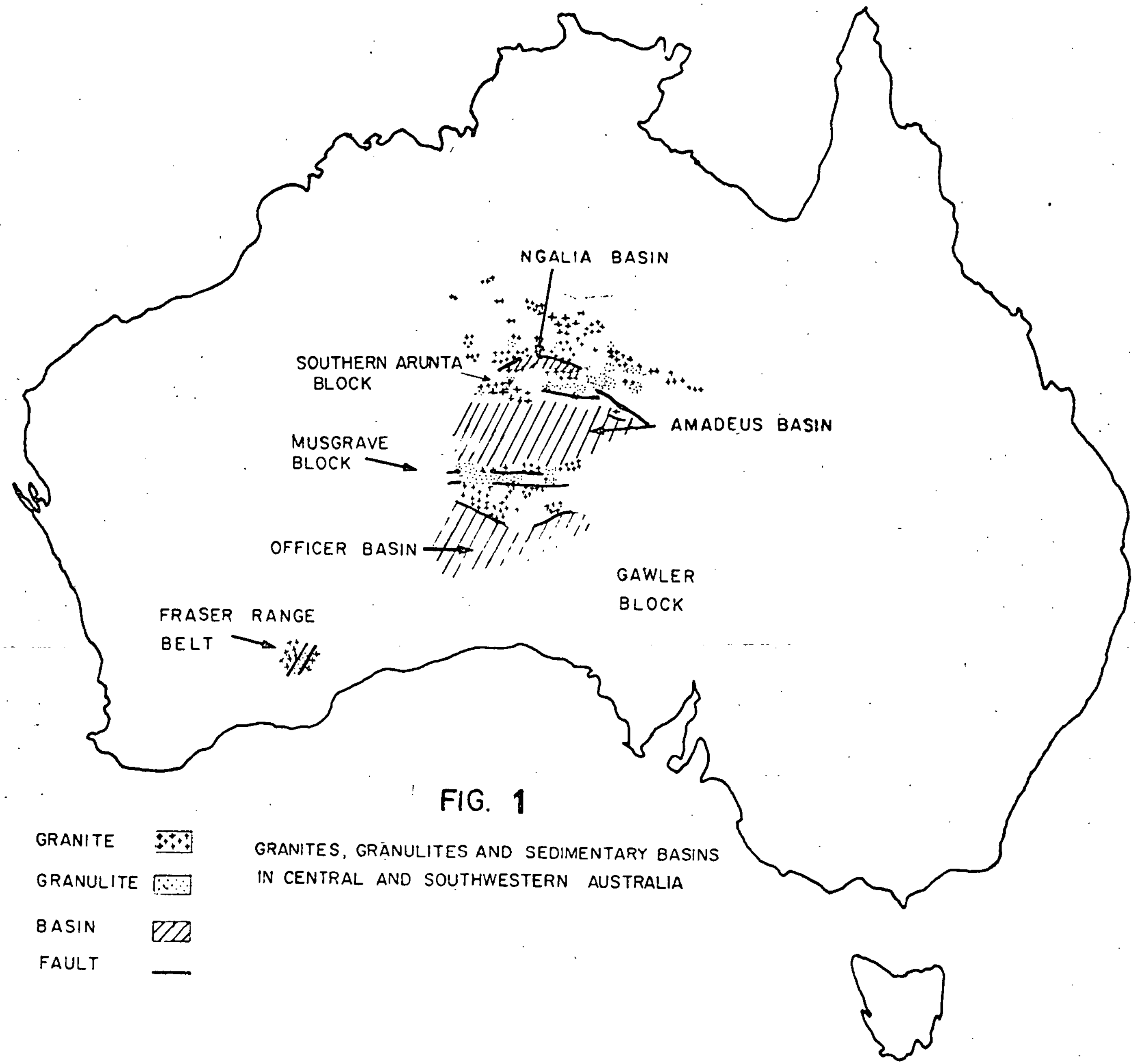


FIG. 1

GRANITES, GRANULITES AND SEDIMENTARY BASINS
IN CENTRAL AND SOUTHWESTERN AUSTRALIA

To accompany Record No. 1974/4

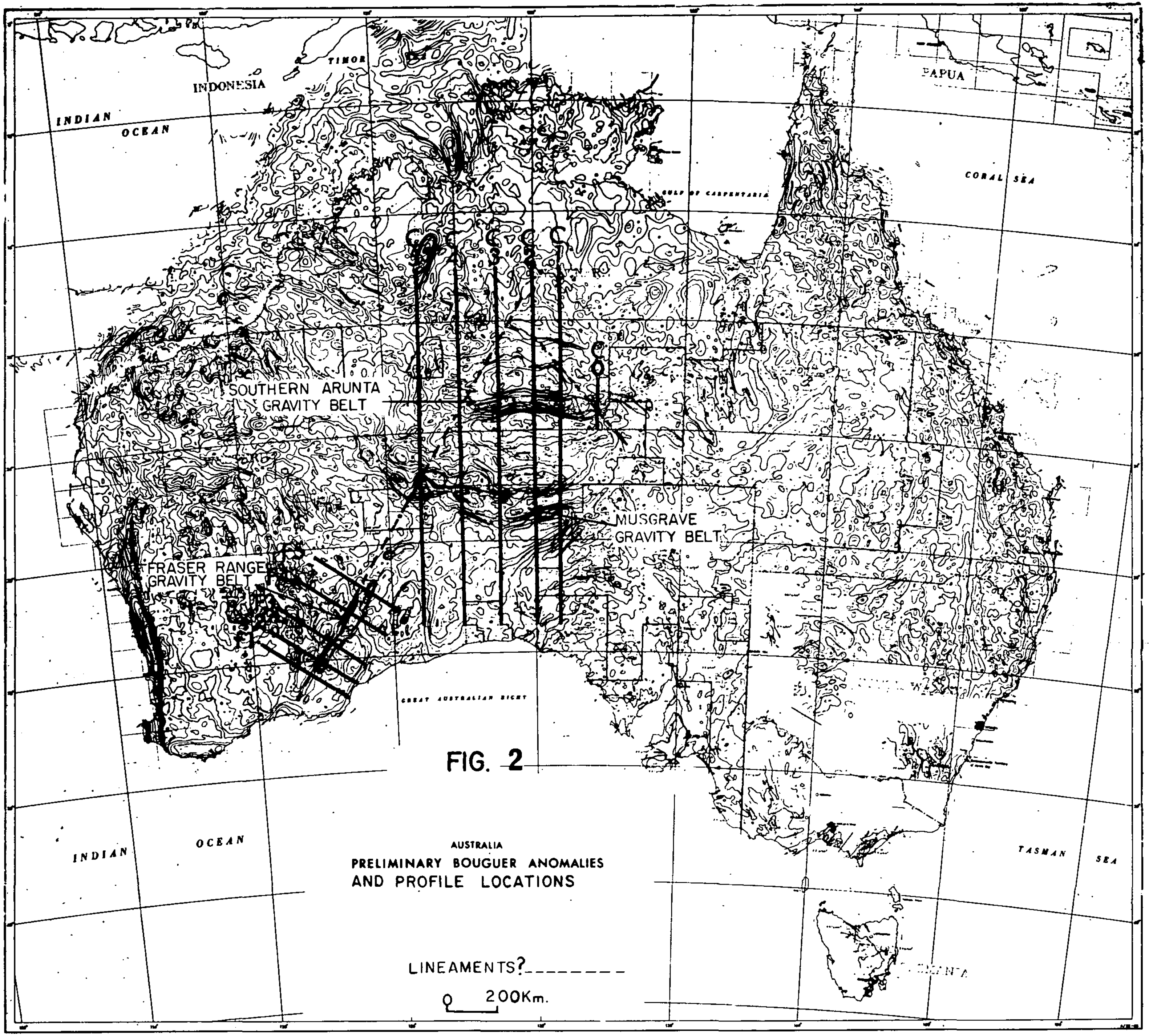


FIG. 2

AUSTRALIA
PRELIMINARY BOUGUER ANOMALIES
AND PROFILE LOCATIONS

A/B2-83A

GRAVITY PROFILES ACROSS FRASER RANGE, W.A.

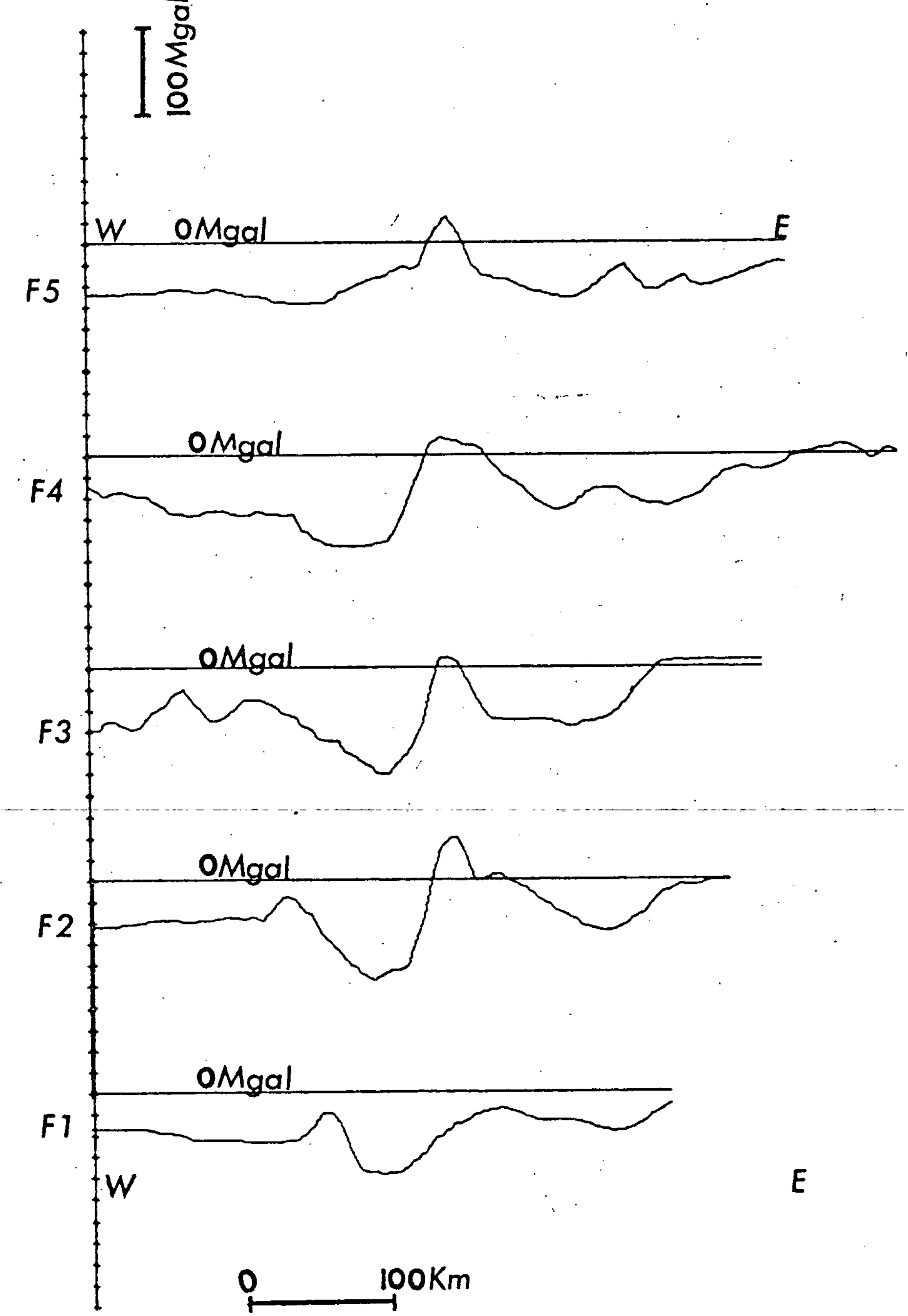


FIG. 3

To accompany Record No. 1974/4

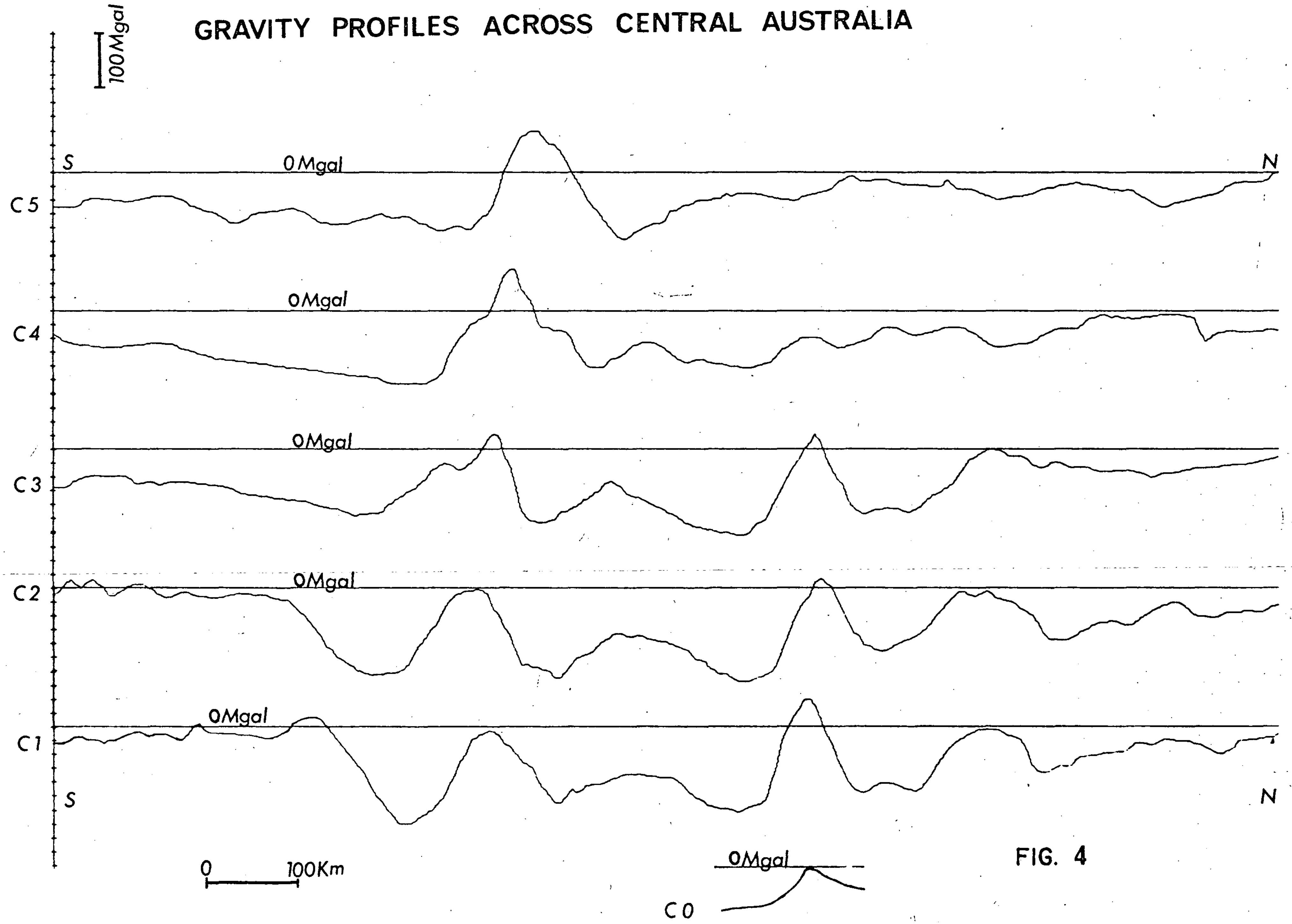


FIG. 4

H51/B2-28A

0.45 gcm^{-3} density contrast; and Mathur (in.prep.) attributes all four major lows in the central Australia region mainly to downwarping of the lower crust, based on the original concept of Marshall & Narain (1954) and Forman (in Wells et al., 1970; Forman & Shaw, 1973). The crustal models shown in Figures 5 and 9 explain the Bouguer anomalies in terms of density contrasts between rock units within the upper 20 km of the crust. However, because interpretations of gravity data are seldom unequivocal, a model such as that of Mathur (in prep.) involving crustal warping is equally plausible in terms of available data. In the gravity models shown in Figures 5 and 9 the local interpretations of granite made by Everingham (1966) and Flavelle (1965) have been extended with some modifications to all six major lows. The lows are postulated to have been caused by large blocks of low-density material consisting of granitic rock and variable amounts of metasediments overlain in the central Australian region by sedimentary basins. The distribution of exposed granitic rocks is sketched in Figure 2. Granites and low density metasediments account for the bulk of exposed rock in the area corresponding to the greater part of the gravity low north of the Ngalia Basin. Similar rocks occur along the northern margin of the Amadeus Basin and include large batholiths in the Mount Liebig and Mount Rennie 1:250 000 geological Sheet areas. Large granitic bodies also crop out at the southern margin of the Amadeus Basin near Kulgera and at the northern margin of the Officer Basin in the Birksgate and Lindsay 1:250 000 geological Sheet areas.

Two interpreted sections are presented, one across the Fraser Range Deformed Belt, and one across central Australia (the Central Australian Deformed Province) including the Musgrave and southern Arunta Deformed Belts. Undeformed areas beyond the deformed belts are included in each section, so that the deformed belt structures can be interpreted in terms of mass variations relative to undeformed crustal layering.

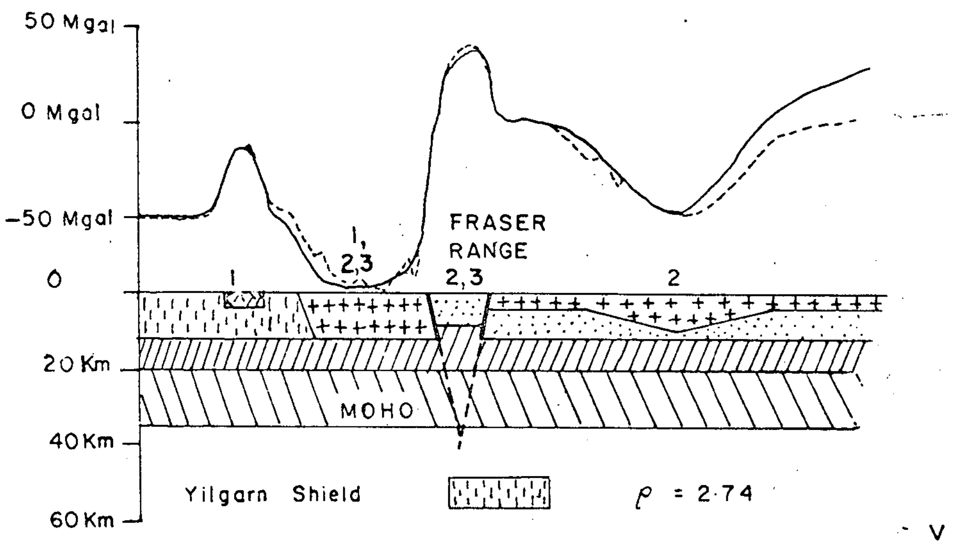
The gravity ridges are interpreted in terms of varying amounts of mass excess caused by the uplift of granulites, and the lows are assumed to be substantially caused by large granitic bodies and variable amounts of metasediments extending down to specific depths. Large-scale compressive forces are postulated to cause the uplift of the granulite belts, and by association the preservation of low-density metasediments and older granites and the formation of new granites.

INTERPRETATION OF THE FRASER RANGE GRAVITY BELT IN SOUTHWESTERN AUSTRALIA

The interpretation of the anomalies associated with the Fraser Range Deformed Belt is made along Section F2, taken across the belt (Fig. 2). This particular section was chosen because detailed gravity information is available along it and the geology is better known than elsewhere in the Fraser Range. The section length is 300 km and includes Archaean gneisses and greenstones of the Yilgarn Shield in the west, Proterozoic granite, the Proterozoic Fraser Range mafic granulite, and the Balladonia granite and associated low-density rocks in the east.

The two granites and the mafic granulite may be interpreted as constituting a structural belt deformed against the Archaean shield by compression in the Proterozoic. Compression may have caused crustal buckling, resulting in the formation of two zones of subsidence flanking a zone of uplift. The subsidence is envisaged as causing the formation and preservation of large granite batholiths, and the uplift thrust mafic granulites into the upper levels of the crust. The upper part of the interpreted section (Fig. 5) is based on the geology of Sofoulis (1966), Wilson (1969), and Arriens & Lambert (1969), and is modelled to consist of three main rock types: Archaean gneiss with a mean density of 2.74 gcm^{-3} to 12 km depth, two granitic bodies of density 2.65 gcm^{-3} both bottoming at about 12 km depth, and a mafic granulite of density 2.95 gcm^{-3}. The lower part of the interpreted section

FRASER RANGE GEOLOGY AND INTERPRETED SECTION – LINE F2



Yilgarn Shield		ρ = 2·74
Greenstones		ρ = 3·0
Granite		ρ = 2·65
Granulite		ρ = 2·95
Intermediate layer		ρ = 2·95
Lower layer		ρ = 3·0

$\frac{V}{H} = 2$

FIG.5

0 Km — 100Km

Sources of information:

1· Sofoulis, J·, 1966

2· Arriens, P·A·, and Lambert, I·B·, 1969

3· Wilson, A·F·, 1969

Actual Gravity - - - - - -

Fault ————

Computed Gravity ————

depicts horizons at 20 and 35 km, based on the seismic results in the eastern part of the Yilgarn Shield (Mathur, in prep.), and also a subsurface granulite layer east of the Fraser Range.

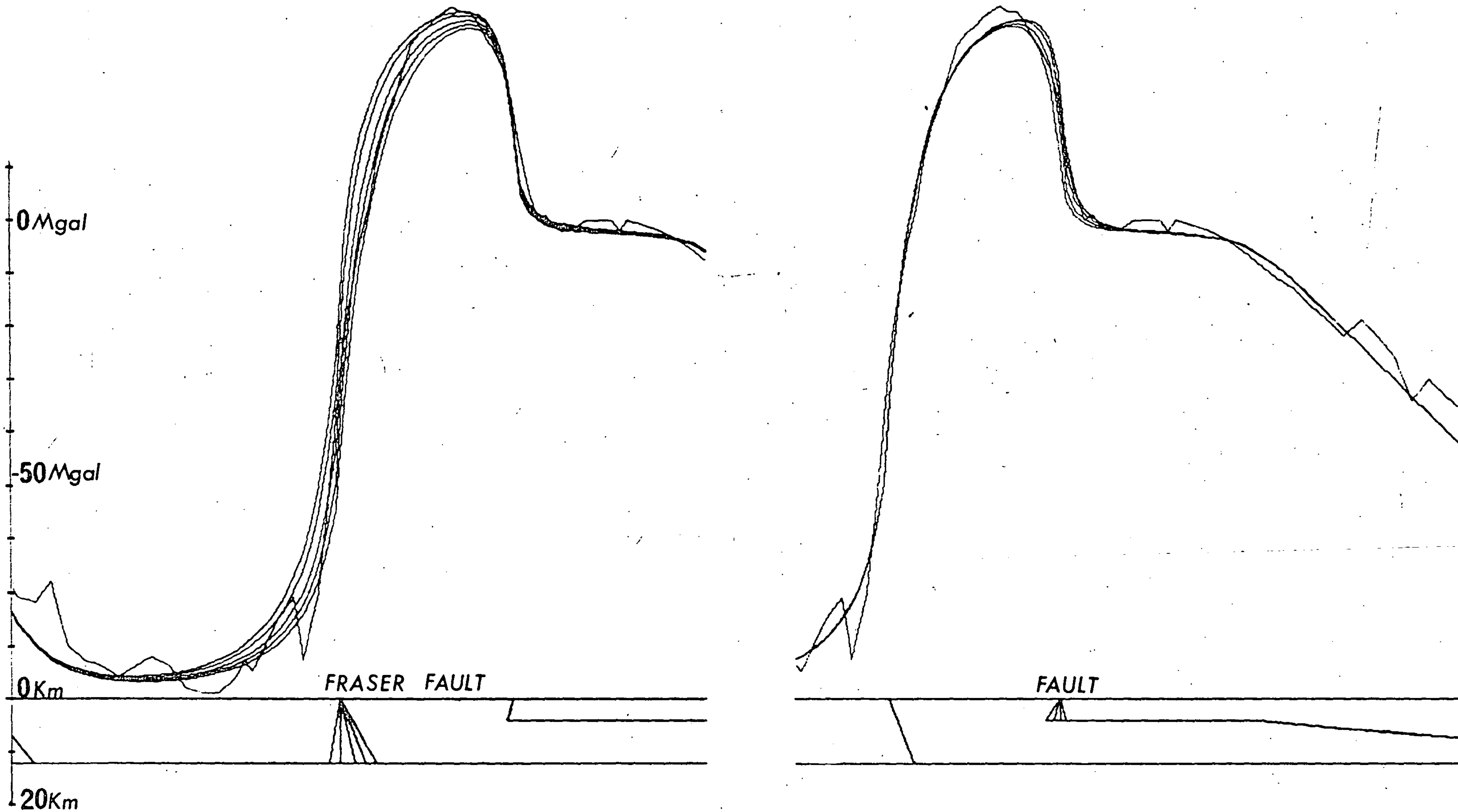
The main features of the interpretation are:

1. The particular shape of the gravity anomaly over the Fraser Range granulite suggests that the granulite may have been thrust at least 4 kms upwards through granitic cover.
2. The granites on either side of the Fraser Range granulite are present to a similar depth.
3. The very close agreement between the interpreted width of the Fraser Range granulite (33 km) and the mapped width (about 35 km) implies that the Conrad and Mohorovicic Discontinuities are both flat under the Fraser Range, as any upward displacement of these horizons would constitute a mass excess at depth, and would have produced a much broader gravity anomaly over the granulite than is observed.

Figures 6, 7, 8 are included to demonstrate the sensitivity of the computed anomaly to changes in various aspects of the interpreted model, and show the degree of resolution of the gravity modelling.

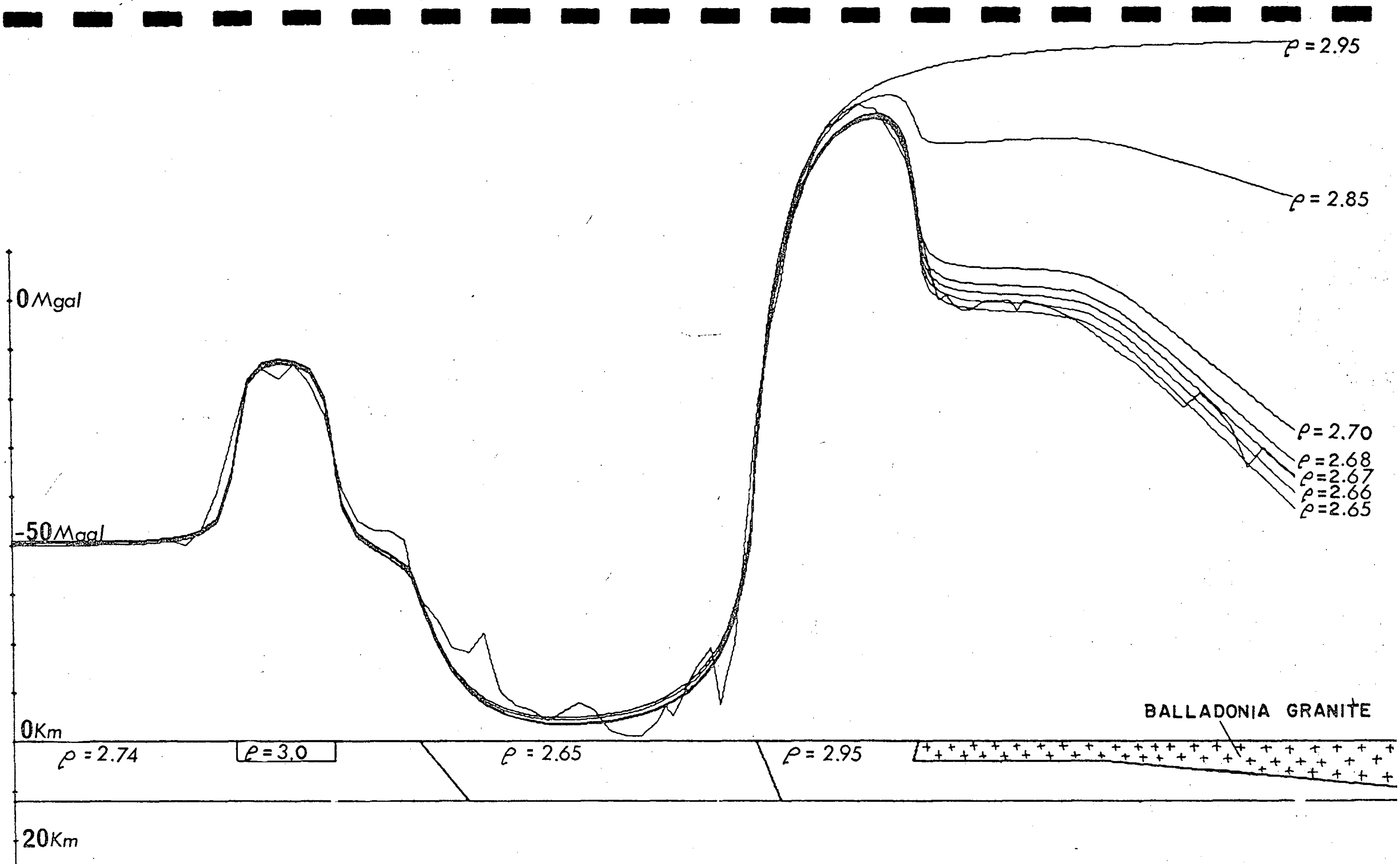
INTERPRETATION OF THE MUSGRAVE AND SOUTHERN ARUNTA GRAVITY BELTS IN CENTRAL AUSTRALIA

The Musgrave and Arunta Gravity Belts are interpreted along C1 (Fig. 1). This line is along 133° longitude and crosses the Gawler Block, the East Officer Basin, the Musgrave Block, the Amadeus Basin, the southern Arunta Block, the Ngalia Basin, and the northern Arunta Block. On the basis of the gravity effects, the area crossed is subdivided into two zones of undeformed crust, in the south and north, and two structural belts of deformation, the Musgrave and Arunta Deformed Belts (Fig. 9). The Officer



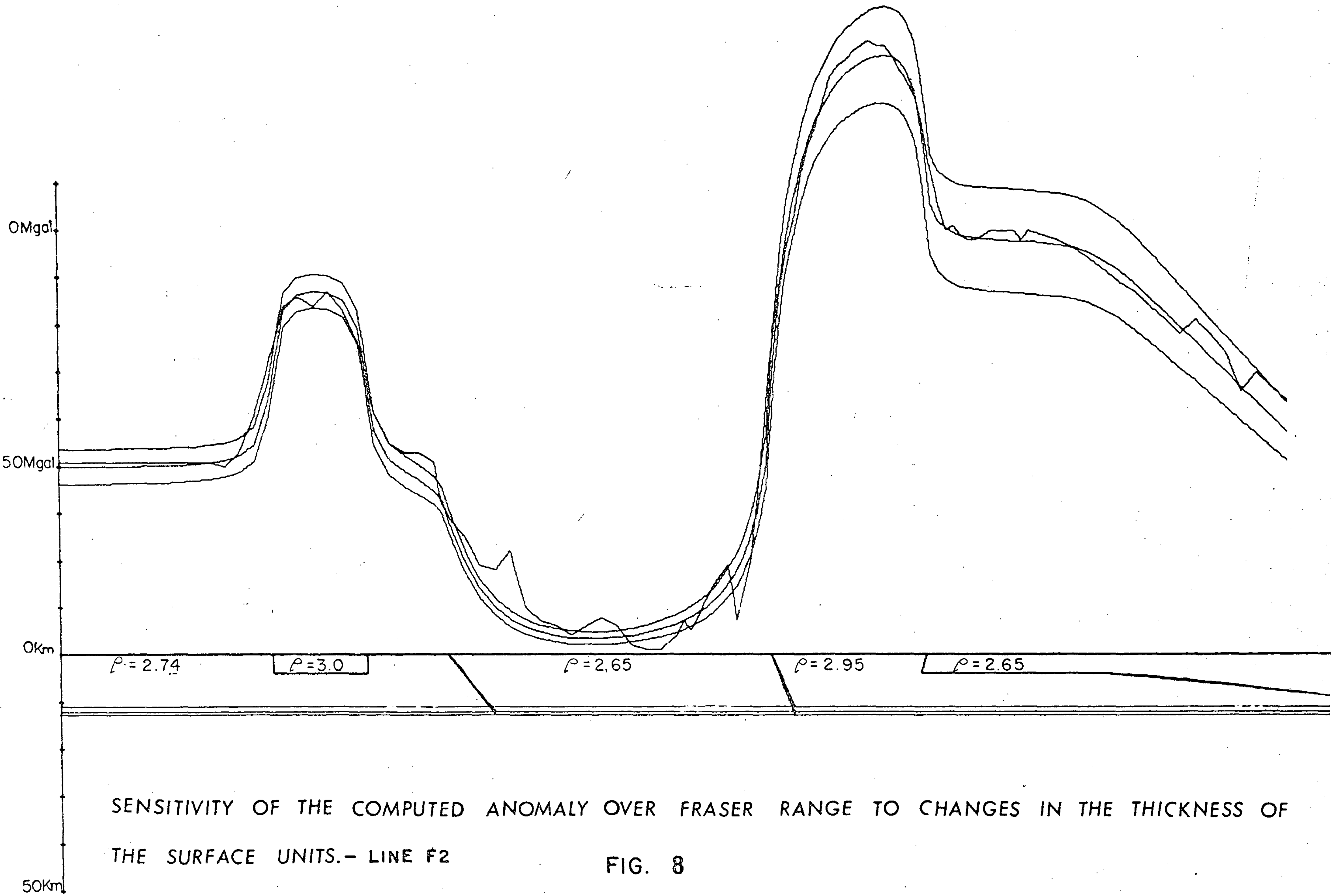
SENSITIVITY OF THE COMPUTED ANOMALY OVER FRASER RANGE TO CHANGES IN THE FAULT ANGLES—
LINE F2

FIG. 6



SENSITIVITY OF THE COMPUTED ANOMALY OVER FRASER RANGE TO CHANGES IN THE DENSITY OF THE BALLADONIA GRANITE.— LINE F2

FIG. 7



SENSITIVITY OF THE COMPUTED ANOMALY OVER FRASER RANGE TO CHANGES IN THE THICKNESS OF THE SURFACE UNITS.– LINE F2

FIG. 8

CENTRAL AUSTRALIA GEOLOGY AND INTERPRETED SECTION ALONG 133° LONG

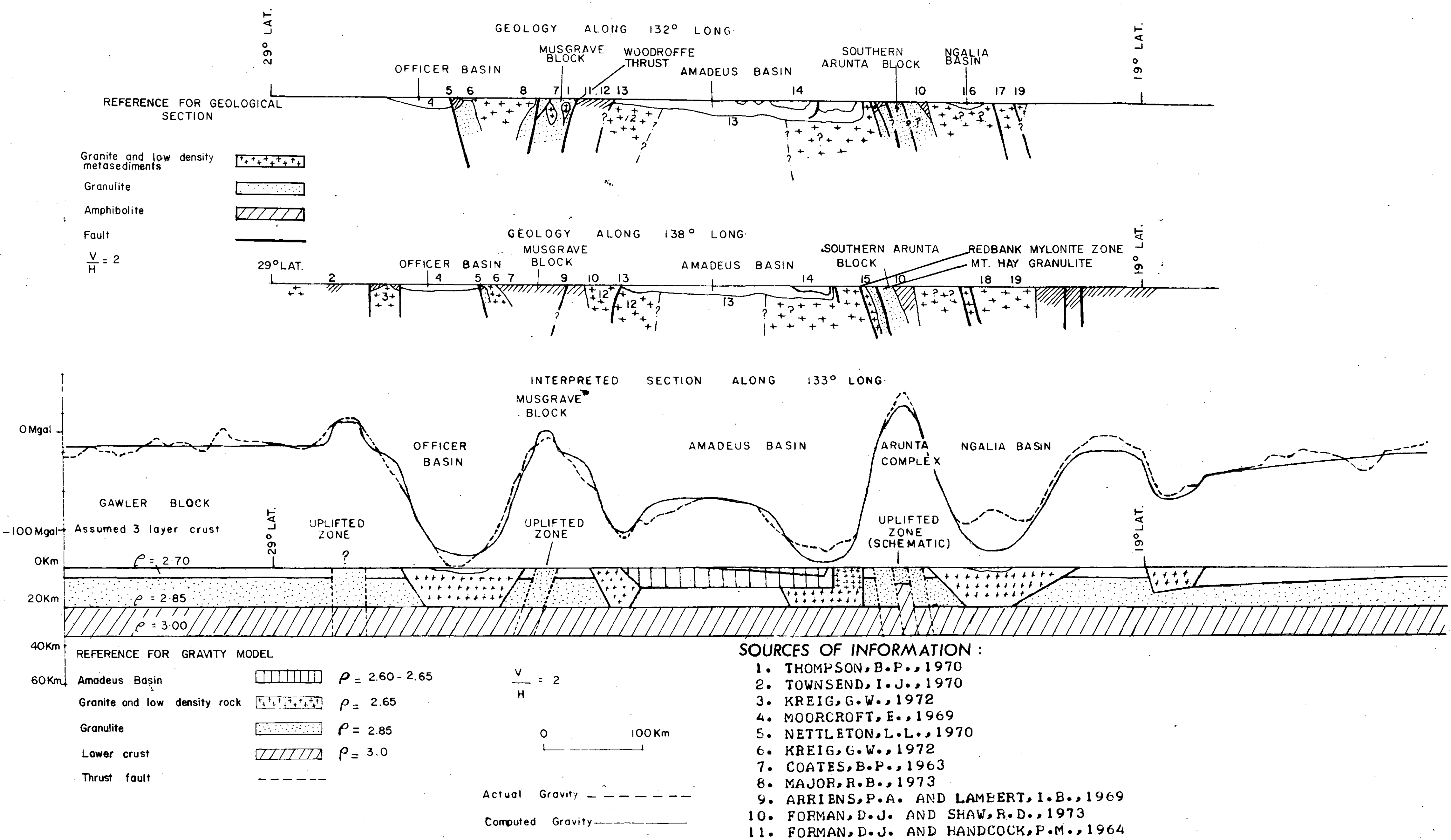


FIG. 9

SOURCES OF INFORMATION :

1. THOMPSON, B.P., 1970
2. TOWNSEND, I.J., 1970
3. KREIG, G.W., 1972
4. MOORCROFT, E., 1969
5. NETTLETON, L.L., 1970
6. KREIG, G.W., 1972
7. COATES, B.P., 1963
8. MAJOR, R.B., 1973
9. ARRIENS, P.A. AND LAMBERT, I.B., 1969
10. FORMAN, D.J. AND SHAW, R.D., 1973
11. FORMAN, D.J. AND HANDCOCK, P.M., 1964
12. STEWART, A.J., 1967
13. YOUNG, G.A. AND SHELLEY, E.P., 1966
14. WELLS, A.T., FORMAN, D.J., RANFORD, L.C. AND COOK, P.J., 1970
15. MARJORIBANKS, R.W. AND BLACK, L.P., IN PREP.
16. WELLS, A.T., MOSS, F.J. AND SABITAY, A., 1972
17. WELLS, A.T., 1972
18. EVANS, T.G. AND GLIKSON, A.Y., 1969
19. SHAW, R.D. AND STEWART, A.J., IN PREP.

Basin and its associated granites, the Musgrave Block upthrust granulites, and the southern Amadeus Basin and its associated granites are included in the Musgrave Deformed Belt. The northern Amadeus Basin and its associated granites, the upthrust granulites of the Arunta Block, and the Ngalia Basin and its associated granites are included in the southern Arunta Deformed Belt. Both belts may be considered to consist of two zones of subsidence flanking a zone of uplift, the subsidence being inferred from the accumulation of sediments, and the uplift from the presence of narrow zones of basic granulites in association with thrust faults.

Our interpretation of the gravity anomalies in central Australia assumes that most of the gravity effects can be accounted for by density variation in the top 20 km of crust (Fig. 9). The anomalies are interpreted in terms of lateral variation in density relative to two areas of undeformed crust at each end of the section. Assuming a mean crustal density of 2.81 gcm^{-3} to 20 km for the undeformed crust, the zones of subsidence can be considered to contain 20 km of granitic material of density 2.65 gcm^{-3}, and the zones of upthrust to contain crust of density 2.85 upthrust 5 km above its level in undeformed crust and in the southern Arunta Block, 12 km of dense lower crustal material of density 3.0 gcm^{-3} all cratonized above the Conrad Discontinuity. The postulated Conrad Discontinuity at about 20 km in central Australia is consistent with its widespread distribution throughout many parts of the Australian continent (Cleary, in press).

Three factors emerge from the interpreted model:

1. The similarity of gravity levels over undeformed crust at each end of the section is consistent with the crust there having a similar composition, and with the postulate that deformation in central Australia was intracratonic.
2. The gravity levels of all four gravity lows are consistent with equal thicknesses of low-density rock, interpreted as granite and lesser amounts of low-density metasediment in each case, over a

distance of 600 km. This suggests that an essentially flat discontinuity, possibly the Conrad at 20 km depth, exists in the central Australian region.

3. The gravity levels over the upthrust zones suggest that up to 12 km of crustal uplift occurred along narrow zones relative to the undeformed crust, and that, if this caused displacements deeper in the crust, they have since been annulled by a process of density equilibration.

It is postulated that at about 1600-1700 m.y. (Shaw & Stewart, in prep.; Marjoribanks & Black, 1973) in the southern Arunta Deformed Belt and at 1000 m.y. or earlier (Thomson, 1970) in the Musgrave Deformed Belt, a strong north-south compressive stress caused the crust to buckle and consequently subside in two zones flanking a zone of uplift. Anatectic granites are envisaged to have formed as sediments and perhaps older granites became deeply buried in the sinking troughs. Magmatic granites may also have formed at greater depths in the deformed zones. By the time crustal movements ceased, vast quantities of low-density material had accumulated to considerable depths. Conversely, in the zone of uplift, dense lower crustal material became cratonized in the upper levels of the crust. The southern Arunta Deformed Belt was reactivated, about 300-400 m.y. (Forman & Shaw, 1973; Shaw & Stewart, in prep.) resulting in similar uplift and subsidence along roughly the same zones and the Musgrave Deformed Belt was similarly reactivated at about 600 m.y. (Forman in Wells et al., 1970; Forman & Shaw, 1973).

It is postulated that after each main deformation the thickness of the structural units was reduced both by surface peneplanation and by their obliteration at depth due to large scale diffusion and largely vertical separation of elements particularly at about the level of migmatization. Additional equilibration of densities at depth might also be expected due to post-uplift phase changes in minerals as a result of adjustment to new PT conditions. Partial disruption of lateral density differences might be a result of granite intrusion late in the tectonic cycle. There is geological evidence that an event involving granite intrusion in the Musgrave Block between 1100-1200 m.y. (Thomson, 1970) extended to the southern Arunta Block as a migmatite event (Marjoribanks & Black, 1973). No igneous activity is known to be associated with the later deformations considered to involve crustal warping and thrusting at 600 m.y. and 400-300 m.y. (Forman & Shaw, 1973). Possibly the effective crustal strength was greater because the level of partial melting had, by that time, dropped to greater depths or because compression was maintained throughout the tectonic cycle. The continuous obliteration below a certain depth of the original density irregularities caused by the deformations may have produced a horizon that is conceivably the Conrad Discontinuity.

The gravity model shown in Figure 9 is a much simplified representation of a complex history, but demonstrates how the gravity effects could be accounted for by density variations in the top 20 km of crust and how low-density rocks may terminate downwards at a common level.

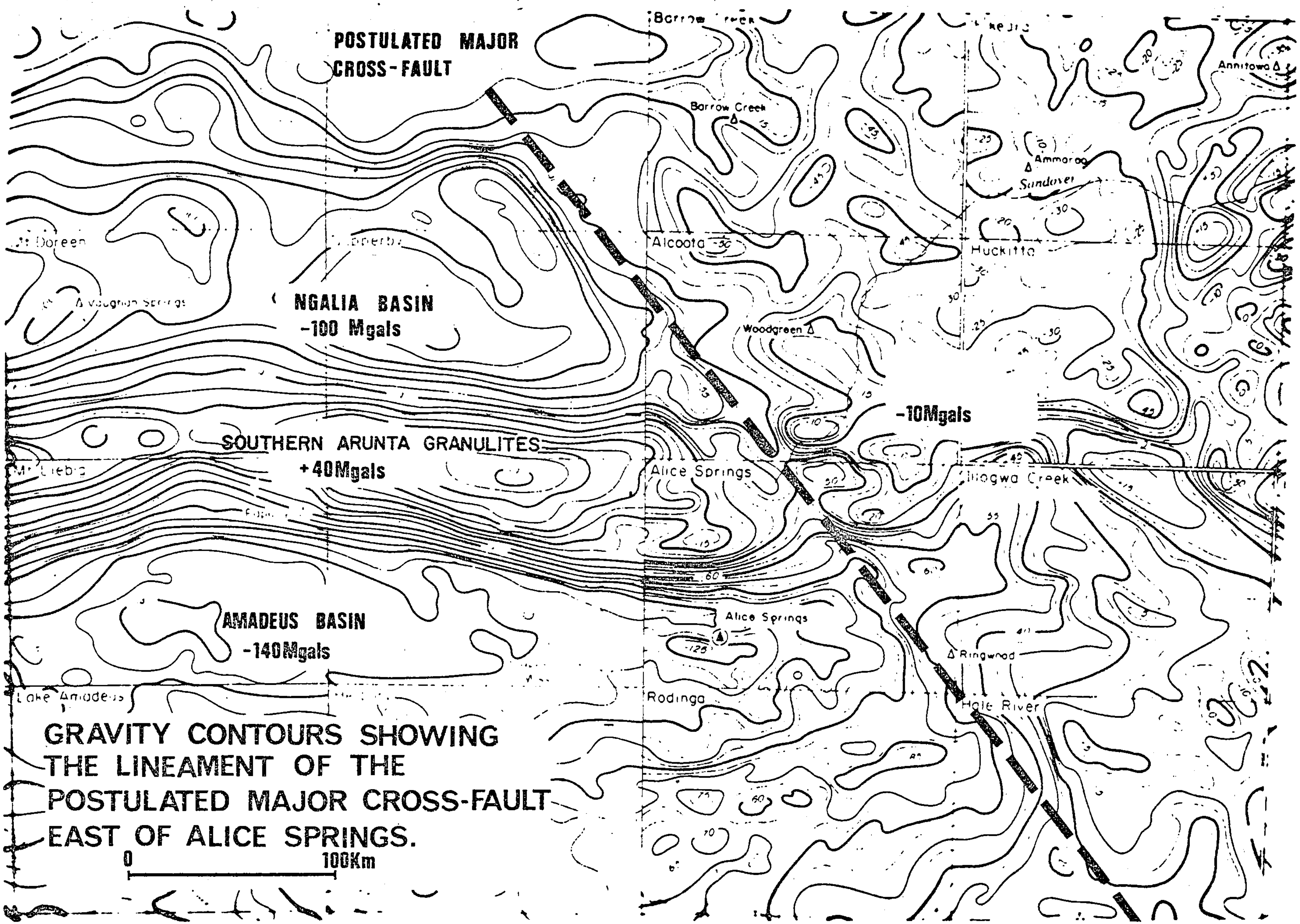
EVIDENCE FOR THE EXISTENCE OF A PRIMARY N-S COMPRESSIVE FORCE IN CENTRAL AUSTRALIA OVER A 1400 M.Y. TIME SPAN

The causes of the uplift of the southern Arunta and Musgrave granulites are not known unequivocally, but circumstantial evidence suggests that the granulites of the southern Arunta Block were elevated by thrusting resulting from a strong north-south compressive force. Crustal buckling and fracturing in response to horizontal compressive forces has been proposed by Marshall & Narain (1954) to account for the main Bouguer anomaly features in the Central Australian Deformed Province. The marked similarity in form, symmetry, and spacial periodicity of the main Bouguer anomaly features could be explained by such compressive deformation, especially if the initial buckles were formed during part of a continuous compressive episode. Forman & Shaw (1973) imply horizontal compression as a cause, but place more emphasis on overthrusting. Continuous or recurring compression would also help to explain the preservation of the original upthrust and downwarped crust, especially during any period of relative plasticity before the crust cooled and cratonized.

The eastern edge of the south Arunta Gravity Belt is truncated by a transverse lineament against which both the gravity ridge and adjacent troughs are terminated abruptly. The change in gravity level of the ridge across the lineament is 50 mgal (Fig. 10). This aspect of the gravity anomalies suggests that the ridge and the two troughs were formed together as a result of an overall process of deformation, and that the overall deformation was terminated laterally by a crustal dislocation. This implies that the deformation is likely to have been caused by compressive stress acting on a relatively rigid plate, since only stress release across a dislocation would have sharply limited deformation along a lineament.

A similar dislocation would be expected to have occurred at the same time on the western side of the deformations, and there is evidence of a gravity lineament which extends from the Fraser Range Deformed Belt, past the western edge of the Musgrave and south Arunta Deformed Belts, and intersects the eastern lineament at a point centrally north of the Central Australian Deformed Province (Fig. 2). It is suggested that an exceptionally large primary north-south compressive force may have acted through the intersection of the two lineaments, causing the uplift of granulites and the subsidence of the flanking troughs.

Geological evidence indicates that the pattern of dominantly east-west structures in central Australia has been produced by a series of events involving overthrusting and overfolding which extended from the mid-Proterozoic to the mid-Carboniferous. In each event the geological



GRAVITY CONTOURS SHOWING THE LINEAMENT OF THE POSTULATED MAJOR CROSS-FAULT EAST OF ALICE SPRINGS.

FIG. **10**

structures can be interpreted to be the result of a major north-south compressive stress of constant orientation. There is evidence for the following events:

1700-1600 m.y.	A major deformed zone (Redbank mylonite zone) separates the south Arunta granulites (Mt Hay granulites) from an adjacent zone to the south containing migmatized granitic gneisses and low-density metasediments. The mylonite foliation of the deformed zone is overprinted by a migmatite event at 1070 m.y. (concordant Rb/Sr total rock and mineral age - Marjoribanks & Black, 1973). The gneisses have been dated at 1620 $\pm$ 70 m.y. (Rb/Sr total rock, op. cit.) and the uplift is possibly of this age or younger. Overthrusting consistent with compressive stress is suggested by the steep northerly dip of the mylonite foliation.
1000 m.y. or earlier	Woodroofe Thrust is thought to be related to the intrusion of mafic and ultramafic igneous rocks (Major, 1970; Thomson, 1970) and related to structures in the granulites (Collerson, Oliver, & Rutland, 1972), the uplift of which has been indicated at 1380 $\pm$ 120 m.y. by Arriens & Lambert (1969) (Rb-Sr total rock). Northerly directed overthrusting and flattening suggest a primary north-south compressive stress.
600 m.y.	The Petermann Range Nappe developed as a large recumbent anticline and complementary syncline involving both crystalline basement and sedimentary cover. Formation of the nappe at 600 m.y. is based on its stratigraphic relationships (Forman, 1966) and Rb/Sr mineral ages for metamorphosed granite intruding gneiss in the core of the nappe (Leggo *in* Forman, 1972). The extreme overfolding in a northerly sense is consistent with a major component of north-south

compressive stress. The Woodroffe Thrust may have been reactivated during the 600 m.y. event (Forman & Shaw, 1973).

300-400 m.y. Alice Springs Orogeny has been dated by K-Ar methods by Stewart (1971) and by Rb-Sr methods by Armstrong & Stewart (in prep.). Deformation involved movement along a zone up to 10 km wide and the southward translation of a number of overthrusts at the northern margin of the Amadeus and Ngalia Basins (Marjoribanks & Black, in prep.; Shaw et al. 1971). This implies a major component of north-south compressive stress.

In each event, the deformations produced are very elongate and regular. These large-scale yet narrow zones of uplift which developed with parallel orientation repeatedly over a time span of 1400 m.y. can be simply interpreted as the product of recurring compressive stress consistently oriented relative to the Central Australian Deformed Province.

CONCLUSIONS

Three very similar structural belts, the Fraser Range, Musgrave, and southern Arunta Deformed Belts, and three corresponding belts of anomalies, the Fraser Range, Musgrave, and southern Arunta Gravity Belts are recognized. Each structural belt is interpreted as a narrow zone of uplift characterized by granulites and thrust faults and flanked by zones of subsidence characterized by sediments and large anatectic and magmatic granites. The three gravity belts have the same form and are an order of magnitude larger in amplitude than any other anomalies of comparable origin in Australia.

The Fraser Range interpretation indicates that two large granites flank the granulite. The large gravity gradients across the faults bounding the granulite indicate that a sharp contact exists between it and the granites, suggesting that the granulite was thrust into a granitic cover.

Both granites are interpreted as bottoming at about 12 km on each side of the granulite, and this may reflect the presence of a crustal horizon at that depth.

In particular, the Fraser Range anomaly negates the possibility of local uplift or warping at depth under the Fraser Range because the width of the anomaly closely matches the known width of the granulite. This strongly suggests that the Conrad and Mohorovicic Discontinuities are flat. The interpretation across central Australia suggests that the discontinuities are flat there also. Mass deficiencies caused by four postulated bodies consisting of granites and variable amounts of metasediment appear to terminate downwards at a common depth, and mass excesses caused by the uplift of the Musgrave granulites can also be placed above the common granite depth. This suggests that the granites and associated metasediments may terminate downwards at a flat discontinuity, possibly the Conrad Discontinuity at about 20 km depth, below which density irregularities do not occur.

Geological evidence suggests that the major east-west structures in central Australia were caused by a recurring primary north-south compressive stress over the interval 1700 - 300 m.y. We believe that compression can also be deduced from the gravity information. The prominent truncation of the gravity features at the eastern edge of the Central Australian Deformed Province suggests that a major NNW crustal dislocation terminated stress and resulting deformation farther eastwards. A similar dislocation is interpreted to extend north-northeast from the Fraser Fault along the western edge of the Central Australian Deformed Province, and, if extrapolated, the two would intersect at a point centrally north of the deformed zone. The deformation of the Fraser, Musgrave, and south Arunta belts can therefore be considered to have occurred between two intersecting major crustal dislocations. The interpreted relationship between the crust dislocations and the Central Australian Deformed Province implies that the deformed province was an intracontinental feature from at least the time of formation of the 1700 m.y. old southern Arunta Deformed Belt.

There is evidence of deformations involving north-south compressive stress in the Central Australian Deformed Province at 1700, 1000, 600, and 300 m.y. Immediately after the main 1700 m.y. and 1000 m.y. deformations, anisotropy may have affected the direction of stress, but considering the length of time and the magnitude and consistency of the later strains involved, it is unlikely that anisotropy markedly affected the stress direction in the more recent events. The overall history of stress in the Central Australian Deformed Province therefore appears to be one of compressive stresses resulting from a more or less consistent north-south primary compression vector. This suggests that the main Australian Precambrian plate did not rotate relative to its surroundings if it underwent continental drift between 1700 and 300 m.y., since this would probably have produced new principal stress directions.

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