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DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD 1976/1

STRESS MEASUREMENT PROPOSALS FOR WESTERN AUSTRALIA

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D. Denham, L.G. Alexander, and G. Worotnicki

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SUMMARY

Determinations of principal stress axes from overcoring techniques at six widely separated sites in the Australian continent and focal mechanism studies from five earthquakes all indicate the presence of regional tectonic stresses acting close to horizontal and higher than would be expected if all the stress was caused by rock loading.

Except for the results in the centre of the continent all observations reveal a predominantly east-west direction for the maximum principal stress. In the eastern half of the continent the axes dip to the east and in the western half they dip to the west. This situation may arise as a result of stresses induced in the Australian Plate as it moves across the Earth's surface. Owing to the ellipticity of the Earth the lithosphere must deform when its latitude changes and hence in the case of the Australian Plate, as it moves northwards the principal radii of curvature of the Earth decrease and the stress regime within the plate will be modified.

The anomalous observations from central Australia both give a north-south maximum principal stress, which is probably a residual tectonic stress from an old orogeny. Thus the residual stresses from the Alice Springs Orogeny (300-400 m.y. B.P.) could still be contributing significantly to the regional stress field at the centre of the continent.

To provide further information on the regional stress field in Western Australia it is proposed to measure the in-situ stress, using overcoring techniques in shallow boreholes, at six sites near the south-west seismic zone (where the Meckering earthquake took place in 1968).

The site requirements call for unweathered competent rock either outcropping or lying very close to the surface in areas of low topographic relief. The six sites tested in May 1975 meet these requirements and it is proposed that the measurements be made early in 1976.

1. INTRODUCTION

That rocks near the surface of the earth are stressed has been known for many years. Mining engineers have had to combat rock-bursts, tunnel deformations and the like for as long as man has excavated underground; similarly earth scientists have recognized that faulting and folding are caused by rocks reacting to stress.

Until recently, no acceptable theory has been proposed that explains the state of stress in the Earth's crust but with the development of Plate Tectonics it has been possible to provide a model that can be used to explain most of the major geological and structural features we observe. The basic hypothesis of Plate Tectonics is that the outer shell of the Earth (the lithosphere) is broken up into a number of comparatively rigid plates which are in relative motion with respect to each other. As the plates interact and move over the surface of the Earth it is presumed that the regional stress regime will change.

One of the problems is that stresses in solids are not directly measurable, rather they are determined indirectly, usually by measuring displacements (or strains), deformations, or the effects of earthquakes. At the lithospheric boundaries, where about 90% of the world's earthquakes occur it is possible to determine the directions of principal stresses, by studying the focal processes of larger earthquakes. In general, the results from any one region give consistent results which fit into the concepts of Plate Tectonics (Denham, 1973). However, within the lithospheric plate the earthquakes are less numerous, they do not occur in any well defined pattern, and their causes are not well understood.

One advantage of the intra-plate environment, however, is that evidence from in-situ stress measurements made in mines and other places can be used to supplement the earthquake information in an effort to delineate the stress regime. Furthermore, the in situ measurements usually provide estimates of the magnitude of the principal stress components, whereas the observations from earthquakes provide only the directions of the principal axes. This report reviews the observations already carried out in Australia and describes a proposal to carry out in situ stress measurements in southwestern Western Australia near the site of the 1968 Meckering earthquake.

2. TECHNIQUES USED TO MEASURE STRESS

The Stansfield at a point is specified by the three normal and three shear components of stress. Several techniques have been devised to obtain these six components and more particularly the directions and amplitudes of the principal stress components (Obert, 1967). Most procedures assume that the medium is linear-elastic; isotropic and homogeneous, and use observed displacements or deformations (strains) to calculate the required stresses. In this report σ_1 is the greatest compressive principal stress, σ_3 the least compressive principal stress, and σ_2 is the intermediate compressive principal stress. Three of the more widely used and reliable methods are described briefly below.

Overcoring techniques

A number of different methods that involve overcoring have been used to measure in-situ stress. Typically a 4-cm diameter hole is drilled into the rock under stress, a strain gauge is inserted, and the hole is overcored by a 15 cm core barrel. The overcoring relieves stresses in the rock surrounding the strain gauge, giving a strain reading. This is converted to stress by determining the elastic properties of the rock sample in the laboratory. Usually two components of principal stress can be determined from a single overcoring observation and three non-parallel holes must be drilled to determine the complete field. Detailed descriptions of overcoring techniques can be found in Obert (1967) and Hooker & Bickel (1972). These techniques have been commonly used in Australia.

Hydrofracture techniques

Hydrofracturing is a recently developed method for measuring in-situ stresses. It consists of hydraulically pressurizing a sealed-off interval inside a borehole until fracturing starts. The fractures are then extended by additional pumping. The pressures recorded during the test can be directly related to the magnitudes of the in-situ principal stresses, and the orientation of the fracture in the borehole yields their directions.

The method uses commercially available packers, pressure lines and pumps, and has been extensively used in the US (Haimson, 1973), although not in Australia.

Earthquake focal mechanisms

Earthquake focal mechanism studies yield two nodal planes, one of which can usually be selected as the fault plane. The P (compressional) axis, T (tensional) axis, and the slip vector on the fault plane can also be inferred from the solution. These parameters are commonly determined by plotting the directions of first motions of the P wave, as recorded on seismographs, on an equal-area projection of the lower focal sphere of the earthquake. The P and T axes are located in the centre of the dilatational and compressional quadrants respectively and are oriented 45° to the nodal planes.

In many studies the P and T axes are assumed to be equivalent to the axes of principal stress. However, this may not be a correct assumption in all cases. McKenzie (1967) argued that since shallow earthquakes usually occur by failure of weak planes associated with pre-existing faults rather than by brittle fracture of a homogeneous material; the orientation of the greater principal stress can be almost anywhere in the quadrant containing the P axis. This is probably an extreme situation and pre-supposes that the stress regime has changed significantly since the faults were first formed. However this possibility should not be overlooked completely.

Sbar & Sykes (1973) in their study of eastern North America chose σ_1 30° from the slip vector in the direction of the P axis and in the plane of the slip vector and the P and T axes. Similarly, σ_3 was chosen 60° from the slip vector in the direction of the R axis.

In this report it is assumed that the P and T axes coincide with the principal stress axes, but the reader should be aware this may not necessarily represent the true situation.

Unfortunately , the values of the principal stress components cannot be determined, although for some earthquakes the stress drop during the earthquake can be estimated (cf. Brune & Allen, 1967).

Several earthquakes large enough to be studied in this way have occurred in Australia and these are discussed in the next section.

3. REVIEW OF PREVIOUS RESULTS FROM AUSTRALIA

Results from earthquakes

Epicentral distribution

Earthquakes with magnitudes greater than 4 that have occurred in the period 1897 - 1972 are shown in Plate 1. There appear to be three main regions of earthquake activity (see Denham et al., 1975; Doyle et al., 1968).

Eastern region. The earthquakes of eastern Australia tend to be associated with the highland belt parallel to the coastal margin. There are no major lineations of epicentres, but rather a diffuse distribution over a wide area, with a few localized clusters of earthquakes where the activity rises above the regional level.

North of Sydney, the frequency of earthquake occurrence appears to decline but this may be due to the poor distribution of seismograph stations in northern New South Wales and Queensland.

Central region. The earthquakes in central Australia extend from the vicinity of Adelaide to the Simpson Desert (26°S, 137°E). It is not clear whether the groups of earthquakes within this region represent separate seismic zones, or whether they should be regarded as belonging to a single tectonic unit. The area immediately to the north of Spencer Gulf (31°S, 139°E) is one of the most seismically active in Australia, and earthquakes have been recorded from there since the installation of the Adelaide station in 1909. The Simpson Desert region has also been very active. Five earthquakes with magnitudes greater than 6 occurred there in the period 1937-41 (Burke-Gaffney, 1952), and another of magnitude ML 6.2 took place in 1972 (Stewart & Denham, 1975).

Western region. Most of Australia's largest earthquakes have occurred in this region. The more important were the Meeberrie earthquake of 1941 and the Meckering earthquake of 1968. The latter produced a surface fault with a throw of up to 2 m which extended for over 35 km. The earthquake activity tends to increase near the coast, and only in the Fitzroy Trough (18°S, 125°E) is there any well developed inland activity.

Focal mechanism solutions

Reliable focal mechanism solutions have been obtained for five earthquakes whose epicentres are shown in Plate 1 and the focal parameters in Table 1.

Meckering, October 1968 (Fitch et al., 1973). The large Meckering earthquake, which occurred near the western edge of the Precambrian Yilgarn Block, generated an arcuate pattern of cracks about 35 km long with a maximum surface slip of about 2 m. The character of the P waves suggests a multiple rupture, and both body-wave and surface-wave observations were used to determine the published solution. Slip on the fault plane is represented by the nodal plane with the north-northwest strike, which is reverse and sinistral in nearly equal amounts. The pressure axis is close to horizontal, dipping by 13 degrees to the west (not 113° as incorrectly printed in Fitch et al., 1973). Plate 2a shows the solution given by Fitch et al.

Calingiri, March 1970 (Fitch et al., 1973). The Calingiri earthquake was much smaller than the Meckering event, and the solution shown in Plate 2b is poorly controlled with only one dilatation on the focal sphere. In fact, the solution obtained by Fitch et al., was constrained to be similar to the solution for the Meckering main shock. In spite of the poor data, the observations indicate a near-horizontal compressional axis.

East Canning Basin, March 1970 (Denham et al., 1974). Fitch et al (1973) gave a solution for the 1970 East Canning Basin (at Lake Mackay) earthquake, but Denham et al (1974) used both regional and distant seismograph solutions and obtained an improved solution which is shown in Figure 3a. Both solutions give a P axis dipping shallowly to the southwest with an almost vertical tension axis. The fault plane is probably the one steeply dipping and striking southeast, which parallels the zone of aftershocks (see Fig. 1).

Simpson Desert, August 1972 (Stewart & Denham, 1974). First motion studies of this earthquake suggest a predominantly strike-slip focal mechanism with the fault plane parallel to the east-northeast trend of the aftershock sequence, which extended for about 120 km. The pressure axis for the main earthquake was approximately horizontal and north-south. Figure 3b shows the focal mechanism solution, which is considered to be very reliable.

Picton, March 1973 (Fitch, in press). The solution for the Picton earthquake is well determined from the comparatively large number of seismographs in southeastern Australia. The pressure axis is close to horizontal and it produces thrust faulting as shown in Figure 3c. The slip took place on the eastward-dipping nodal plane that is nearly parallel to the western margin of the Sydney Basin.

Other studies

At least two other studies have been carried out on the focal mechanisms of Australian earthquakes. The first was by Cleary (1967), who used the recordings at ten local stations to analyse a magnitude 3½ earthquake which occurred near Gunning in 1961. A replot of first motions for this earthquake using Cleary's data and improved travel-times (Paine, pers. comm., 1975) is shown in Figure 4a. Clearly it is not possible to determine a reliable solution from these results, and the northeast-southeast compressive forces proposed by Cleary are dubious.

The second study was by Stewart & Mount (1972) who used the amplitudes of S-waves recorded on short-period vertical instruments to infer the style of faulting extant in the Adelaide Geosyncline. Figure 4b shows the active faulting they propose for the region. This model requires maximum compressive stresses lying approximately horizontal and trending north-south. The data used in their study have not been published so it is difficult to assess its reliability.

In-situ stress measurements

Several in-situ stress measurements carried out in Australia will be reviewed briefly State by State.

Western Australia

Mount Charlotte Mine, Kalgoorlie (Bowling, 1963; Bamford, 1971)

Measurements were made using flat jacks at 24 sites at the 3 and 5 levels of the mine.

The object of the tests was to assist in designing the layout of the Mount Charlotte stope by determining primary rock stress conditions and in-situ deformation moduli of the rock in the mine. Flat jacks were used to measure the in-situ stress either parallel or perpendicular to the axis of the main drive, or the cross-cut at the 5 level.

Table 2 summarizes the results obtained.

TABLE 1

Earthquake Focal Mechanism Solutions for the Australian Continent

Date	UT Time h	m	s	Lat°S	Long°E	Depth Km	Magnitudes MB	ML	MS	Poles of Nodal Planes trend	plunge	Axis of Compression trend	plunge	Axis of Tension trend	plunge	Null axis trend	plunge
14 Oct 68	02	58	51	31.58	117.00	15	6.0	6.9	6.8	308 062	45 22	271	13	0.20	50	169	36
10 Mar 70	17	15	11	31.01	116.54	15	5.7	5.9	5.1	067 326	40 14	282	16	023	39	172	46
24 Mar 70	10	35	18	22.05	126.61	15	6.2	6.7	5.9	046 199	20 68	218	24	058	64	310	07
28 Aug 72	02	18	52	24.74	136.92	7	5.6	6.2		323 218	26 27	181	01	271	39	090	50
09 Mar 73	19	09	15	34.17	150.32	21	5.5	5.5	5.3	265 040	36 44	064	06	323	65	157	24

Table 2. Rock Stresses - Mount Charlotte Mine (30.74°S, 121.47°E)

Test Series depth	Number of Sites per Computation	Azimuth	Rock Stress MPa	Standard Deviation (MPa)
Level 3	6	N 142° E	17.7	1.4
92m		N 52° E	15.1	
		Vertical	11.2	
Level 5	10	N 142° E	19.1	2.1
152m		N 52°E	10.6	
		Vertical	10.4	
Cross cut	6	E-W	10.6	3.4
Level 5		N-S	12.1	
152m		Vertical	7.9	

(Youngs Modulus 70 GPa)

The primary vertical stress obtained is much higher than the stress which might be expected from consideration of the rock cover alone. Assuming the rock to have a density of about $3t/m^3$ then the expected vertical stresses at levels 3 and 5 should be about 2.8 and 4.5 MPa respectively. Similarly, the horizontal stresses are much larger than would be expected.

The maximum principal stress appears to be approximately parallel to the orebody, and tectonic forces must be present in the region to produce the observed situation. Whether these forces are related to the formation of the orebody or are part of a regional picture cannot be determined from these measurements alone.

Kambalda Nickel Mines (Dyson, 1971a and 1971b)

Using a United States Bureau of Mines (USBM) 3-component borehole deformation gauge, underground rock stress determinations were carried out from the 3 level plat of the Durkin Mine haulage shaft. A total of 15 independent diametral deformations was recorded, after overcoring 3 diamond-drill holes oriented in 3 mutually different directions.

The results obtained are listed below in Table 3.

Table 3. Rock Stresses - Durkin Mine (31.20°S, 121.67°E)

Depth	Number of observations	Principal Stresses	MPa	Azimuth degrees E of N	Elevation degrees.
		Major	21.6	102	24
85m	15	Intermediate	8.6	306	63
		Minor	1.5	196	10

The calculated vertical rock stress from Table 3 is about 7.4 MPa which is much higher than the 2.5 MPa which would be expected from the effects of rock cover alone. Similarly, there is a very high horizontal stress field acting in a predominantly east-west direction. No standard deviations or standard errors are given in Dyson's (1971a and b) work.

Northern Territory

Warrego Mines (Peko Wallsend, pers. comm; Worotnicki, pers. comm.)

A comprehensive series of stress measurements were carried out by CSIRO at the Warrego Mine for Peko Wallsend. USBM and Soft Inclusion (SI) gauges were used at three sites in the mine and principal stresses were determined for a number of sets of observations and values of Poissons ratio (σ).

The final report on the measurements was not available at the time of writing (July 1975), but a tabulation of the main results has been provided by Peko Wallsend, and all the USBM results with $\sigma = 0.25$ have been abstracted and are listed in Table 4. It appears that the vertical stress is of the same order as that which would be expected from the rock cover. However, horizontal stresses are about twice the vertical stresses with the east-west stress being greater than the north-south.

Table 4. Principal Rock Stresses - Warrego Mine (19.45°S, 133.95°E.

Test Site	Number of equations	Principal Stresses MPa		Azimuth degrees E of N	Elevation degrees
Site 1	27	Maximum	21.2	99	8
$\sigma = 0.25$		Intermediate	10.8	07	18
Pillar 36		Minimum	7.2	213	71
Depth 241m					
Site 2.	27	Maximum	12.0	68	03
$\sigma = 0.25$		Intermediate	8.9	159	15
Country Rock		Minimum	3.5	326	75
Depth 241m					
Site 3,	36	Maximum	24.5	243	17
$\sigma = 0.25$		Intermediate	11.2	135	46
Depth 319m		Minimum	8.3	347	40

The errors in the stress measurements are not quoted but would probably be of the order of 2 MPa.

Amadeus Basin (Palm Valley, Gosses Bluff and Ooramina; Rough, 1974).

The overcoring measurements in the Amadeus Basin were carried out to measure the stress field in the region when it appeared that the reservoir rocks in the Palm Valley gas field were under strongly directional horizontal stresses. This was first suspected from the pressure responses when the Palm Valley No.3 well was hydraulically fractured. Previously there had also been 'out-of-gauge' problems encountered in the extremely hard orthoquartzite penetrated by many Amadeus Basin wells. After coring with diamond core heads, and then re-entering the hole with a rock bit, it was found that the shape of the hole had changed and the cored intervals had to be reamed before drilling could be resumed.

The stress-relief measurements were made at each test site using the standard borehole deformation overcoring techniques.

On the Palm Valley structure five test holes were drilled, each to depths of about 3 m, and 35 individual determinations were carried out. Four were drilled near Palm Valley No.1 well (24.00°S, 132.77°E), and the fifth (E) near Palm Valley No.3 well (24.01°S, 132.62°E).

Table 5 summarizes the results.

Table 5. Palm Valley - Stress Measurements

Site	Azimuth of Principal Stress Axis (deg W of N)	Ratio of Principal Stresses (T1/T2)	Number of Observations
A	1.4 ± 2.8	1.6 ± 0.1	7
B	28.1 ± 3.2	2.0 ± 0.3	5
C	32.1 ± 2.9	2.8 ± 0.3	7
D	17.9 ± 3.0	3.9 ± 1.1	4
E	27.6 ± 1.8	2.9 ± 0.9	2
Weighted means	22.8 ± 5.1	1.7 ± 0.4	

(Errors are standard errors of the means)

Two sets of measurements were made on the Ooraminna structure (24.00°S, 134.16°E) but the data are not so reliable as those obtained at the Palm Valley Sites. Averaging the 5 readings gives the principal stress direction as 8.98 ± 8.37°E of N and the T1/T2 ratio as 3.78 ± 0.64.

At Gosses Bluff (23.82°S, 132.30°E) one hole in steeply dipping strata gave a principal stress direction of 8.45 ± 15.85° W of N and a T1/T2 value of 1.20 ± 0.07.

If these sets of measurements are representative of the stress regime in the Amadeus Basin then although there is some scatter in the observations the results indicate a predominantly north-south direction for the maximum principal stress.

Queensland

Mount Isa (Alexander, Brady & Friday, 1976; Edwards, 1971; Herget, 1968: Hoskins, 1967; Mathews & Edwards, 1968)

The five references cited above describe various studies of the stress field in the Urquhart Shale at Mount Isa. Herget (1968) concluded that if any residual tectonic stresses exist then these should be at right angles to the bedding plane of the shales because the graphite-coated bedding planes would enable stress to be released along the bedding planes.

Hoskins' results of 1967, when he used flatjacks, borehole deformation gauges, and a borehole strain gauge rosette bear out this conclusion. Hence the results listed in Table 6 may not give a reliable picture of the regional stress field.

More recent information on the Mount Isa stress field has been obtained by Alexander et al.(1976) from tests in a bored raise at 1000 m, results are also given in Table 6.

Table 6. Rock Stresses - Mount Isa Mine (20.78°S, 139.48°E).

Depth m	Stresses (MPa)		Azimuth	Dip
664	Maximum	21.6	E - W	45° to E
	Intermediate	16.4	N - S	horizontal
	Minimum	12.4	E - W	45° to W
1089		16.3		vertical
		17.7	N - S	horizontal
		24.8	E - W	horizontal
1000	Maximum	40	95	27
	Intermediate	30	104	- 62
	Minimum	20	187	- 4

However, the overall situation is one of a predominantly east-west stress field acting at right angles to the bedding planes which are oriented north-south and dip 60° to the west.

New South Wales

Cobar (Stephenson & Murray, 1970)

One of the best sets of in-situ stress measurements carried out in Australia was completed at the Cobar Mine. Borehole Strain Transducers were used in a number of boreholes at both the 1200 and 1800 ft levels, and close agreement was found in both the magnitudes and directions of the stress field at each level. Seven sites were selected and a summary of the results is shown below in Table 7.

Table 7. Principal stresses - Cobar (31.50°S, 145.82°E)

Depth m	Stresses MPa		Azimuth E of N	Dip
366	Maximum	14.8	86	37
	Intermediate	11.2	176	0
	Minimum	4.6	267	55
588	Maximum	31.2	108	28
	Intermediate	24.6	14	7
	Minimum	10.3	273	61

At both levels the principal stress acts approximately east-west and dips at about 30° to the E.

Earlier work at Cobar by Carrard & Alexander (1966), using flat jacks, gave good agreement on the ratio of the vertical to transverse stress components ($\sim$ 1:1.4), but the flat jack work gave values of the stress field about twice as large as those observed from the strain rosette measurements.

North Broken Hill Mine (Friday, pers. comm.)

Measurements have been carried out using flat jacks, cylindrical jacks, and a borehole strain gauge over-coring technique.

Friday (pers. comm.) considered that the over-coring method gave the best results and the measurements he carried out gave consistent observations.

Table 8 summarizes the results.

Table 8. Principal Stresses - North Broken Hill (31.97°S, 141.43°E)

Depth m	Stresses MPa		Azimuth E of N	Dip degrees
1098	Maximum	42.7	88	25
	Intermediate	28.3	180	05
	Minimum	16.5	278	63

The standard deviation of the residuals is listed as 14.5 MPa from 71 equations.

Kangaroo Tunnel - Shoalhaven River (SMEC, pers. comm.)

In 1973 stress measurements were carried out by the Snowy Mountains Engineering Corporation in the Kangaroo Tunnel of the Shoalhaven Scheme (34.75°S, 150.40°E) using USBM borehole deformation gauges and flat jacks. The measurements were made in an adit to the main tunnel at a depth of about 73 m. The results give a vertical stress of 1.8 MPa and maximum and minimum horizontal stresses of 1.5 (N 341°E) and 0.7 (N 71°E) MPa respectively. However, the tunnel is situated in rugged country beneath a north-south spur which has an elevation change of about 400 m in 1.7 km. It seems, therefore, that the maximum horizontal stress is controlled by the local topography because it parallels the spur. The readings obtained in the tunnel probably do not represent the regional stress field present in the crust.

NSW Collieries(Barnes, 1963)

A series of underground measurements were carried out using hydraulic flat jacks in the coalmines near Wollongong during 1961 and 1962. Serious problems were encountered owing to the non-elastic behaviour of the coal and the shales; however, satisfactory conditions were attained in the sandstone roof of the mine opening at Bulli, in the sandstone roof and floor at Coal Cliff, and in the rock roof at Corrimal. All these mines are situated close to the northeast-striking 400-m coastal escarpment and this fact together with the joint patterns in the rock probably control the stress field. Table 9 summarizes the reliable measurements at Coal Cliff and Bulli.

Corrimal Colliery (34.37°S, 150.90°E). Twenty sites in coal and rock were tested but only two sites 7 and 8 in the roof rock were considered reliable. These were located about 350 m below the surface and 1 m of rock had to be removed from the roof before the measurements could be carried out. The horizontal stress field in two directions, N 45°E and N 135°E was found to be 19.3 MPa and 15.5 MPa respectively. These measurements are not sufficient to determine the principal stresses.

Coal Cliff Colliery (34.25°S, 150.98°E). Of the eleven sites tested in the colliery only six were considered to be reliable. These were made at a depth of 460 m below the surface. The stress component in the northeast direction (parallel to the Wollongong escarpment) appears to be the largest but not enough measurements were carried out to determine the stress field completely.

Bulli Colliery ($34.30^{o}S$, $150.79^{o}E$). Measurements at eight sites in the roof above the conveyor heading all gave evidence of a tensional regime. This was probably caused, at least in part, by the excavations because the tensile stress is higher nearer the intersecting cut throughs. It is therefore very unlikely that the observations at Bulli are typical of the regional virgin stress.

Table 9. Horizontal Stresses in NSW Collieries

Coal Cliff (460 m)		Bulli (340 m)	
Azimuth	Stress (MPa)	Azimuth	Stress (MPa)
N (45^{o})E	7.9	N-S	- 0.8
E - W	3.3	"	- 1.7
E - W	2.4	"	- 2.3
N - S	1.9	"	- 0.9
N - S	- 0.2*	E-W	0.0
N - S	1.9	"	- 0.5
		"	- 1.4
		"	0.3

* tensional not compressive stress.

Victoria. Southeastern trunk sewer (W. Peck, 1969)

USBM cells and flat jacks were used in the Silurian mudstone encountered in section 3 of the south-eastern trunk sewer tunnel. Measurements were made at two sites (A & B), of which the site B data are considered to be the most reliable. At each site the stress components were measured vertically and horizontally, with the horizontal observations being made parallel and perpendicular to the axis of the tunnel.

The vertical stress measurement, with the USBM cell, of 1.0 MPa is very close to the vertical stress caused by overburden loading of 1.1 MPa. However, the horizontal stresses are much higher than would be expected from overburden loading alone and this indicates that horizontal residual stresses of tectonic origin are present in the area. Unfortunately, because the measurements were only taken in directions parallel and at right angles to the tunnel axis, it is not possible to calculate the direction of the principal stress axis. Table 10 summarizes the results.

Table 10. Stresses, southeastern Trunk Sewer Tunnel.

Location 37.90°S, 145.07°E - tunnel axis N163.75°E depth 45 m

	Flat jacks		USBM cell
	Site A	Site B	Site B
Azimuth	Stress (MPa)	Stress (MPa)	Stress(MPa)
Vertical	1.0	0.9	1.0
11 el to tunnel	0.5	1.0	1.1
+ to tunnel	1.6	1.3	1.4

Tasmania

Five sites in Tasmania have been examined by the Hydro-Electric Commission in connection with the investigation of sites for dams and underground power stations. Table 11 summarizes the results.

Poatina (Colebatch et al. 1959; Endersbee & Hofto, 1963)

The measurements near the site for the underground power station were carried out in 1959 and 1960 using flat jacks at at least 12 sites. The rock was a mudstone with a compressive strength of about 110 MPa.

Cethana (Mitchell & Paterson, 1970)

The stresses at 18 sites under the right abutment of the Cethana Dam in the north of Tasmania were measured using flat jacks. The rock type was a quartzite-conglomerate with a compressive strength of about 135 MPa.

Fisher Pressure Tunnel (Maddox, 1970).

The stress measurements were taken at four sites about 800 m in from the western portal of the Fisher Tunnel, which is a 'mole'-bored tunnel of 2.4 m diameter. The rock at the site consisted of sandstone and siltstone with a compressive stress of about 40 MPa. The measurements were made using flat jacks.

Gordon Power Station. Access Tunnel (Roberts & Andric, 1975).

The site tested was in the power station access tunnel about 430 m in from the portal. The access tunnel passes under a ridge between the Gordon River and an adjacent valley. The stress measurement site is under the highest point of this ridge. The rock is mainly foliated quartzite with a compressive strength of about 80 MPa. Both flat jacks and photoelastic borehole gauges were used to carry out the measurements.

Gordon Power Station (Roberts and Andric, 1975)

Rock measurements have been made at about 30 sites in adits and excavations associated with the power station in both quartzite and schist. It appears that the schist is partly destressed with virgin rock stresses of only about 1/3 to 1/4 of those in the quartzite. The results in Table 11 are those taken in an explanatory adit in quartzite where the rock has a compressive strength of about 110 MPa.

Table 11. Stress measurements in Tasmania

Site	Azimuth E of N	Stress MPa	Site	Azimuth E of N	Stress MPa
Poatina	vertical	8.5	Cethana	vertical	14.0
d = 160m	125	16.5	d = 90m	165	22.0
41.82°S	35	12.5	41.48°S.	75	16.0
146.92°E			146.13°E		
Fisher Tunnel	vertical	11.0	Gordon	vertical	10.0a 11.0b
d = 260m	172	5.5	Access tunnel d = 260m	86	10.0 7.0
41.67°S	82	2.5	42.74°S,	176	10.0* 7.0*
146.30°E			145.97°E		
Gordon Power Stn	vertical	11.0	a, flat jack measurements		
	86	21.0	b, borehole gauge		
d = 200					
42.74°S	176	23.0	* assumed to be equal to the stress at 86°.		
145.98°E					

There were not enough measurements at any site to determine the principal stress components; however, the horizontal components are higher than would be expected from rock loading alone. This indicates that tectonic stresses are present and there is a suggestion from the data in Table 11 that the maximum principal stress axis is aligned more to the north-south than to the east-west.

Summary of previous results

All the in-situ stress measurements, except those at Bulli, and all the observations from earthquakes indicate the presence of regional tectonic stresses acting close to horizontal and higher than would be expected if all the stress was caused by rock loading. Plate 5 shows the directions of the maximum principal stress axes for all reliable determinations that were available in July 1975. Apart from the measurements in the Amadeus Basin and the observations from the 1972 Simpson Desert earthquake, the predominant direction of the maximum principal stress is east-west with a tendency for it to dip towards the edge of the continent.

Apart from the normal rock loading effect there are at least two other main factors that determine the regional stress field. The first arises as a residual tectonic stress from old orogenies. Thus residual stresses from the Alice Springs Orogeny (300 - 400 m.y. B.P) could still be contributing to the general north-south stress field that is observed in the Amadeus Basin and the Simpson Desert.

The second factor arises as a result of stresses induced in lithospheric plates as they move across the Earth's surface. Owing to the ellipticity of the Earth, the lithosphere must deform when its latitude changes. Hence, in the case of the Australian Plate, as it moves northwards the principal radii of curvature of the earth decrease and the stress regime within the plate will change.

One additional factor which may be significant results from the stresses induced by the addition or removal of overburden and associated thermal effects, (Haxby & Turcotte, 1975). This factor may become important when thicknesses of the order of 10-15 km are involved.

4. PROPOSED STRESS MEASUREMENT SITES IN WESTERN AUSTRALIA

The results discussed in the previous chapter indicate a pattern in the stress field for the southwestern region of Western Australia. Both the earthquake observations and the in-situ stress measurements suggest a predominantly compressive east-west direction for the regional stress field. To investigate this situation further it is proposed to measure the in-situ stress, using overcoring technique in shallow boreholes, at six sites near the southwest seismic zone. The method proposed will be similar to that used by Hooker & Johnson (1969) in stone quarries along the Appalachian Piedmont and the Quachita Tectonic Belt. Hopefully, these experiments will provide additional information on the regional stress field and on any relation there is in WA between earthquake occurrence and the stress field.

The site requirements call for unweathered competent rock, either outcropping or lying very close to the surface, in areas of low topographic relief. Six sites were tested in May 1975 and the results are described below. The locations are shown in Plates 6 and 7.

Site 1. Manmanning (30.87°S. 116.93°E).

This is situated about 1 km west of the homestead owned by Mr I. Cousins and about 1 km south of the Wongon Hills/Manmanning road. Plate 8 shows this location on the Land Department map. Six small charges were exploded as indicated on the time distance plots on Plate 9 and the P wave velocity of the rock close to the surface is about 5.7 km/s. It is recommended that the hole be drilled close to shot 3 where the rock is flat and access for the rig would be easy.

Site 2. Goomalling (31.39°S. 116.85°E).

Site 2 is located about 500 m south of the homestead owned by Mr P.E. Drake-Brockman, where there is a massive outcrop of hard competent rock covering several square kilometres. It was not possible to measure the velocity of the main part of the rock because the geophones could not be secured to the ground. However, a spread was laid out at the edge of the rock where a thin cover of soil was present. The observed P wave velocity was about 4.0 km/s, but since the rock beneath the spread may be slightly weathered (because it is covered by moist soil) this value is probably lower than the value for the unweathered rock where there is no soil cover. Plate 8 shows the site location, Plate 9 the time distance plots, and Plate 10 two photographs of the rock. There are several places on this outcrop which would be suitable for the stress measurements, and it is recommended that the final selection be left until the drill is on site, when the access situation can be fully evaluated.

Site 3. Meckering (31.69°S. 116.99°E).

This is the closest site to the epicentre of Meckering earthquake of October, 1968, and it is shown in relation to Mr P. Kelly's homestead in Plate 11. Plate 13 shows a photograph of the proposed site, and Plates 6 and 7 show its position relative to the recent earthquake activity and the other five sites. Plate 12 shows the time distance plots from the refraction experiments. The results are not as meaningful as those obtained at the other sites, but, as it is very close to the epicentre of the Meckering earthquake, it is recommended that the hole be drilled near shot point 8.

The mean velocity of the rock near the surface is about 4.4 km/s, but the scatter in the estimates is larger than at the other sites and the irregularities are easily seen in Plate 12.

Site 4. Quajabin Peak (32.21°S, 117.20°E).

This site is located on the roadside adjacent to the property of Mr A.D. Richards. Plate 11 shows the detailed map of the site, Plate 12 the time distance plots, and Plate 13 is a photograph of the site. The roads did not correspond to those shown on the 1:100 000 Brookton Sheet because of recent roadworks, but there should be no problem in identifying the site, which is a large flat slab of gneiss on the roadside. The average velocity is about 4.4 km/s and it is recommended that the drill be located close to shot 3.

Site 5. Brookton (32.37°S, 117.23°E).

Plate 14 shows the site location, Plate 16 a photograph of the site, and Plate 15 the time-distance plots of the shots. The average velocity is about 5.5 km/s, and it is recommended that the hole be drilled near shot point six. The site is about 20 km east of Brookton and located on the property of Mr W.F. Bowring.

Site 6. Popanyinning (32.66°S, 117.14°E)

Plate 14 shows the site location, Plate 16 a photograph of the site, and Plate 15 the time-distance plots. No determinations of the velocity were made because of a small pocket of weathering towards the western end of the spread, which is clearly seen on the plots between shot points 2 and 3. However, a rock sample was taken from a nearby outcrop and was found to have a velocity of 4.4 km/s, so the site is considered to be satisfactory. It is recommended that the drill be located between shot points 3 and 4. The land is owned by Mr N. Francis.

5. RECOMMENDATIONS

1. That the proposed joint BMR/CSIRO investigation into the regional stress field in southwest WA proceed as planned for early 1976. These experiments will test overcoring methods in shallow boreholes, and if successful will not only provide information on the regional stress field but will provide unique data on the relation between stress and earthquake occurrences in an intra-plate environment.

2. That the six sites described in section 4 be tested in numerical order. All the sites appear to meet the requirements of providing competent solid rock of low topographic relief cropping out. However, in case there is a skin effect owing to shallow weathering it is recommended that about 3m be reamed out before the overcoring is started.

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Record No 1976/1

LOCATION OF AUSTRALIAN EARTH AND EPICENTRES OF SHOCKS FOR WHICH FOCAL MECHANISM ARE AVAILABLE

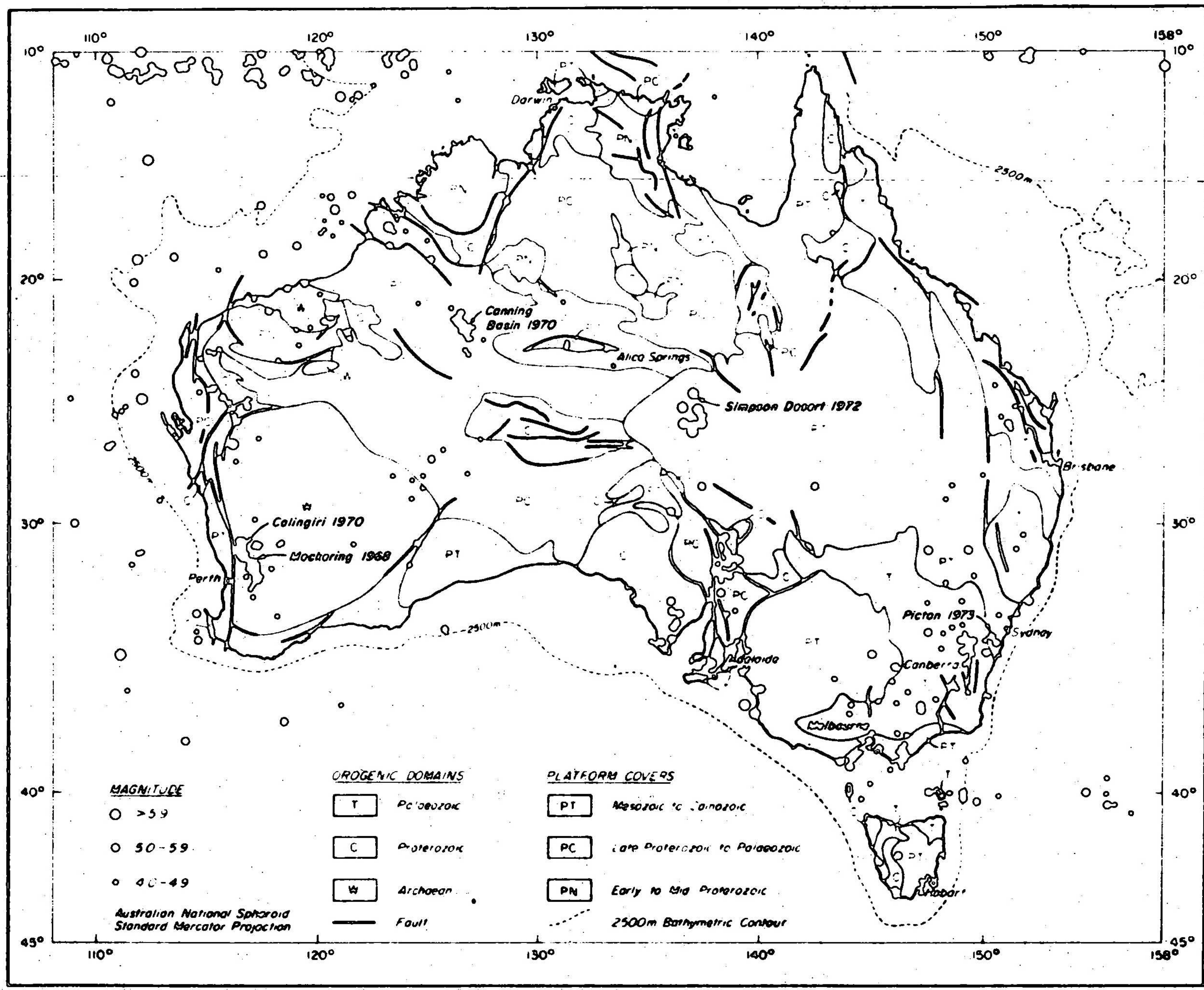
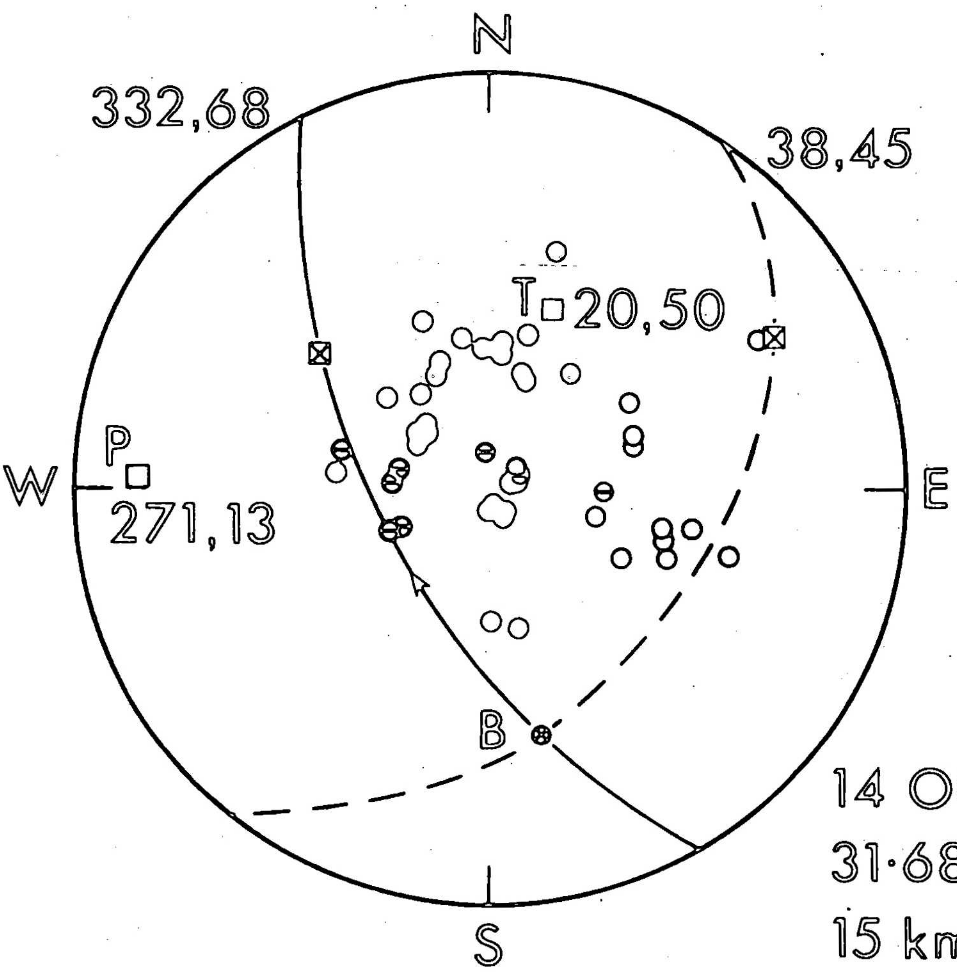


PLATE 1

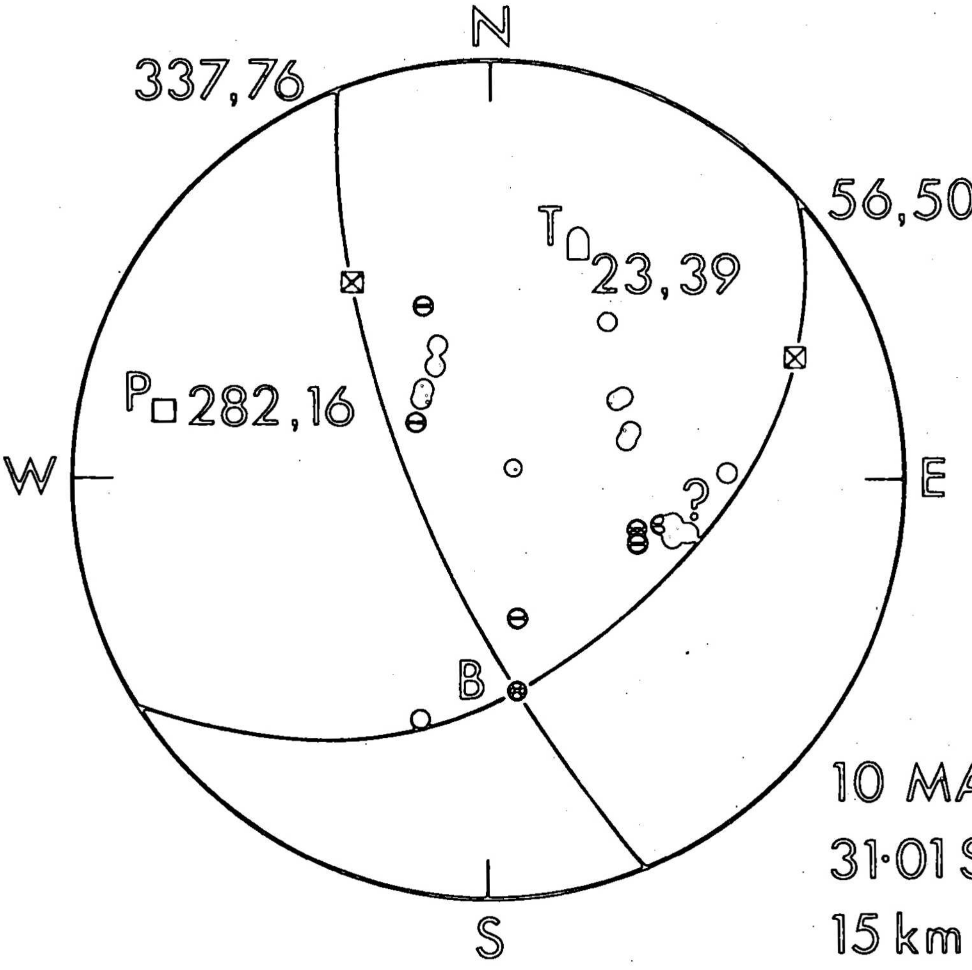
A/B9-123A

PLATE 2a



14 OCTOBER 1968
31·68 S 117·00 E
15 km *MECKERING*

PLATE 2b



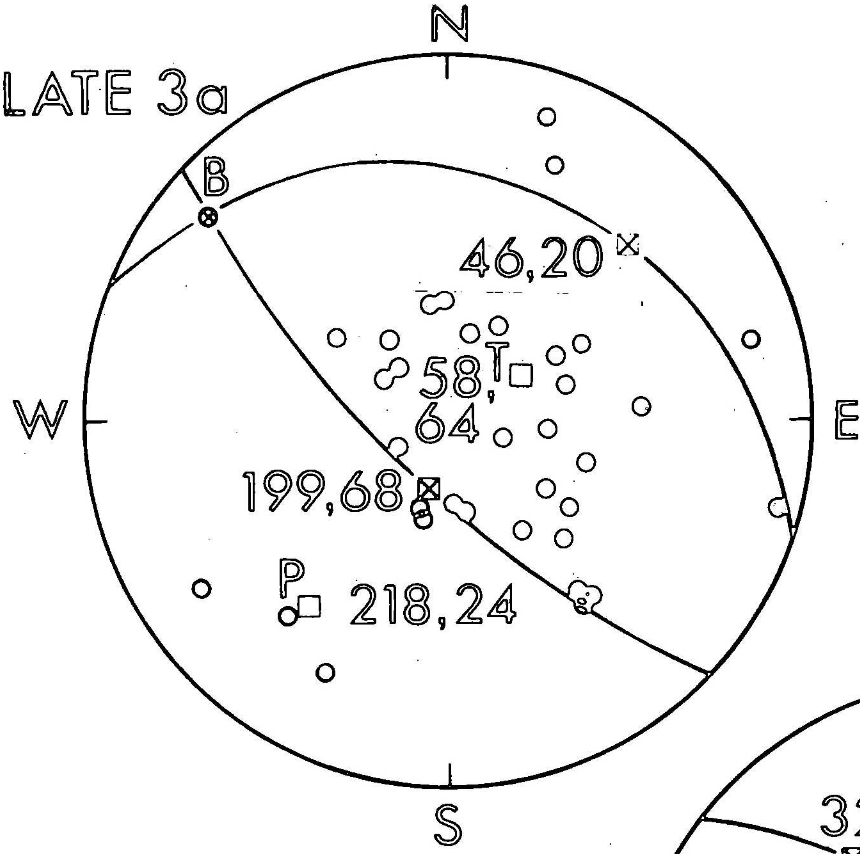
○ COMPRESSION
o DILATATION
⊖ EMERGENT
□ PRESSURE AXIS
□ TENSION AXIS
⊠ NODAL POLE
⊗ B AXIS

10 MARCH 1970
31·01 S 116·54 E
15 km *CALINGIRI*

Record No.1976/1

A/B9-124 A

PLATE 3a



24 MARCH 1970
22·05 S 126·61 E
33 km EAST
CANNING BASIN

PLATE 3b

28 AUGUST 1972
24·74 S 136·92 E 7 km
SIMPSON DESERT

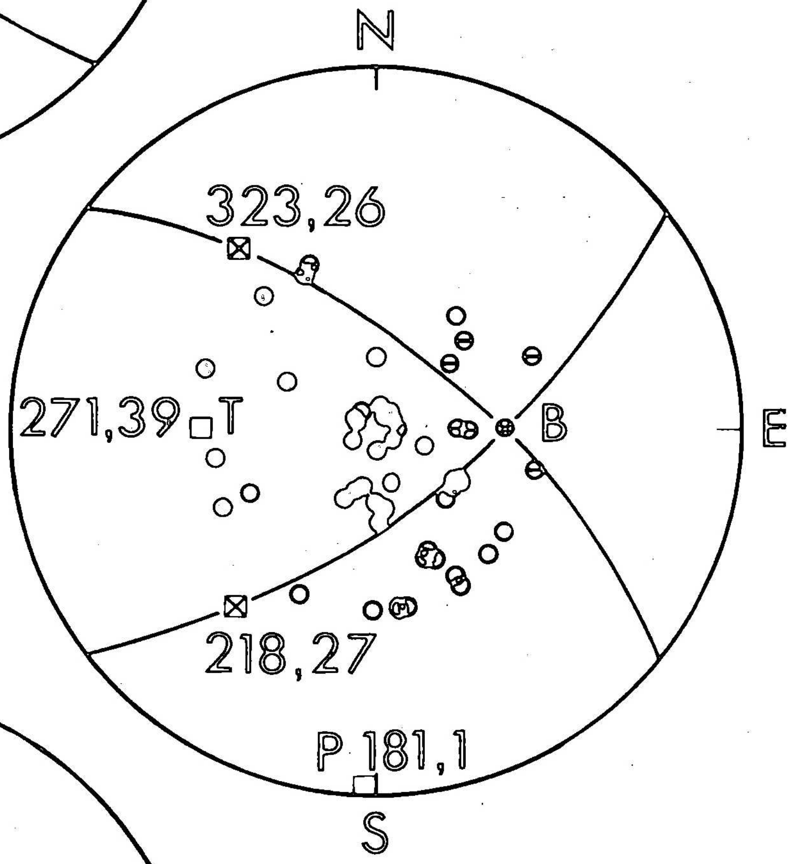
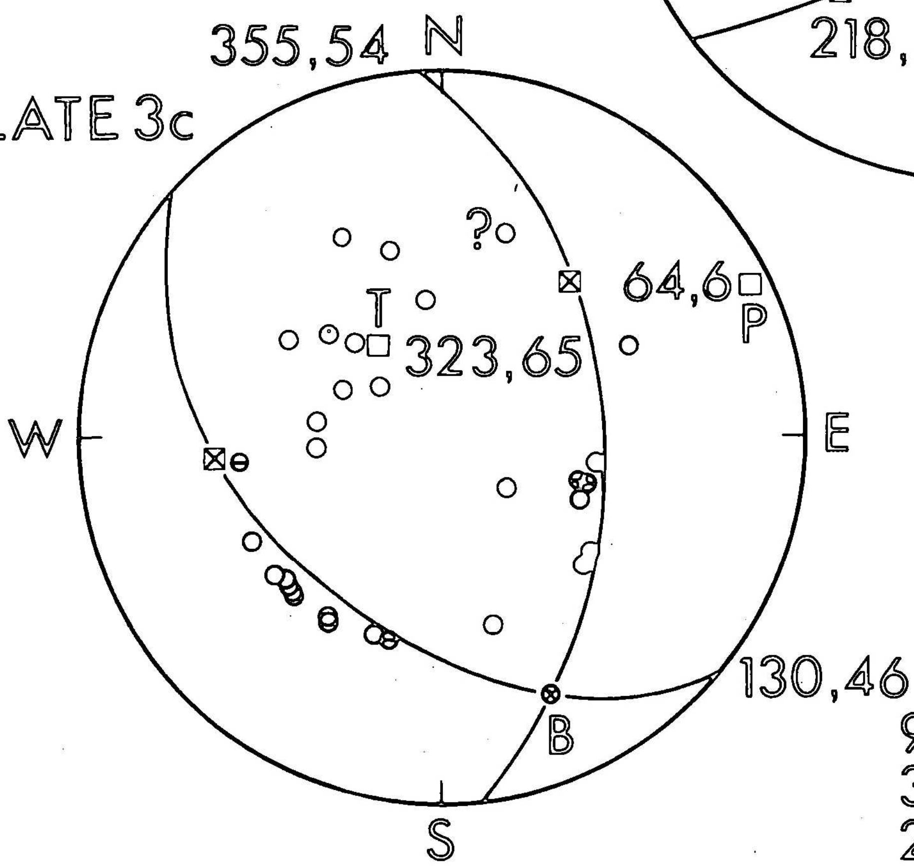


PLATE 3c

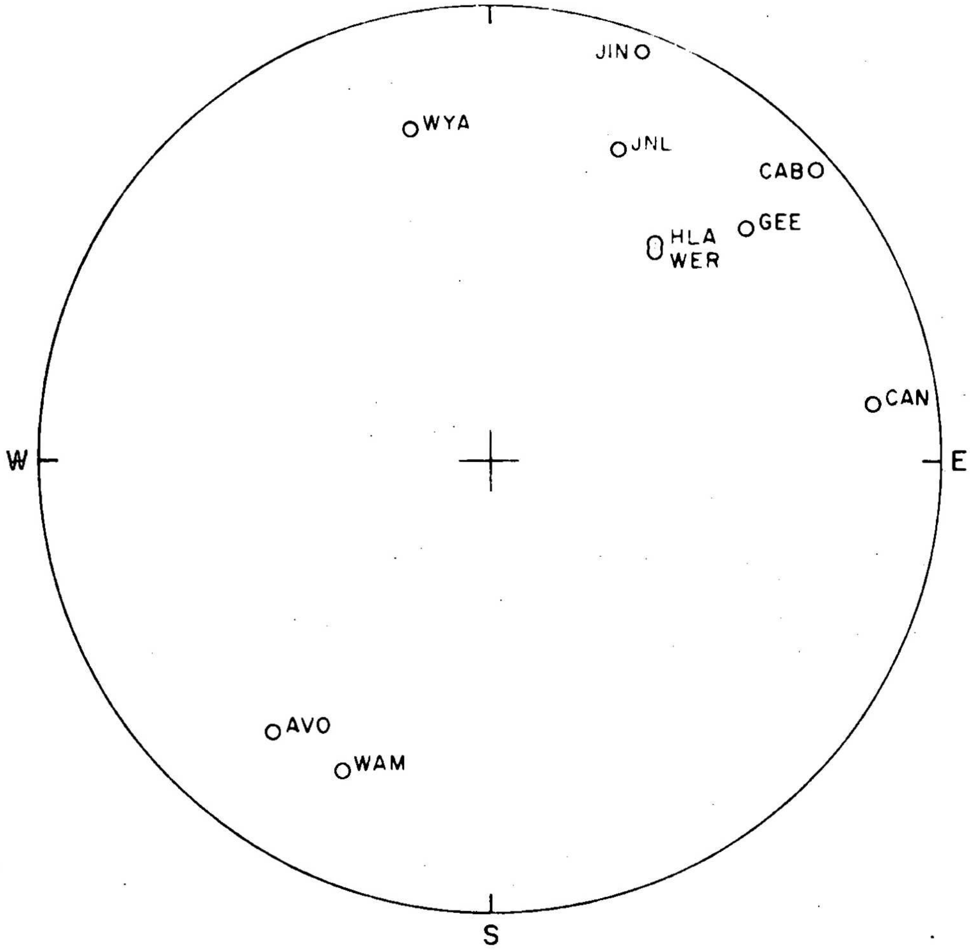


9 MARCH 1973
34·17 S 150·32 E
21 km PICTON

- COMPRESSION
- DILATATION
- EMERGENT
- PRESSURE AXIS
- TENSION AXIS
- NODAL POLE
- B AXIS

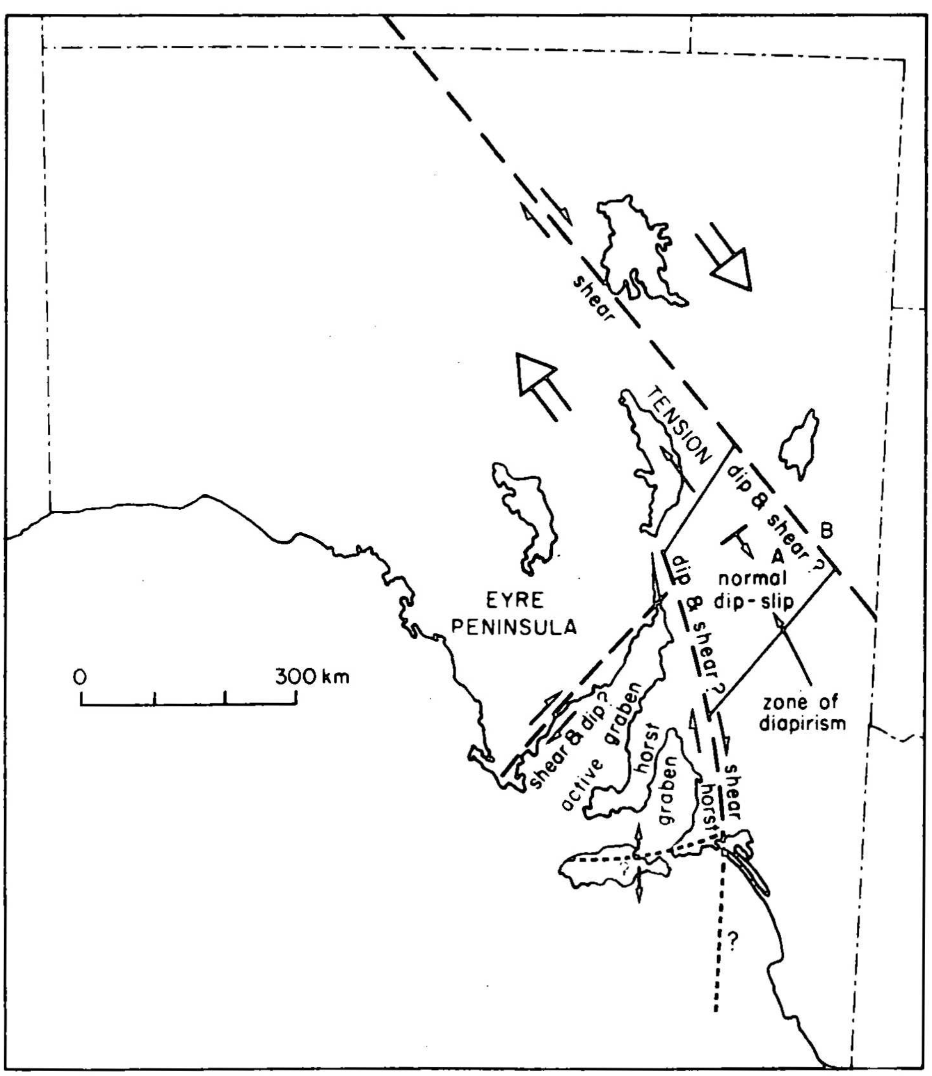
A/B9-125 A

PLATE 4a



8 FEBRUARY 1961
35·28°S 149·31°E
h = 9 km *GUNNING*

PLATE 4b



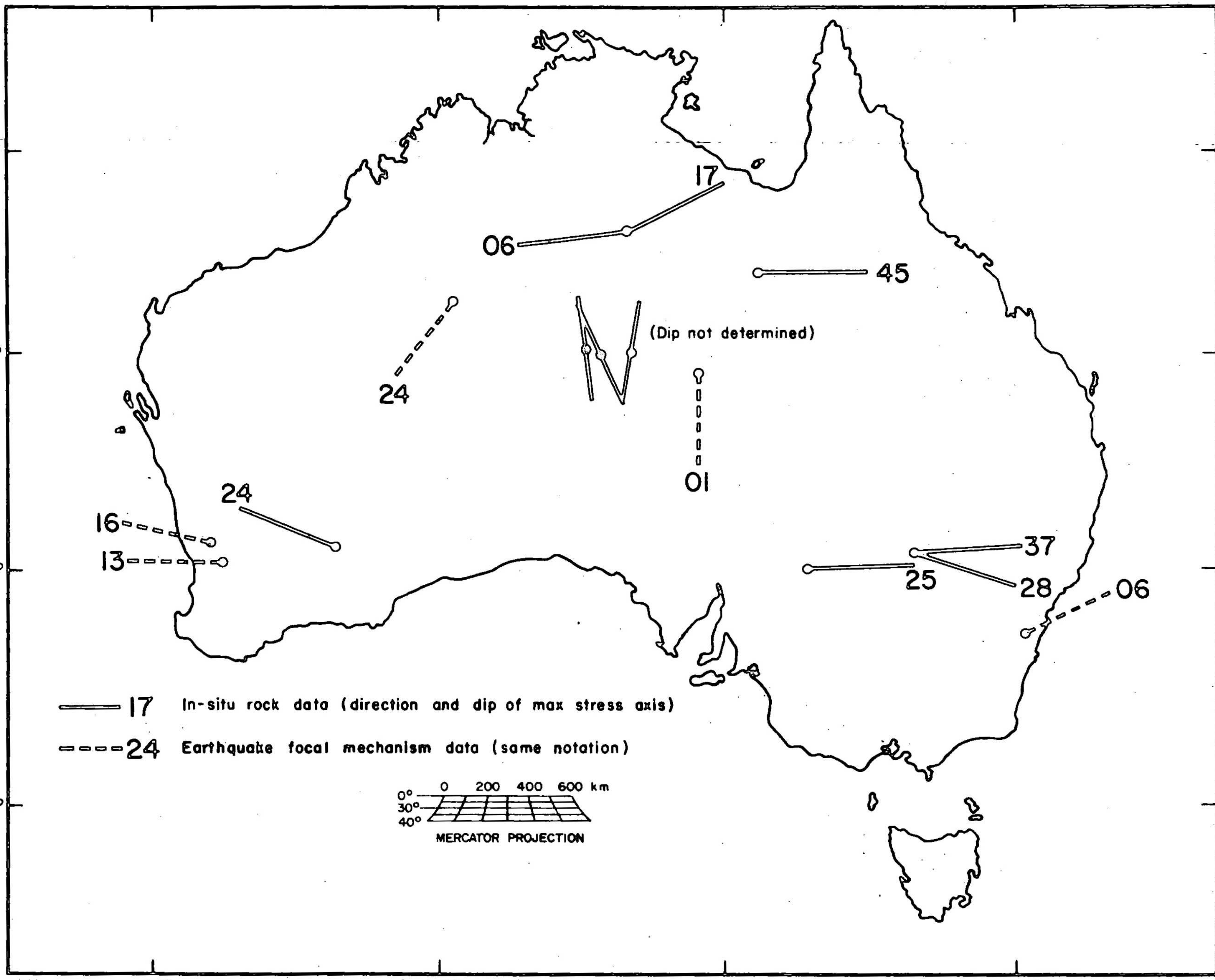
EARTHQUAKE
MECHANISMS
AND ZONES OF
ACTIVE TECTONISM
IN SOUTH AUSTRALIA

Record No 1976/1

SA/B10-1A

PLATE 5

DIRECTIONS OF MAXIMUMUM PRINCIPAL STRESS
AXIS FOR RELIABLE DETERMINATIONS



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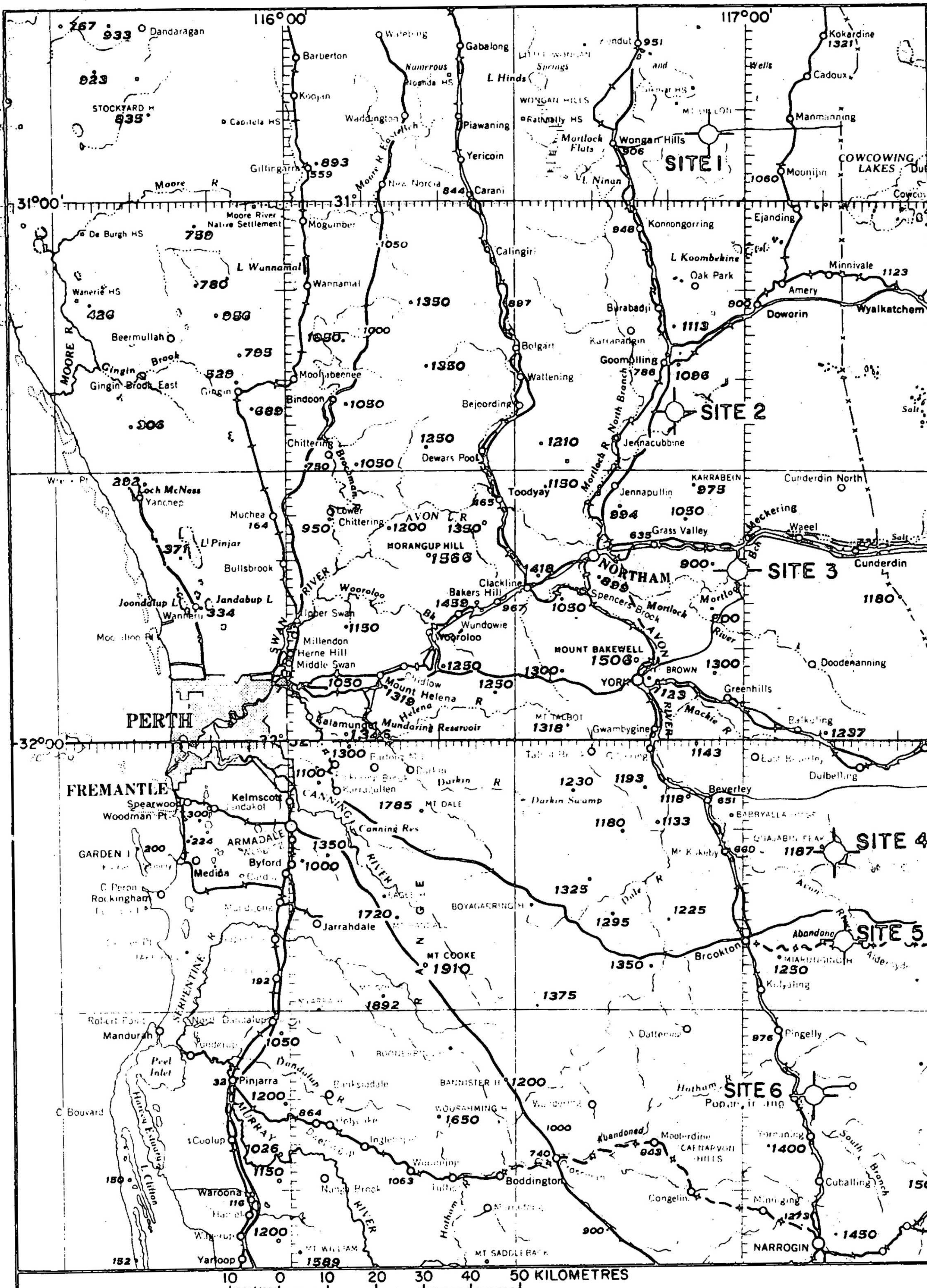
(Based on A/BO-67A)

A/B10-39A

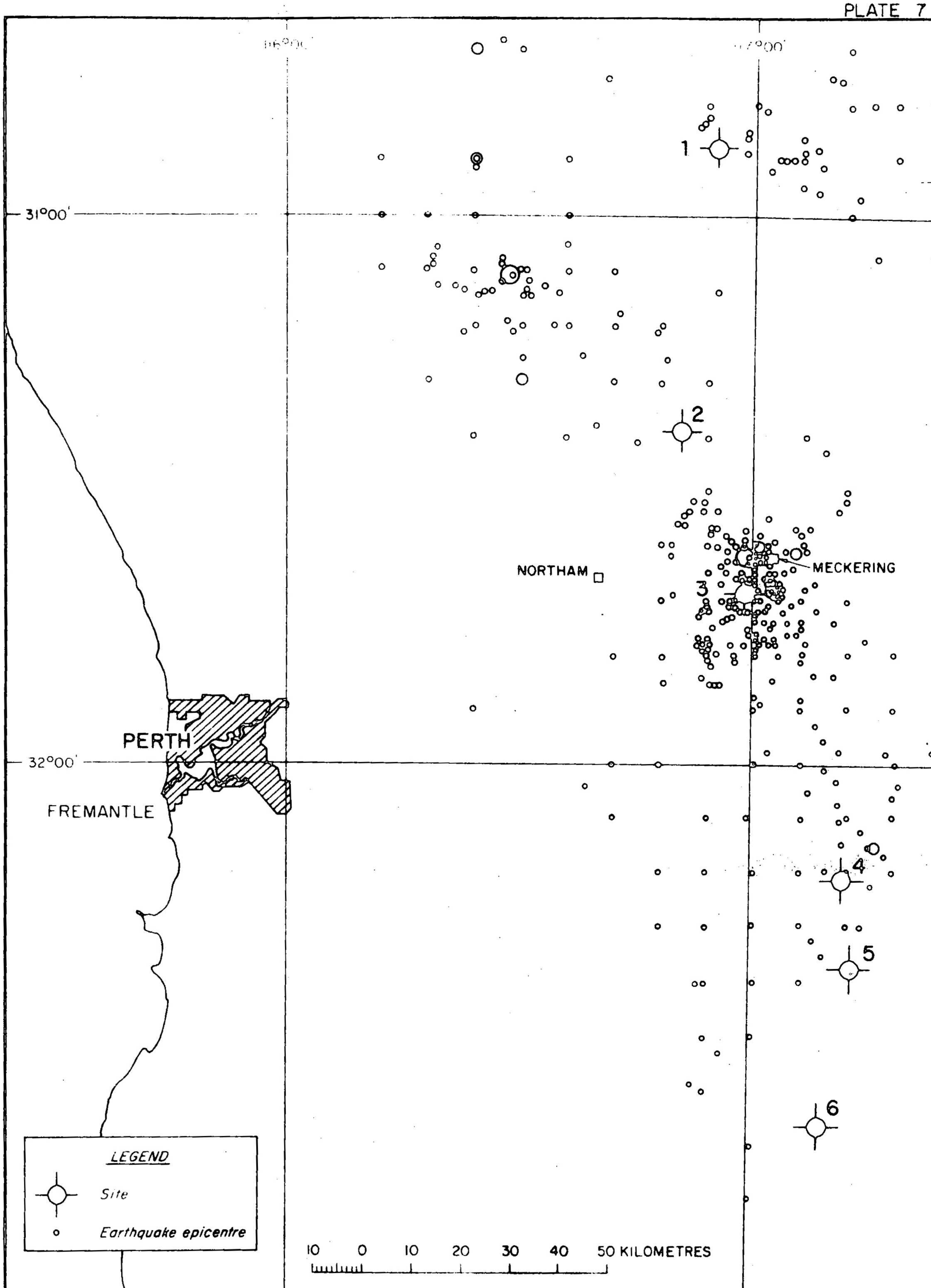


PROPOSED SITES FOR IN SITU STRESS MEASUREMENTS

Record No.1976/1

H50/B10-1A

PLATE 7

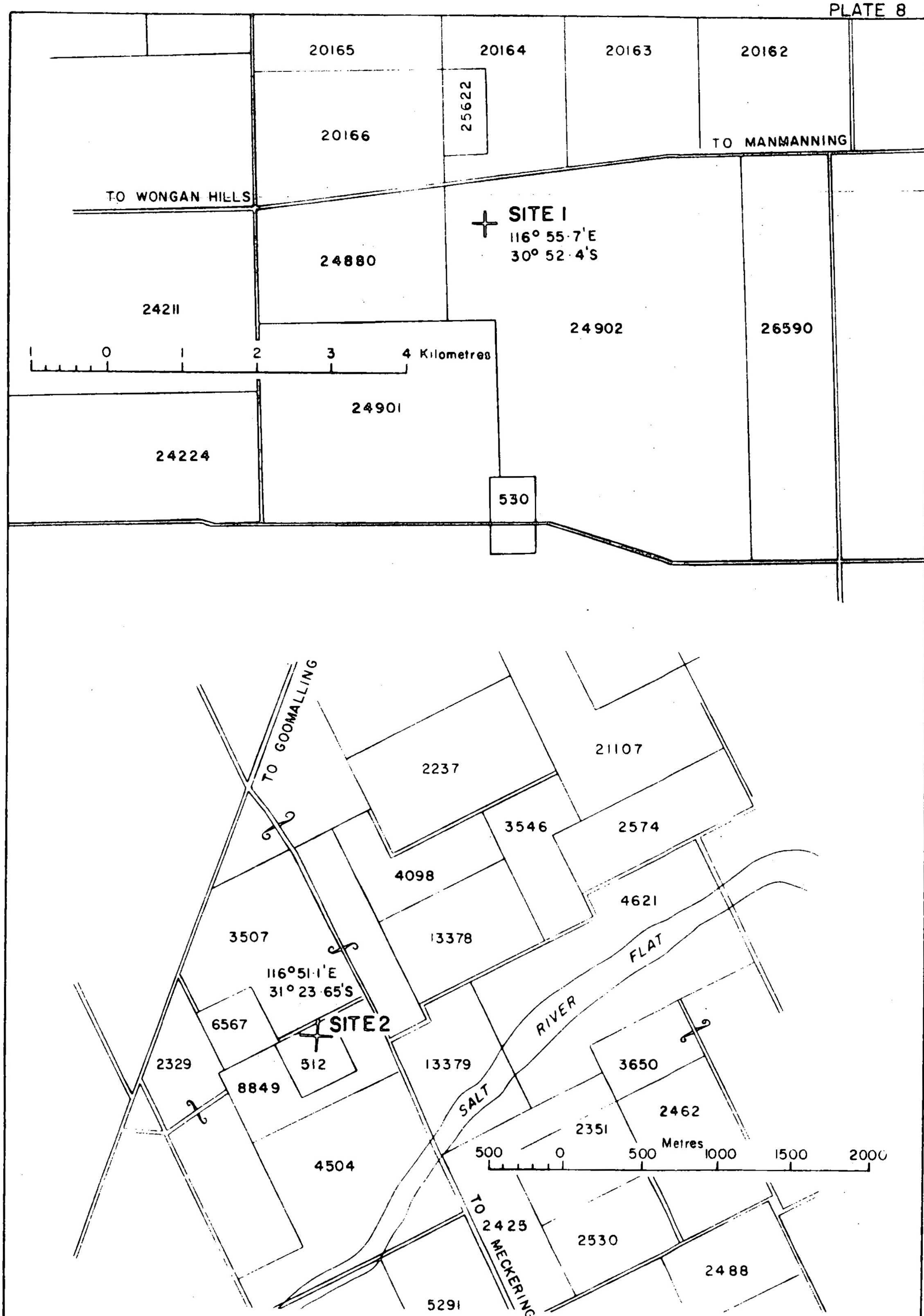


DISTRIBUTION OF EARTHQUAKES NEAR PROPOSED STRESS MEASUREMENT SITES

Record No 1975/161 and 1976/1

H50/B10-4A

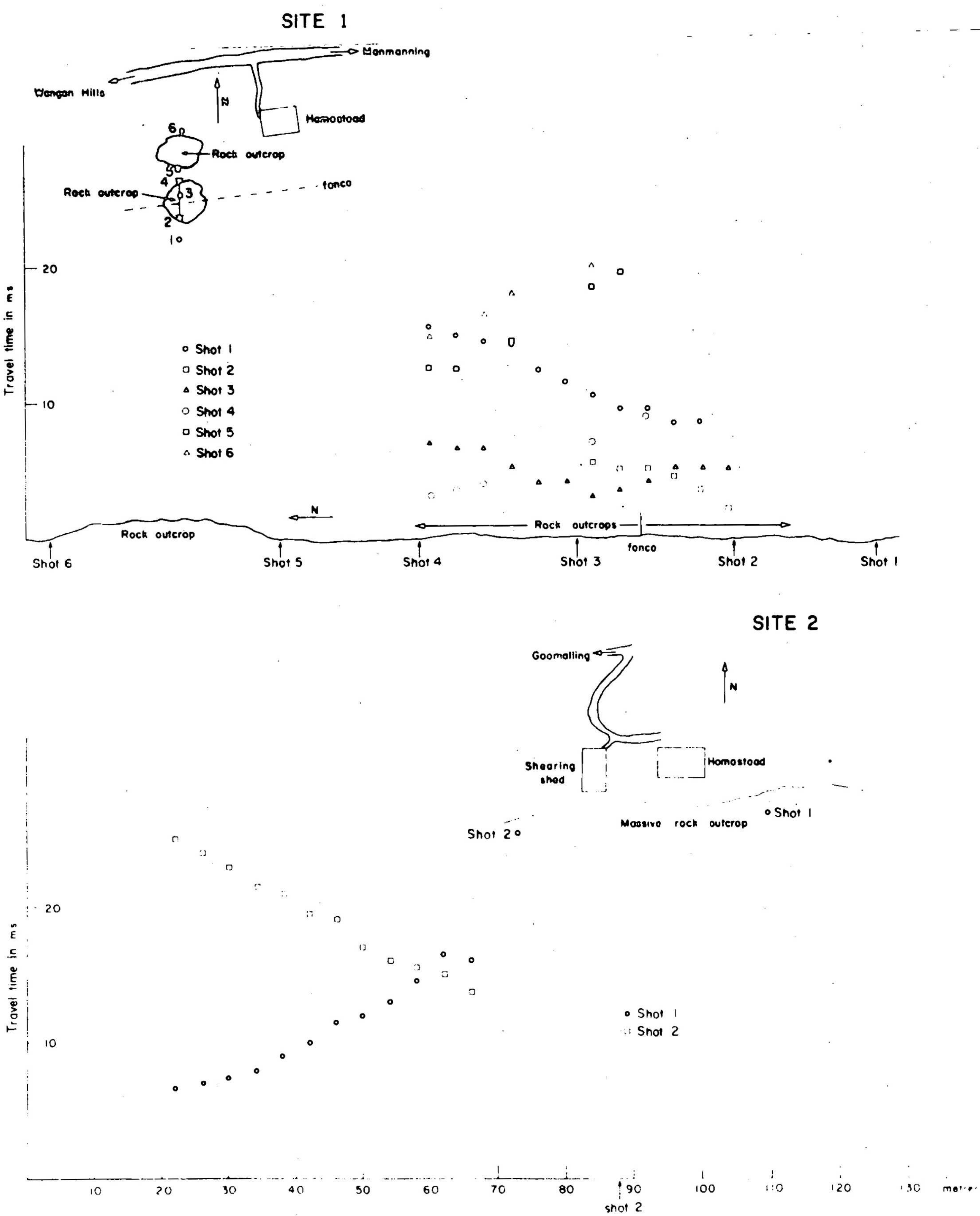
PLATE 8



LOCATION OF SITES 1 & 2

Record No 1976/1

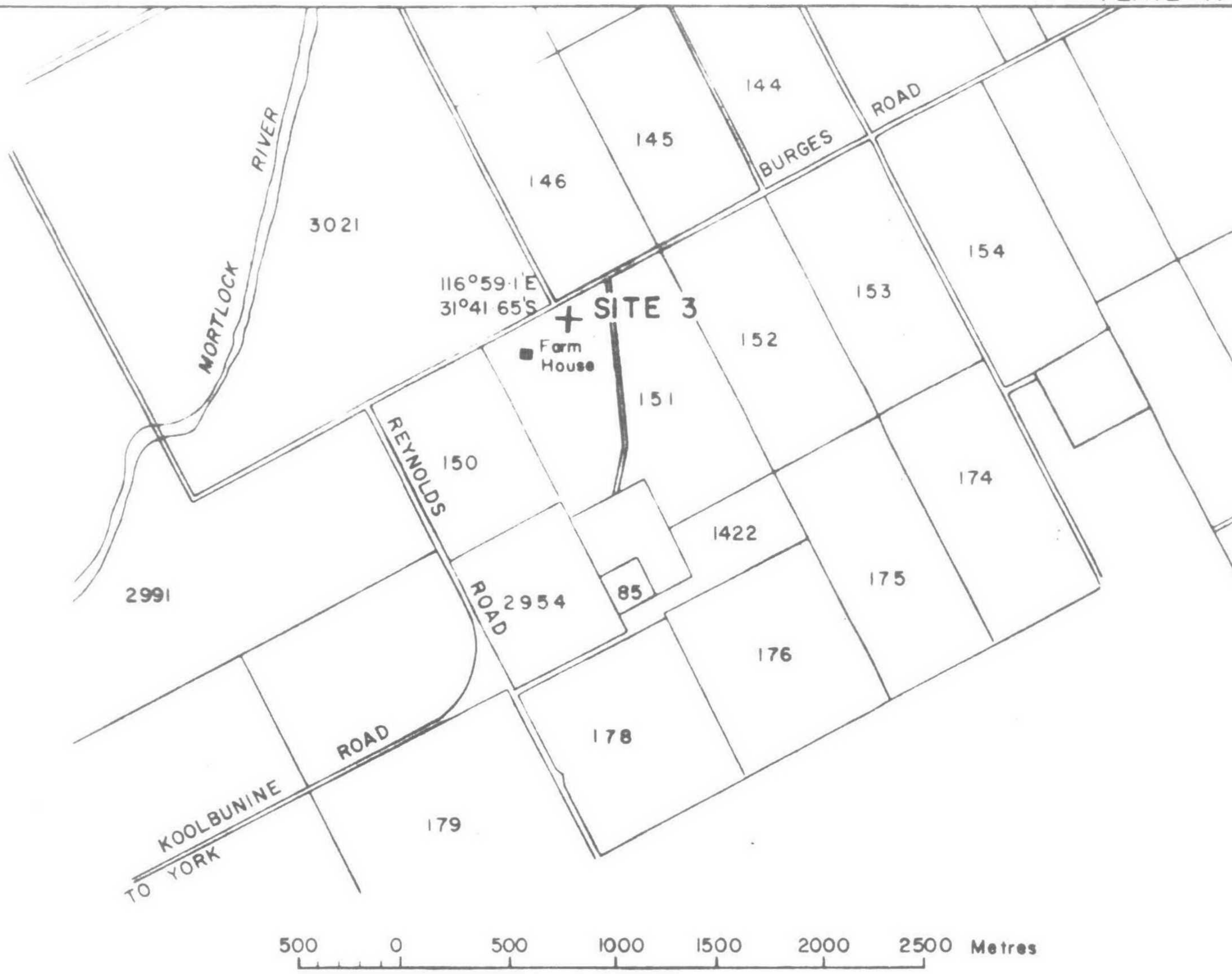
H50/B10-2A

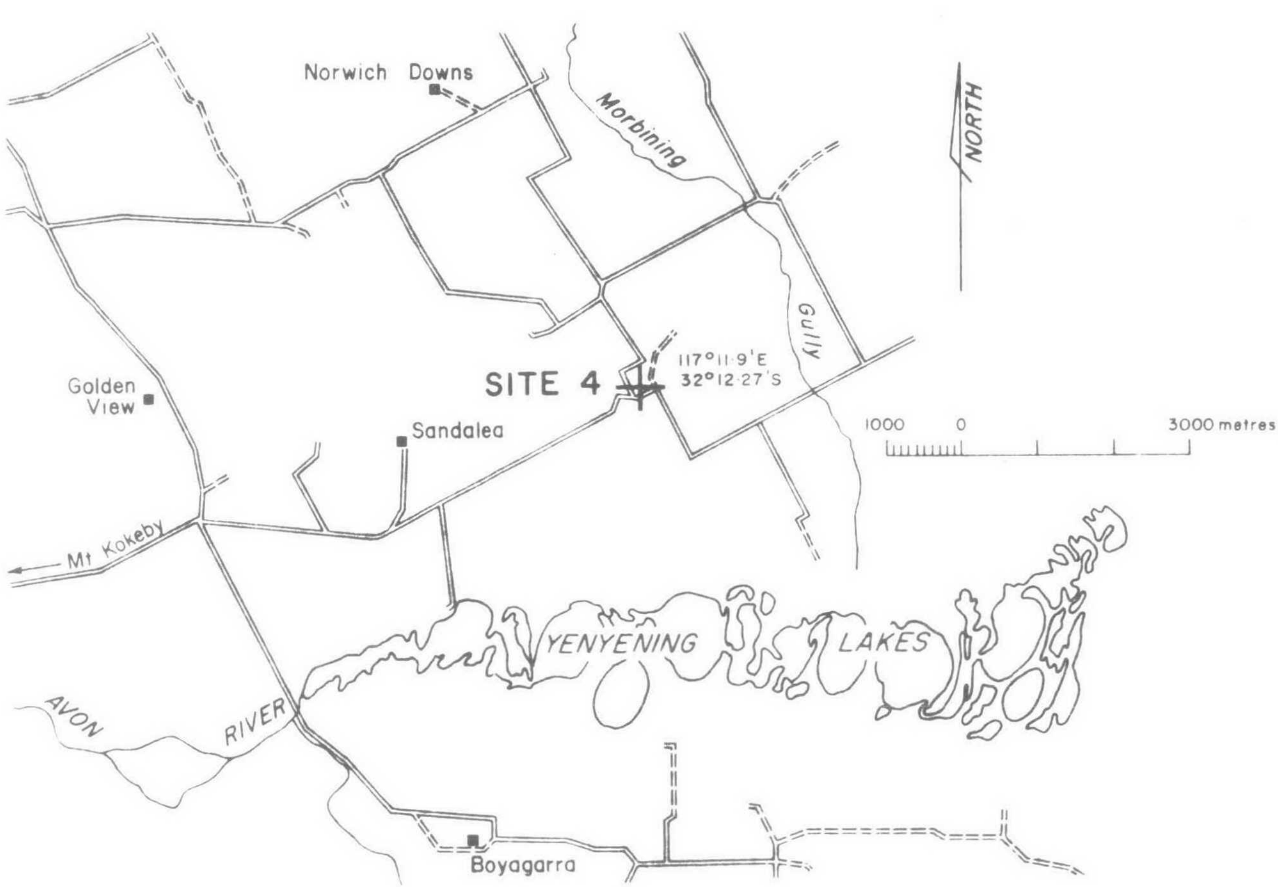


TIME-DISTANCE PLOTS FOR SITES 1&2

STRESS MEASUREMENT SITES 1975

Site 2 - Goomaling





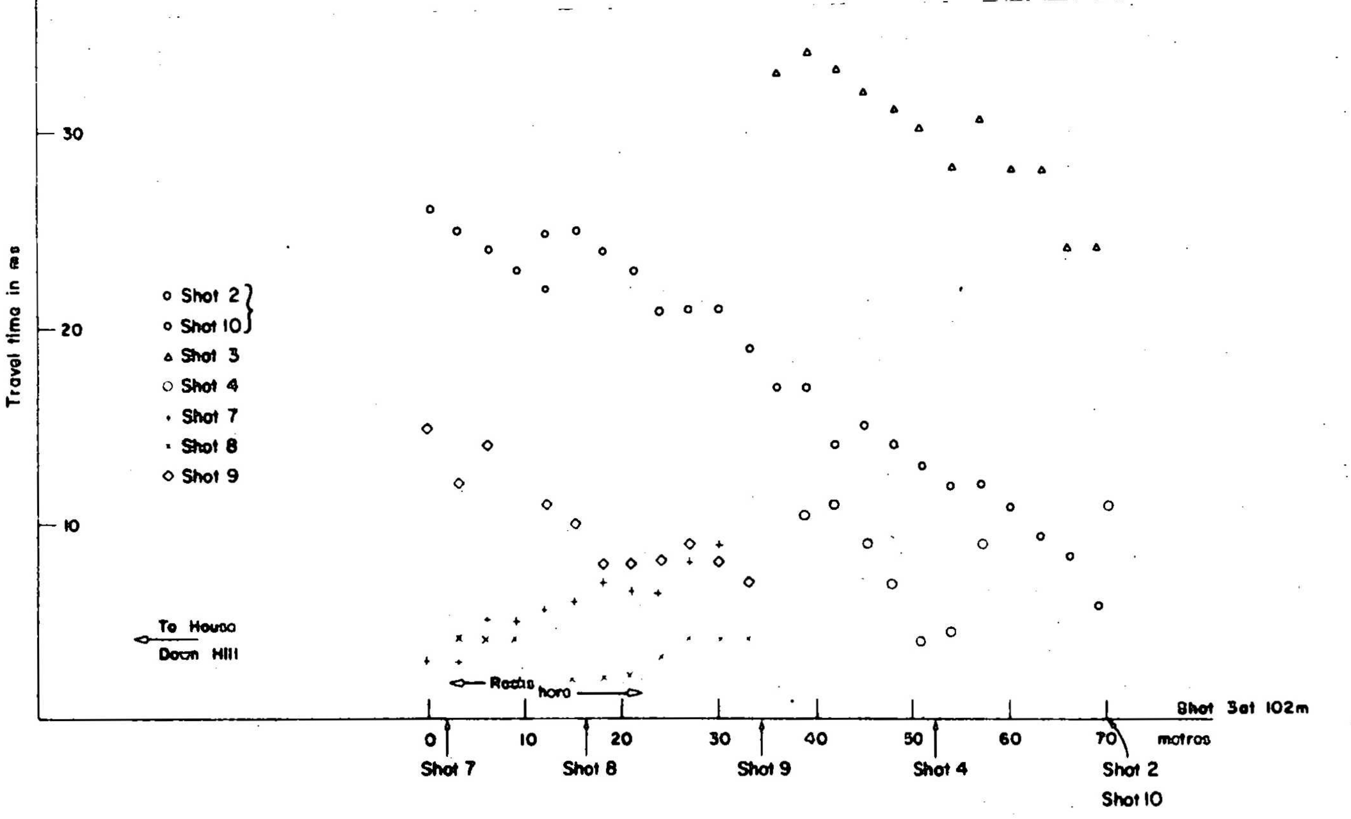
LOCATION OF SITES 3&4

Record No.1976/1

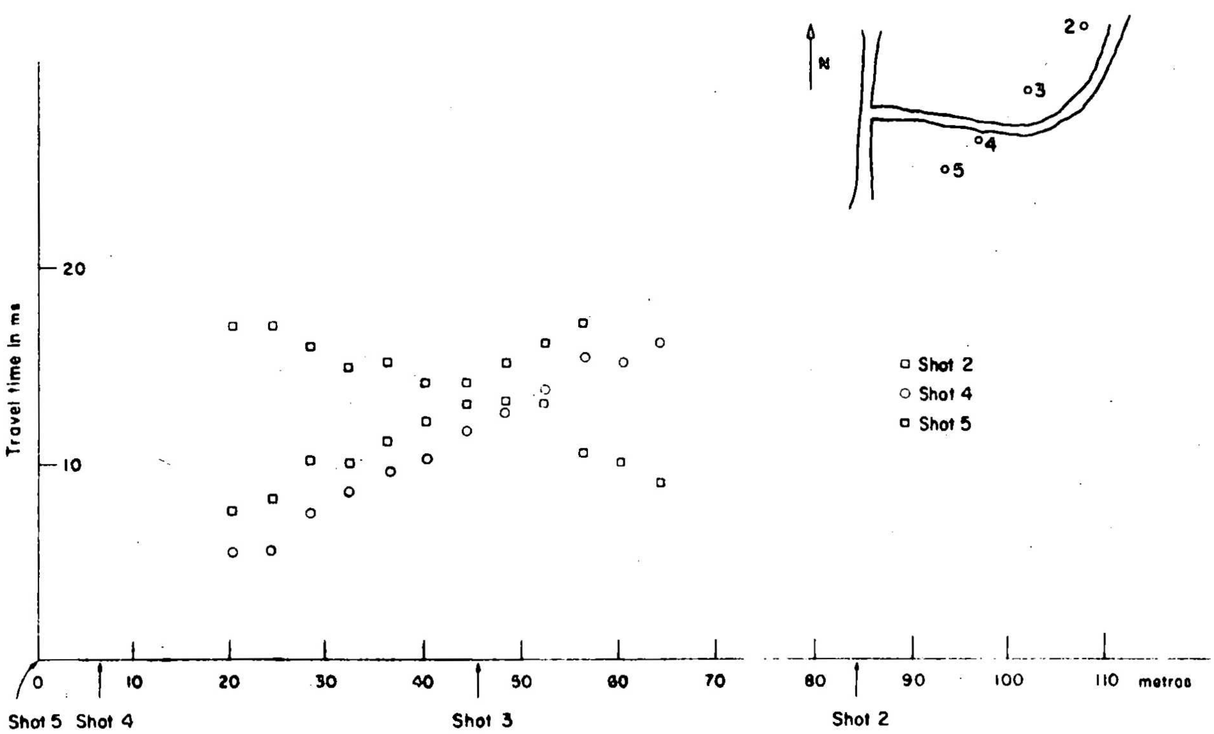
H50/B10—3A

PLATE 12

SITE 3



SITE 4

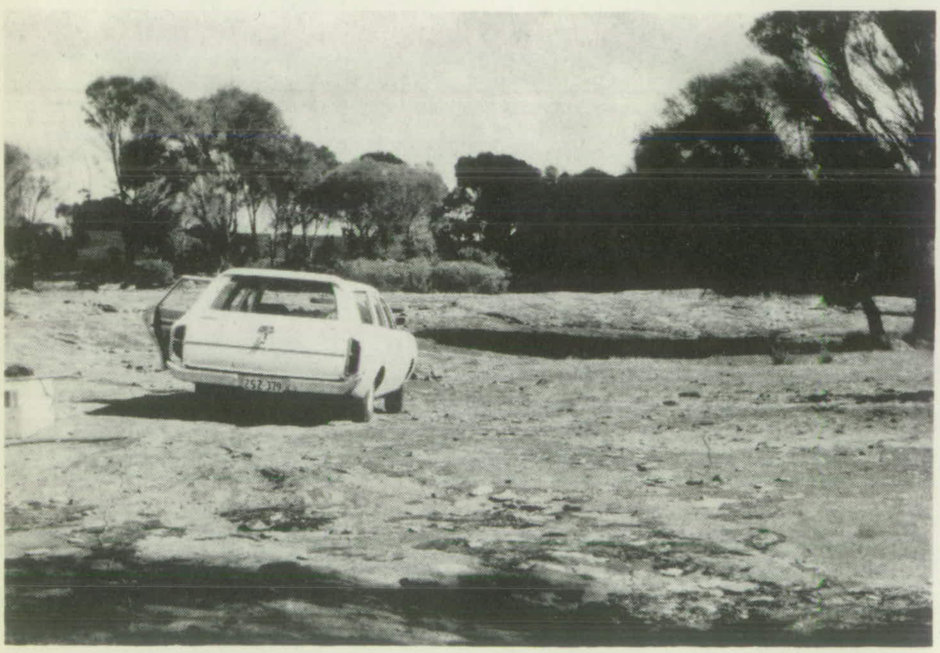


TIME-DISTANCE PLOTS FOR SITES 3 & 4

STRESS MEASUREMENT SITES 1975

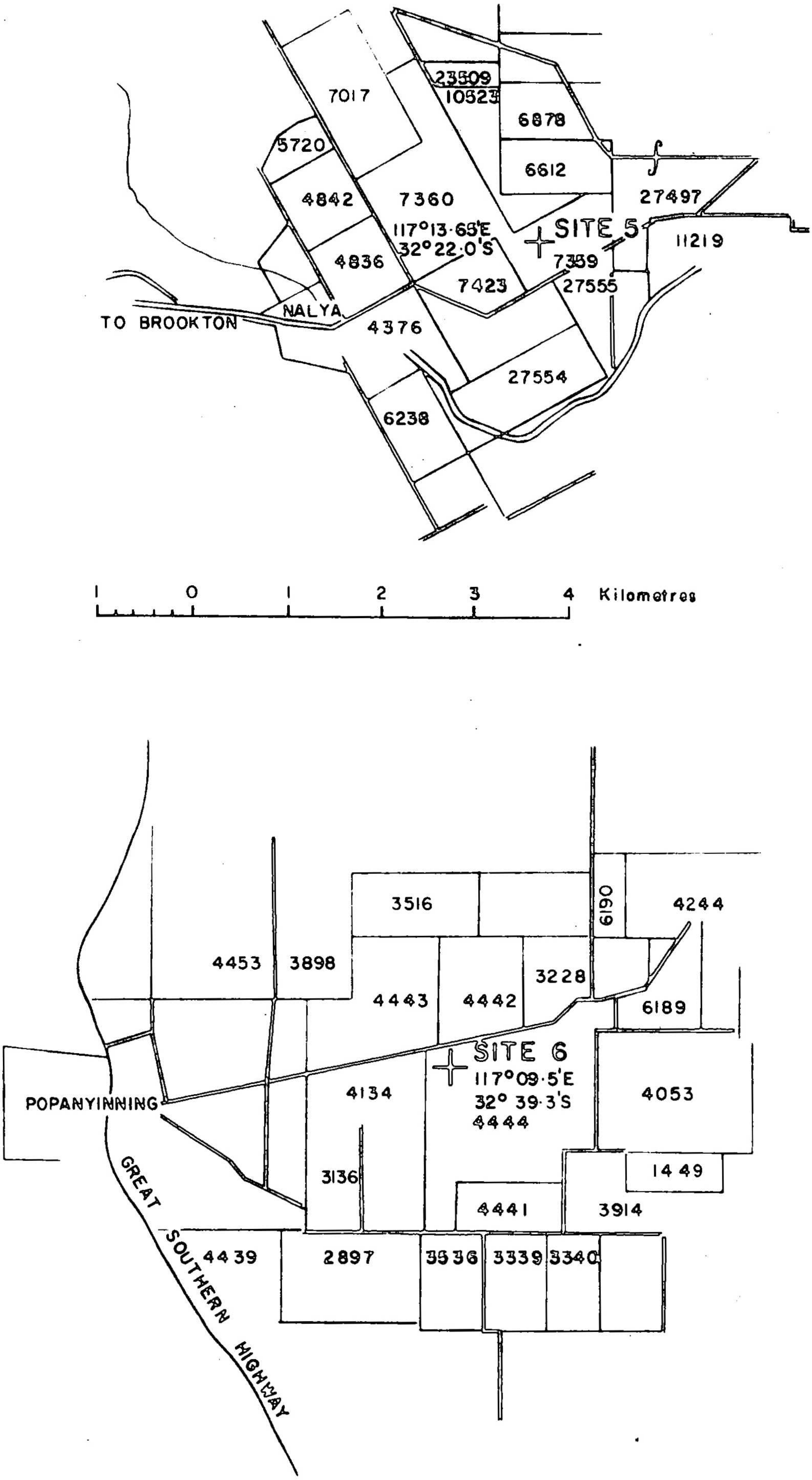
(a)

(b)



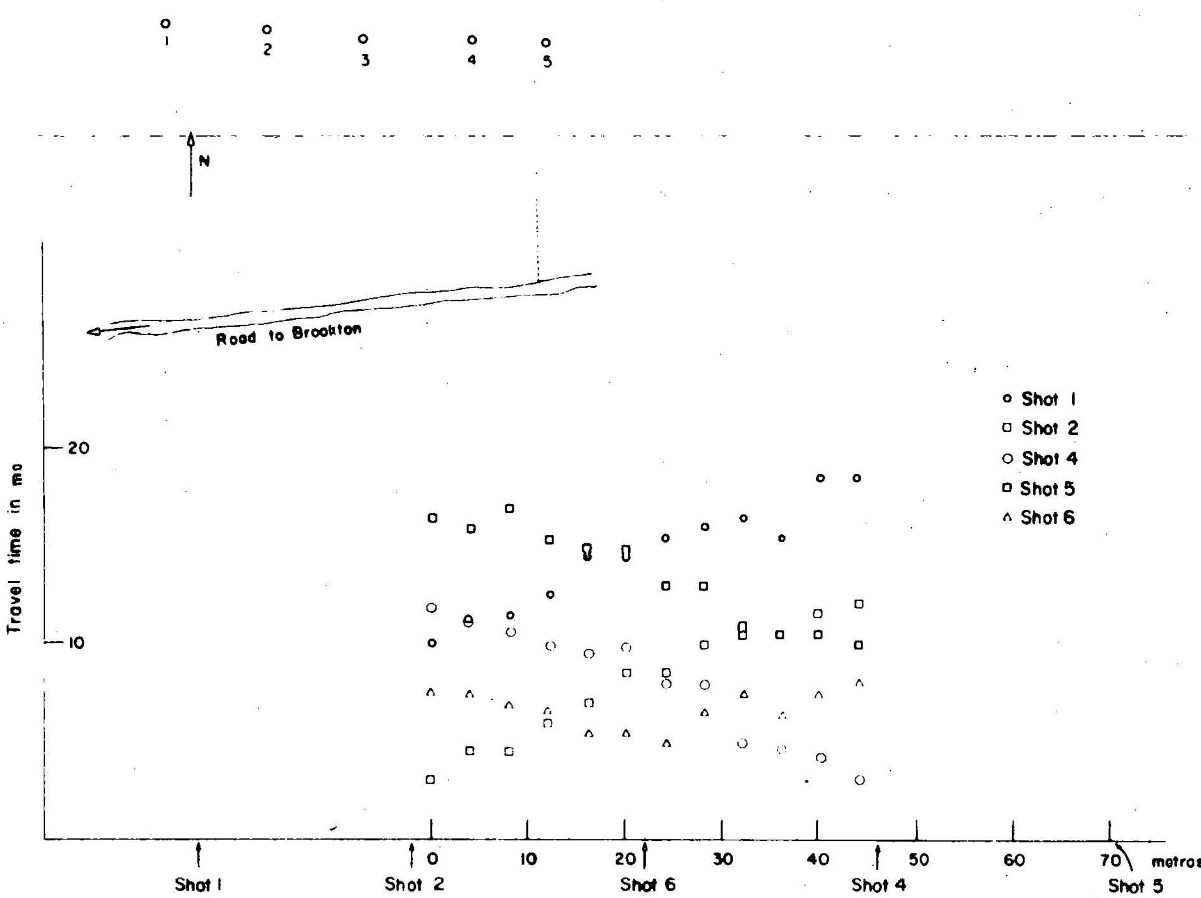
(a) Site 3, Kelly's farm near Meckering

(b) Site 4, Quajabin Peak

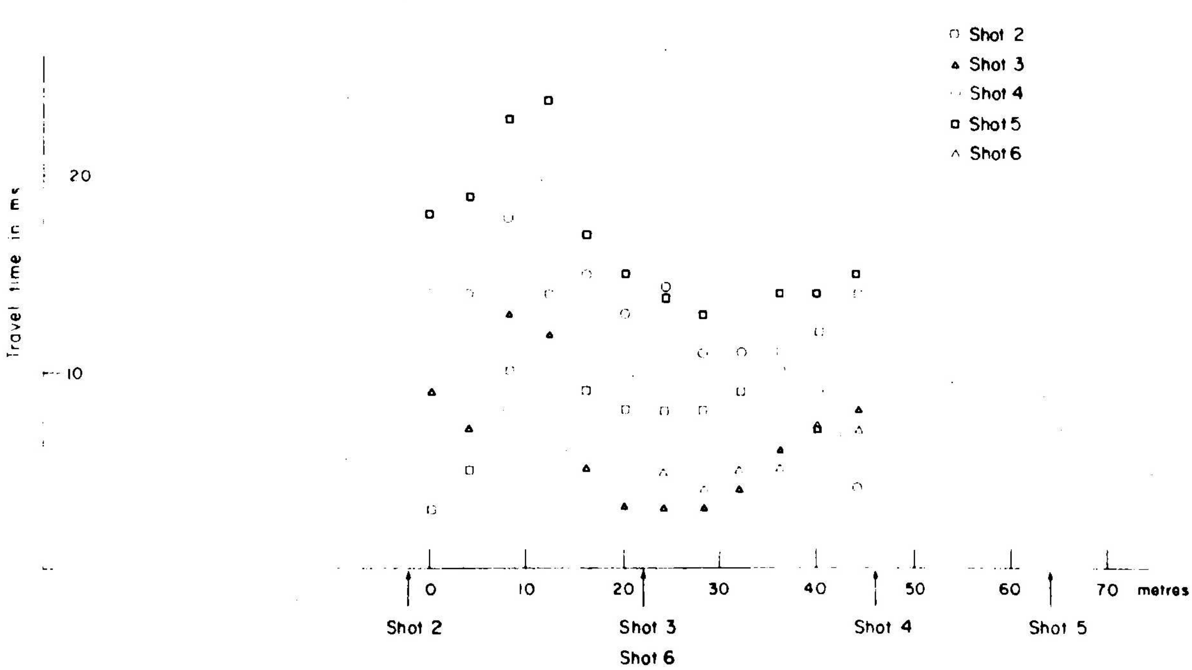


LOCATION OF SITES 5 & 6

SITE 5



SITE 6



TIME-DISTANCE PLOTS FOR SITES 5 & 6

Record No. 1976/1

I50/B10-2A

STRESS MEASUREMENT SITES 1975

(a)

(b)

(a) Site 5, near Brookton

(b) Site 6, Popanyinning