Journal of Structural Geology, Vol. 12, No. 5/6, pp. 761 to 766, 1990
Printed in Great Britain

0191-8141/90 $03.00+0.00
Pergamon Press plc

Australia's large earthquakes and Recent fault scarps

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(*Received* 10 *February* 1989; *accepted in revised form* 9 *March* 1990)

Abstract—Nineteen large earthquakes up to magnitude *Ms* 6.8 have occurred within continental Australia this century and at least seven Recent prehistoric fault scarps have been discovered. The magnitude of the earthquake causing each of these prehistoric fault scarps has been estimated from the observed fault length and maximum scarp height, and none exeeds magnitude 7.0. Their occurrence demonstrates that the Australian plate is undergoing significant internal deformation but as yet there is no model to explain their cause nor the likely site of the next large earthquake. The absence of earthquake epicentres on the current Tectonic Map of Australia is a regrettable omission.

INTRODUCTION

In modelling plate motions on the Earth's surface, Earth scientists make an inherent assumption that the plates are rigid. It transpires that this assumption is not a bad approximation for interplate studies, having resulted in the successful prediction of several plate boundary earthquakes at seismic gaps. But the present-day occurrence of mid-plate earthquakes in Australia and other continental areas testifies to the continuing internal deformation of the plates, a process which has continued since the beginning of geological time. The current rate of deformation varies greatly from one continent to another, the southwest corner of the Asian continent, including most of China, is clearly undergoing the most rapid change, the consequent earthquakes causing great suffering and social upheaval. Only in Antarctica have there been very few detectable earthquakes since the beginning of this century when the first seismographs were widely distributed. Resolving the cause of mid-plate tectonism holds out the only chance for Earth scientists to develop a useful earthquake prediction program in intraplate regions akin to that along the plate edges, but to date no useful physical models exist.

Recent reviews of Australian seismicity include the first analysis treating the continent as a whole by Doyle *et al.* (1968), and a follow-up by Denham *et al.* (1975). In the latest review, Denham (1988) has identified the need to "determine where the next large earthquake is likely to take place" as the challenge of the next decade. Fredrich *et al.* (1988) have modelled the waveforms of recent large Australian earthquakes which confirm earlier studies (Denham *et al.* 1977, Everingham & Smith 1979) that their foci were at shallow depth and their mechanisms are indicative of a pervasive horizontal compressive stress in the continental crust.

LARGE HISTORICAL EARTHQUAKES IN AUSTRALIA

Within a 12 hour period on 22 January 1988, three large earthquakes ruptured the Australian Precambrian shield near Tennant Creek in the Northern Territory after a year long foreshock sequence. Prior to January 1987 only two minor earthquakes had ever been located in that region. The 1988 earthquakes had magnitudes of 6.3, 6.4 and 6.7, and a complex 35 km long thrust fault scarp split the ground surface (Jones *et al.* in press). The scarp had a maximum vertical throw of 2 m and the fault a surface dip of 30°. An extensive aftershock sequence continues through November 1989 with several events per month exceeding magnitude *Ml* 4.0.

Since 1901 when the first seismographs were installed in Australia, at Melbourne, Adelaide and Perth, 16 large earthquakes (magnitude of 6 or more) have been recorded in continental Australia and there have been a further three large aftershocks or related earthquakes (Table 1; after Everingham *et al.* 1987). The large earthquakes are not exclusively confined to the Shield, although 17 of the 19 that have occurred this century were located in Precambrian basement (Fig. 1).

The largest earthquake recorded in Australia was on 29 April 1941 near Meeberrie, Western Australia, 600 km north of Meckering (Everingham *et al.* 1982). This earthquake was felt over almost one-third of the continent and had a surface wave magnitude of 6.8 (Everingham *et al.* 1987). The epicentre, taken as the centre of the MM VIII isoseismal contour (Everingham *et al.* 1982), has an accuracy of no better than 50 km, but a 43 km long fault scarp has subsequently been found (Williams 1978) 21 km from this epicentre. Their causal relationship however is not generally agreed upon. Hart and Rockel (Williams 1978) dated four of the largest and oldest of the many Mulga trees (Acacia ancura) growing in alluvium at the base of the scarps, and not in the surrounding hardpan, and concluded that the scarps were about 90 years old. Williams attributed the faulting to an earthquake which was strongly felt in the Geraldton district in 1885 (Everingham 1968) but for which no epicentre can be determined. A scarp conducive to tree germination may have predated the 1941 earthquake, there was similar circumstantial evidence for a pre-existing fault at Marryat Creek in South Australia (McCue *et al.* 1987) prior to formation of the fault scarp of 30 March 1986, but the coincidence of scarp and 1941

Table 1. Large Australian earthquakes, 1873–1988

Source*	Date d	m	y	Time h	m	s	Lat (°S)	Long (°E)	Depth† (km)	*Ml*‡	*Ms*‡
ET	15	12	1873	04	00		26.25	127.5	0 G		6.0
MML	13	07	1884	03	55		40.5	148.5	0 G	6.2	
ET	05	01	1885	12	20		29.0	114.0	0 G		6.5
MML(b)	12	05	1885	23	37		39.8	148.8	0 G		6.5
MML	26	01	1892	16	48		40.3	149.59	0 G	6.6	
ADE	10	05	1897	05	26		37.33	139.75	0 G	6.5	
ADE	19	09	1902	10	35		35.0	137.4	14	6.0	
UQ	06	06	1918	18	14	24.0	23.5	152.5	15	6.2	5.7
EDG	08	02	1920	05	24	30	35.0	111.0	0 G		6.0
BMR	16	08	1929	21	28	23.4	16.99	120.66	33 N		6.6
EDG	12	04	1935	01	32	24	26.0	151.1	0 G	6.1	5.4
BMR	29	04	1941	01	35	39.4	26.92	115.80	0 G	7.0	6.8
BMR	27	06	1941	07	55	49.0	25.95	137.34	0 G		6.5
BMR	14	10	1968	02	58	50.6	31.62	116.98	5	6.9	6.8
BMR	24	03	1970	10	35	17.6	22.05	126.61	0 G	6.7	5.9
BMR	28	08	1972	02	18	56.2	24.95	136.26	10	6.2	
MUN	03	10	1975	11	51	1.8	22.21	126.58	0	6.2	
BMR	06	05	1978	19	52	19.6	19.55	126.56	17	6.2	
BMR	23	04	1979	05	45	10.8	16.66	120.27	10	6.6	5.7
BMR(a)	25	04	1979	22	13	57.4	16.94	120.48	1	6.1	
BMR	02	06	1979	09	47	59.3	30.83	117.17	5	6.2	6.1
CGS	25	11	1983	19	56	7.8	40.45	155.51	19	6.0	5.8
BMR	22	01	1988	00	35	57.4	19.79	133.93	5		6.3
BMR(b)	22	01	1988	03	57	24.3	19.88	133.84	5		6.4
BMR(b)	22	01	1988	12	04	55.8	19.94	133.74	5		6.7

*ET—Everingham & Tilbury (1972).
EDG—Everingham *et al.* (1987).
MML—Michael-Leiba (1989).
a,b—aftershock, related event.
†G,N indicate depth restrained, or set at normal depth, by the locating geophysicist.
‡Magnitude scale either Richter (local) *Ml* or surface wave *Ms*.

epicentre near Meeberrie is strong support for their association.

For their magnitude, Australian earthquakes have a far greater felt area than those in countries along plate margins, such as New Zealand or California, as do earthquakes in other shield areas including the Eastern United States (McCue 1975). A typical example of an Australian isoseismal map, that for the largest of the 1988 Tennant Creek earthquakes, is shown in Fig. 2. There is rapid attenuation of high intensities close to the epicentre, indicative of very shallow depth, but then slow attenuation at large distance and low intensity. With the known population distribution in Australia, it is doubtful that a large earthquake could have occurred after about 1875 without being widely felt and reported.

Most notable of all historical Australian earthquake sequences was that in Bass Strait off northeastern Tasmania which commenced in April 1883 and lasted until at least late 1892. Ripper (1963) has documented some 2540 earthquakes felt in northeastern Tasmania in that time, four of which caused damage in Tasmania and were felt widely in Victoria and New South Wales. Michael-Leiba (1989) was able to estimate magnitudes and epicentres of the larger events from the extent and locus of their felt intensities. At least three of the earthquakes exceeded magnitude 6 (Table 1) as perhaps did the largest aftershock of the 1892 event just 10 minutes after the mainshock.

An occasional large Australian earthquake has occurred without a significant aftershock sequence, the most recent being that near Marryat Creek in South Australia on 30 March 1986 (McCue *et al.* 1987). The Alice Springs seismic array is 380 km north of the epicentre and is capable of detecting aftershocks down to magnitude 2 at this distance. Only five exceeded magnitude *Ml* 2.9 and the largest had a magnitude of *Ml* 3.7 until 11 July when an *Ms* 5.3 earthquake occurred. This was in turn followed by only a few small aftershocks which terminated the sequence.

Obviously there is a great variation in both the mainshock and aftershock patterns of Australian earthquakes as illustrated by these three examples. The lack of aftershocks cannot be attributed to a regionally variant crust as a similar behaviour is observed following smaller earthquakes in a very localized area in Eastern Australia. A re-orientation of principal stress axes occurred (Jones *et al.* in press) during the Tennant Creek series which could easily account for the observed aftershock variability. For example, rotation of the P axis by approximately 45° without a change in the B axis would reduce the shear stress on the fault and choke any subsequent movement and aftershock activity.

PREHISTORICAL EARTHQUAKES

Surface faulting has accompanied all large onshore earthquakes since and including that at Meckering in 1968, and all the mechanisms were shallow angle thrusts. Another six Recent prehistoric scarps have been identi-

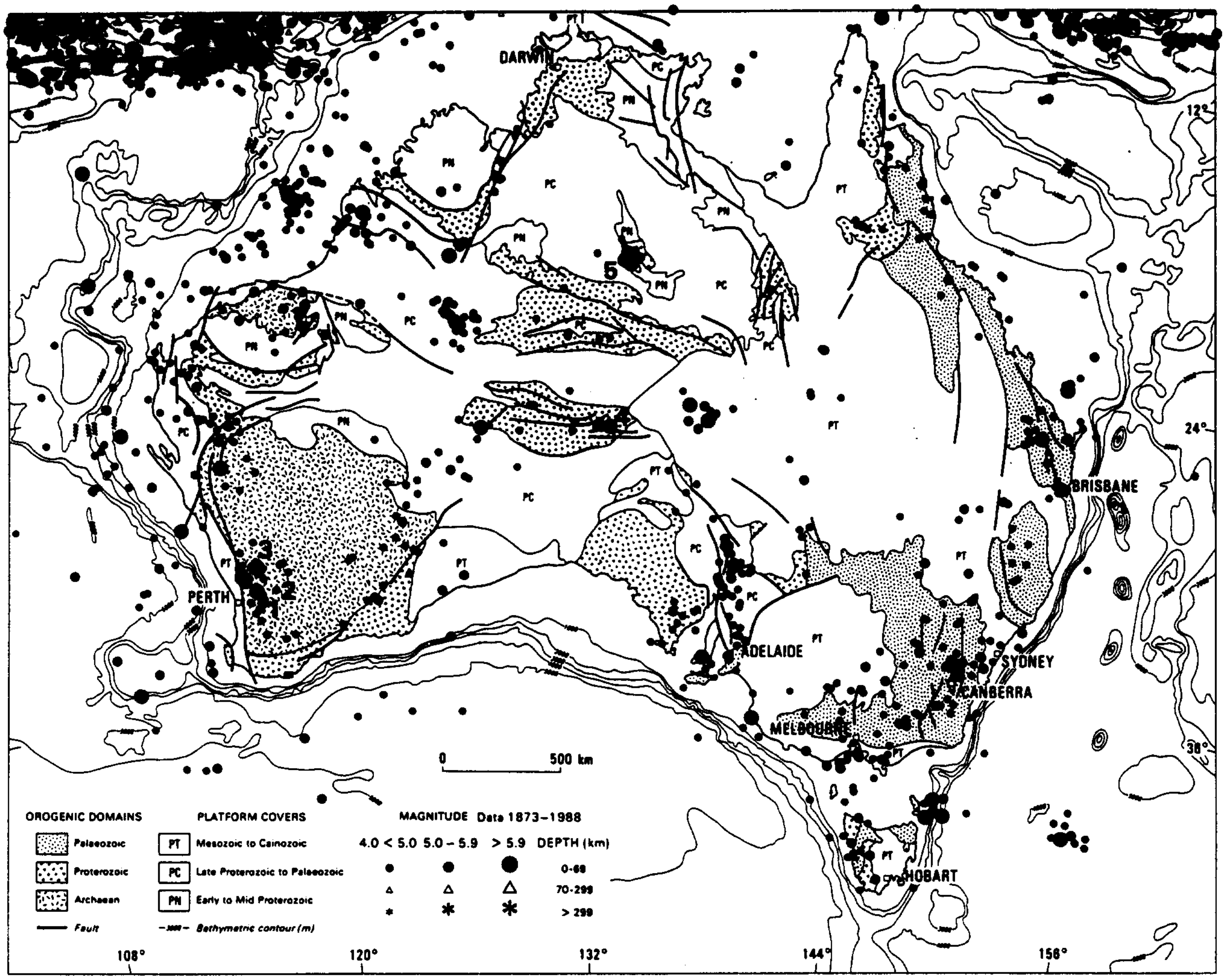

Fig. 1. Australian seismicity 1873–1988, the numerals indicate the epicentre of (1) the Meckering Scarp, (2) the Calingiri Scarp, (3) the Cadoux Scarp, (4) the Marryat Creek Scarp and (5) the Tennant Creek Scarp from Table 1.

fied, four in the Australian shield and two in the Lachlan Fold Belt (Table 2). This is not an exhaustive list of scarps; Hale & Roberts (personal communication 1977) have identified another Holocene scarp in Tasmania, the Gell River Fault, 50 km north of the Lake Edgar scarp; and rejuvenation of Palaeozoic faults has occurred in New South Wales, Victoria and the Australian Capital Territory (Twidale 1974, Hills 1975).

Observation of the data in Table 2 indicates there is a simple relationship between the magnitude and length of faulting of historical earthquakes so at least the size, if not the date of occurrence of the causative prehistorical earthquake can be determined. Least-squares fit of the length of faulting L (km) and maximum scarp height u (m) against earthquake magnitude for the historical earthquakes of Table 1 (Fig. 3) enables an order of magnitude estimate of the magnitude of the earthquake causing the scarps in Table 2. The relevant equations are:

$$Ml = 1.65(0.15) \log L + 4.11(0.18)$$

$$Ml = 0.75(0.10)\, u + 5.04(0.17),$$

where the standard deviation is shown in brackets.

Estimates of the magnitude of the earthquakes determined from both the mapped length of the fault and its maximum height are included in Table 2 but data are scarce and these estimates must be used with caution; multiple shocks may have contributed to the displacement thereby exaggerating the magnitude, and no allowance has been made for erosion since the dates of scarp formation are unknown.

No technique has yet evolved for predicting where or when the next large earthquake will occur within the Australian plate. Statistically there is a 67% probability that another will occur sometime within the next 5 years which is the approximate recurrence interval for an earthquake of magnitude 6 or more. Identification and mapping of all Recent scarps would give invaluable information on the long-term recurrence rate of large earthquakes, on a maximum size if any, and on their likely geographical extent. Our current 100 year data set is too short to answer these important questions.

GEOGRAPHICAL DISTRIBUTION OF AUSTRALIAN EPICENTRES

An epicentre map of magnitude 4 or greater earthquakes that have occurred between 1873 and 1988 has been plotted (Fig. 1) from the BMR's 'Earthquake Data File'. The data file is by no means complete, it starts with a single entry for 1873 and few events were located until the late 1950s when sensitive instruments were installed and the Australian Seismographic Network was greatly expanded as a result of BMR and Australian University involvement in the International Geophysical Year programs.

There is no one-to-one correlation between earthquakes and geological structure but several associations of epicentres with gross physiographic features are apparent on Fig. 1; there are noticeably more earthquakes in continental than oceanic crust, at least within 100 km of the coastline where seismographic coverage is adequate. More earthquakes occur in Precambrian basement in the west of the continent than in the younger Tasman Fold Belt in the east where a broad seismic zone does appear to coincide with the Eastern Highlands. Lastly, what once appeared to be a discrete Adelaide Geosyncline Seismic Zone in South Australia (Sutton & White 1968, McCue 1975), seems now to be part of a broader semicircular belt of earthquakes along the eastern edges of the Precambrian Gawler and Yilgarn Blocks and the southern edge of the Musgrave Block. It appears then to terminate at the continental shelf. There is however no clue as to where the next earthquake will occur. The Tennant Creek earthquakes came as a surprise, not only to the local residents and seismologists, but to seismologists worldwide, as did the fact that there was not just one but three large earthquakes and in a 12 hour period.

Furthermore, foci of all Australian earthquakes with

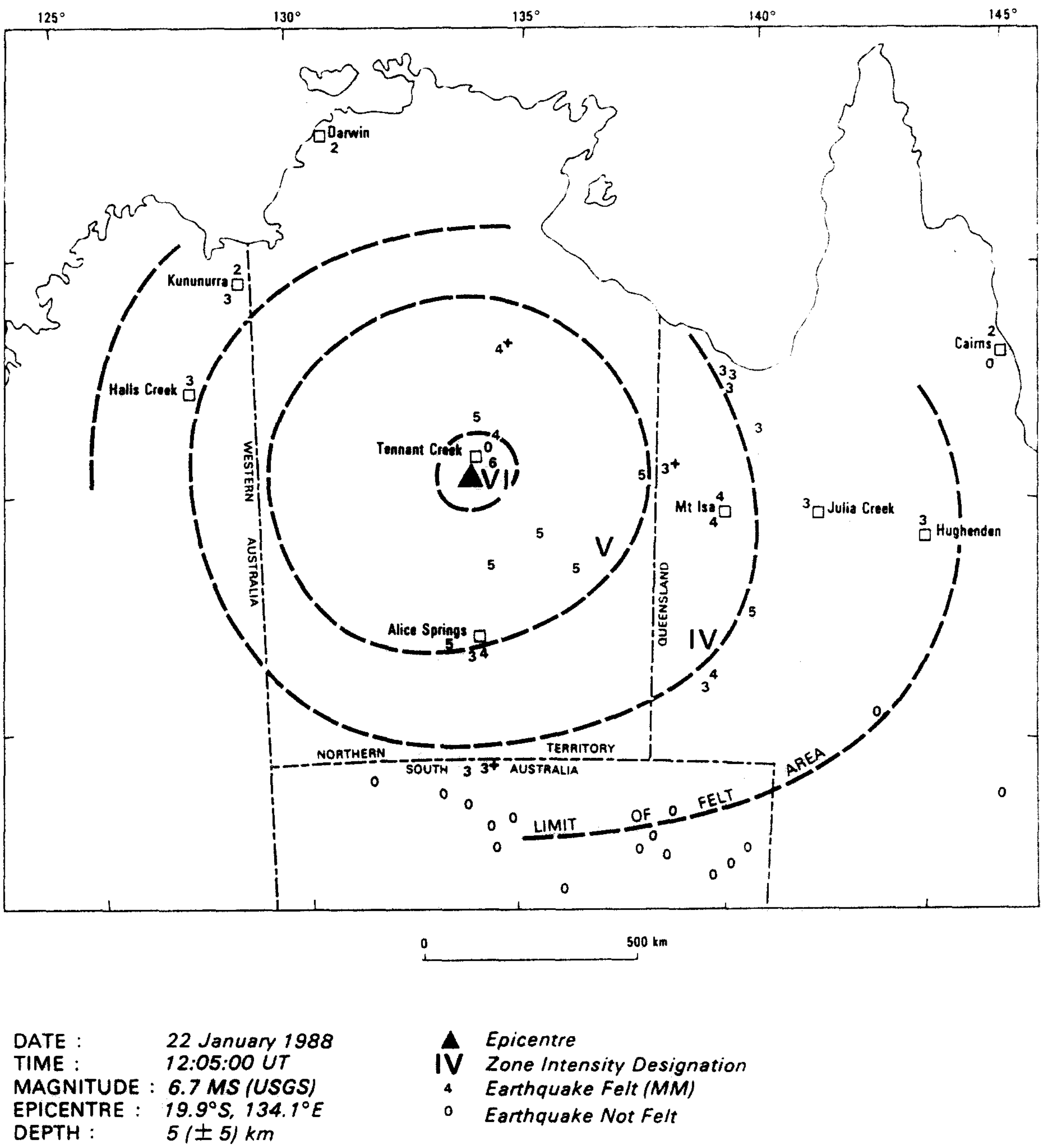

Fig. 2. Isoseismal map for the third and largest of the Tennant Creek, Northern Territory, Australia, earthquakes on 22 January 1988.

Table 2. Recent fault scarps in Australia

Region/earthquake date	Lat (°S)	Long (°E)	*Ms**	Fault length (km)	Fault scarp height (m)
Prehistorical					
Hyden, WA	32.5	119.0	6.8/—	40	?
Lort River, WA	33.5	121.25	6.8/6.6	40	2
Merredin, WA	31.6	118.25	6.1/—	16	?
Mt Narryer, WA	26.5	116.25	6.6/6.0	43	1–1.5
Cadell, NSW	36.0	144.75	6.9/6.6	50	2
Lake Edgar, Tas	43.0	146.4	6.1/7.0	15	2–3
Historical					
Meckering, WA 14 October 1968	31.6	117.0	6.8	37	2.5
Calingiri, WA 10 March 1970	31.1	116.5	5.1	3.5	0.3
Cadoux, WA 2 June 1979	30.8	117.2	6.0	15	1.3
Marryat Creek, SA 30 March 1986	26.2	132.8	5.8	13	0.8
Tennant Creek, NT	19.9	133.7	6.3		
Tennant Creek, NT	19.9	133.7	6.4		
Tennant Creek, NT 22 January 1988	19.9	133.7	7.7	35	2.0

*Estimated from fault length/maximum scarp height, Fig. 3.

well constrained locations occur at shallow depth within the crust, most within a few kilometers of the surface. The Tennant Creek aftershocks outline a plane dipping at 35° to a depth of at most 9 km (Bowman *et al.* in press) and near Dalton, NSW, in Eastern Australia, the foci of many of the microearthquakes are as shallow as 1 or 2 km (McCue *et al.* 1989). These are well above depths usually quoted for the brittle–ductile transition zone or base of the seismogenic zone in continental regions (Hobbs *et al.* 1986).

DISCUSSION

Earthquakes up to magnitude *Ms* 7.0 have occurred in continental Australia but there is no evidence in the

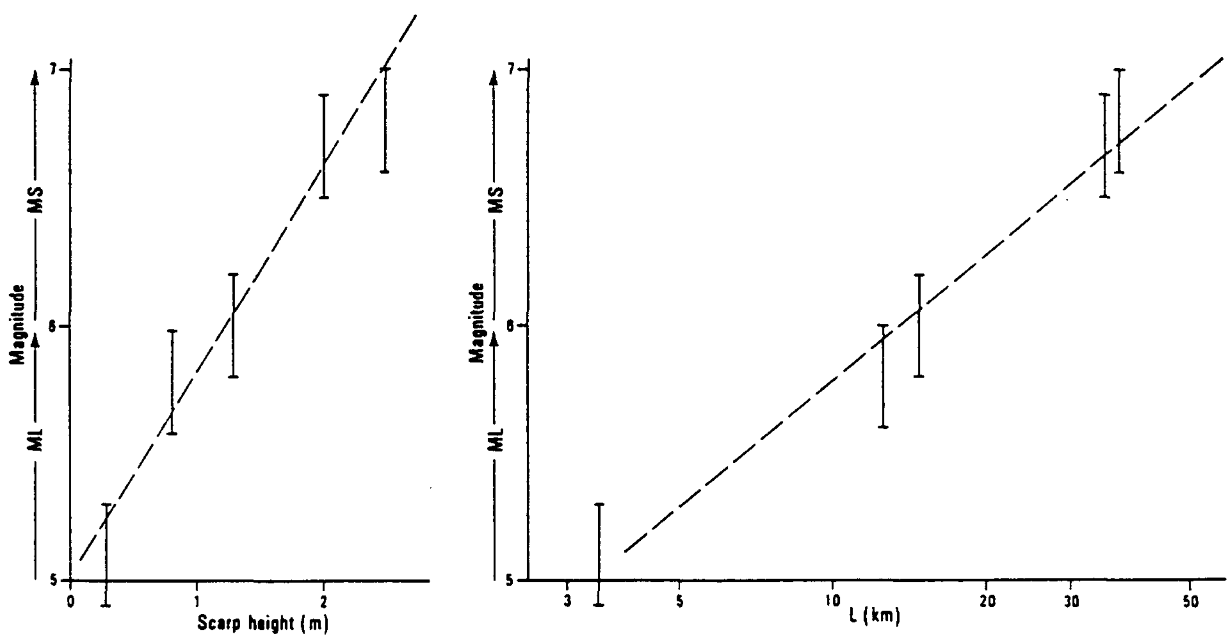

Fig. 3. Observed fault length and maximum vertical displacement of Australian earthquakes as functions of earthquake magnitude *Ms* from Table 1.

scant study of Recent faults to indicate that larger earthquakes have occurred in that time. Nor have there been repetitive cycles of activity at the one site in either the historical or Recent data, although there may be some evidence for this, in the geomorphology and empirical scarp height versus magnitude data, on the Cadell Fault.

Past attempts have been made to develop earthquake risk maps of continental Australia from which zone maps were developed for the building Code (AS2121-1979, SAA Earthquake Code, Standards Association of Australia, Sydney), with input from the engineering and architectural professions. The aim of the codes is to equalize the risk of structural damage in normal buildings throughout the country by imposing standards of design and workmanship on owners of structures outside the designated zone zero regions. Two of the three large earthquake sequences that have occurred since that building code was legislated in 1979; at Marryat Creek, South Australia (McCue *et al.* 1987), and Tennant Creek in the Northern Territory (Jones *et al.* in press) were in areas designated Zone 0 on the map, i.e. no horizontal shear forces or restrictions on building type were required to be included in the building design. It is time now that the broader Australian Earth science community provided some input into the risk mapping process by providing a framework for the forecasting of the most likely sites of future earthquakes. The mapping and dating of Recent faults would be an essential part of such a study along with a continuing analysis of the seismicity and earthquake mechanisms and modelling of the mid-plate tectonism.

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