The Beacon, WA earthquake swarm commencing January 2009

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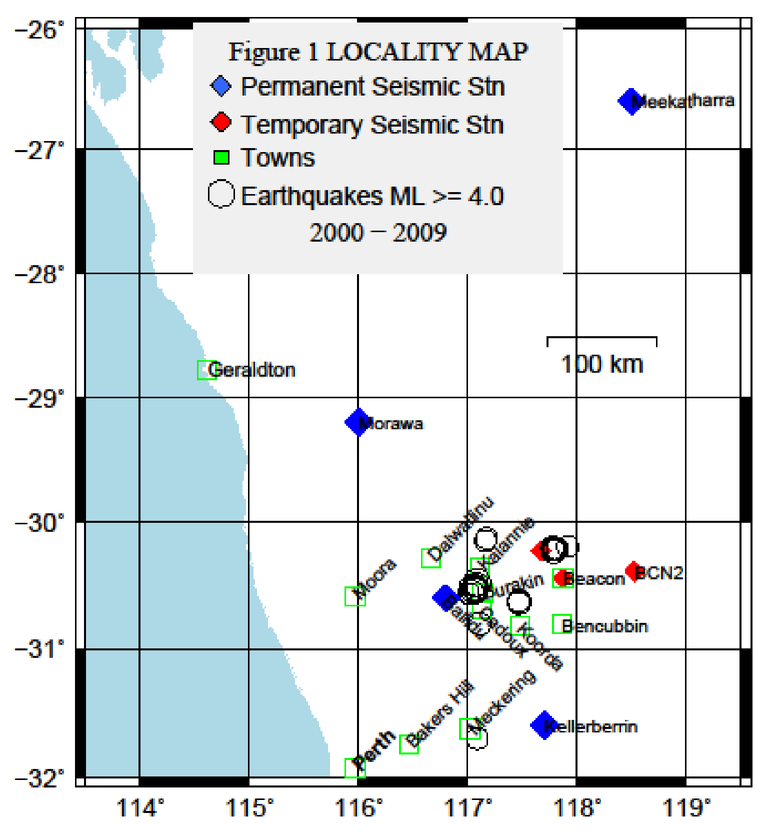
Abstract

A significant earthquake swarm occurred near Beacon, in the northern wheatbelt of Western Australia, commencing on 30th January 2009. Over 270 events were located there by Geoscience Australia over the subsequent seven months, although the majority of these were in the first 48 hours. Two temporary seismographs were deployed in the area 4 days after the swarm commenced. The station closer to the activity unfortunately only collected data for about two weeks. A third station was installed 25 km from the epicentre in late March 2009, and is now the only remaining station in the area. The initial location of epicentres showed a strong SW-NE trend. However, much of this apparent trend has been shown by temporary station data to be due to poor earthquake locations. Although no highly accurate locations have been made, the data suggest that all events were within a 2km diameter epicentral zone. There are no particularly unique geological or geophysical features at this location. Focal depth results are ambiguous, but the events are probably of 5 km depth or less. The epicentral zone was active to a lesser extent two years before the onset of the January 2009 activity burst. Renewed activity occurred in early March 2009, and sporadic events, mostly less than ML 2.0, occurred from April til mid August 2009, approximately 6 months after the swarm began. Recent epicentre plots suggest that other nearby swarm locations have produced recent minor activity, suggesting that a resurgence of swarm activity at these locations might be expected in the future.

Introduction

The southwest seismic zone (SWSZ) of Western Australia is a well recognised area of elevated seismicity (Doyle, 1971, Leonard, 2008), and earthquake swarms are common within it (Dent, 2008). The SWSZ is poorly defined, but Beacon (**Figure 1**) is on the approximate north-easterly boundary of the zone. Previous swarms in the Beacon area have been identified and plotted as part of a larger study by Dent (2008). An earthquake swarm is defined as having a number of events within a limited spatial area, 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 (Gibson et al, 1994). They are commonly only of a few weeks duration, but may continue for much longer periods



Major seismic activity ~30 km northwest of Beacon began on the afternoon of January 30th, 2009 and was monitored by Geoscience Australia (GA) in Canberra. Most of the activity occurred in the first 48 hours, and 106 events were located by 2400 hrs (UTC) on Feb 01. Numerous felt reports were received from residents in the immediate vicinity, and the most remote report was received from Baker's Hill, about 60 km ENE of Perth **(Figure 1).** The ML 4.5 event on March 5th prompted front-page headlines in the major Perth daily newspaper. This series of earthquakes represents one of the most significant seismic episodes in Australia in the last 20 years, eclipsed only by the nearby Burakin sequence of 2002 – 2003 (Leonard, 2002).

Table 1 - Temporary stations deployed at Beacon

STN	Latitude	Longitude	On-off	Instrumentation
BCN1	-30.2274	117.6729	0030 4feb-05th Feb	Kelunji Classic @ 200 s/s with CMG5 1 MB memory card
BCN1	“ “	“ “	05th Feb – 04th Mar	Kelunji Classic – gain reduced 10 > 1 & card swapped (full by 17th Feb)
BCN1	“ “	“ “	04th Mar –23rd Jun	Kelunji Echo – no data recorded
BCN2	-30.3922	118.5241	0900 4th Feb – 4 Mar	Kelunji Echo with CMG3T, 2GB card (27 events by 0430 5th Feb)
BCN2	“ “	“ “	4th Mar – 23rd June	Kelunji Echo – continuous recording at 100 s/s
BCNS	-30.4511	117.8687	23 March >>	PSN, continuous recording at 200 s/s

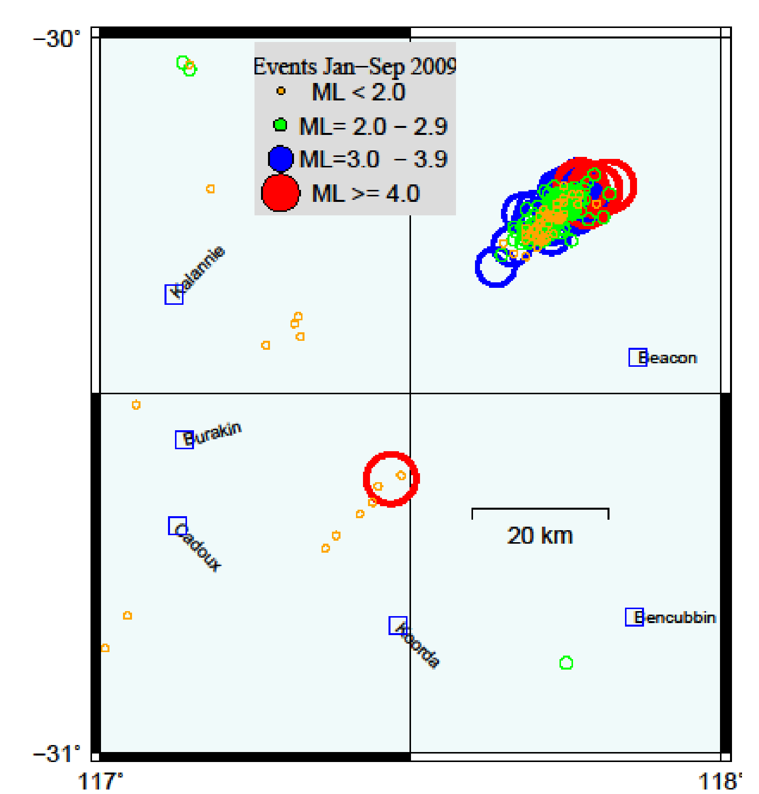


Figure 2. Epicentres Jan- Sept 2009

GA's Perth-based technician deployed two temporary triggered stations in the area (BCN1 and BCN2 – **Table 1**) which began recording on Feb 4th 2009. A third station (BCNS) was deployed by the author in late March 2009. Unfortunately, due to equipment malfunction, only about two weeks of data were recovered from the closest station (BCN1).

Recent seismicity of the region

Recent seismicity is plotted on **Figures 1 and 2**. On Fig 1, earthquakes of magnitude 4.0 and above from 2000 to 2009 for the region surrounding Beacon are plotted. **Figure 2** shows seismicity near Beacon from January to September 2009.

The seismicity shown on **Figure 1** represents some significant earthquake swarms, most of which were plotted in Dent, 2008. The events of **Figure 1** can be grouped into 9 significant seismic "episodes", as listed in **Table 2.** Principal among these was the major Burakin activity (episode 2) of 2001-2003 (Leonard, 2002). Another significant swarm took place north of Koorda in 2004 (episode 3), and included several events of magnitude over 4.0. Another began near Kalannie in 2005 (episode 7), and continued until March 2006, when a new activity centre commenced at Beacon (episode 8), in the same location as this 2009 swarm (episode 9). A temporal plot of the Beacon 2006 swarm contained in Dent (2008) is reproduced in **Figure 3,** and the epicentres are plotted again on **Figure 6**. The largest event of the 2006 swarm was ML 3.0.

Table 2. Major seismic episodes near Beacon since January 2000

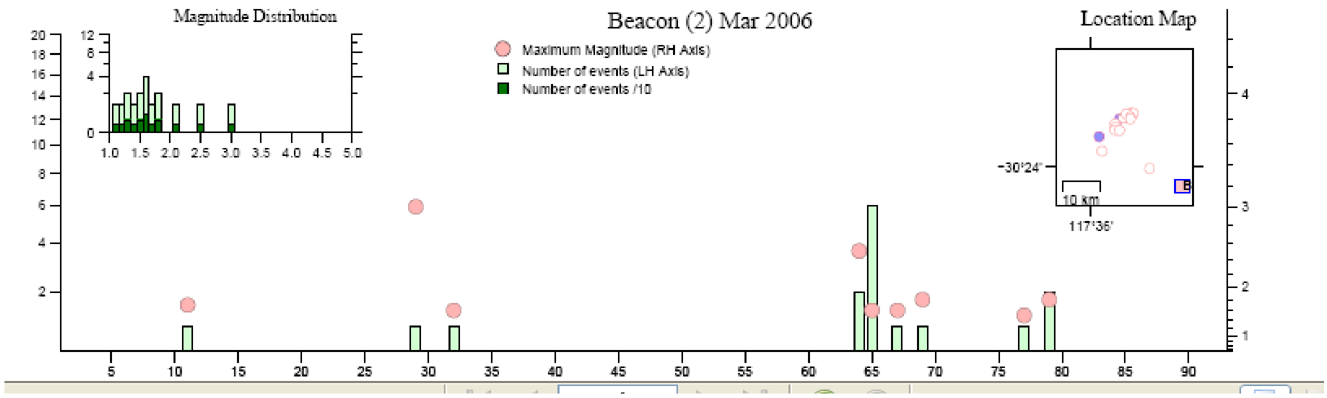
#	Location	Date	Latitude	Longit.	Biggest event ML	Comments
1	Cadoux *	Sep 2000	117.1	-30.6	3.6	Sep 2000 Pre-Burakin swarm (Leonard 2001)
2	Burakin *	2001- '03	117.07	-30.5	5.2	Active 2001 – 2003 (3 events of ML 5 & above)
3	N of Koorda *	Nov 2004	117.472	-30.633	4.4	Active to March 2005 (& later?)
4	W of Burakin	Apr 2005	117.0	-30.57	4.0	April 2005 swarm
5	Beacon	May 2005	117.9	-30.2	4.1	ML 3.6 aftershock on same day (May 01)
6	Cadoux	June 2005	117.03	-30.56	4.5	ML 4.3 nearby on same day (12 June)
7	N of Kalannie *	Sep 2005	117.16	-30.15	4.0	21 Sep 2005 - large EQ's continued until at least March '06
8	Beacon *	Mar 2006	117.7	-30.28	3.0	March– May 2006 – same location as 2009 swarm
9	Beacon	Jan 2009	117.8	-30.25	4.6	Present study
						* - indicates activity plotted in Dent (2008)

The small grouping of epicentres in the top left of **Figure 2** is close to the Kalannie swarm of 2005 (episode 7 in **Table 2**) and suggests a continuation of events from that swarm into 2009. The magnitude 4.2 event ~ 20 km N of Koorda and nearby events are in roughly the same location as the Koorda swarm of 2004 and also suggests continuing activity at that location.

Table 3 Significant events of the Beacon Swarm (includes events ML >=3.8)

Date	Time	Long	Lat	Mag	Dep	Comments
30 Jan 2009	0549	117.810	-30.252	**2.7**	**0**	**First located even**t of swarm. Total of 43 located events until 2400 UTC
30 Jan	0550	117.663	-30.293	3.4	0	
30 Jan	1725	117.784	-30.214	3.8	0	
30 Jan	1733	117.774	-30.212	4.1	0	
31 Jan	**0847**	**117.784**	**-30.230**	**4.6**	**2**	**Largest event**
31 Jan	1155	117.798	-30.215	4.4	0	
31 Jan	1618	117.781	-30.202	3.8	0	
01 Feb 2009	0042	117.819	-30.209	4.0	0	
01 Feb	2157	117.795	-30.214	4.0	0	
19 Feb	2228	117.795	-30.233	3.8	2	
05 Mar	**1253**	**117.774**	**-30.208**	**4.5**	**0**	**2nd Largest event**
05 Mar	1331	117.745	-30.211	3.8	0	
25 Jun	1516	117.468	-30.619	4.2	0	~ 40 km SW of Beacon. May be related to 2004 swarm activity N of Koorda

Figure 3. The Beacon 2006 swarm (from Dent, 2008)

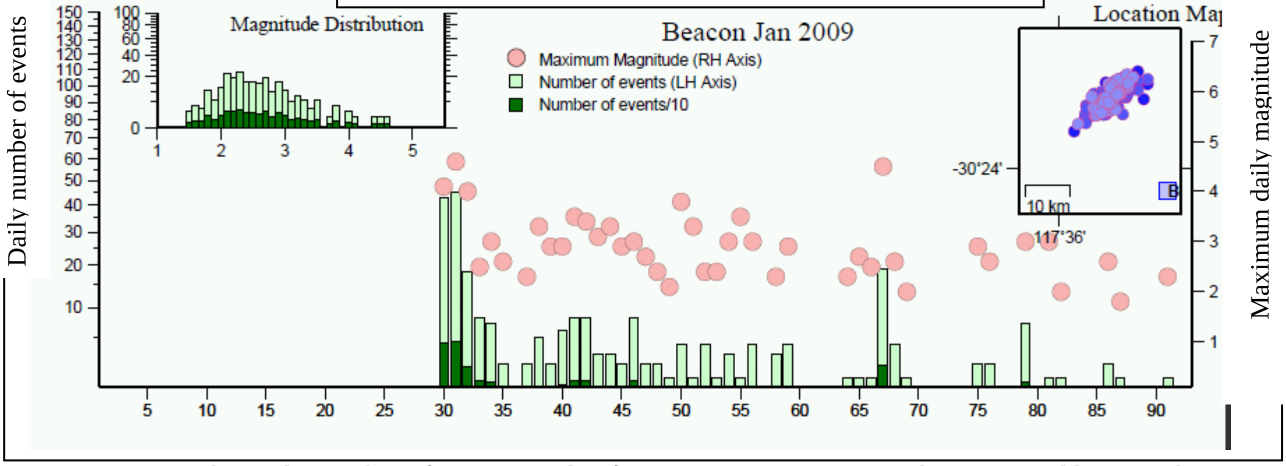


Event history of the swarm

The most active period of the swarm was the first 48 hours, and two of the largest events (ML 4.6 and ML 4.4) occurred. approximately 24 hours after swarm initiation. Over 270 swarm events were located by GA up until mid August 2009, when activity seems to have finally ceased. Although the majority were in the first three days, a brief resurgence of activity occurred on March 5th 2009. The second largest event of the swarm (magnitude 4.5) occurred on this day. Significant events from the swarm are listed in **Table 3.**

Following the method of graphically depicting swarms used by Dent (2008), **Figure 4** represents the first two months of the

Figure 4 Graphical representation of Beacon 2009 swarm.



2009 Beacon swarm. It shows the number of events per day from January 01 to 31 March 2009, in addition to the event locations, the largest daily magnitude, and the distribution of earthquake magnitudes within the swarm.

The epicentre plot in **Figure 2** shows a pronounced NE-SW trend in the GA located epicentres of the 2009 swarm. This may suggest that the earthquakes are occurring along a lineament (i.e. a causative fault), or may be due to errors in earthquake locations. One of the objectives of this report is to investigate this trend.

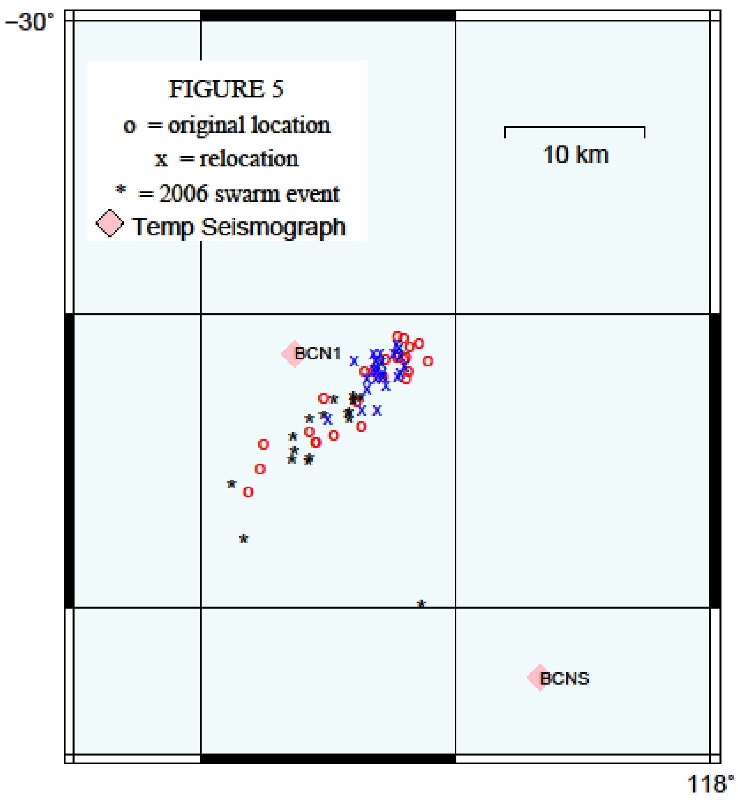
Felt effects

Felt reports were received from the largest events were received from as far away as Baker's Hill, (~ 70 km east of Perth, and 220 km SW of the epicentres). The swarm was in a relatively unpopulated area, and the nearest farm (Max Lancaster's) was about 5 km of the events. Events down to ML less than 2 were regularly felt by the residents, and the largest events are estimated to have produced Modified Mercalli (MM) intensities of between VI and VII at the farm house – various objects were broken as a result of the largest tremors, cupboard doors thrown open, and contents strewn about (*"The West Australian",* 10th March 2009).

Temporary station deployment

As noted earlier, two stations were deployed in the area by GA on 4th Feb. Initially, Kelunji "Classics" were deployed, but these were later replaced by Kelunji "Echoes". A third station ("Public Seismic Network", continuous recording – Dent 2007) was deployed by the author at the primary school in Beacon on March 24. Station locations, instrumentation and operational periods are shown in **Table 1**.

Figure 5 – Effect of Relocations



One of the GA stations (BCN1) was deployed at Lancaster's farm, close to the epicentre, and the other (BCN2) about 80 km to the east. The station configuration was designed to assist in ground-motion attenuation studies. The station near the epicentre (BCN1) recorded only briefly, and BCN2 was withdrawn in June 2009.

The equipment and set-up at the Beacon Primary School (BCNS) is similar to that described by Dent (2007). Data are recorded on a personal computer at 200 samples per second, using GPS timing. The sensor is a 3 component 4.5 Hz geophone. Compressed data are sent via the internet at hourly intervals to a website maintained by the Australian Centre for Geomechanics (ACG). This station continues to operate (as at November 2009).

To achieve a significant improvement in hypocentral accuracy, about five temporary stations would be desirable, including one about 2 – 3 km from the epicentres. In this case, the few stations deployed means that only a modest improvement of hypocentral accuracy is possible, even under ideal conditions.

The hypocentral details for the events currently in the GA catalogue were computed by GA analysts as part of routine monitoring procedures. The smaller events were often located using only three stations (i.e. KLB, BLDU and MORW). Consequently, the uncertainty in the earthquake coordinates is relatively high.

All useful data from BCN1, over its short operational life have been used to relocate events. However, the data suggest that BCN1 did not synchronise with GPS timing for several days after its deployment, further limiting the usefulness of its data. Data recorded at BCNS, in conjunction with data from BCN2, which operated relatively successfully, have been used to relocate all events of ML 1.9 and above, from 24th March 2009, to 30 June 2009.

In the relocation process, maximum weighting was given to the temporary stations - i.e., it was ensured that the residuals of their phase arrivals were no more than 0.1 seconds. Thus, the overall standard deviation of "residuals" might not significantly improve, and the errors quoted by the location program for latitude/longitude might not improve, but the adopted locations give better fits for the very close stations. Relocated events are listed in **Table 4** and plotted on **Figure 5.**

Focal Depths

As noted by Gibson et al (1994), to constrain earthquake depths, it is essential that one of the seismographs should be near the earthquake epicentre, preferably at a horizontal distance not greater than the earthquake depth. They also state that it is preferable to have six or more recorders in a network. While the station BCN1 was close (~ 6 km) to the epicentres, the other condition for accurate locations/ focal depths (i.e. numerous well-distributed stations) is not met. Therefore the depth determinations for earthquakes in this swarm (by GA, and the relocations presented here) are relatively unreliable. However, the relatively constant S-P interval at BCN1 of 0.8 seconds means that the focal depths could not exceed 5 km.

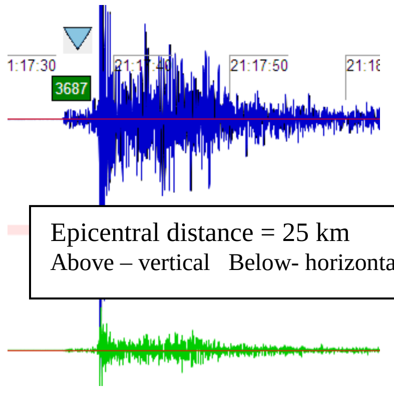
There are only two previous temporary station deployments in the region which have used six or more recorders, including some close to the epicentre. One was in 1983 in the Cadoux region (Dent, 1991) and the other was in the Burakin region in 2001-02 (Leonard, 2002). The latter of these has more potential for reliable focal depth estimations because of the better equipment and timing available. Relocations of 69 earthquakes using data from the 2001-02 survey (Allen et al, 2006) indicate a maximum focal depth of 2.4 km, a result supported by other recent work in the SWSZ (e.g. Dent 2008b). The relocations presented here are all of shallow depth. In most cases, the EQLOCL program suggested solutions of slightly negative depth, and have therefore been constrained at a depth of 1 km. Some of the original GA locations were of 5 km or more depth, and the relocations of these events have produced the biggest variance with the original solutions.

An alternative method of depth estimation is by identification of *Rg* phases associated with the earthquakes (Kafka, 1990).

Table 4 - Event Relocations

Date	Time	Long	Latitude	Mag	Dep	SD	# pha	Relocated long	Relocated lat	Dep	SD	# pha	Comment
31 Jan	0859	117.637	-30.322	3.0	8.5	.016	5	117.699	-30.273	1C			No extra data
07 Feb	0801	117.728	-30.240	2.7	0	.205	6	117.754	-30.244	1C	.14	5	
07 Feb	1648	117.745	-30.231	3.3	0	.399	10	117.737	-30.232	0C	.084	6	BCN1 not synched
07 Feb	2137	117.696	-30.258	3.2	2	.318	8	117.738	-30.238	1C			
08 Feb	0313	117.754	-30.230	2.6	0G	.527	8	117.745	-30.250	0C	.265	5	
08 Feb	1028	117.690	-30.288	2.9	5G	.491	8	117.738	-30.266	0C			
09 Feb	0102	117.759	-30.217	2.9	0	.546	8	117.741	-30.234	0C	.15	5	
10 Feb	1224	117.759	-30.231	3.5	0	.456	13	117.756	-30.229	0C	.156	7	
11 Feb	1513	117.778	-30.232	3.4	3	.60	10	117.735	-30.228	.24	.084	8	
11 Feb	2321	117.726	-30.277	3.2	4.2	.338	9	117.730	-30.252	0C	.08	7	
13 Feb	1619	117.735	-30.240	3.1	0G	.265	7	117.737	-30.232	0C	.081	5	
13 Feb	1702	117.754	-30.215	3.3	0	.478	8	117.740	-30.227	0C	.081	8	
13 Mar	0408	117.690	-30.288	2.8	11.2	.366	7	117.751	-30.242	1C	.154	8	No extra data
24 Mar	0443	117.743	-30.243	2.6	3.3	.138	7	117.753	-30.222	2.2	.035	8	
29 mar	0250	117.133	-30.035	2.2	6.0	.226	6	117.176	-30.028	1.8	.208	8	remote
29 mar	1012	117.722	-30.26	2.3	1.4	.276	8	117.726	-30.266	1C	.19	8	
03 Apr	1402	117.649	-30.289	1.7	12.2	.357	8	117.720	-30.233	1.3	.226	6	
06 Apr	2023	117.043	-30.81	1.9	7.4	.136	6	117.109	-30.749	1.6	.167	7	Remote
07 Apr	0823	117.704	-30.283	1.9	5.9	.292	7	117.756	-30.238	1C	.088	7	Big move
18 Apr	2020	117.771	-30.22	2.1	0G	.533	8	117.756	-30.241	1C			BCS U/S
21 Apr	0843	117.754	-30.227	2.5	0.9	.227	7	117.755	-30.224	.27	.171	9	
06 may	2259	117.761	-30.244	2.8	0.2	.308	8	117.737	-30.245	0.6	.09	9	
12 may	0355	117.761	-30.23	3.1	0	.463	10	117.73	-30.245	.88	.083	9	
18 may	1720	117.763	-30.24	2.0	2	.478	9	117.742	-30.244	2.0			
18 may	2048	117.764	-30.223	2.1	2	.40	11	117.742	-30.241	.06	.104	9	

Figure 6(A)
BCNS 09 Aug 2009



Epicentral distance = 25 km
Above – vertical   Below- horizontal

Earthquakes of about 2 km depth or less commonly have a well-developed *Rg* phase seen at the more distant stations. Typical seismograms for Beacon events (in this case 09 Aug 2009, ML 2.7) from BCNS and MORW are reproduced here (**Figure 6 A&B).** *Rg* phases are not apparent on these seismograms, and McCue (pers comm., 2009) suggests on the basis of these observations that the events probably have depths of approximately 5 km or greater.

Effect of relocations

Events have been relocated using the program EQLOCL, the same program as used by the GA analysts for the original set of locations. Because of the relatively few temporary stations, and their limited operational periods, the new locations are not particularly rigorous, but they do lessen the uncertainties. One of the main influences on the relocations appears to be the assignment of focal depth. From previous good epicentral determinations in the region (e.g. from the Burakin swarm - Leonard 2002) it is expected that the depths will be of the order of 2 km or less. If the EQLOCL program tries to give a location at a negative value (i.e. above sea level), the hypocentres have been constrained to 1 km by the author (or 0 km for earlier solutions by the GA analysts). However, in some cases, the GA solutions have been constrained to depths of 5 km, or in some cases 10 km. In many cases, these are the events which lie to the southwest of the main group of epicentres. The author has checked a number of such locations, and found that all events are probably better constrained to 1 km depth. Furthermore, arrivals from distant stations like Rocky Gully, Kambalda and Forrest were deferred. The effect of these relocations (**Figure 5**) is to bring the epicentres back to the main grouping of events.

In summary, the collection of relocated events shows considerably less scatter than the original set of locations, and the NE-SW trend from the original determinations has largely been eliminated. However, it should be noted that some relocations still have a considerable degree of uncertainty. Most relocated epicentres fall within a

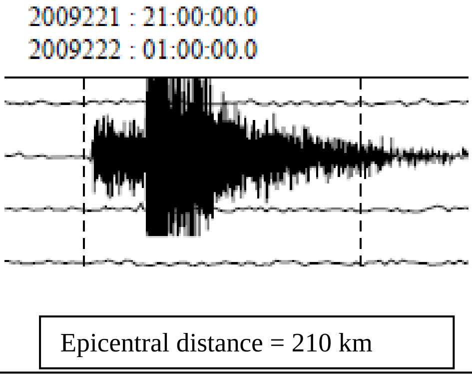


Figure 6(B)
MORW 09 Aug 2009
(vertical component)

circle of about 2 km diameter, centred on 30.22 S, 117.74 E. Given that there are still uncertainties in the locations, it is possible, or even likely, that the focal zone is even smaller than that suggested by the epicentre plot. Interestingly, initial inspections of geological and geophysical maps (albeit of low resolution) show no particular features at this location which could possibly correlate with seismic activity.

The effect of relocations using temporary data to bring epicentres to almost a point source is consistent with other micro-earthquake surveys, eg Leonard (2002) at Burakin, WA, and Levinson & Leonard (2001) at Sutton, NSW.

Note that the earth velocity-depth model used (WA2, Dent 1990) may not be precise enough to use at the very small hypocentral distances used here. Recent work for other purposes (P. Somerville, Pers. Comm., 2009) has suggested a thin surface layer (~ 2km) of relatively low velocity is appropriate. A revised model may reduce some of the uncertainties found here.

Magnitude distribution

On **Figure 7** the numbers of events in each 0.1 unit interval of the Local Magnitude (Richter) scale is plotted. The steady slope of this curve between ML 2.3 and ML 4.1 suggests that the catalogue of events from the swarm is complete from ML 2.3 and above – i.e., some ML 2.2 events were probably not located, with the number of missed events increasing as the magnitude level goes down. Most of the missed events probably occurred in the first 48 hours of the swarm, when event numbers were extremely high.

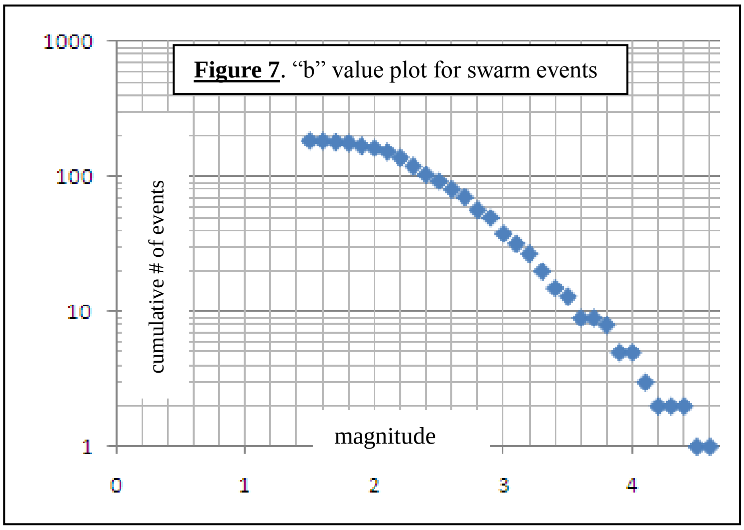


Figure 7. “b” value plot for swarm events

The steady slope of this graph is akin to the conventional “*b*” value of Gutenberg & Richer (1944), representing recurrence rates of earthquakes. This slope is not normally identified in earthquake swarms, because of the generally relatively small number of events, and low magnitudes. The values have been plotted again in the traditional method of computing “b” values (**Figure 7**), and results in a “*b*” value for earthquakes in the swarm of approximately 0.86. This is much higher than the b value quoted by Leonard (2008) for events in South West Australia (which includes the Beacon region) of 0.58, but similar to b values quoted for North West Australia (0.85) and Southern Australia (0.99). The gradient of the slope shown here may prove to be a characteristic of swarms in the SWSZ.

These data also indicate that the distant stations which were used to locate the small events have greater sensitivities than may have been assumed by other studies (eg, Dent, this volume) - i.e., MEEK consistently detects ML 2.0 events at distances of approx 400 km, and MORW apparently consistently records ML 1.6 events at approx 200 km.

Daily plots of the continuous data from the BCNS station also show smaller events that have not been located, or added to the GA database. These are all probably of magnitude < 2.0. Location of these smaller events has not been attempted at this stage.

Significance of the 2009 Beacon swarm

A comparison of the plot of events from this swarm (**Figure 4**) with similar plots from other recent Australian swarms (Dent 2008), indicates that, over the last 20 years, the Beacon 2009 swarm has been surpassed, in terms of events numbers and magnitudes, only by the nearby Burakin swarm of 2001-2003. Prior to that, only the Tennant Creek series of events, from 1988 onwards (Bowman, 1992), and the Norseman, WA swarm of 1985-87 (Dent, 2008) have been more significant periods of seismic activity. We may expect continued seismic activity at Beacon from the fact that a swarm at apparently the same location occurred in 2006 (**Figure 6**), and possibly earlier swarms as well (e.g. May, 2005).

The ML 4.2 event on 25th June, approximately 40 km to the SW of the main swarm activity, appears to be related to the 2005 swarm north of Koorda, and not related to the current swarm. However, Leonard (2002) concluded that separate swarm centres around Burakin in 2002 -2003 were probably related, as they may prove to be here.

The epicentres shown on **Figure 2** indicate continuing activity at the locations of previous earthquake swarms in the region, suggesting the possibility of resurgence of activity at these centres, (as with the Beacon 2009 swarm).

On a larger scale, it is possible to speculate that there is a connection between all the major events which have occurred since 2000 and are listed in **Table 1**. They are all relatively close geographically, and in the same general region as the major Cadoux event (ML 6.1) of 1979 (Lewis et al, 1981).

Conclusions

The Beacon 2009 earthquake swarm is one of the major seismic episodes in Australia in the last 20 years. The NE-SW trend in epicentres is probably not real, and was introduced by having insufficient data to achieve reliable locations. The swarm was poorly monitored in terms of number of stations deployed, and sampling rates used.

The best located epicentres lie within a circle (on the surface) of approximately 2 km diameter, and it may be assumed that the majority of the ~300 located events also lie within this circle, and are only outside of it because of poor quality data or inappropriate weighting of phases by analysts when locating the events. There are no readily apparent geological or geophysical features at this location which may suggest a cause for the seismic activity.

There is ambiguity relating to the most appropriate focal depths to be assigned to the events. Computer solutions using station phase arrival data suggest a focal depth close to the surface (< 2 km), but the waveforms suggest a greater depth (~ 5 km), because of the lack of development of an *Rg* phase.

The 2009 swarm was in the same location as the 2006 swarm (within experimental error), and much larger than that swarm. The 1995 swarm was close to the 2009 swarm, and considering experimental error, may also have been in the same location. Events are still occurring at the locations of earlier swarms north of Koorda and north of Kalannie. On this basis, activity at these locations, as well as NW of Beacon, can be expected in the future.

Acknowledgements

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