Graphical representation of some recent Australian Earthquake Swarms, and some generalisations on swarm characteristics

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ABSTRACT

Data for forty-one earthquake swarms between 1983 and 2007 have been extracted from the Australian earthquake catalogue and used to graph the distribution of events within the swarm in time, space and magnitude. Western Australia experiences swarm activity more frequently than the other states, and this activity may represent the dominant form of seismic activity in the "Southwest Seismic Zone", as it is in the Eyre Peninsula of South Australia. Distinction of swarm events from aftershocks has important implications for the statistical analysis of earthquake occurrence (e.g. for "declustering" an earthquake catalogue). Swarm locations may represent places of unrecognised geological significance and have importance as zones of heightened earthquake risk. Swarms also seem to be more common in areas of granitic geology. Swarms noted here seem to confirm the presence of a NE - SW trend in epicentres in the Southwest Seismic Zone of WA, as initially noted by Dentith & Featherstone (2003). In particular, a previously unnoticed linear feature may exist between York and Bonnie Rock (which includes the location of the 1968 Meckering earthquake). Other important swarms from elsewhere in Australia have also been graphed.

Introduction

Swarms are an important but little understood component of Australian seismicity, and perhaps "earthquake cluster" may be a more generic and better term to use for the events discussed herein. Swarms are significant in that they can be precursory activity for major seismic activity (e.g. Burakin, 2000 – Leonard, 2002), and they can represent a large percentage of events in the earthquake catalogue, with important implications for recurrence studies. Their characteristics need to be better understood to distinguish them from the better-known form of clustering known as aftershocks.

Australian swarms have been noted in the annual summaries of activity, state-by-state, in the now-discontinued Annual Seismological Report (ASR) series, published by A.G.S.O. (now Geoscience Australia, or GA). These reports covered the period 1980 – 1999, and identified most of the swarms described here, the majority of which are in the Southwest Seismic Zone (SWSZ) of Western Australia. Denham *et al* (1987) described seismicity in the SWSZ as not occurring in well defined lineaments, but rather in spatial clusters which seem to bear no relation to either rock type or topography, although a recent discussion of the seismicity of the region (Sinadinovski, 2004) failed to mention this phenomenon.

The only naturally occurring Australian swarms to be described in any detail so far were the Eugowra, NSW sequence in 1994 (Gibson *et al*, 1994) and at Yeelanna, on the York Peninsula of South Australia in 2002-03 (Love, 2004). A swarm in the Cooper Basin of SA, induced by a geothermal test drilling program has been extensively described (e.g. Asanuma *et al*, 2004, 2008). Love's investigation of the Yeelana, SA seismic activity concluded that swarms represent the normal activity in that area, and that the location of each swarm appears to be different. Some details of swarms near Ongerup, in SWWA, and Bradford Hills (northern Victoria) were reported in the ASR for 1991.

There are varying definitions of what constitutes an earthquake swarm. Gibson *et al* (1994) describe a swarm as having a number of events within a limited volume, lasting over a period from hours to months, with the largest event well after the start of the swarm, and not having a magnitude significantly greater than the second-largest event. Love (2004) uses a slightly more specific criterion, in that the largest and second-largest events have magnitudes differing by less than 0.5 magnitude units.

In this report, swarms identified from the ASR series and other sources have been plotted to show the distribution of events in time, the maximum magnitude on each day, the distribution of magnitudes of events within the swarms, as well as the degree of geographic clustering. It is hoped to thereby show the range of behaviours within the generic term "swarm".

TABLE 1

Swarms, 1983 – 2007, referred to in text

DATE	LOCATION	# events	Figure #	Region	Temp Inst?
1983 Jan	Gnowangerup	6	**Not plotted**	SWWA	
1987 Jan	Tennant Ck	41	**Fig 2.1**	NT	Yes
1987 Feb	Bream Ck Tas	27	Fig 3.1	TAS	
1987 Dec	Wyalkatchem East	13	Fig 3.2	SWWA	
1988 Jan	Tennant Ck	694	**Fig 2.2**	NT	Yes
1988 June	Bunnaloo, NSW	24	Fig 3.3	NSW	Yes
1989 July	Pingrup	5	Fig 3.4	SWWA	Yes
1989 July	Margaret River	14	Fig 3.5	SWWA	
1989 Dec	Wagin	13	Fig 3.6	SWWA	
1990 Mar	Peterborough	13	Fig 3.7	SA	
1990 Apr	Ballidu	21	Fig 3.8	SWWA	Yes
1991 Mar	Ongerup	3	Not plotted	SWWA	Yes
1991 Nov	Quairading	34	Fig 3.9	SWWA	Yes
1991 Apr	Bradford Hills	49	Fig 3.10	Vic	Yes
1992 July	Lake MacKay	8	**Fig 2.3**	WA	
1992 Nov	Chillagoe	9	Fig 3.11	Qld	
1991 Nov	Moralana	63	Fig 3.12	SA	Yes
1992 Dec	Mukinbudin	13	Fig 3.13	SWWA	Yes
1994 Mar	Wyalkatchem (West)	13	Fig 3.14	SWWA	
1994 May	Kellerberrin (East)	9	Fig 3.15	SWWA	
1994 Sep	South of Nyabing	6	Not plotted	SWWA	
1994 Aug	Eugowra NSW	85	Fig 3.16	NSW	Yes
1994 Nov	York	27	Fig 3.17	SWWA	Yes
1994 Nov	Myrtle Springs	33	Fig 3.18	SA	
1995 Mar	Nyabing North	27	Fig 3.19	SWWA	
1995 May	Beacon (1)	12	Fig 3.20	SWWA	
1996 Mar	Kellerberrin (1)	137	**Fig 2.4**	SWWA	Yes
1997 Aug	Kellerberrin (2)	75	**Fig 2.5**	SWWA	
2000 Jun	Bonnie Rock	7	Fig 3.21	SWWA	
2000 Sep	Sth of Burakin	28	Fig 3.22	SWWA	
2001 Mar	Bruce Rock	13	Fig 3.24	SWWA	
2001 Sep	Burakin (1)	68	Fig 3.23	SWWA	
2001 Dec	Burakin (2)	98	**Fig 2.6**	SWWA	Yes
2002 Mar	Burakin (3)	217	**Fig 2.7**	SWWA	Yes
2001 Dec	Sutton NSW	15	Fig 3.25	NSW	Yes
2002 Sep	Fish Ck Vic	11	Fig 3.26	Vic	
2003 Oct	Yeelanna SA	8	Fig 3.27	SA	Yes
2003 Dec	Innamincka SA	10	Fig 3.28	SA	Yes
July 2004	Nyabing	7	Not plotted	SWWA	
2004 Nov	Koorda	22	Fig 3.29	SWWA	
2005 Sept	N of Kalannie	46	Fig 3.30	SWWA	
2006 Mar	Beacon (2)	16	Fig 3.31	SWWA	

The identification of foreshocks, aftershocks, and presumably swarm events is important when defining the seismicity parameters for a region – e.g., when studying the SWSZ, Sinadinovski (2004) used a "declustered" data set, where identifiable foreshocks and aftershocks (using a procedure described by Sinadinovski, 2000) were removed. Using a similar declustering algorithm, Leonard (2008) found that declustering removed 63% of events from the catalogue for south-west Australia, and 39% of events from the catalogue as a whole.

Dawson *et al* (2008) note that small magnitude earthquake clusters have previously been found to represent foreshock behaviour of moderate sized earthquakes, quoting the 1987 activity at Tennant Creek as an example. Investigation by Dent (2008) reveals that this may also have been the case for the 2007 Katanning earthquake in southern WA, although it does not seem to apply to the majority of recent earthquake clusters identified in this report.

Data

As noted above, swarms have been identified in the "Annual Seismological Report" series (ASR), published by AGSO, as well as annual reports from the Mundaring Geophysical Observatory, and publications by other state-based agencies. Some swarms have undoubtedly been missed in this procedure, and many probable swarm-type events have not been listed because only two or three events have been detected and added to the catalogue. Swarms identified are listed in Table 1. A number of the swarm/aftershock clusters were monitored by field seismograph deployments, and are also indicated in Table 1.

The catalogue used was prepared by Gary Gibson (events to mid 2007) and made available to Geoscience Australia. It includes many small events not presently added to the GA "Quakes" data base. A subset of the Gary Gibson catalogue, excluding pre-1983 events, was prepared, and programs written to extract events from within specified geographic and time ranges. This subset contains just over 23,000 events.

The locations of the swarms listed in Table 1 are plotted on Figure 1-a (for all Australia) with more detailed plots (Figures 1-b and 1-c) for the northern and southern portions of the Southwest Seismic Zone. Earthquake epicentres from the catalogue since 1983 (magnitude 2.5 and above) are also plotted on Figs 1b and 1c. Some important pre-1983 swarms, or swarm-like events, are also plotted on Figure 1 – i.e. Flinder's Is. 1883, Simpson Desert 1937, Lake MacKay 1970 and West Wyalong, 1982.

Swarm data were extracted from the catalogue subset, by searching a .2 x .2 degree block, with the general swarm location at the centre. The swarm data have been plotted (Figures 2 & 3) showing daily event distribution over a three month period, and event locations and magnitude distribution over this period has also been plotted. Because the larger swarms have many events, the swarm plots had to be divided into two groups, with different limits on the axes. Figure 2 shows seven plots of the larger swarms, although Figures 2.4/2.5 (Kellerberrin) and 2.6/2.7 (Burakin)

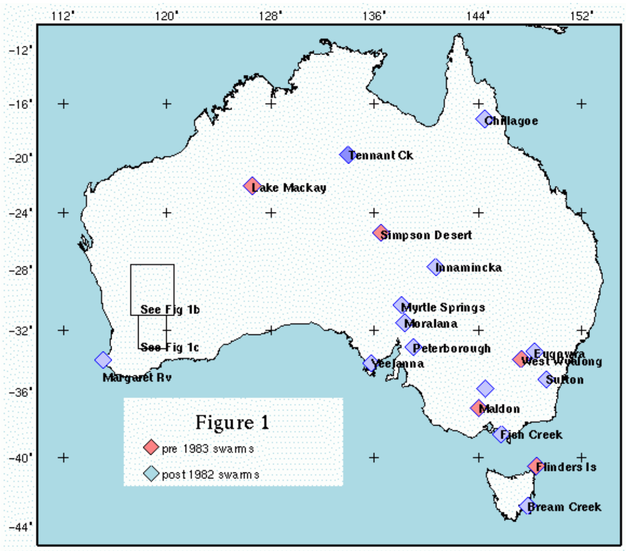

Figure 1(a) - *Locations of Swarms referred to in text*

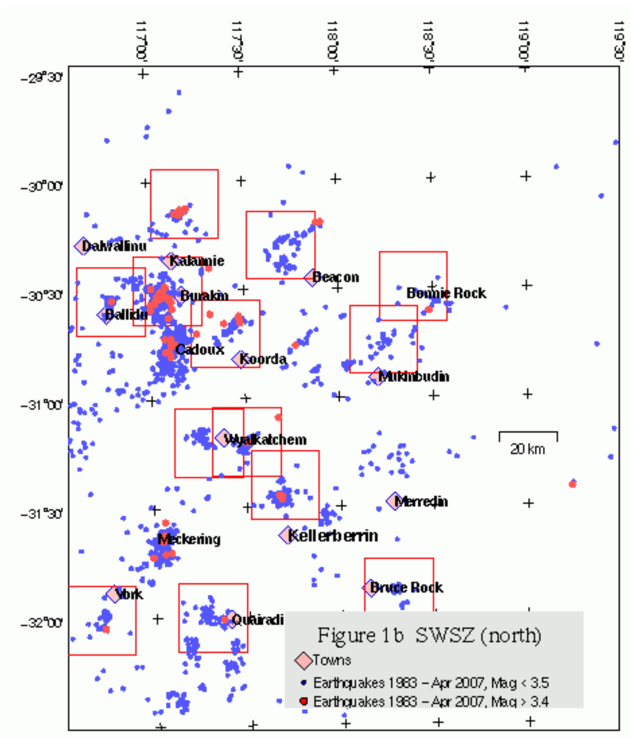

Figure 1(b) - *Swarm locations, SWSZ (North). Boxes show search area for events*

actually show segments of two very long-lasting swarms – in the case of Burakin, well over a year. Figure 3 contains the remainder of the swarms plotted, with axes set to lower limits, so more detail can be observed.

A limitation of these plots is when many significant events occur on a single day. Only the maximum magnitude for each day is plotted on figures 2 and 3, and if a swarm is of particularly short duration, the distribution of events with time is not well demonstrated.

Note that more research would undoubtedly result in the identification of many more swarms than have been presented here, although the swarms listed in Table 1 probably represent the most significant swarms between 1983 and 2007.

Results

Table 1 indicates that although swarms have occurred in all states, they appear to be far more common in WA than any other state, and, in particular, the south-western portion of WA. South Australia is also well represented. This result might be expected as they are the two most seismically active states (Leonard, 2008).

The most significant recent activity in WA was near Burakin (Leonard 2002, 2003). This activity began in August 2000, followed by a gradual decline, but much more significant activity resumed a year after the initial phase commenced, with a magnitude 5.0 event on 28 Sep 2001, and more than 16,000 aftershocks. It was the highest level of seismic activity experienced in Australia since the 1988 Tennant Creek (NT) earthquakes (Leonard, 2002). The precursory activity (figure 3.22), beginning 12 months before the major phase, also mimics the precursory activity seen at Tennant Creek in 1987, although on a smaller scale.

Plots in Figure 1 for the Burakin region show activity for the periods Sept-Nov 2000 and Sept 2001-May 2002. The Sept - Nov 2000 sequence shows a clear NE-SW trend, and the epicentre insert has been plotted on a larger scale to display this trend more clearly. Leonard (2003) suggests the existence of some kind of stress transfer process, linking the Sept 2000 activity with the Burakin activity a year later.

The plot of activity at Kalannie (Fig 3.30) represents a segment of the activity which occurred there between Sep 2005 and Jan 2007, as described in Dawson *et al* (2008).

In northern WA, an interesting but brief swarm occurred close to Marble Bar on 28 Jan 1988, when three events with respective magnitudes of 4.8, 4.6 and 5.0 were recorded. An example of probable aftershock activity in the

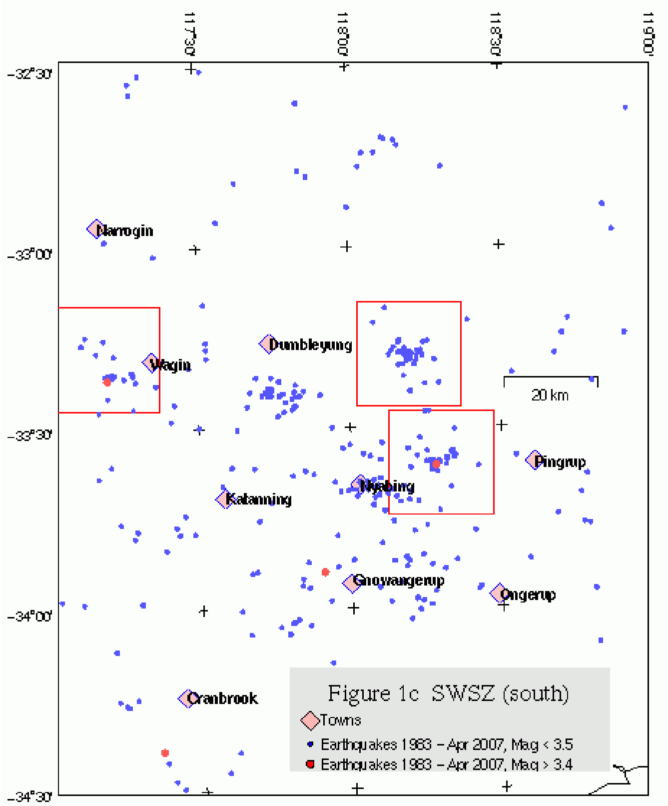

Figure 1(c) - *Swarm locations, SWSZ (South)*

Lake MacKay region in 1992 is shown in Fig 2.3. The probable main shock occurred in 1970, but considering the remoteness and poor seismic coverage of the locality, large events prior to 1970 can not be ruled out.

South Australia

Important swarms have occurred at Yeelanna, Moralana and Myrtle Springs and the Department of Primary Industries and Resources of SA PIRSA deployed temporary seismographs at each of these swarms. An important swarm also occurred at Innamincka in the far north of the state in 2003, but this swarm was artificially induced by engineering works designed to test the feasibility of a proposed geothermal energy project. Over 10,000 events, up to a maximum magnitude of 3.7 were located, although only the 10 largest of these are listed in the Gibson catalogue. The activity has been described in detail in a series of papers, eg Asanuma *et al*, (2004), Asanuma *et al*, (2008).

The Yeelanna swarm was discussed in detail by Love (2004), using data from the temporary stations. The 12 most accurately located events occurred within an area of 1 square km, but only the largest events were included in the Gary Gibson catalogue. Love identified 12 swarms on the Eyre Peninsula between 1960 and 2003, six of which were in the immediate vicinity of Yeelanna, although each swarm occurred in a slightly different location.

At Moralana, in the Flinders Ranges, a swarm of hundreds of events occurred between Nov 1991 and Feb 1992, of which the largest was ML 3.5. Sixty one of these events were located, assisted by a temporary network which operated for 3 weeks in Feb 1992. The network indicated that the events occurred over a small area (5 km x 3 km), and the best located events had depths of about five km.

Victoria

The Bradford Hills swarm was described in limited detail in the 1991 ASR (McCue & Gregson, 1994). It began in April 1991 and continued until July 1992, although there were periods of little activity. A network of digital seismographs was installed soon after the swarm started, and allowed accurate location of many events, including the largest event (ML 3.5 on May 3, 1991). The earthquakes were shallow, and most were less than 3 km deep.

A sequence near Fish Creek (~50 km east of Wonthaggi), which would be better described as a mainshock – aftershock sequence, is also plotted for comparison.

New South Wales

In 1988 series of events occurred near Bunnaloo in southern NSW (near Echuca, Vic). Bunnaloo is 150 km north of Bradford Hills. This series was instrumentally monitored by the SRC (later ES&S) of Melbourne.

An important swarm event occurred at Eugowra in July – August 1994 (Fig 3.16).This was described in some detail by Gibson *et al* (1994). Many small events (less than ML 1.0) were recorded, but not listed in the catalogue. As with similar sized events at Gnowangerup and Ongerup (Dent, this volume), many of these small events could be clearly heard by local residents.

A swarm of relatively small events occurred close to Sutton, just north of the ACT, in 2001. Several portable seismographs were deployed in the area by GA to better define this sequence.

In 1982, just before the start of the catalogue subset, an important series of events occurred near West Wyalong, in southern NSW. This series of events was only about 100 km southwest of the 1994 Eugowra sequence.

Queensland

There are few swarms reported from Queensland. Perhaps the most significant is near Chillagoe, in far North Queensland, in 1993. Most of the events in this swarm have been given the same location, and maps of earthquake epicentres do not indicate the significance of this location.

Tasmania

The best studied swarm in Tasmania is at Bream Creek, ~50 km east of Hobart (November 1986 - April 1987, Michael-Leiba 1989). However, a very significant series of large events occurred to the NE of Tasmania between 1883 and 1887, including two events deduced to be over magnitude 6 (McCue, 1995). Over 2000 felt events were catalogued by Ripper (1963) over this time span although locations were not estimated. This possibly represents the most significant series of seismic events in Australian history.

Northern Territory

Like the Lake Mackay series in Northern WA starting in 1970, the Tennant Ck. series is probably best described as a main-shock/ aftershock sequence. However, the three main events, all on 22 Jan 1988, were relatively close in magnitude, as occurs in earthquake swarms. Plots showing the initial phases of activity in 1987 and 1988 are shown in Figures 2.1 & 2.2. Like the Lake MacKay series, seismicity levels in the area remain elevated, even 30 years after the initial events.

Another significant series of events occurred on the SA/NT border between 1937 and 1941, and was responsible for a significant "bulls-eye" on the first published earthquake risk maps for Australia (McEwin *et al*., 1976). Five events over Mag 5 were located there between 1937 and 1941, with the 3 largest being similar in magnitude (6.0, 5.9 and 5.8). It can be assumed that many other events occurred but were not located.

Repeating swarms

Some of the swarms listed in Table 1 lasted over a year, with periods of quiescence. However, they may be considered to be a single swarm. In some regions swarms can be separated by a large number of years (10 years, in the case of Beacon – Figure 3.20 and 3.31). The fact that locations which have experienced swarms are more likely to experience future swarms elevates the seismic risk for these areas. The area of the York swarm (1994) experienced further activity in July 2008.

Focal Depths

Leonard (2008) states that hypocentral depths for Australian earthquakes generally range between 8 and 18 km, except for Southwest Australia where they are typically shallower than five km. Swarms offer probably the best opportunity to get accurate focal depths for Australian events - because they generally continue for some time, it allows the opportunity to deploy field equipment and record them with precision before most of the activity has passed. Some of the most accurate focal depth data have come from the deployments at Bradford Hills (Vic), Eugowra (NSW), and Yeelanna and Moralana in South Australia. Gibson *et al* (1994) state that the Eugowra events are very shallow, i.e., 0 to 1.2 km depth. Love (2003) indicates a depth for the Yeelanna events of 2.8 km, +/0.6 km, and gave an estimate of preferred depths for the Moralana and Myrtle Creek swarms of 4 km and 6 km respectively (pers. comm.. 2008). Leonard (2002) states that the Burakin events were all in the top five km of the crust, but a review of the best locations, from archives at Geoscience Australia, suggests depths of 2 km or less for the events. This agrees with depths from other well located events from swarms at Kellerberrin and York (Dent, 1999).

The Bradford Hills swarm, near Maldon in northern Victoria was also monitored in detail with portable digital seismographs by the Seismology Research Centre of Melbourne. Depths for these events were also determined to be of the order of 2 km deep or less.

Discussion

Only the plot of Tennant Ck events, Jan – Mar 1988, shows a clear logarithmic decay in the frequency of aftershocks, as expected of a typical aftershock sequence. There is also a constant decrease in event frequency with increasing magnitude. Of the other plots in Figures 2 and 3, only the plot of the South Australian Moralana sequence (Nov 91 – Jan 92) shows similar consistencies in decay patterns, and might therefore be called a true aftershock sequence. The irregular patterns seen in the other plots may be what is to be expected in an earthquake swarm. However, Leonard (2003) ascribes the complicated pattern of events noted at Burakin as being caused by multiple overlapping main-shock/aftershock sequences. Although all the well-located swarm events have shallow depths (of the order of 2 km or less), this may be a feature that distinguishes swarm activity from more "normal" activity, particularly in the eastern half of Australia.

Relationship to regional geology

There may be a connection with Archaean Shield environments. Although the Bradford Hills and Eugowra swarms were not in a shield environment, the general geology of the regions was described as granitic (Gibson *et al*, in McCue & Gregson, 1994, Gibson *et al* 1994). In exceptional cases where swarms are very precisely monitored, e.g. Eugowra, the presence of a fault plane, not otherwise apparent, is suggested (Gibson *et al*, 1994). The Bradford Hills swarm was also very close to the active Muckleford Fault. This suggests that swarms may indicate the existence of some geological feature not otherwise apparent from geological or geophysical mapping. Their presence has been suggested by a preliminary interpretation of the Burakin swarm (Leonard 2003), but this activity awaits further investigation.

With reference to the SWSZ, Dentith & Featherstone (2003) suggested that although the general trend of the zone was to the SSE, it may be transected by faults normal to this trend, citing a NE trending zone of epicentres near Narrogin to support this hypothesis. This zone is not apparent in the plot of post-1982 earthquakes, but the epicentre plot shown on Fig 1b suggests an important lineation of epicentres between York and Bonnie Rock, passing through Meckering. In addition, similar trends may be interpreted north of this zone, joining the swarms at Cadoux, Koorda and Beacon.

Features of swarm aerial distribution.

A review of known neotectonic features in the SW of WA was made by Clark (2005). This shows fault scarps suspected of having been formed in the last 50,000 years or so. The recent fault scarps include those at Meckering, Cadoux and Calingiri. Regions of high seismicity are found around the Cadoux and Meckering neotectonic points, as may be expected. However, the swarm localities described here do not show significant positive correlation with neotectonic points as catalogued by Clark (2005).

It should be noted that while swarms in WA noted above are predominantly within the Archaean Yilgarn block, and more specifically in the southwest section of it, this may be an artefact of the greater human population, and distribution of seismographs in this region. A greater density of seismographs around Australia may reveal the presence of significant swarm activity in regions not currently recognised as prone to this activity.

Conclusions

Earthquake swarms are significant phenomena in Australian seismicity, and can include very large events, as exemplified by the Flinders Island swarm of the 1890s, to the very smallest, to the extent that they miss instrumental detection. Although they also occur in all Australian states, they seem to be most frequent in the south west seismic zone of Western Australia and the Eyre Peninsula of South Australia, both regions of Achaean geology. All swarms seem to be very shallow. Swarms can be of very long duration - of the order of a couple of years or more. Swarms can also be related to main-shock/aftershock activity, and may represent precursory activity to major seismic events.

There may be a continuum between aftershock activity and earthquake swarms. Earthquake swarms can have important implications for earthquake recurrence studies, as areas where swarms have been demonstrated to occur may be subject to higher degree of future activity.

Within an individual swarm locality, locations in general are not well enough resolved to indicate any linear or planar nature of earthquake hypocentres.

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