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RECORD No. 1965/97

THE CRUSTAL STRUCTURE OF THE SOUTH-WEST OF WESTERN AUSTRALIA

by

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SUMMARY

From data collected by the Mundaring Geophysical Observatory since 1959, it has been found that the south-western part of Western Australia has an unusual and complex crustal structure, the most interesting features of which are:

(a) The Darling Fault, one of the Earth's major faults, where the displacement of the crystalline basement rocks is about 20 km;

(b) A high mantle velocity of 8.48 km/s;

(c) An intermediate crustal layer with a velocity of 7.24 km/s at a shallow depth (14 km) beneath the Shield;

(d) The Yandanooka/Cape Riche Lineament, where a zone of seismicity is associated with changes in gravity, geomorphology, and geology;

(e) Increased crustal thickness compared with the normal Shield regions to the east. Average crustal thickness for the area is about 45 km.

1. INTRODUCTION

The material contained in this Record was originally presented as a paper at the Symposium on Crustal Structure at the University of Tasmania in August 1964. It is a brief account of the present knowledge of the Earth's crust and upper mantle in south-western Australia, the area of principal interest being the south-western part of Western Australia including the Perth Basin south of Geraldton and part of the Precambrian Shield immediately to the east of the Perth Basin.

In July 1959, the Mundaring Geophysical Observatory seismograph, situated on the Precambrian Shield about fifteen kilometres east of the Darling Fault, came into operation. Early comparisons of the records from this seismograph with those from the Perth Observatory seismograph, which was situated west of the Darling Fault and on the sediments of the Perth Basin, showed that the P-phases from distant earthquakes were delayed by 1.6 seconds at Perth, relative to Mundaring. This indicated that the Perth Basin was deeper than suspected, or that there were crustal or mantle differences beneath the two observatories.

Since then, the Mundaring Geophysical Observatory has been collecting data for a study of the Earth's crust locally. These data include the results of seismic refraction and reflection work, the results of gravity surveys, and the seismic information from distant earthquakes.

2. SEISMIC SURVEY RESULTS

Refraction work was initiated in 1960, when depth-charge explosion from the research ship VEMA (of the Lamont Geological Observatory) were recorded at distances of up to 360 kilometres, the recordings being made on the seismograph at Mundaring Observatory. The VEMA had been engaged in a seismic survey of the off-shore part of the Perth Basin.

Later, in December 1962, arrangements were made with scientists from the Scripp's Oceanographic Institute vessel ARGO to explode four charges in the Perth Basin after the ship left Fremantle. These explosions were recorded at the Mundaring Observatory, at a field station further east on the Precambrian Shield, and by a research ship about 150 kilometres west of Fremantle.

The results, although indicating an unusual crustal structure, were inadequate for accurate interpretations, and more recordings were desirable. Hence, with the cooperation of the Royal Australian Navy and the Commonwealth Scientific and Industrial Research Organisation during August 1963, six more depth-charges were exploded from the DIAMANTINA between Geraldton and Cape Naturaliste. Recordings of these events were made by seismographs at the Mundaring Observatory, at semi-permanent field stations at Grass Valley and Narrogin, and by a roving field station. The positions of the shots and the recording sites are shown in Plate 1.

The field stations at Grass Valley and Narrogin operated continually during the latter half of 1963 and one of their purposes was to supply Raleigh-wave phase-velocity data.

In addition to the depth-charges, several timed quarry blasts near Perth were recorded by the outstations, by temporary field stations, and at Mundaring Observatory (Plate 1).

By the end of 1963, it became possible to calculate a crustal model from refraction results. Preliminary interpretations showed that crustal structure of both the Perth Basin area and the adjoining Shield region were unusual.

As an independent check on the refraction results, attempts to record deep crustal reflections were made by a Bureau of Mineral Resources (B.M.R.) prospecting seismic party during May and June 1964. Plate 1 shows the shot positions; the recording instruments were close to the shot in each case. On the Shield, possible reflections with normal incidence were recorded from the Mohorovicic discontinuity and from the top of a lower crustal layer. Also recorded were events believed to be reflections from the lower crustal layer beneath the Perth Basin. The results were in agreement with the refraction results.

Crustal structure from seismic refraction work

Plate 2 shows travel times from explosions in the Perth Basin that were recorded by stations on the Shield. Plate 3 shows results obtained from shots made by the B.M.R. prospecting seismic party and from quarry explosions, made and recorded on the Shield.

An outline will now be given of the procedure adopted in calculating a crustal model:

As the thickness of sediments with a low seismic velocity (about 3 km/s) was known to be variable over the Perth Basin, corrections to travel times were made for shots made in the Perth Basin so that the low-velocity sediments were, in effect, replaced by rocks with the P1 velocity of 5.38 km/s at the various shot-points. The corrections were made on the basis of the results of the refraction traverse of the VEMA and a B.M.R. aeromagnetic survey.

Velocities of P1 (5.38 km/s), P2 (7.24 km/s), and Pn (8.48 km/s) were determined by the method of least squares from the data shown in Plate 2. By use of the same data it was also possible to ascertain whether or not the velocities P2 and Pn differed beneath the Perth Basin and the Precambrian Shield. This was achieved by computing 'shot-to-shot' velocities (using travel times from different shot-points to a selected station) and 'station-to-station' velocities (using travel times across the station network from any selected shot-point). The results are shown in Plate 4. No significant differences were noted although the calculated P2 velocity was greatest beneath the Basin (shot-to-shot velocity) and the Pn velocity greatest beneath the Shield (station-to-station velocity).

A crustal model was not calculated from the travel-time data shown in Plate 2 because they are derived from waves that have mixed crustal paths, i.e. waves that are refracted down through the Perth Basin crust and back up through the Shield crust. The crustal columns for the Perth Basin and the Precambrian Shield are evidently different because the Perth Basin P1 velocity is too low for the granite and gneiss that crop out on the Shield. However, by use of the data shown in Plate 3, it was possible to measure crustal parameters for the Shield area and then, allowing for these, use the data in Plate 2 to measure these parameters for the Basin area.

Plate 5 shows a preliminary east-west crustal cross-section through Perth, the notable features being:

(a) The crustal thickness (42 km) in the Shield region of south-western Australia is slightly greater than in other regions of the Shield (36 km).

(b) The crust is calculated to be even thicker (46 km) beneath the Perth Basin, which could indicate that the Darling Fault extends into the mantle.

(c) There is a high Pn velocity (8.48 km/s) beneath the entire region over which the seismic work was done.

(d) Two main crustal layers are found beneath the Shield and beneath the Perth Basin. The upper crustal layer is different in the two regions as P1 velocities of 6.18 km/s and 5.38 km/s were measured respectively. The velocity of the lower crustal layer (P2 velocity of 7.24 km/s) appears to be uniform for both regions.

(e) The depth of the lower crustal layer in unusually shallow (14 km) for a shield region for the P2 wave is not usually recorded as a first arrival in shield regions.

(f) In the central regions of the Perth Basin the vertical throw of the Darling Fault could be as great as about 20 km (about 66,000 feet). Here the P1 velocity of 5.38 km/s is too low for plutonic rocks and indicates the presence of a section of unmetamorphosed sedimentary rocks, which, on the basis of exploration seismic work, is most likely of pre-Permian age. It is to be noted that throughout the Basin, relatively low-velocity sediments of variable depth (0 - 7 km), and possibly of Permian and younger ages, overlie the section with a P1 velocity of 5.38 km/s.

(g) The P1 velocity (5.38 km/s) is approximately the same as the basement velocity (5.3 - 5.5 km/s) determined by the VEMA along the traverses made in the central parts of the Basin. To the west of Cape Naturaliste and off the south coast (Plate 1, traverses 33, 33R, 35, 35R, 36, and 36R), the basement velocity was about 6 km/s, which is typical of granitic rocks.

South coast results

Travel times for P-phases from underwater shots (Plate 1 - traverses 33 and 33R and shot X5; Plate 3 - MV, N5, M5 and G5 between 200 and 300 kilometres distance) on the continental shelf west of the Cape Leeuwin/Cape Naturaliste Precambrian block were treated separately from the Perth Basin shots, and it was found (Plate 3) that both the P2 and Pn times were about one second later than travel times at similar distances on the travel-time curves for shots made on the Shield to the east of the Basin.

By allowing for the times of travel within the Shield it was possible to calculate a crustal model for the Precambrian area west of the Basin. Assuming that P1, P2, and Pn velocities for both areas were identical, the depths to the base of the first and second crustal layers were estimated to be 22 and 48 km respectively. A structural model for the southern Perth Basin is shown in the lower section of Plate 5.

Interpretations of records of shots to the south-east of Cape Leeuwin are uncertain as the initial phases were barely discernable and the travel times (Plate 3, for distances greater than 300 km) are not mutually consistent and fit either the P2 travel-time curve for shots made on the Shield or the Pn travel-time curve for the shots west of Cape Naturaliste, where the crustal structure is possibly similar.

Normal reflections

Perth Basin. Recognisable events were recorded at time intervals of 3.66, 7.4, and 9.2 seconds and were interpreted as shown below:

Reflection time (seconds)	Reflector depth (km)	Mean velocity (km/s)	Refractor depth (km)
3.66	5.4	2.94 (0 - 5.4 km)	-
7.4	15.5	5.38 (5.4 - 20.3 km)	-
9.2	20.3		19.8

Shield. Reflection data for shots made on the Shield are shown below:

Reflection time (seconds)	Relative quality	Reflector depth (km)	Mean velocity (km/s)	Refractor depth (km)
4.41	A	13.6	6.18 (0 - 14 km)	-
4.81	A	14.9	7.24 (14 - 42 km)	13.9
9.70	B	32.6		-
11.22	B	38.1		-
11.35	A	38.6		-
11.61	B	39.5		41.5

3. ANOMALIES IN P-WAVE TRAVEL TIMES FROM DISTANT EARTHQUAKES

Travel times for waves from earthquakes also indicate unusual upper earth structure in the south-western part of Western Australia.

Mundaring-Perth differences in P-wave travel times

Comparison of arrival times at Mundaring Observatory (on the Shield) and at Perth Observatory (in the Perth Basin) showed that P-waves at Perth have a time delay of 1.6 seconds relative to Mundaring. This value applies to waves travelling vertically. All but 0.15 second of this delay is explained by the crustal differences between the two stations and, because the 0.15 second discrepancy is within experimental error, it seems unlikely that significant variations in the mantle occur beneath the two seismological stations.

Residuals of P-wave travel times from distant sources

It has been found that, at Mundaring, P-waves from more distant sources (greater than 25°) have larger negative residuals from standard travel-time curves than at other Australian stations. For example, Doyle and Webb (1963) found that at a given epicentral distance the P-waves will arrive at Mundaring approximately 1.25 seconds earlier than the averaged arrival time for eastern Australian stations. If this is assumed to be due to the above-normal mantle velocity beneath the regions around Mundaring, it can be shown that there could be Pn velocity differences to a depth of about 200 km. This is based on a mean Pn velocity of 8.13 km/s for eastern Australia.

Australian Pn velocity determinations are shown in Plate 6. The velocities illustrated were determined by Bolt, Doyle, and Sutton (1958); Doyle, Everingham, and Hogan (1959); Cleary and Doyle (1962); Cooney (1962); Doyle and Everingham (1964); and Everingham (in preparation). The velocity for the path from Timor and northern New Guinea to Mundaring was calculated from travel times of the Pn-phase at great distances where it is not the first arriving P-wave. The highest Pn velocities are beneath the Precambrian Shield region. Similarly, high velocities have been found beneath the older geological regions of Northern America (Herrin and Taggart 1962). It was interesting to find that R. Green of the University of Tasmania and J. Brooks of the Port Moresby Geophysical Observatory each has evidence (personal communications) that the Pn velocity may be even less than the lowest values shown in Plate 6 for regions furthest from the Shield, namely Tasmania and northern New Guinea.

4. THE YANDANOOKA/CAPE RICHE LINEAMENT

On the basis of the geomorphology, seismicity, and gravity anomalies of the south-western part of Western Australia, it has been suggested (Everingham, in preparation) that a change in the crust, and possibly the upper mantle, probably occurs along a zone running in a south-south-easterly direction between Yandanooka and Cape Riche. This has been tentatively named the Yandanooka/Cape Riche Lineament, the features of which are shown in Plate 7.

It may be seen that a zone of seismicity (Plate 10) coincides with the junction of two physiographic regions, the Salt Lake Division and the South-West Division of(Jutson 1934, p 75). It also coincides with the eastern boundary of an area where rocks of granulite facies crop out and is therefore associated with a change in the grade of metamorphism. Wilson (1958, p 81) suggested that a fault may separate the granitic rocks near the Darling Fault zone from the high-grade gneisses to the east.

A change in Bouguer anomaly also occurs along the Lineament (Plates 8 and 9). Bouguer anomalies to the east range from minus 40 to minus 60 milligals, whereas on the extreme south-west of the Shield, values are positive and in the range 0 to 20 milligals. The general rise in the gravity anomalies (about 60 milligals) takes place across the zone of seismicity and the minus 20-milligal contour (which represents the centre of the gravity change) lies within the active zone throughout its length (Plate 7).

Another feature of the Lineament is that to the north it cuts the Darling Fault near Yandanooka, where

(a) The throw of the Darling Fault since the earlier Palaeozoic is small compared with its throw in regions to the north and south;

(b) The Urella Fault has formed parallel to the Darling Fault and has a throw since the early Palaeozoic comparable with the Darling Fault further to the south;

(c) The Darling Fault changes its trend to run parallel to the Urella Fault and also parallel to the direction of the Lineament.

It can be seen that this region of seismicity and its associated features is of extreme interest in regard to the tectonic history of this part of Western Australia.

5. GRAVITY INTERPRETATIONS

Plate 9 shows the profile of Bouguer gravity anomalies across the Western Australian Shield region (Everingham, 1965). Interpretations of anomalies across the Perth Basin and seawards have not been completed for this Record.

Based on the structural model of the Shield around Mundaring and the 60-milligal gravity change across the Yandanooka/Cape Riche Lineament, a crustal model can be proposed for the normal Shield regions (where mean Bouguer anomalies are about minus 50 milligals). The model has to be consistent with the results of seismic refraction work between Southern Cross and Maralinga (described by Bolt, Doyle, and Sutton, 1958) and the proposed model for an average Shield region is illustrated in Plate 5. The crustal thickness of the average Shield areas is probably 35 - 42 km and the thickness of the lower crustal layer 0 - 21 km.

One main uncertainty encountered in the gravity interpretation is the effect of the upper mantle. In the above interpretation the effect is assumed to be negligible, whereas in fact this may not be so. Where the change in the mantle velocity, from 8.48 km/s to 8.21 km/s, occurs is unknown. If crustal changes are any indication of mantle changes the latter could occur either along the Yandanooka/Cape Riche Lineament or east of Kalgoorlie at the Fraser Range orogenic zone. Travel-time curves for areas of the Archaean Shield to the east of the Yandanooka/Cape Riche Lineament would be an asset to studies of the effect of the upper mantle on gravity anomalies.

Although the subject of this Record is primarily concerned with crustal structure in the extreme south-western part of the State, a feature of interest is illustrated in Plate 9. Here it may be seen that, over a large part of the Shield, Bouguer anomalies are in the range of minus 40 to minus 60 milligals, but that to the east and west of this region large negative anomalies occur. Zones of negative anomalies, of which these are part, occur around the western, southern, and south-eastern margins of the Archaean Shield and future surveys could reveal similar anomalies around the northern and north-eastern margins. The negative anomalies over the Perth Basin are largely caused by light sediments, whereas elsewhere they are believed to be due to granite cores in orogenic zones formed during Precambrian times.

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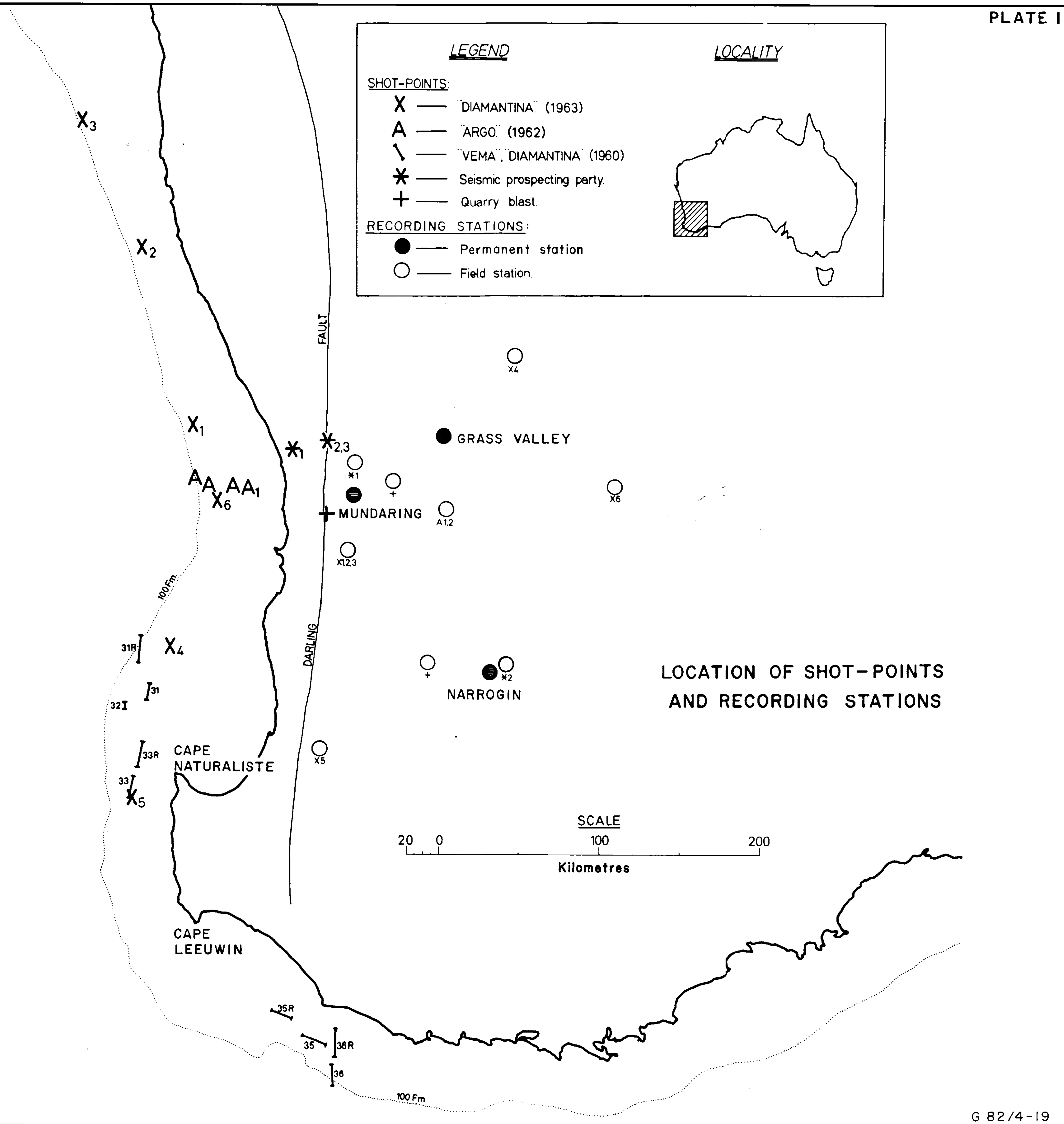
PLATE I



LOCATION OF SHOT-POINTS AND RECORDING STATIONS

G 82/4-19

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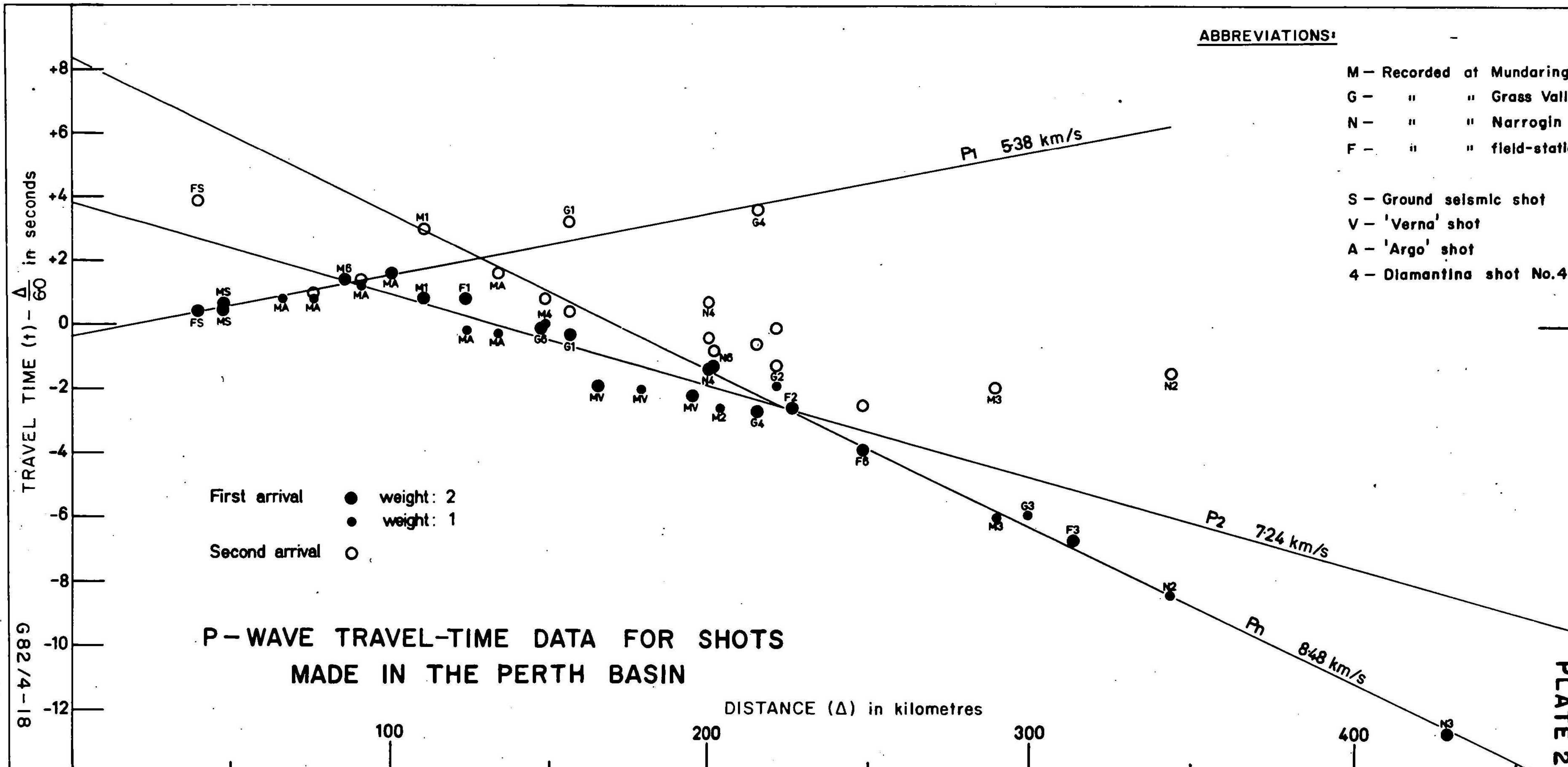

P — WAVE TRAVEL-TIME DATA FOR SHOTS MADE IN THE PERTH BASIN

PLATE 2

G82/4-18

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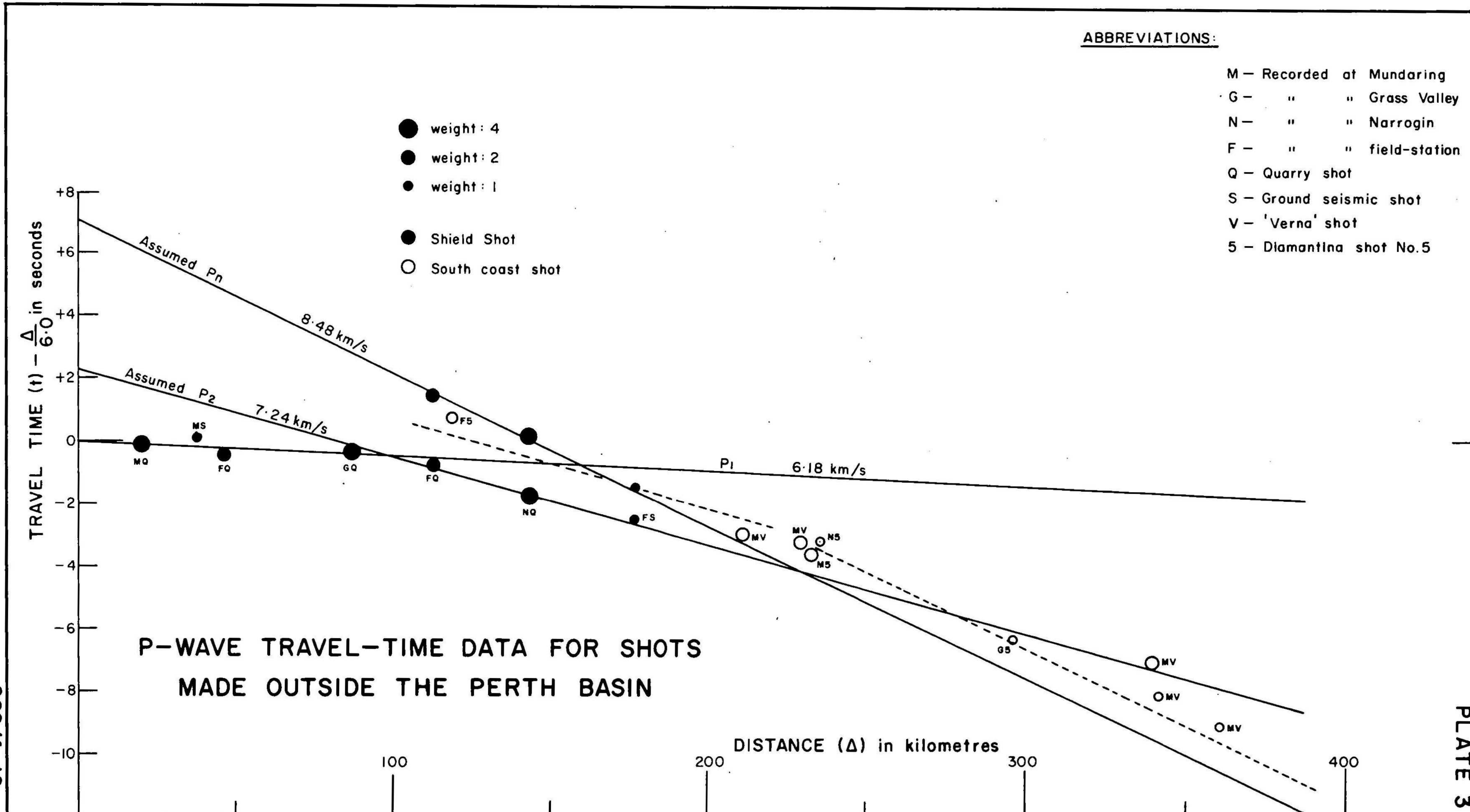

P-WAVE TRAVEL-TIME DATA FOR SHOTS MADE OUTSIDE THE PERTH BASIN

PLATE 3

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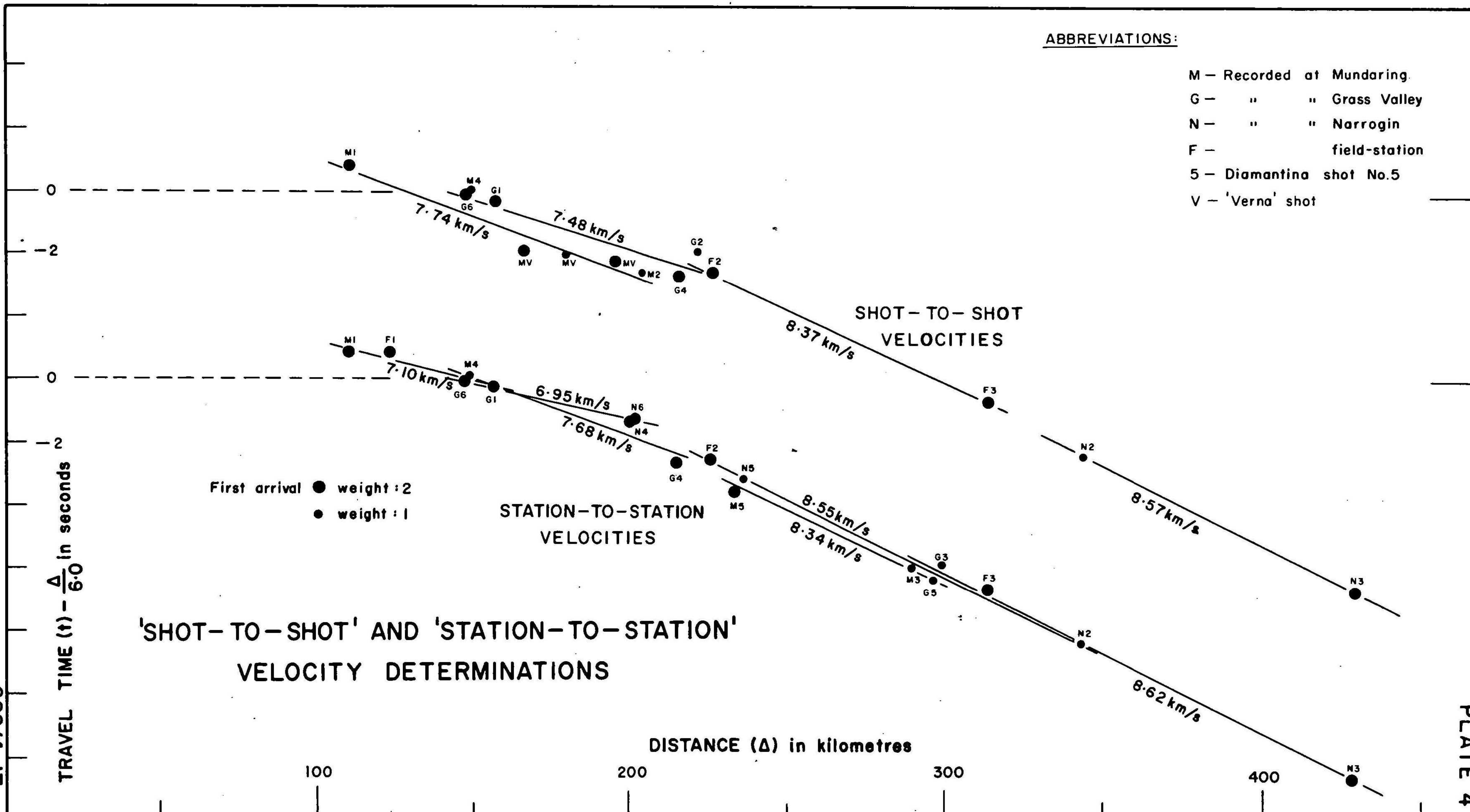
G82/4-16



'SHOT-TO-SHOT' AND 'STATION-TO-STATION' VELOCITY DETERMINATIONS

PLATE 4

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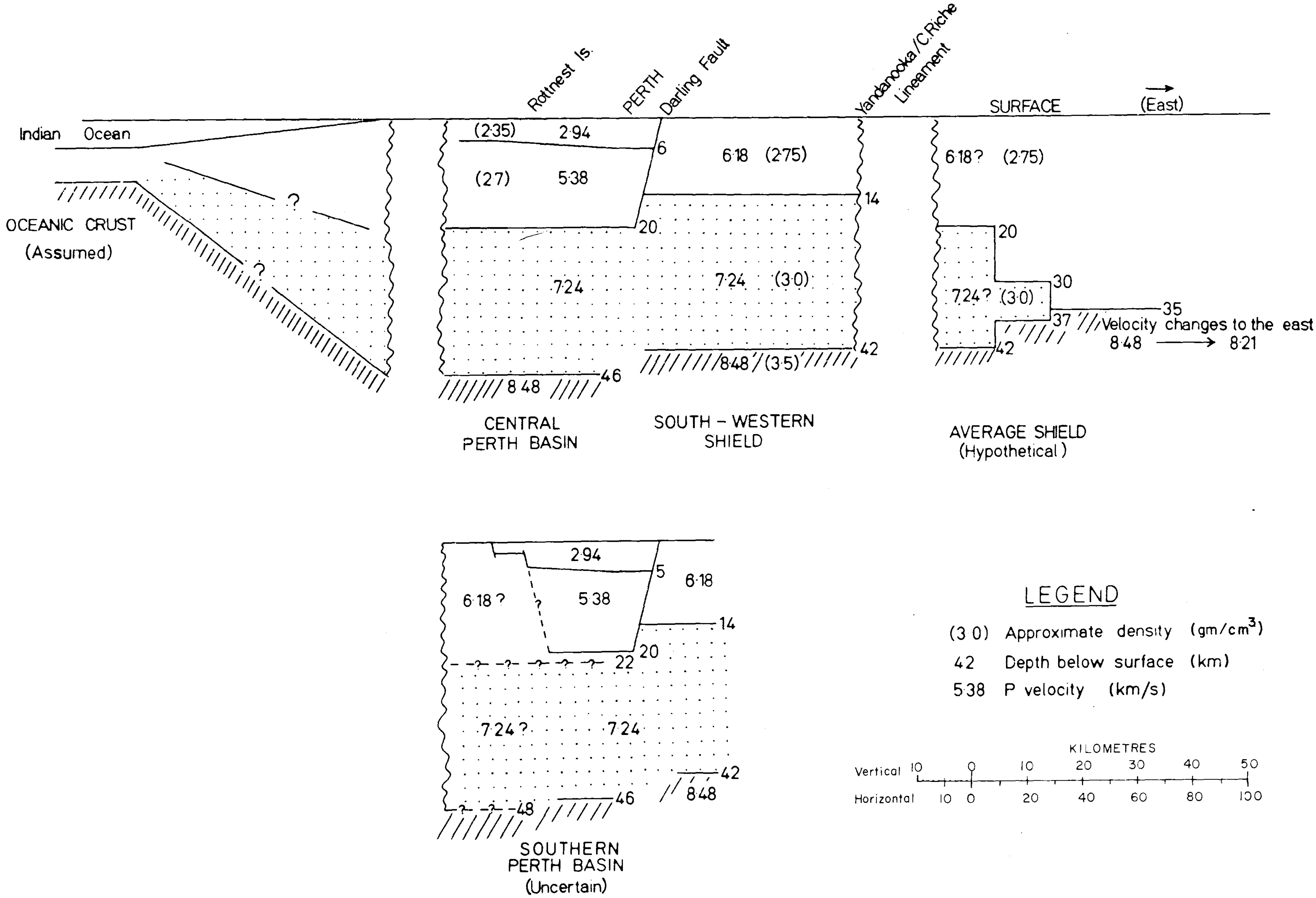
PLATE 5



CRUSTAL STRUCTURE OF SOUTH—WESTERN AUSTRALIA

G 82/4-13

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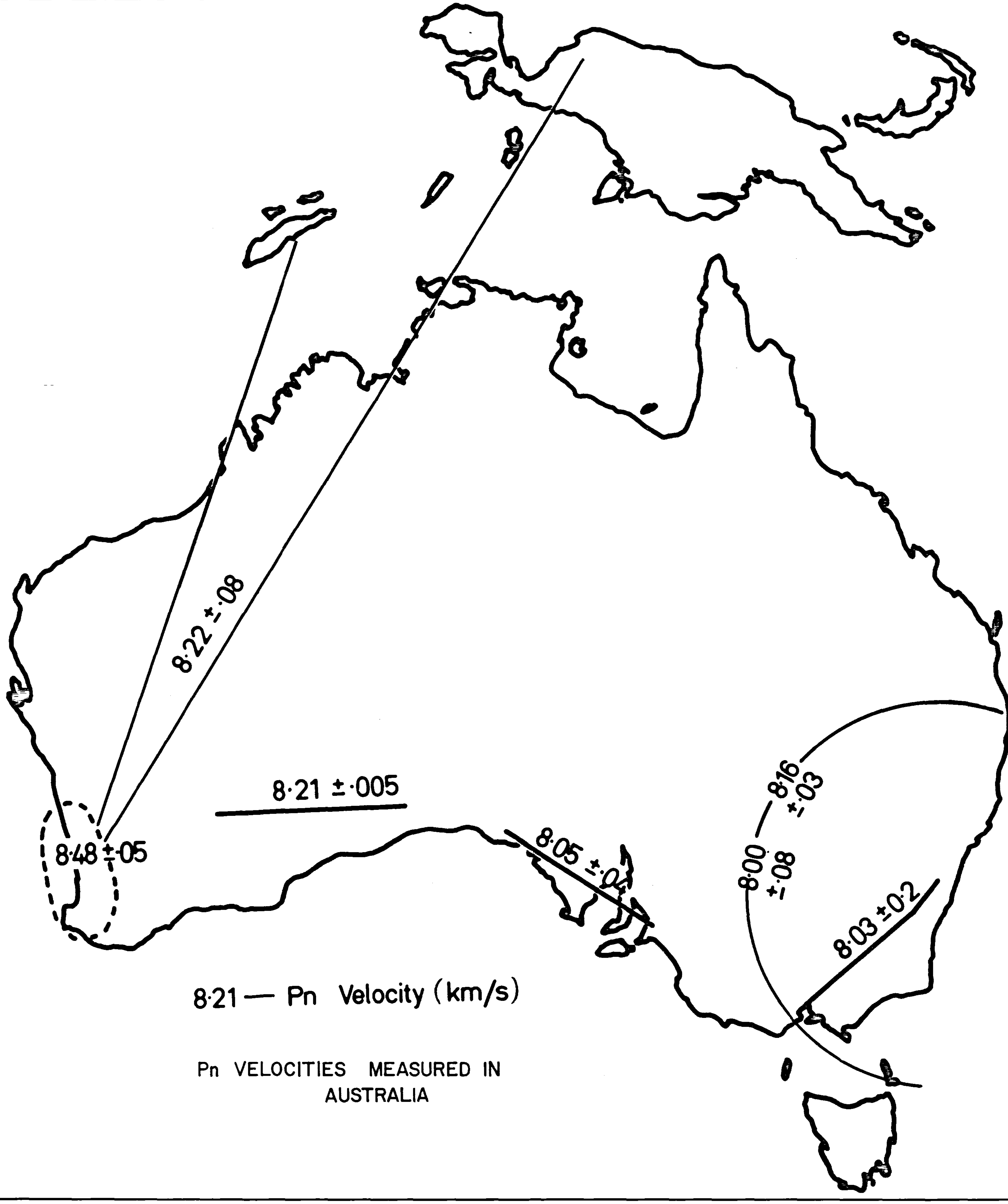
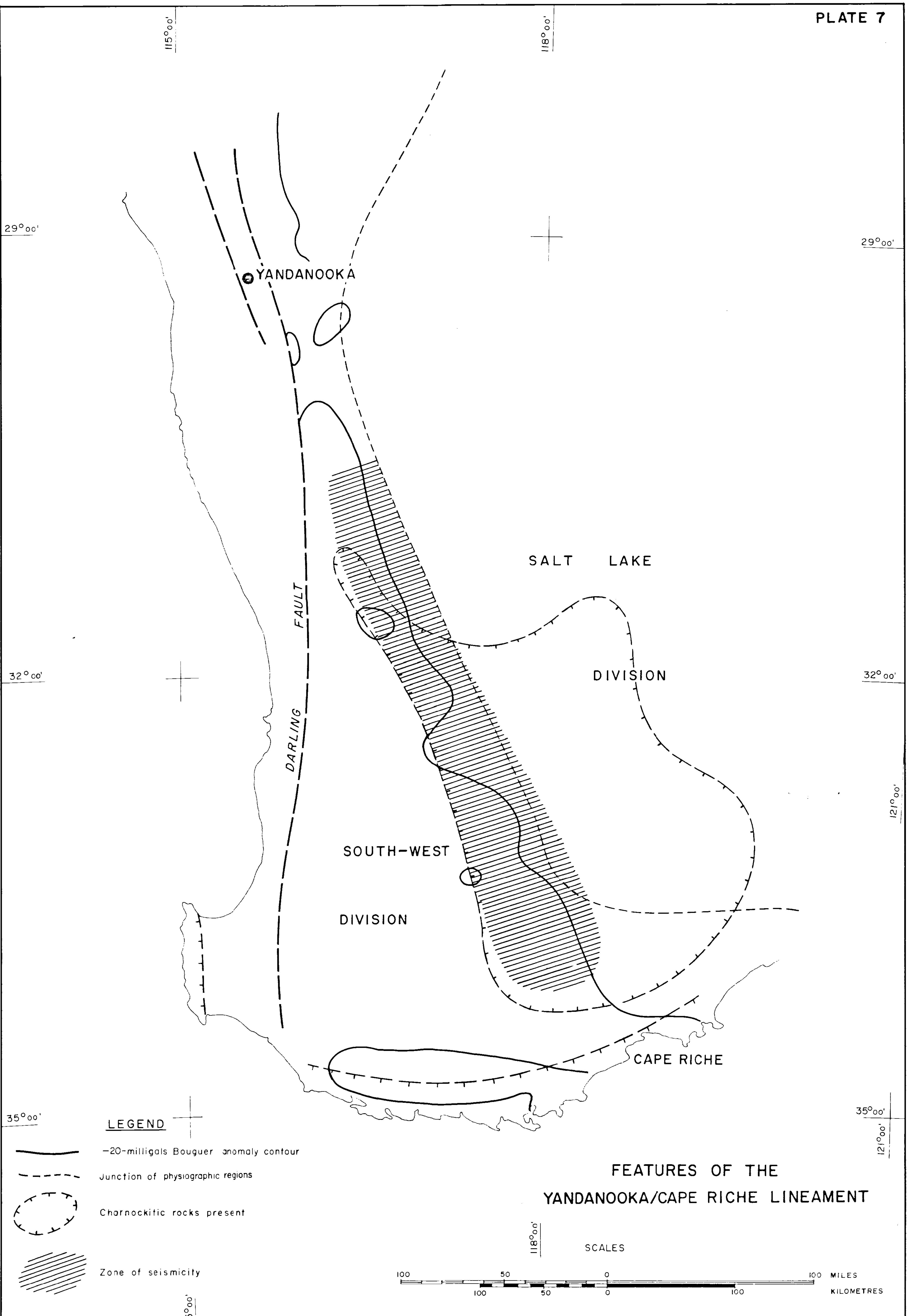


Pn VELOCITIES MEASURED IN AUSTRALIA

G 82/4-15



FEATURES OF THE YANDANOOKA/CAPE RICHE LINEAMENT

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82/4-8

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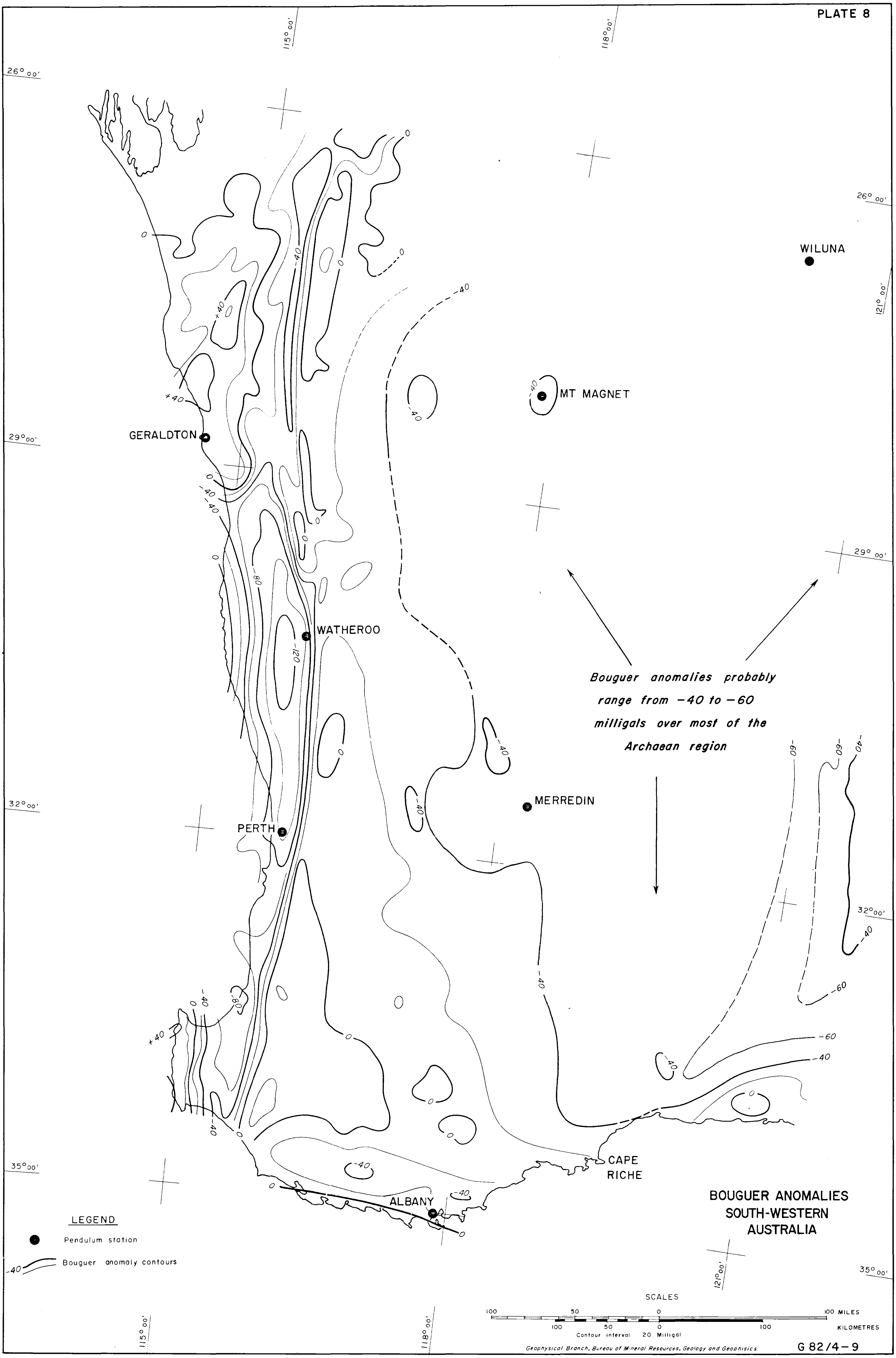

BOUGUER ANOMALIES
SOUTH-WESTERN
AUSTRALIA

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics.

G 82/4-9

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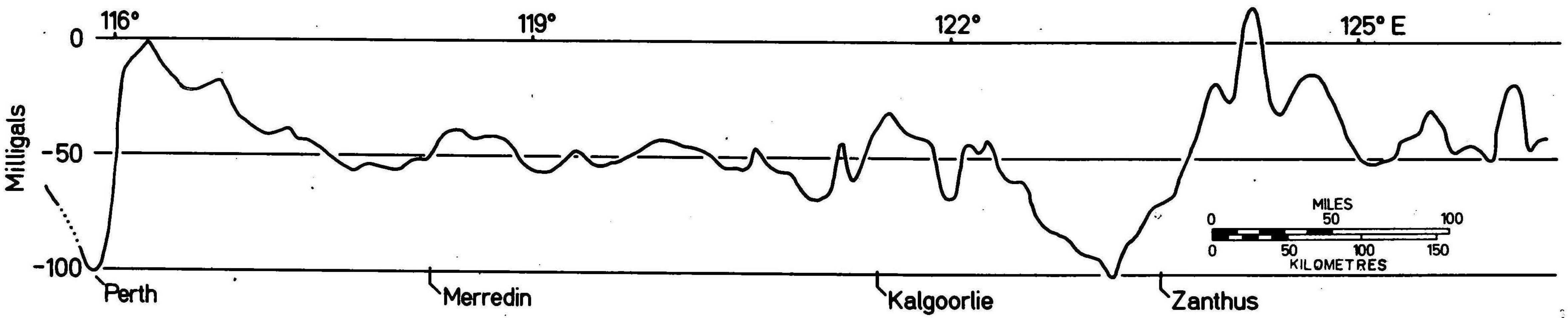

BOUGUER ANOMALIES ACROSS THE SOUTHERN ARCHAEAN SHIELD REGION

PLATE 9

G 82/4-14

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