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SEISMICITY OF THE AUSTRALIAN CONTINENT

By H. A. DOYLE, I. B. EVERINGHAM AND D. J. SUTTON

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ADELAIDE
SOUTH AUSTRALIA
1968

SEISMICITY OF THE AUSTRALIAN CONTINENT

By H. A. DOYLE, I. B. EVERINGHAM & D. J. SUTTON

(With 2 Tables and 5 Text-Figures)

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ABSTRACT

Data on Australian earthquakes up to 1966 are presented. The most active area in the continent is the Adelaide seismic zone. The epicentres follow quite closely the trend of the Flinders and Mt Lofty Ranges, and appear to be associated with the South Australian rift zone. Some seismic zones such as that in southwestern Australia may be associated with structural boundaries at depth in the crust and upper mantle. On the other hand there is little seismicity along some marked faults such as the 1000-km long Darling Fault in Western Australia.

All reliable depth determinations for Australian foci so far place them within the crust, mostly the upper crust. Such shallow crustal continental earthquakes should perhaps be regarded as a special class.

INTRODUCTION

The Australian continent is adjacent to some of the most seismically active regions of the globe, in particular to the Southwest Pacific belt from Indonesia and New Guinea to New Zealand. To the south and west of the continent are the moderately active mid-ocean ridges of the Southern and Indian Oceans. However, Australia itself has been called the quiet continent and seismically this is true, as only Antarctica, which is almost completely aseismic, has less contemporary activity. The fact that these two southern continents, and the African continent, are so inactive needs to be taken into account in any theory of Earth history.

Both have large Precambrian shield areas, and Australia also has the lowest relief (averaging about 300 m) and is perhaps the least deformed of all the continents, with no active volcanoes and no very high mountains (David, 1950). The Australian shield or platform occupies the western and central parts of the continent (Fig. 1), with some intracratonic basins and geosynclines. In the east are the Great Artesian and Murray Basins, with the Eastern Highlands forming an extended arc along the east coast. These highlands are within the Tasman Geosynclinal Zone, a large irregular geosynclinal area, the southeast portion of which is sometimes referred to as the Lachlan Geosyncline. The Tasman Geosynclinal Zone has a history of persistent tectonism extending from the Cambrian (Hills, 1965). It may extend westward under the Murray Basin to the Adelaide Geosyncline. However, it cannot extend very far off the southeast coast of Australia, as gravity and seismic data indicate a true ocean structure beneath the Tasman Sea (Standard, 1961). The crustal structure of Australia so far examined is normal continental (*e.g.* Doyle & Everingham, 1964, found a 40 km crustal thickness in southern Australia).

Although Australian seismicity is low it has practical as well as scientific importance. A few earthquakes of magnitude $m \geqslant 5\frac{1}{2}$ occur each year, and small local earthquakes in some areas are detected at the rate of several per month by short-period seismographs of high magnification. These tremors are not in the main of sufficient magnitude to be noticed by nearby inhabitants, but occasionally damage occurs. An earth tremor* was felt at Port Jackson, New South Wales, within a few months of the arrival of the First Fleet in 1788, and an earthquake was reported from the Lake George area of New South Wales (probably the Gunning zone) in 1828 (Anon., 1829). Explorers such as Sturt noted earth tremors in western New South Wales, the Flinders Ranges and in northwest Australia (see Clarke, 1869; Cleland, 1912).

Melbourne has been disturbed by several tremors since the first noted in 1841 (Gregory,

* We find the term tremor, or earth tremor, useful to denote a small earthquake, often not felt. (The pioneer seismologist J. A. Ewing defined it as a small earthquake, imperceptible without instrumental means.)

1903). Adelaide experienced the most destructive earthquake in our history on 1 March 1954, when some millions of pounds worth of damage was claimed to have occurred to buildings (Kerr Grant, 1956). The largest recorded earthquake within the continent (excluding New Guinea) was that in sparsely inhabited country about 300 km southeast of Carnarvon, Western Australia, in 1941; this was of magnitude $m = 6 \cdot 8$ (Clarke, Prider & Teichert, 1955). A shock of larger magnitude ($m = 7 \cdot 4$) occurred outside the continental shelf, 800 km northwest of Carnarvon in 1906, and was felt along the west coast from Albany to the Port Hedland region, and also at sea by RMS *Omrah* at Latitude 21·3°S, Longitude 105·5°E.*

Among the first accounts of earthquakes in Australia were those of Jevons (1859) on tremors in New South Wales, and Clarke (1869) in which the 'father of Australian geology' referred to a catalogue of earthquakes in Australasia but did not publish it. Ellery (1874) reported a Gippsland earthquake, and referred to Clarke's catalogue as containing 160 events up to 1868, but this included New Zealand earthquakes. Biggs (1885) and Shortt (1886) reported the Tasmanian swarm of earth tremors of 1883-1886, when over 2,500 tremors were felt in northeast Tasmania. Later Dodwell (1910) produced an account of the seismicity of South Australia and what is now part of the Northern Territory, and Taylor drew up a map of felt earthquakes in New South Wales based on records kept by weather observers (in Jose *et al.*, 1912). Gregory (1903) and Howchin (1910) also discussed Victorian and South Australian tremors.

A seismological committee was formed by the Australasian Association for the Advancement of Science which made available earthquake report sheets and published some lists for a time (see Reports, 1892-1913). This committee also encouraged the installation of Milne seismographs at State astronomical observatories in Australia and New Zealand.

A brief discussion of the seismicity of the whole continent was given by Gutenberg & Richter (1949) and they listed only ten earthquakes of magnitudes (M) 5·3 to 7. This was followed by the more detailed map of Burke-Gaffney (1952), and the redetermination of some epicentres by Bolt (1959). Since then, and particularly in 1958-1959, there has been a great development of seismological stations in this country (Doyle & Underwood, 1965). From five or six stations of generally low sensitivity, the number has grown to over forty. The latest development is the instalment of a 20 km × 20 km seismic array with twenty seismometers near Tennant Creek (N.T.) by the U.K. Atomic Energy Authority, and operated by the Australian National University. Thus data on Australian seismicity are accumulating at a much greater rate than before. However, large areas of the continent are still not adequately covered by seismic stations, particularly in northwest Australia.

New Guinea could be considered as part of the Australian continent, being within the 100-fathom (180 m) contour. However, the seismicity of New Guinea is not dealt with here. Brooks (1965) has discussed the seismicity of the eastern half of the island (Papua and Australian New Guinea).

DATA

For the epicentres included in the tables and in Figure 1, a lower limit of magnitude $m = 4 \cdot 5$ ($M_L = 3 \cdot 5$) has been adopted. This limit is rather low because of the need to make use of as many data as possible, without, however, causing unacceptable distortion arising from non-uniform station distribution. In Figures 2 to 5 epicentres down to magnitude $m = 4$ ($M_L = 3$) are included to show the seismic zones more clearly. The low magnitude epicentres (up to 1966) are mostly listed in the papers cited.

In the Appendix a discussion is given of the different methods of determining magnitude, about which there is some confusion We have preferred the P wave magnitude m, and have converted magnitude values to this scale where necessary, as discussed in the Appendix.

Table I lists the more reliable epicentres prior to 1959 when the large expansion of Australian stations occurred. Most of these have been discussed before by Burke-Gaffney (1952) and Bolt (1959), but are presented here for completeness. Several were determined from felt reports, but appear to have reasonable accuracy despite lack of instrumental data.

Table II lists the more recent epicentres

* Whilst this paper was in press, an earthquake of magnitude 7 occurred near Meckering, Western Australia, at Lat. 31·7°S, Long. 117°E on 14 October 1968, causing severe damage in the town. This shallow focus earthquake was located in the southwestern seismic belt and is now the strongest recorded in Australia. Surface faulting occurred over a distance of 27 km.

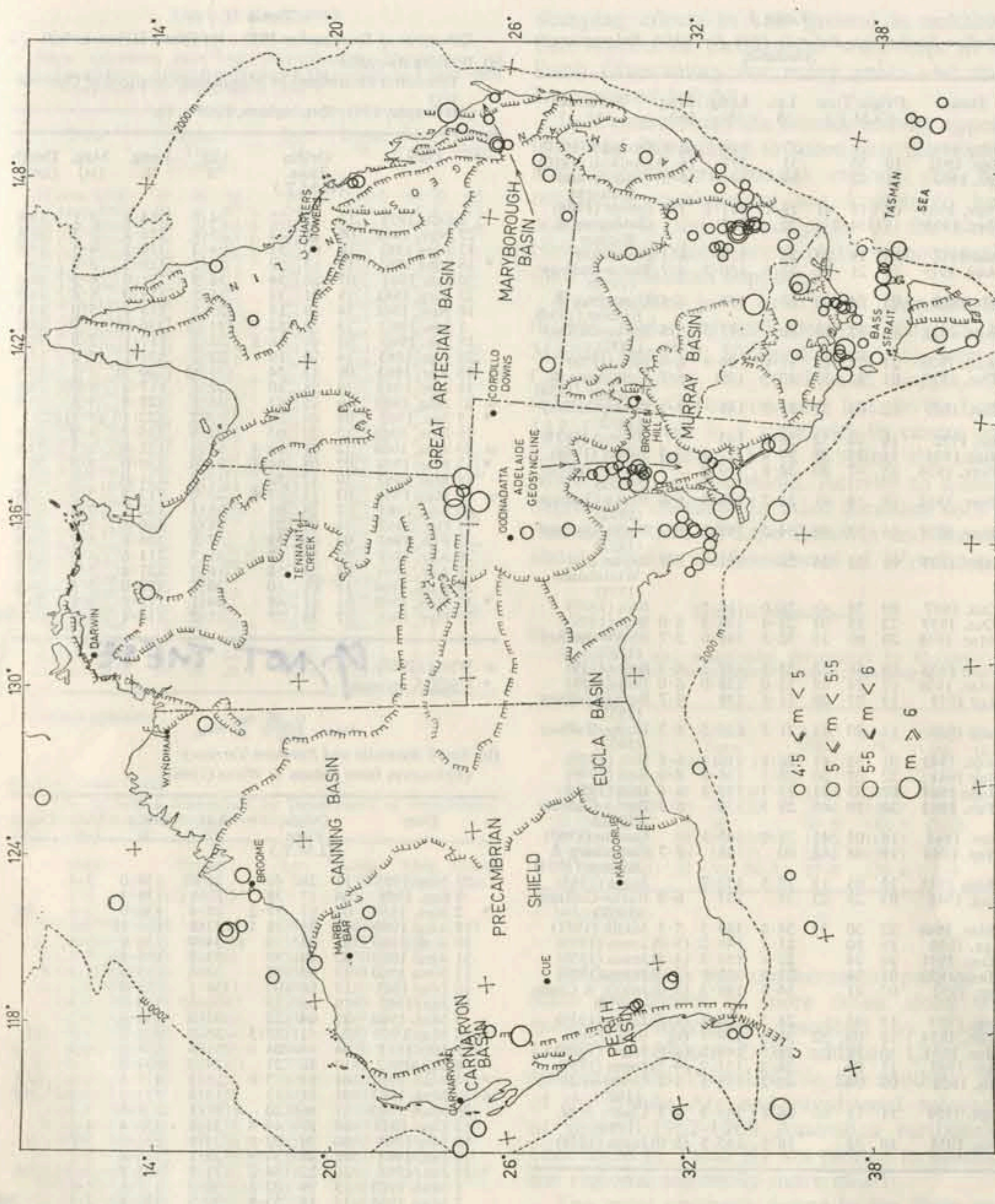

Fig. 1. Seismicity of Australia.

(1959 to 1966 inclusive), grouped by States. These are all instrumentally located and most are reliable to ± ¼ degree, and better for epicentres within close networks. Apart from approximate depth determinations by the U.S. Coast and Geodetic Survey for larger shocks, depths are given only for well recorded earthquakes near seismic networks. The symbol R denotes an approximate depth assumed by the U.S.C.G.S. from preliminary data.

We will now discuss the data in more detail by States, as in the Tables.

Western Australia

The seismicity of Western Australia has been discussed recently by Everingham (1968*a*) From 1901 till 1958 there was only one seismic station in the whole of this vast State. However, the Bureau of Mineral Resources has now installed three stations in the

TABLE I

Australian Earthquakes Prior to 1959 for which Epicentres are Available.

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Reference
10 May 1897		37	140	(6·6)	Dodwell (1910)
19 Sep. 1902	10 30	35	137	(6·3)	Dodwell (1910)
6 Apr. 1903	11 52	39	144	(5·5)	Gregory and Baracchi
19 Nov. 1906	07 18 41	19·1	111·8	7·4	Stover (1966)
18 Dec. 1913	13 54·0	20	147		Gutenberg & Richter
6 June 1918	18 14 24	24	152	6·1	(doubtful)
15 Aug. 1919	10 21 21	33·5	150·7	4·7	Burke-Gaffney (1952)
8 Feb. 1920	05 24 30	35	111	6·4	Gutenberg & Richter (1954)
10 Apr. 1922	10 47 39	40	147·5	5·5	Burke-Gaffney (1952)
16 Aug. 1929	21 28 22	17·0	120·9	6·4	Bolt (1959)
28 Dec. 1929	01 22 53	40	149	5·7	Gutenberg & Richter (1954)
27 Oct. 1930	02 03 51	34·5	149	5·7	Burke-Gaffney (1952)
2 Sep. 1932	18 22 32	38·3	145		Holmes (1933)
12 July 1934	14 24 27	14·8	112·3	6·3	Stover (1966)
10 Nov. 1934	23 47 40	34·9	150·0	5·3	Burke-Gaffney (1952)
18 Nov. 1934	12 58 41	34·5	149·5	6·0	Burke-Gaffney (1952)
21 Nov. 1934	06 32 06	34·5	149·2	5·3	Burke-Gaffney (1952)
12 Apr. 1935	01 32 24	26	151	5·7	Bryan & Whitehouse (1938)
28 Oct. 1937	09 34 43	26·0	136·5		Bolt (1959)
20 Dec. 1937	22 35 02	25·4	136·5	6·0	Bolt (1959)
24 Mar. 1938	20 03 33	35·5	146·0	5·7	Burke-Gaffney (1952)
17 Apr. 1938	08 56 22	25·5	137·2	6·3	Bolt (1959)
26 Mar. 1939	03 56 05	32·0	138·0	6·0	Bolt (1959)
1 May 1939	19 07 29	31·4	138	4·7	Burke-Gaffney (1952)
5 June 1939	12 20 43	31·5	138·5	4·7	Burke-Gaffney (1952)
29 Apr. 1941	01 35 41	26·8	116·1	6·8	Bolt (1959)
4 May 1941	22 07 30	26·3	136·9	6·0	Bolt (1959)
27 June 1941	07 55 51	25·7	137·8	6·6	Bolt (1959)
14 Feb. 1942	20 50 43	29·5	136	5·3	Burke-Gaffney (1952)
2 Nov. 1944	14 05 43	38·0	145·9		Gaskin (1945)
14 Sep. 1946	19 48 42	40	148	5·7	Gutenberg & Richter (1954)
11 June 1947	10 03 13	25·5	152·7		Jones (1948)
6 Aug. 1948	03 29 23	37	137	6·0	Burke-Gaffney (1952)
10 Mar. 1949	22 30 33	34·8	149·3	5·3	Joklik (1951)
5 Apr. 1950	19 50	21·1	149·2	(5·0)	Jones (1959)
30 Dec. 1951	20 34	25·8	150·9	(4·5)	Jones (1959)
24 June 1952	01 34	25·5	152·8	(5·0)	Jones (1959)
7 Sep. 1952	05 41	34·8	149·3	(5·0)	Joklik & Casey (1952)
3 Dec. 1953	15 43	24·5	151·5	(4·5)	Jones (1959)
28 Feb. 1954	18 09 52	34·8	138·7	(6)	Bolt (1959)
19 Sep. 1954	10 38	28·5	148·5	(4·5)	Jones (1959)
1 Feb. 1955	11 09	26·2	151·2	(4·5)	Jones (1959)
1 Jan. 1958	00 07	42·2	146·1	5·7	Green *et al.* (1967)
1 Sept. 1958	11 18 02	36·4	149·3	4·7	Cleary *et al.* (1964)
1 Dec. 1958	10 38	16·5	145·5	(5·0)	Jones (1959)

southern part of the State and the Public Works Department has operated one at Kununurra since 1966. Only three accurate epicentres had been located in the Western Australian region up to 1958. Among these was that of 29 April 1941, about 300 km southeast of Carnarvon and of magnitude (m) 6·8, the largest earthquake recorded beneath the Australian continent until the recent Meckering event. It had a radius of perceptibility of about 850 km,

TABLE II

Epicentres of Earthquakes 1959—1966 for which m ≥ 4·5.

(a) *Western Australia*

Epicentres determined by Mundaring Geophysical Observatory (McGregor, 1967; Everingham, 1968 *a*, *b*).

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Depth (km)
3 Oct. 1959	12 07 22	34·5	114·5	5·1	18*R*
27 Nov. 1959	06 25 22	25·8	116·2	5·3	18*R*
12 June 1961	18 00 51	34·2	114·5	4·5	18*R*
• 18 June 1961	16 13 58	20·1	119·3	5·6	13
30 July 1961	07 28 34	36·9	121·0	4·5	18*R*
23 Aug. 1961	18 01 33	18·5	119·0	5·4	18*R*
10 Nov. 1961	14 59 14	37·5	118·4	5·0	18*R*
1 Jan. 1962	23 29 52	(34·0)	(126·0)	5·0	18*R*
18 Jan. 1963	05 49 16·8	32·2	117·1	5·8	18
26 Feb. 1963	14 10 19	22·2	121·1	5·2	18*R*
15 Apr. 1963	00 43 54	(21·8)	(120·3)	5·1	18*R*
18 Apr. 1963	19 58 10	32·3	117·2	4·8	18*R*
≠ 27 Aug. 1963	19 15 43	16·6	128·6	5·8	33*R*
• 7 Sep. 1963	08 44 35	13·2	122·1	(5·5)	(256)
19 Nov. 1963	17 52 05	31·0	116·3	4·9	18*R*
≠ 23 Mar. 1964	22 41 14·4	17·8	122·8	5·9	33*R*
• 12 May 1964	07 08 44·6	11·0	126·0	5·6	33
18 May 1965	10 17 52	17·5	121·0	5·0	18*R*
≠ 19 May 1965	02 13 47·6	25·0	112·5	5·9	0*R*
10 Sep. 1965	12 24 01	18·1	122·2	5·2	18*R*
11 Oct. 1965	04 07 27	26·9	110·5	5·2	18*R*
23 Feb. 1966	03 40 13	37·8	106·8	5·3	18*R*
26 Apr. 1966	03 58 17	31·7	111·6	4·8	18*R*
30 Apr. 1966	03 24 58	16·9	121·0	5·0	18*R*
29 Aug. 1966	13 01 10	30·0	109·0	5·4	18*R*
• 13 Nov. 1966	03 41 48	24·1	111·9	5·6	33*R*
25 Dec. 1966	22 34 27	31·0	116·4	4·5	18*R*

≠ White (1968) OR NOT THESE

• USCGS epicentre

(b) *South Australia and Northern Territory*

(Epicentres from Sutton & White (1968)).

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Depth (km)
21 May 1959	11 28 46	31·4	139·0	5·4	
9 Sep. 1959	04 17 30	32·7	138·2	5·3	
• 2 Nov. 1959	01 17 57·2	33·4	136·0	5·9	0*R*
18 Aug. 1960	15 04 48	33·8	136·15	5·3	
30 Aug. 1960	21 23 10	34·0	136·0	5·3	
31 Aug. 1960	02 14 50	33·5	136·4	5·4	
12 Nov. 1960	23 03 08	34·6	135·5	5·4	
10 June 1961	15 58 00	34·5	135·0	5·2	
10 Jan. 1962	19 36 25	36·35	139·8	5·1	
3 Mar. 1962	22 04 22	33·0	136·0	5·2	
• 16 May 1962	21 41 35·5	35·5	137·7	5·5	25
7 July 1962	04 30 04	31·3	138·6	4·6	
6 Sep. 1962	14 48 21	34·5	139·0	4·5	
• 14 Mar. 1963	01 57 35·0	25·7	137·4	5·5	33*R*
≠ 28 Mar. 1963	01 31 13	15·4	133·3	5·7	0*R*
29 Mar. 1963	21 56 20	31·1	138·5	5·1	
3 Dec. 1963	04 59 44·4	31·9	138·4	4·6	
12 July 1964	00 39 02·8	34·1	134·7	5·0	9
17 Jan. 1965	02 48 34·9	28·1	135·8	5·2	
• 25 Jan. 1965	20 22 54·2	31·9	138·5	5·6	0*R*
1 Mar. 1965	13 39 02·8	30·3	138·1	4·8	
2 Mar. 1965	15 18 53·9	30·5	138·2	5·8	
14 Mar. 1965	12 47 42·3	31·9	138·5	5·7	3
4 June 1965	10 45 10·3	32·0	138·6	5·3	4
+ 28 Aug. 1965	00 26 38·8	32·2	138·3	5·3	16
+ 28 Aug. 1965	00 45 41·4	32·4	138·2	4·9	25
22 Nov. 1965	22 15 09·7	33·8	134·3	4·8	
14 Sep. 1966	17 25 36·7	31·7	141·4	4·7	11
17 Oct. 1966	00 27 04·7	34·4	136·0	5·0	
23 Nov. 1966	20 48 03·4	34·4	139·3	5·3	19
Ø 3 Dec. 1966	06 06 37	08·8	135·5	5·3	
7 Dec. 1966	02 49 38·9	33·2	139·0	4·7	

• Sutton & White (1966*a*)

+ Sutton & White (1966*b*)

≠ White (1968)

Ø USCGS epicentre.

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SOURCES ADE CAN } AUST. ~~see~~ Dept. of MINERAL

TABLE II (Continued)

(c) *Victoria and Tasmania*

Most epicentres have been determined by Department of Geophysics, Australian National University, and have been re-examined by Underwood (1967).

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Depth (km)
28 Jan. 1960	23 36 56	36·8	147·1	(4·7)	15
1 June 1960	05 18 47·6	36·8	145·4	4·5	12
20 Oct. 1960	20 22 04·6	38·6	146·5	4·7	8
21 Oct. 1960	14 47 57·0	38·9	146·5	4·6	
24 Dec. 1960	16 42 08·5	39	143·5	5·8	
22 Jan. 1961	14 43 55	39·5	155·5	4·7	
22 Jan. 1961	18 39 45	40	155·5	4·7	
3 Feb. 1961	14 37 45	40	148·5	4·7	
10 Apr. 1961	14 10 32·6	37·1	144·1	4·7	
11 Apr. 1961	00 35 23·4	38·3	146·5	4·7	
• 1 June 1961	09 35 35·7	38·4	144·2	4·7	5
1 June 1961	13 19 51	38·3	144·1	4·9	29
12 Sep. 1961	07 13 09·4	40·7	156·6	4·9	
9 Oct. 1961	23 43 14·3	39·2	145·9	4·7	
10 Oct. 1961	13 36 08	39·2	145·9	4·7	
10 Jan. 1962	05 40 31	38·5	146·5	4·5	
10 Jan. 1962	06 12 17	38·5	146·5	4·5	
27 Mar. 1962	17 54 22·2	37·9	146·5	4·5	6
14 June 1963	19 23 47·8	38·6	146·4	5·2	2
3 Nov. 1963	12 00 44·3	43·3	146·0	(5·0)	
• 14 Nov. 1964	10 53 01	40·0	144·3	5·0	
17 Nov. 1964	21 16 18·5	38·4	146·4	4·7	16
• 18 Mar. 1965	18 09 31·1	40·2	149·6	5·5	
8 May 1965	06 25 53·2	38·7	149·2	4·5	27
• 14 Sep. 1965	12 34 36·3	38·7	144·2	5·5	
14 Sep. 1965	12 44 57	After shock		4·5	
• 14 Sep. 1965	12 53 13	38·7	144·3	6·0	
3 May 1966	19 07 53·1	37·0	147·1	5·7	8
5 July 1966	22 26 39·4	39·6	145·0	4·8	
17 Oct. 1966	17 12 30·8	37·9	146·2	4·6	18
27 Oct. 1966	00 25 46	40·0	154·5	5·2	
15 Dec. 1966	19 08 29·1	40·4	155·4	5·8	

• USCGS epicentre. —CAN—

(d) *New South Wales*

(Most epicentres determined by Department of Geophysics, Australian National University.)

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Depth (km)
• 18 May 1959	06 12 59·2	36·2	148·7	5·5	17
12 Oct. 1959	21 23 (40)	31	151·5	(5)	
6 Sep. 1960	02 58 01	34·4	150·9	4·5	
6 Oct. 1960	19 34	33	148·5	4·7	
9 Dec. 1960	06 57 11	33·5	151·5	4·5	
8 Feb. 1961	18 56 47	35·3	149·3	4·5	
13 Feb. 1961	19 23 19	33·9	149·0	4·5	
16 May 1961	06 52 54	31	147·5	(5)	
+ 21 May 1961	21 40 03·0	34·5	150·5	5·8	19
23 Nov. 1961	01 17 (25)	33·5	149	(4·8)	
16 Jan. 1962	06 15 52	32·2	149·2	4·9	
29 Sep. 1962	01 31 35	34·4	150·0	4·5	
15 May 1963	18 22 33	34·9	149·3	4·5	
8 Jan. 1964	23 30 28	34·1	147·9	4·5	14
13 Mar. 1964	08 07 36	33·9	148·2	4·5	
21 Mar. 1964	02 18 39	34·2	149·2	4·5	
29 May 1964	09 46 33	34·8	149·2	4·5	4
19 Dec. 1964	16 44 (16)	33·7	148·2	4·5	
22 Apr. 1966	03 26 52·7	34·2	148·2	4·5	

• Cleary, Doyle & Moye (1964)

+ Cleary & Doyle (1962)

CAN

being felt from Port Hedland to Albany and Kalgoorlie (Everingham, 1968*a*). At Meeberrie Station near the epicentre, ground cracks were found oriented meridionally in a narrow zone 35 m long. They were up to 10 cm wide and 12-15 cm deep. Whether these were only slumping effects in soft ground is unknown. Felt reports of earthquakes were kept at the Perth Observatory for many years and these have proved helpful.

In Western Australia seismic activity appears to be mainly confined to zones near the western and northwestern coastal regions and only occasional earthquakes are known to have occurred in the inland parts of the shield. Nevertheless shield areas may be more active than is sometimes supposed.

Earthquakes have been most frequent (a) in the region around Broome, (b) in the Marble Bar-Port Hedland area, (c) west of Carnarvon near the continental margin, (d) southeast of Carnarvon near Lat. 26°S, Long. 117°E, and (e) in a zone with its centre near Lat. 32°S, Long. 117°E crossing the south-western part of the shield. Activity to a lesser degree has occurred in other localities such as that to the west of Cape Leeuwin and the area about 130 km southsoutheast of Wyndham.

TABLE II (Continued)

(e) *Queensland*

(Epicentres and magnitudes determined by University of Queensland Seismological Station; courtesy of Dr J. P. Webb.)

Date	Origin Time (G.M.T.)	Lat. °S	Long. °E	Mag. (*m*)	Depth (km)
19 Oct. 1960	11 36 31	21·0	148·8	4·7	
17 Nov. 1960	05 00 20	27·4	150·7	5·1	
28 Dec. 1961	07 36	28·5	142·5	(5·6)	
15 Jan. 1964	08 59 55	18·0	143·3	4·9	
3 Mar. 1964	06 13 35	25·4	151·7	4·5	
+ 3 June 1965	21 59 56·3	27·8	150·1	5·4	

+ White (1968)

Epicentres in the northernmost part of the State are shown in more detail along with geological structures described by Veevers (1967) in Figure 2. In addition U.S.C.G.S. epicentres for 1960-1967 in the southern part of the Banda Arc and provisional epicentres of several 1967-1968 Australian earthquakes (not listed in Table II) are plotted to illustrate the regional seismicity more clearly.

The most northerly towns in the State such as Wyndham, are occasionally shaken by earthquakes in the Timor region, but there may also be local activity. The Kimberley Block may prove to be more active than shown here when seismic stations are set up in the northwest in the future.

In the region illustrated in Figure 2 the intense seismicity associated with the orogenic zone passing through the Timor region predominates and there is comparatively little activity south of the 200-m bathymetric contour marking the edge of the Australian continent. Here, the majority of continental epicentres occur in an arcuate zone around the western end of the Canning Basin where three earthquakes (1929, 1961, 1964) have been large enough to be well recorded on overseas seismographs.

the intensified seismicity at its junction with the Canning Basin axis.

Since the establishment of Mundaring seismic station, and later Kalgoorlie and other temporary stations, by the Bureau of Mineral Resources, many low magnitude earthquakes have been located in a minor seismic zone across the southwest corner of the State. The

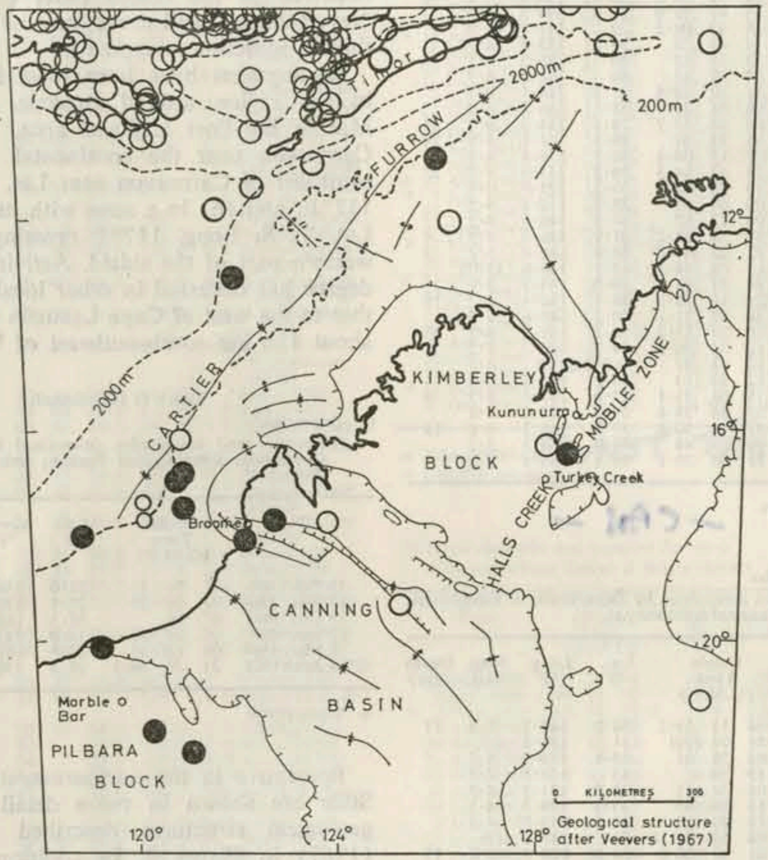

Fig. 2. Seismicity and geological structures, northwestern Australia. Larger circles, $m > 4{\cdot}4$; smaller circles, $4{\cdot}0 < m < 4{\cdot}4$ Earthquake epicentres not listed in Table II are shown by open circles, Australian epicentres being obtained from Mundaring Observatory annual reports for 1967 and 1968 and the remainder from U.S.C.G.S. Earthquake Data Reports.

Evidence for downwarping seaward of the Canning Basin is given by the tectonically depressed nature of the continental shelf margin there (Fairbridge, 1967), hence seismic activity could indicate that the warping is continuing within the arc of epicentres. Bouguer gravity contours trend perpendicularly to the coast, suggesting that the basin extends far offshore. Stresses associated with the Cartier Furrow may influence the warping and explain

epicentres are shown in Figure 3, which includes smaller magnitude events not listed in Table II. This seismic zone has been referred to as the Yandanooka-Cape Riche Lineament (Everingham, 1968*a*) and may have some relation to deep structure across the southwest corner of the Shield.

Partial coincidence of this zone of seismicity with landscape zones outlined by Mulcahy (1967) is of interest. The junction of the Salt

Lake and Sand-plains region with the Younger Laterites is of significance because it marks the limit of preservation of the Tertiary drainage system, and a climatic control for its present position has been suggested (Mulcahy, 1967). However, some parallelism with the zone of seismicity is also apparent, which suggests that the formation of the present landscape may also have been influenced by tectonic processes such as differential uplift or a change in tilting across the active lineament. Bouguer gravity anomaly contours also trend parallel to the zone of seismicity and interpretations of gravity, seismic-refraction (Everingham, 1965), and electromagnetic data (Everett & Hyndman, 1967) indicate that a change in crustal or upper-mantle features could take place across this seismic zone. Furthermore, the active zone can be correlated with geological features and data suggest that the lineament has been a zone of tectonic importance at various times during and since the Precambrian (Everingham, 1968*a*). The northnorthwesterly projection of this zone meets the Darling Fault where it changes from a northerly to a northwesterly strike.

Possibly because of the lack of recorded data, other active regions in the western part of the State do not show clear trends and their tectonic implications are obscure. Earthquakes

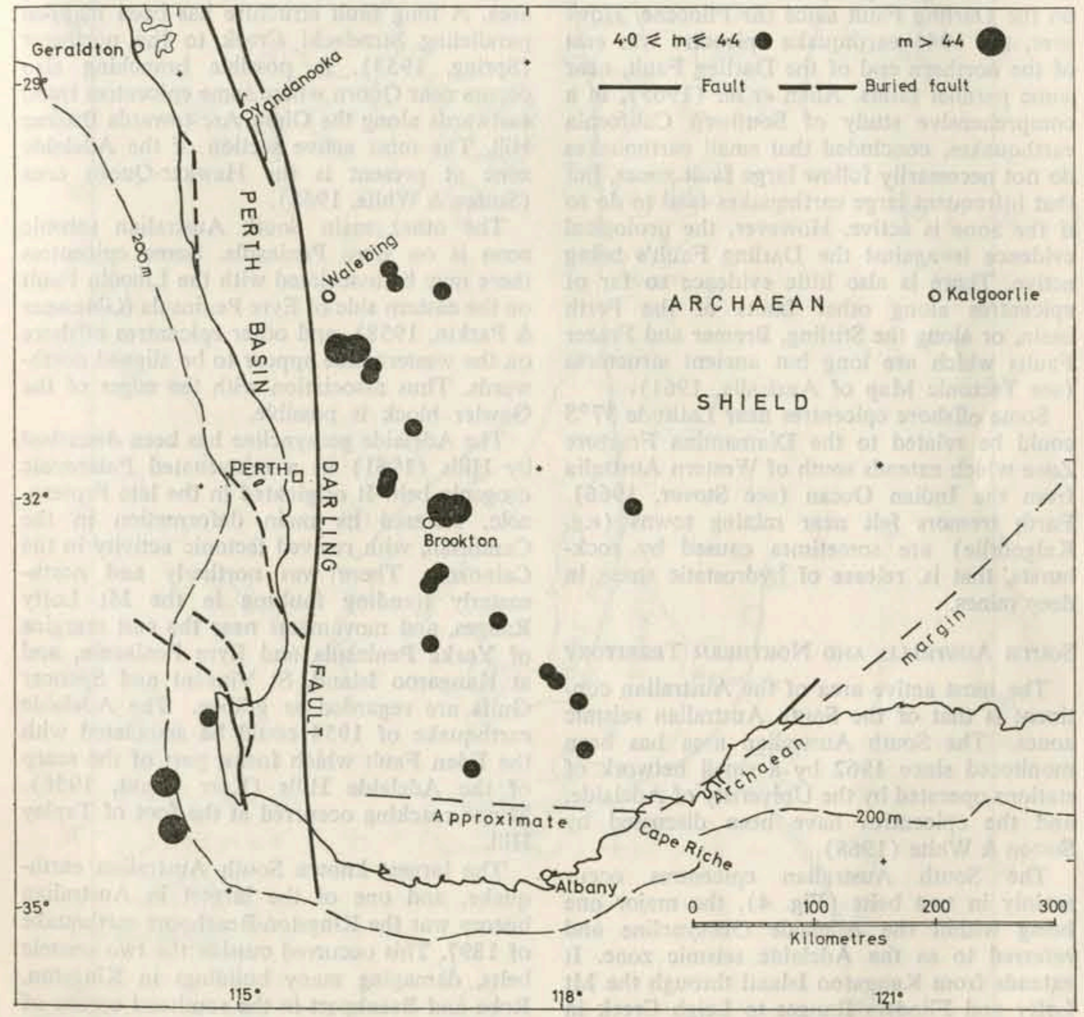

Fig. 3. Southwestern Australian seismicity. Epicentres of smaller earthquakes obtained from Everingham (1968 *a*, *b*) and McGregor (1967).

may be related to upper-mantle effects along the west coast region where primarily tensional stresses have occurred since the Precambrian to form the Perth and Carnarvon Basin structures. It is interesting to find that the central basin regions along the western coast are almost aseismic at present, with stress adjustments apparently taking place along each side of the basins but not exactly at their margins.

It is an interesting fact that few epicentres are close to the 1,000-km long Darling Fault which marks the western boundary of the shield and eastern boundary of the Perth Basin. A major negative gravity anomaly exists over this basin and the region is isostatically unbalanced. There is no geological evidence of movement on the Darling Fault since the Pliocene. However, the 1941 earthquake epicentre was east of the northern end of the Darling Fault, near some parallel faults. Allen *et al.* (1965), in a comprehensive study of Southern California earthquakes, concluded that small earthquakes do not necessarily follow large fault zones, but that infrequent large earthquakes tend to do so if the zone is active. However, the geological evidence is against the Darling Fault's being active. There is also little evidence so far of epicentres along other faults of the Perth basin, or along the Stirling, Bremer and Frazer Faults which are long but ancient structures (see Tectonic Map of Australia, 1961).

Some offshore epicentres near Latitude 37°S could be related to the Diamantina Fracture Zone which extends south of Western Australia from the Indian Ocean (see Stover, 1966). Earth tremors felt near mining towns (*e.g.* Kalgoorlie) are sometimes caused by rock-bursts, that is, release of hydrostatic stress in deep mines.

South Australia and Northern Territory

The most active area of the Australian continent is that of the South Australian seismic zones. The South Australian area has been monitored since 1962 by a small network of stations operated by the University of Adelaide, and the epicentres have been discussed by Sutton & White (1968).

The South Australian epicentres occur mainly in two belts (Fig. 4), the major one being within the Adelaide Geosyncline and referred to as the Adelaide seismic zone. It extends from Kangaroo Island through the Mt Lofty and Flinders Ranges to Leigh Creek in the north. The epicentres generally follow the ranges and also the western boundary of the Upper Proterozoic Sequence and the fold trends in that part of the geosyncline. They curve around to the east of Lake Torrens. It will be of interest to see if future data to the north show trends towards the western side of Lake Eyre where Wopfner & Twidale (1967) report earth tremors and mound springs aligned meridionally. Dodwell (1910), from early reports of earth tremors, mapped active areas south and west of Lake Eyre, and farther north towards Oodnadatta. Another possibility is for continuation of the Adelaide zone north-east towards the Cooper Creek Basin where some epicentres have been mapped. Laherrere & Drayton (1965) show geophysical evidence for trends in both these northwesterly and northeasterly directions from the Leigh Creek area. A long fault structure has been mapped paralleling Strzelecki Creek to the northeast (Sprigg, 1953). A possible branching also occurs near Quorn where some epicentres trend eastwards along the Olary Arc towards Broken Hill. The most active section of the Adelaide zone at present is the Hawker-Quorn area (Sutton & White, 1968).

The other main South Australian seismic zone is on Eyre Peninsula. Some epicentres there may be associated with the Lincoln Fault on the eastern side of Eyre Peninsula (Glaessner & Parkin, 1958), and other epicentres offshore on the western side appear to be aligned northwards. Thus association with the edges of the Gawler block is possible.

The Adelaide geosyncline has been described by Hills (1961) as a rejuvenated Palaeozoic orogenic belt. It originated in the late Proterozoic, suffered its main deformation in the Cambrian, with revived tectonic activity in the Cainozoic. There was northerly and northeasterly trending faulting in the Mt Lofty Ranges, and movements near the east margins of Yorke Peninsula and Eyre Peninsula, and at Kangaroo Island. St Vincent and Spencer Gulfs are regarded as gräben. The Adelaide earthquake of 1954 could be associated with the Eden Fault which forms part of the scarp of the Adelaide Hills (Kerr Grant, 1956). Minor cracking occurred at the foot of Tapley Hill.

The largest known South Australian earthquake, and one of the largest in Australian history was the Kingston-Beachport earthquake of 1897. This occurred outside the two seismic belts, damaging many buildings in Kingston, Robe and Beachport in the southeast corner of the State (Howchin, 1910). It was felt from Port Augusta to Melbourne and parts of Tas-

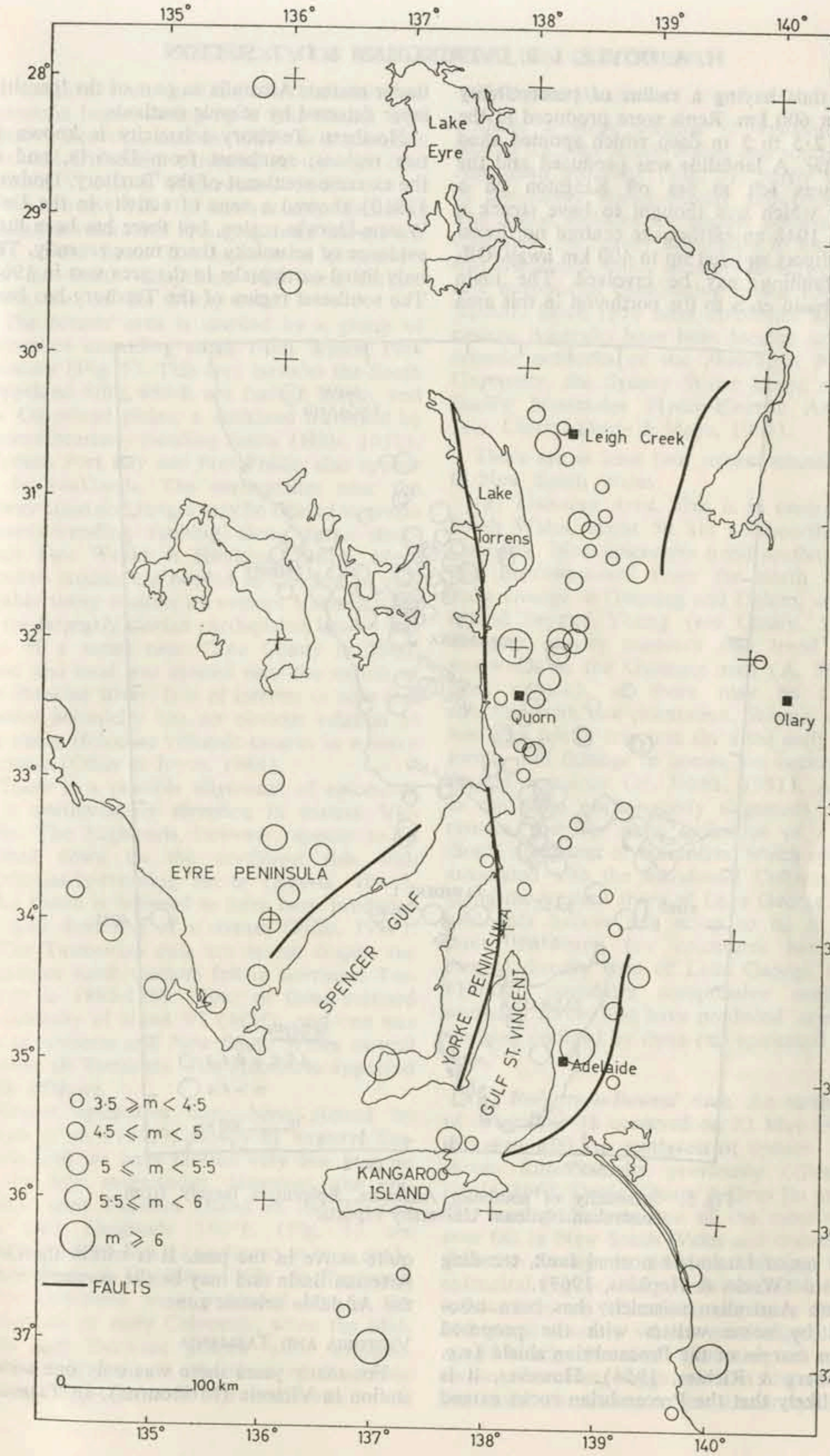

Fig. 4. South Australian seismic zones. Epicentres from Sutton & White (1968); with some major faults, by courtesy of Tectonic Map Committee.

mania, thus having a radius of perceptibility of about 600 km. Rents were produced in the ground 2·5 to 3 m deep which spouted sand and water. A landslide was produced and the shock was felt at sea off Kingston on a steamer which was thought to have struck a reef. In 1948 an earthquake centred northwest of Beachport was felt up to 400 km away. Offshore faulting may be involved. The main Otway basin ends to the northwest in this area at the major Lucindale normal fault, trending eastward (Weeks & Hopkins, 1967).

South Australian seismicity has been associated by some writers with the proposed eastern margin of the Precambrian shield (*e.g.* Gutenberg & Richter, 1954). However, it is quite likely that the Precambrian rocks extend under eastern Australia as part of the 'granitic' layer detected by seismic methods.

Northern Territory seismicity is known in two regions; southeast from Darwin, and in the extreme southeast of the Territory. Dodwell (1910) showed a zone of activity in the Daly Waters-Darwin region, but there has been little evidence of seismicity there more recently. The only listed earthquake in the area was in 1963. The southeast region of the Territory has been quite active in the past. It is within the Great Artesian Basin and may be the northern end of the Adelaide seismic zone.

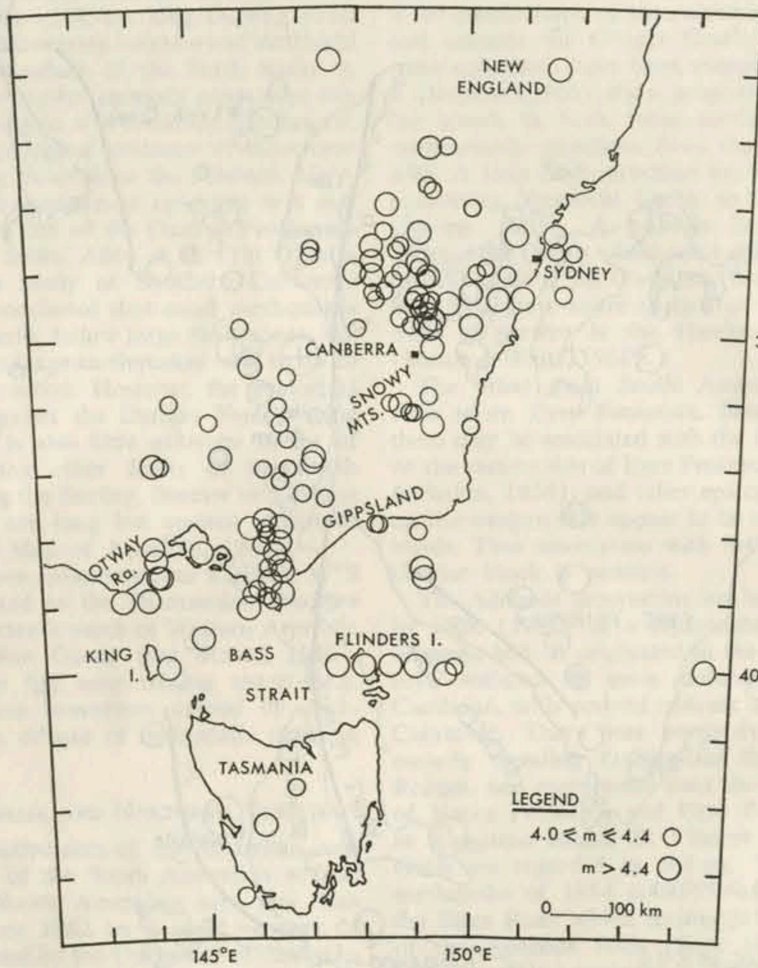

Fig. 5. Seismicity of southeast Australia. Epicentres largely from Australian National University reports.

Victoria and Tasmania

For many years there was only one seismic station in Victoria (Melbourne). In Tasmania, for the first time, in 1957 the University of Tasmania began setting up a four-station telemetered network, and in 1963 the Australian National University extended its network into Victoria (Doyle & Underwood, 1965).

Underwood (1967) has recently discussed Victorian seismicity. It is greater in the eastern half of the State. The main areas of activity are the South Gippsland Hills and farther north, and off the Otway coast.

The former area is marked by a group of epicentres extending north from Wilson Promontory (Fig. 5). This area includes the South Gippsland Hills which are faulted horsts, and the Gippsland plains, a sunkland traversed by eastnortheasterly-trending faults (Hills, 1951). Western Port Bay and Port Phillip also appear to be sunklands. The earthquakes near the Otway coast and ranges may be related to northeasterly-trending faulting along these structures (see Weeks & Hopkins, 1967). More detailed studies are needed to check this, preferably using stations in western Victoria. One of the largest Victorian earthquakes known was one of a series near Cape Otway in 1903. Sand and mud was ejected near the mouth of the Hopkins River. It is of interest to note that present seismicity has no obvious relation to the many Holocene volcanic centres in western Victoria (Ollier & Joyce, 1964).

There is a possible alignment of epicentres in a northwesterly direction in eastern Victoria. The Highlands, however, appear to be faulted down on the northwest side with northeasterly-trending faults (Beavis, 1961). Lake Omeo is believed to have been produced by fault damming of a stream (Hills, 1951).

The Tasmanian data are sparse despite the swarm of earth tremors felt in northeast Tasmania in 1883-1886. Four of these reached an intensity of about VI (*MM*), and one was felt in Victoria and New South Wales as well as over all Tasmania. The epicentres appeared to be offshore.

Recent epicentres have been plotted by Green *et al.* (1967), mostly in western Tasmania, but we have plotted very few because of the low magnitudes. However, the epicentres near Flinders Island in the Tasman Sea near Longitude 156°E (Fig. 1) are intriguing. Bass Strait is believed to be a sunkland (Weeks & Hopkins, 1967). In Tasmania major structures were produced late in the Cretaceous or early Cainozoic, when the Midlands and Derwent gräben were initiated. There are four main directions of Cainozoic faulting, between north and northwest.

New South Wales

Quite a large number of epicentres are plotted for New South Wales, and southeastern Australian generally (Fig. 5), partly because of the higher station-density and population. The region includes the highest portion of the continent, the Snowy Mountains in the Southeast Highlands, which were produced by Cainozoic movements culminating in the Kosciusko 'Epoch'. Since 1958 most epicentres in southeastern Australia have been located using the seismic networks of the Australian National University, the Sydney Water Board and the Snowy Mountains Hydro-Electric Authority (*e.g.* Cleary, Doyle & Moye, 1964).

There are at least four minor seismic zones in New South Wales:

(a) *Gunning Area.* This is in central New South Wales, about 50 km northnortheast of Canberra. Most epicentres trend southeastward and northwestward from the north end of Lake George to Gunning and Dalton, and may extend beyond Young (see Cleary, 1967*a*). Bouguer gravity contours also trend northwestwards in the Gunning area (A. Flavelle, *pers. comm.*), so there may be a deep structure with this orientation. Seismic activity has been felt in this area since the early settlements, and damage to homes has occurred on several occasions (*cf.* Joklik, 1951). As well as the main northwesterly alignment of epicentres, there is some indication of a meridional alignment of epicentres, which could be associated with the meridional Cullarin scarp along the western shore of Lake George. Some geologists believe this scarp to be a recent fault. However, few epicentres have been located directly west of Lake George. Cleary (1967*a*) postulates compressive northwest-southeast forces that have produced large-scale wedging outlined by these two epicentral directions.

(b) *Robertson-Bowral Area.* An earthquake of magnitude 5½ occurred on 22 May 1961 in this area, 100 km southwest of Sydney. It had shown little activity previously (Cleary & Doyle, 1962; Doyle, Cleary & Gray [in prep.]). The earthquake was one of the most widely ever felt in New South Wales and caused considerable damage to old stone buildings in the epicentral region, and also a landslide. It was followed by an aftershock sequence of over 100 earth tremors which were aligned in a northwesterly direction. Direction of motion studies, however, suggested that the fault of the main shock was a northeasterly-striking reverse fault. The aftershocks may delineate secondary faulting, orthogonal to the main fault.

(c) *Snowy Mountains and Monaro Plains.* This area in the Southeastern Highlands has a scattering of epicentres mainly on and to the east of the main range (Cleary, Doyle & Moye, 1964). An earthquake of magnitude 5 occurred north of Berridale in 1959, and direction of motion studies suggested a primary, northeasterly-trending reverse fault here also, parallel to the Crackenback-Thredbo valley. After-shocks were aligned northwestward along possible wrench faults. These may be related to the large wrench fault of Lambert & White (1965).

(d) *New England Area.* Earthquakes are felt in this area occasionally and a few epicentres have been located, but seismic stations are required in northern New South Wales to delineate the seismicity more accurately there.

Thus northwesterly trends are apparent in some minor seismic zones in New South Wales. This was somewhat unexpected as the structural trends are mainly meridional in southern New South Wales and much of Victoria, for example, the Palaeozoic granitic batholiths. However, near the border there are some northeasterly- and northwesterly-trending structures. The northwesterly epicentre alignments apparently represent contemporary tectonic movement in the crust not always apparent in surface geology.

The continental shelf and coast of New South Wales have not shown much seismicity. The coast has a narrow continental shelf and the tablelands step down rather abruptly to the coastal plains. Jaeger & Browne (1958) suggested the possibility of seismicity being associated with coastal and off-shore faulting. There is a little evidence of this along the central coast of New South Wales according to Doyle, Cleary & Gray (1968), who report small magnitude earth tremors in a study of the Sydney Basin seismicity. Epicentres also tend to follow the western margin of the Sydney Basin.

QUEENSLAND

This State appears to have quite a low level of seismicity. Queensland epicentres for 1950-1958 were given by Jones (1959), and Dr J. P. Webb has kindly made available data on some recent ones. There was no seismological station in the State until 1937 when a Milne-Shaw instrument was set up at Brisbane, and Charters Towers station did not begin recording till 1957, so that the data may be biased to the southeast of the State.

The great majority of epicentres are within the highlands and coastal areas, the main areas of known highly folded and faulted rocks. Detailed correlation with faults and other structures cannot be made on present data. However, it may be noted that earthquakes have occurred in the Maryborough Basin and to the west of this structure. These include the Gayndah earthquake of 1935 which may have been associated with known northnorthwesterly-trending faults through the region (Bryan & Whitehouse, 1938). On the day following this earthquake, subsidence and a crack 35 m long parallel to the faulting were found on a railway embankment near Abercorn.

Queensland's largest known earthquake was that of 6 June 1918 ($m = 6{\cdot}1$). Its position is uncertain, but we have taken Gutenberg & Richter's position near the coast. Hedley (1925) reported that it was felt from St Lawrence to the New South Wales border, and west to Roma.

The St George tremor of 1954 was close to one of the deepest parts of the Great Artesian Basin, in the Surat sub-basin. Eighteen tremors were felt at Georgetown in January-February 1964; the main earthquake only is listed here.

Queensland, like Australia as a whole, is made up of three basic structural elements; a Precambrian block which is in the northwest and north; sedimentary basins, dominated here by the Mesozoic and Cainozoic Great Artesian Basin in the centre; and a geosynclinal element, the Palaeozoic Tasman Geosyncline in the east. Within the last are the Eastern (or Northeastern) Highlands and the coastal plains (Hill & Denmead, 1960). The Highlands are a series of ranges and plateaux with scarps to the east and trend northnorthwestwards, roughly parallel to the coast.

De Keyser (1963) recently reported evidence for a major fault in Queensland, 1,000 km long and forming the western boundary of part of the Tasman Geosynclinal Zone. No obvious correlation can be seen yet between this fault and seismicity.

DISCUSSION

Seismic activity on the Australian continent may be divided into three general regions:

1. Near the coastal areas of Western Australia, plus a minor seismic zone across the southwest corner of the State.

2. The South Australian seismic belts near the rift zone area, with possible extensions to the north.

3. The Eastern Highlands within the Tasman Geosyncline, with some particular seismic zones such as the Gunning zone in New South Wales.

Future improved data may reveal other active regions in northwest Australia and the interior. The Kimberley block, which is bordered by mobile zones, may show significant seismicity. Permanent seismic stations are desirable in northwest Australia, and also central Australia, to check this.

The most obvious correlation is that of the Adelaide seismic zone with the Mt Lofty and Flinders Ranges and the nearby rifts. The foci occur mainly beneath the ranges rather than below the rift or graben structures. The rifts include Lakes Torrens and Eyre, the latter the lowest area on the continent, 16 m below sea level. This region is often thought of as the eastern edge of the Western Australian shield.

There is appreciable seismic activity also in the highest portion of the continent, the Snowy Mountains, but to a lesser degree. Richter (1958) pointed out that seismicity does not necessarily match structures in detail. For example, the seismicity of the Rocky Mountains is much lower than that of the California Coast Ranges.

The Gunning seismic zone in New South Wales is not associated with marked topography, but it does cut across a lower portion of the Great Divide between the northern end of the Southeastern Highlands and the Blue Mountains area. In southwest Australia the Yandanooka-Cape Riche zone coincides with major fold directions in the metamorphic rocks. There is some evidence of changes in crustal and upper mantle structure across the zone (Everingham, 1965; Everett & Hyndman, 1967). Thus it may be argued that these seismic zones are associated with structural boundaries in the crust and perhaps the upper mantle. Kanasewich (1965) reported greater seismicity along geological boundaries in the Canadian shield.

There is good evidence of significant differences between shield regions and areas of younger uplift. Heat-flow values are twice as high in southeast Australia as on the Western Australian shield (Howard & Sass, 1964); and Cleary (1967*b*) has found delays in teleseismic *P* travel times to southeast Australia relative to those of the shield. Travel-time delays correlate with high heat flows and appear to be caused by different structures and higher temperatures in the upper mantle (Hales & Doyle, 1967).

Tasmania and Victoria are notable for graben structures and extensive volcanics, and south of Tasmania a ridge-like structure extends without quite meeting the Antarctic mid-ocean ridge. This South Tasmania ridge has shown very little seismic activity, and could have some similarities to the Kerguelen-Gaussberg 'aseismic' ridge in the southern Indian Ocean. It suggests the possibility that the high heat flows of Tasmania and southeast Australia were produced by a formerly active oceanic ridge, extending under the continent. Heirtzler *et al.* (1968) show two meridional fracture zones in the Southern Ocean, one trending towards Tasmania, and the other towards the Adelaide rift zone. They are associated with displacements of the mid-ocean ridge south of Australia. The Australian structures have also been associated by some geologists with the Trans-Antarctic Mountains and other features of the Antarctic continent.

The Tasman Sea basin appears to be aseismic, apart from some epicentres grouped near Latitude 40°S, Longitude 156°E. These epicentres may have some relation to activity near Flinders Island farther west (Underwood, 1967). Thus the question arises as to whether there is a westnorthwesterly striking seismic zone across Bass Strait from Longitude 156°E to Flinders Island and farther westwards or northwestwards.

There are some epicentres near the edges of the Canning and Sydney basins (*e.g.* Doyle, Cleary & Gray, 1968) but correlation with basin structures should not be over-emphasised. There is surprisingly little seismicity along some extensive known faults. This is of particular interest in the case of the 1,000-km long Darling Fault in Western Australia. This is one of the longest fault structures in the world and marks the western edge of the Western Australian shield. There is also little seismic evidence so far for the proposed Darling lineament in New South Wales of Hills (1956). However, three epicentres in Queensland are near the northeastern extension of the lineament. Rudd (1961) has suggested its continuation into the Surat Basin, and it may also be related to the inferred Redan fault near Broken Hill.

All reliable depth determinations for Australian epicentres place the foci within the crust, mostly the upper crust. No certain examples of foci within the mantle have yet occurred. Australian seismicity is similar in this and other ways to that of much of North America, Africa and Central Asia. According to Solov'ev (1961), 'in the zone of block-faulted mountains (of Central Asia), not a single creditable case is known where the focus would have been located fully below the Earth's crust'. Such shallow crustal continental earthquakes may have quite different mechanisms from those of deep earthquakes and from those of ocean-ridge earthquakes, and should perhaps be placed in a special class of earth movement.

Another feature is that Australian earthquakes have a much greater radius of perceptibility for a given magnitude than given by Gutenberg & Richter (1956) for California earthquakes. Richter (1958) also noted a greater area of perceptibility for shocks in eastern North America. It is possible that unusual structure reduces the felt area in California.

Richter has likened the Eastern Highlands to the American Appalachians and Ozarks which have similar minor seismicity and no contemporary volcanism. They appear similar also to the Ural Mountains of Russia. The South Australian rift zone is akin to that of the St Lawrence area of North America. We have therefore in Australia and North America large shield areas with minor seismic activity, rift zones bordering part of the shield, and Palaeozoic mountain chains beyond with minor activity.

Such earthquakes in the upper crust (depths normally less than 20 km) can be explained by the classic Reid model of strain release by fracture. This model has serious objections for deep earthquakes, but explains many features of shallow earthquakes (Mogi, 1967), such as the occurrence of aftershocks at shallower depths than the main shock as observed by Cleary & Doyle (1962) for the Robertson earthquakes.

The sources of stress are usually thought to be thermal imbalance in the upper mantle, perhaps with convective motion producing traction on the overlying cooler and more brittle layers, which cannot adjust fast enough by creep. Of great interest is the possible relation of seismic zones to mantle convection. Runcorn (1967) has attempted to derive the global stress-patterns exerted by convection currents on the crust from satellite gravity data. He shows northnortheasterly-oriented stresses over the Australian continent produced largely by convection from the Antarctic mid-ocean ridge south of Australia. Carey (1958) and others believe that northwesterly tensional fractures have been important in eastern Australia. On the other hand Cleary (1967*a*) and Underwood (1967) have argued for north-westerly-directed compressive forces at present in southeastern Australia from direction of motion studies.

Some analyses of the magnitude frequency relations for Australian earthquakes appear to show large regional differences in the parameter b of the equation

$$\log N = A + b\,(8 - M)$$

where N is annual frequency and M magnitude.

Everingham (1968*a*) obtained a value for b close to 1·0 for the southwestern Australia seismic zone, and Sutton & White (1968) obtained a similar value for the South Australian seismic zones, a value found in many parts of the world. However, Underwood (1967) obtained a high value of 1·4 for the Gunning zone, and 0·6 for Victorian earthquakes. According to Scholz (1968), high b values may be related to more ductile rock. The low value for Victoria could also be due to insufficient data, this is certainly the case for the b value of 0·4 given by Miyamura for all Australia, and quoted by Allen *et al.* (1965), as only early Australian data were used.

Finally, it needs to be remarked that despite the comparatively low level of Australian seismicity, moderate sized earthquakes ($m = 5$-6) occur frequently enough to be a potential danger, and this should be borne in mind in the design of large structures, particularly in the Adelaide area.

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APPENDIX

Magnitude Determination

Magnitude is a quantity that is intended to rate earthquakes according to their 'size'. It is determined from the trace amplitude on a seismogram and ideally, of course, all such determinations from seismograms obtained at different locations should yield the same value of magnitude for a particular earthquake. Intensity, on the other hand, 'refers to the degree of shaking at a specified place. This is not based on measurement but is a rating assigned by an experienced observer using a descriptive scale' (Richter, 1958). It is the latter figure that is usually of interest to insurance assessors and others concerned with earthquake damage.

The procedure for determining magnitudes is far from straightforward and the complexities involved are clearly indicated by Richter (1958), Båth (1966), and others. Chiefly because of the different characteristics of seismograms with differing epicentral distance and depth of focus, three main types of magnitude scale have emerged —local magnitude scales, surface wave magnitude scale (M), and body wave magnitude scale (m).

The original local magnitude scale (M_L) was devised by Richter for earthquakes in Southern California using standard Wood-Anderson seismographs. With the installation of many short period, high-magnification, electromagnetic seismographs (*e.g.* Benioff instruments), it has been possible in some regions to obtain consistent Richter local magnitudes from the records of such instruments after allowing for the different magnification and assuming the same amplitude-distance relation found by Richter for Southern California. This is the procedure adopted for small local Western Australian earthquakes by Everingham (1968*a*) who uses the mean maximum amplitude of the horizontal components of the S phase recorded by short-period Benioff seismographs at Mundaring. Magnitudes determined by the Department of Geophysics at the Australian National University assume the same amplitude-distance relation as Richter but are based on peak-to-peak amplitudes on seismograms from Benioff short period vertical instruments in the A.N.U. network. Although the original Wood-Anderson seismometers are horizontal instruments, this method gives internally consistent results and gives values consistent with the Richter scale (M_L). Richter gives the relationship between the local magnitude scale (M_L) and the body wave magnitude scale (m) as $m = 1{\cdot}7 + 0{\cdot}8\ M_L - 0{\cdot}01\ M_L^2$ which is closely approximated by

$$m = 1{\cdot}8 + 0{\cdot}73\ M_L \quad \ldots (1)$$

in the M_L range from 1 to 6 (White, 1968). The magnitudes given in Table II(c) and II(d) are values of m obtained from measured M_L values using this equation.

In general it is difficult to extend a local magnitude scale beyond about 600 km, and a magnitude scale has been developed, initially devised by Gutenberg and Richter, which uses the computed ground amplitude of surface waves with periods near 20 seconds. This scale (designated M) was particularly useful when few stations were equipped with high-magnification, short-period instruments. According to Richter (1958) this scale is related to the body wave scale (m) by the equation

$$m = 2\cdot5 + 0\cdot63\ M$$

Most of the magnitudes in Table I were originally determined as surface wave magnitudes and have been converted to body wave magnitudes (m) by this equation.

Since deep focus earthquakes do not register surface waves of appreciable amplitude with periods near 20 seconds, it is obvious that a magnitude scale for such earthquakes must be founded on records of body waves. Such a scale (m) already mentioned above, was devised by Gutenberg, and requires a knowledge obtained from seismograms of log (A/T) where A is the amplitude of the ground motion and T the corresponding period. The value of m is determined from the equation

$$m = A_0 + \log (A/T)$$

where A_0 is an empirical constant which is a function of distance and must be determined. Everingham (1968*a*) has adopted this procedure for larger earthquakes in Western Australia recorded at Mundaring and uses modified values of the constant A_0 which are applicable to paths that cross the Western Australian shield. By comparing values of the Richter local magnitude scale (M_L) with the body wave magnitudes obtained from the Mundaring records (m_{MUN}) for a number of earthquakes at about 100 km distance, and using Equation (1), he finds the relation $m = m_{MUN} + 0\cdot4$. The magnitudes (m) in Table II(a) were obtained by substituting determined values of m_{MUN} in this equation.

In South Australia, an attempt was made initially to measure magnitudes according to the Richter local magnitude scale but it was found that such a procedure resulted in magnitudes that increased with distance. As a result it was necessary to set up a modified scale (White, 1968) which is also based on the maximum peak-to-peak amplitude obtained from Benioff short-period vertical records. This scale is in fact based on the simple law that the maximum peak-to-peak ground velocity is inversely proportional to the epicentral distance. According to White, the relationship between the South Australian magnitude (m_L) and the body wave magnitude (m) is conveniently given by $m = m_L + 1\cdot0$. Magnitudes for the listed South Australian earthquakes are values of m obtained from measured values of m_L and the equation above.

Anthony

~~WKY~~ WKU (WKY)

wrongly identified

in JAN/FEB 1966

Dennis