

## A NE lineation of epicentres northeast of Perth – fact or fiction? A review of earthquake hypocentres in the region, 2005

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### Abstract

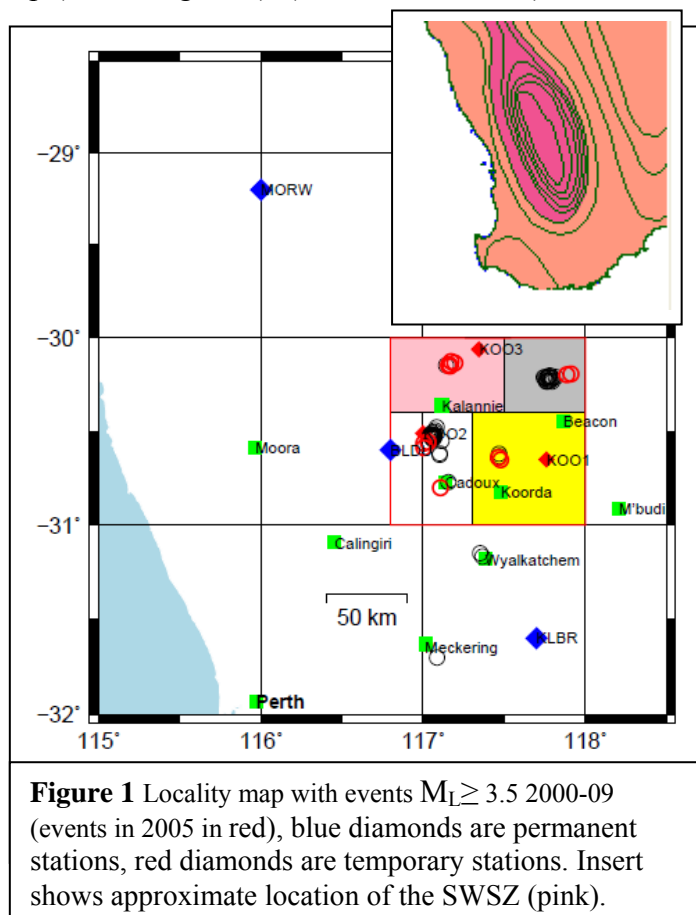
A plot of raw epicentres from the GA database suggests a strong northeast lineation in epicentres in the northern southwest seismic zone, about 250 km northeast of Perth. However, a program of relocating selected events in the region in 2005, assisted where possible by new data from a temporary seismograph network in the area, removes much of the observed trend. The movements are much more noticeable in the small events, which would be expected to be poorly located in any case. A north-northeast trend in epicentres in the Burakin region is however reinforced. All of the relocations have a focal depth of 5 km or less.

### 1. Introduction

The “southwest seismic zone” or SWSZ is a term coined by Gordon (1980) to describe an ill-defined area of elevated seismicity, first identified by Everingham (1965). With the benefit of a further 40 years of seismic data, its modern boundaries can be approximated by the region of higher risk as shown on the Australian earthquake hazard map (insert, Figure 1), (McCue et al, 1991)

In recent decades, the northern part of this zone has hosted a number of very significant earthquakes, i.e. Meckering 1968  $M_S$  6.9, Calingiri 1970  $M_B$  5.7, Cadoux 1979,  $M_S$  6.1, as well as the Burakin seismic swarm of 2001 – 2003.

Earthquake clusters or swarms are an important feature of seismicity in the SWSZ, and a report on Australian earthquake swarms by Dent (2008) suggested the presence of an NE-SW lineation in epicentres from the northern regions of the SWSZ. Such a lineation would suggest the earthquakes were associated with faults or at least zones of weakness at the locations and orientations suggested by the trends. It might be expected that such faults or zones could be delineated by geological or geophysical mapping. However, a report on the Beacon swarm of 2009 (Dent 2009) suggested that a NE trend in that cluster was due to poor earthquake locations.



This report aims to review similar trends visible in epicentres, between January and December 2005. The area selected for study in this report is 30 – 31° south, 116.8 – 118° east (Figure 1). This particular area and time interval has been selected because of the existence of a network of three temporary seismic stations near Koorda (~250 km NE of Perth). Data from this network have not been

examined in detail before. The area has been further divided into four zones (Koorda, Cadoux, Beacon and Kalannie), each of which contains at least one major cluster location.

Events of Richter Magnitude ( $M_L$ )  $\geq 3.5$ , 2000 – 2010, located by Geoscience Australia (GA) in the study region are shown in Figure 1. The events of 2005 are shown in red.

Location	Period	Reference
Nth of Cadoux	Sep-Oct 2000	Leonard & Boldra (2001)
West of Burakin	2001-03	Leonard (2002)
North of Koorda	2004-05	Allen et al, (2006) p573
West of Burakin	Apr 2005	
Nth of Beacon	May 2005	
Cadoux	June 2005	
Nth of Kalannie	Sep 2005	Dawson et al. (2008)
Nth of Beacon	Mar 2006	Dent (2008)
Nth of Beacon	Jan- Apr 2009	Dent (2009)

Dent (2009) identified 9 significant “seismic episodes” in the region between 2000 and 2009, five of which occurred, or partly occurred in 2005.

The object of this paper is to investigate the reality of the trends observed in the epicentral plots by relocating selected events, using data from the Koorda network where possible.

## 2. The data set

There were 160 GA located events in the study area during 2005, the majority of which occurred in the Cadoux zone. 13 of the 160 events had magnitudes  $\geq 3.5$ , and these are listed in Table 2.

**Table 2. Larger ( $M_L \geq 3.5$ ) GA located events in the study region in 2005**

DATE	GMT	Lat (S)	Long (E)	$M_L$	Depth (km)	SD	No. of Arrivals	Location
03 Jan	0040	30.652	117.479	3.5	1.5	.264	11	North of Koorda
16 Mar	0127	30.639	117.464	<b>4.2</b>	2.6	.506	17	North of Koorda
12 Apr	1159	30.588	117.005	3.5	2G	.266	8	SW of Burakin
12 Apr	1200	30.564	117.005	<b>4.0</b>	0G	.233	6	SW of Burakin
01 May	0943	30.194	117.912	<b>4.1</b>	2.7	.592	15	North of Beacon
01 May	1538	30.198	117.807	3.6	0G	.651	12	North of Beacon
12 June	1051	30.802	117.108	<b>4.3</b>	2.2	.539	12	4 km SW of Cadoux
12 June	2036	30.558	117.030	<b>4.5</b>	7.6	.408	12	West of Burakin
21 Sep	2246	30.148	117.159	3.9	2G	.274	13	North of Kalannie
21 Sept	2259	30.151	117.167	3.7	0.5	.344	14	North of Kalannie
22 Sep	0352	30.126	117.173	<b>4.1</b>	3.1	.404	22	North of Kalannie
22 Sep	1834	30.142	117.159	3.9	4.5	.464	16	North of Kalannie
25 Nov	2032	30.134	117.195	3.6	2.2	.331	13	North of Kalannie

(Under Depth, G = assigned depth)

## 3. The Koorda network and Kelunji data

The Koorda network consisted of three digital Kelunji recorders, KOO1, KOO2 and KOO3. The locations & operational periods are listed in Table 3. KOO1 and KOO2 were installed in early 2005 in response to the ML 4.4 event North of Koorda in Nov 2004. KOO3 was installed in early 2006, and consequently its data have not been used in this review of 2005 events.

The Kelunji recorders data-sampled at 100 s/s, and their data are therefore of higher quality than that from the permanent (ANSN) network, which generally sample at 20 to 40 s/s. However, the recorders only had a small amount of memory and operated in the “triggered” mode. This meant that if the settings were not optimal, events could be missed, or the memory could fill with false triggers.

**Table 3. Seismographs used in the relocation process**

CODE	Location	Lat (S)	Long (E)	Remarks	Operational period
KOO1	North of Koorda	30.6498	117.7598	Kelunji 100 s/s	01 Mar 2005 - 20 Feb 2007
KOO2	NW of Burakin	30.5102	116.9991	Kelunji 100 s/s	25 Jan 2005 - 23 Aug 2006
KOO3	Near Kalannie	30.0620	117.3449	Kelunji 100 s/s	11 Jan 2006 ?- 24 Feb 08
MORW	Morawa	29.0683	116.0388	Telemetered 40 s/s	Started as MRWA June 84
BLDU	Ballidu	30.6147	116.7091	Telemetered 40 s/s	Started as BAL Aug 82
KLBR	Kellerberrin	31.5915	117.7546	Telemetered 40 s/s	Started as KLB Sept 81
MUN	Mundaring	31.9783	116.2083	Telemetered 40 s/s	Opened July 1959

Data from the permanent network have been archived, and cannot easily be retrieved. Consequently it has not been possible to review phase data previously scaled by GA analysts.

Data from the Koorda temporary stations also contain phase data from other smaller events, which were not considered locatable by GA, though the data may be useful in some future study.

### Relocation methods

Earthquakes have been relocated using EQLOCL and earthmodel WA2 (Dent, 1990), by revising the original GA locations. This is the program and model as used by GA to locate WA earthquakes from 1986 (K. McCue, Pers. Comm.) to late 2009. New methods have since been introduced at GA, based on the “Antelope” seismic analysis system (of Boulder Technologies, USA) to locate earthquakes from July 2009 on.

The relocation solutions have been weighted to ensure that phase arrivals from the closest stations, (which generally are the sharpest), have the smallest residuals. More distant stations (> 400 km) are generally given no weight (even if they appear to fit), because such arrivals are usually emergent. Also uncertainties in the velocity model means there is more uncertainty in the computed arrival times with increasing epicentral distance.

### Location accuracy

The EQLOCL program lists suggested errors in the coordinates (latitude, longitude and depth) it produces, but these are approximate only. Location accuracy is also indicated by the standard deviation (SD) of arrival residuals, in combination with the number of arrivals used in the solution.

The SD values of the original GA locations, and of the relocations, are given alongside the epicentres in the tables below. The SD for GA locations are usually ~ 0.3secs or greater. Relocations presented here generally achieve ~ 0.15s, which suggests a substantial reduction in the uncertainties of the hypocentres. Table 4 is an approximate guide to error in coordinates (lat & long) versus SD of residuals, and the number of arrivals used.

SD	Error (Arrivals=6)	Error (Arrivals=9)
.1	+/- 2 km	+/- 1 km
.2	+/- 5 km	+/- 3 km
.3	+/- 10 km	+/- 5 km
.4	+/- 20 km	+/- 10 km

**Table 4** approx relationship between location error and Standard Deviation of phase residuals

### Focal depths

Except for locations made during 2001-2003, when a relatively dense network of temporary stations operated in the area, all depth values in the region should be regarded as a “guide” only. The EQLOCL solutions for some events (using the WA2 model) have negative depths, and these have been constrained to 0 or 1 km depth.

Almost all events are less than 5 km deep, as is to be expected from SWSZ events (e.g. Dawson et al., 2008). No WA earthquakes have yet been definitely shown to have depths of greater than 8 km, and all well-located events are usually of 3 km or less.

Some of the GA (EQLOCL) solutions have what may be considered unreasonable depth estimates from the computer locations (i.e. greater than 8 km). Therefore, when relocating these events, focal depths were constrained to 1 km if a more realistic depth is not determined. Sometimes, in the location process, anomalous arrivals have been identified, and when these data are deferred, the resulting solutions are actually much “tighter” than the original GA locations.

### Criteria for relocation

Events have been selected for relocation on three basic criteria

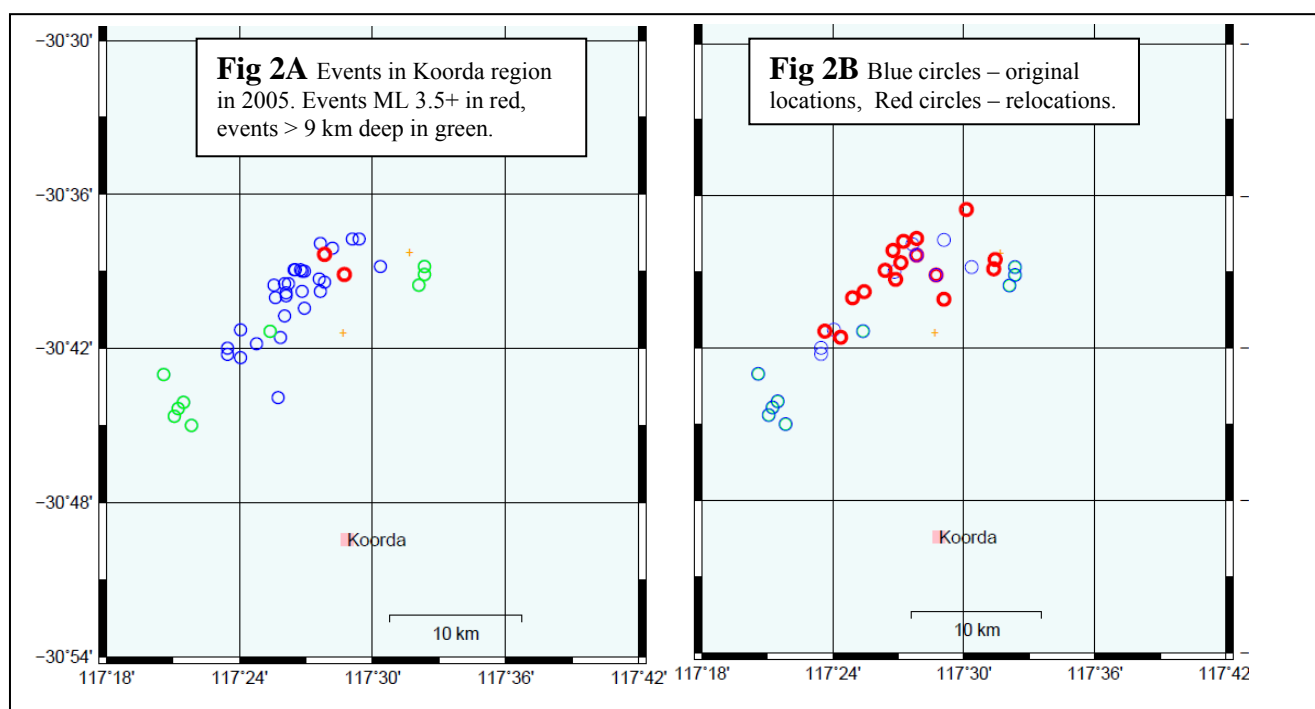
- 1) New data are available from the KOO network
- 2) The events are outliers from the main cluster location or
- 3) The events have been assigned an unusual depth

## 4. Discussion of individual source zones

### 4.1 North of Koorda (30.4 – 31.0° S, 117.3 – 118.0° E)

Activity commenced here in November 2004, with an ML 4.4 event. The area appears to be devoid of significant activity before 2004. The activity following the Nov 2004 event was the reason that the Koorda network was installed. KOO1 is about 40 km east of the active area. The 14 events in the zone in 2005 are listed in Table 5 and plotted on Figure 2A. Six of these events have “dubious” depths – i.e. 9 km or more.

This cluster was treated briefly by Dawson et al. (2008) and referred to as the “East Cadoux cluster”. Allen et al. (2006) also referred to the activity, which they considered to be an extension of the 2001-



## 2003 Burakin activity.

The events in this region also constitute a swarm, (and were plotted by Dent 2008) but the events were relatively poorly located. Figure 2A shows a pronounced northeast trend. Unfortunately, little temporary station data are available to improve locations from this zone.

Relocations are plotted on Figure 2B. Six events have depths of ~ 10 km or more, and these form the southwest “tail” of the group. Relocation of these events brings them close to the surface, and back into the main grouping of events (which are also about 1 km deep). The result is that, while the northeast trend still exists, it is now less pronounced.

**Table 5. Significant events in the Koorda zone in 2005**

Date	GA location		M <sub>L</sub>	Depth (km)	SD	# arr	Remarks	Relocation		Depth (km)	SD	# arr
	Lon (E)	Lat (S)						Lon (E)	Lat (S)			
24 Nov 2004	117.472	30.633	4.4	0G	.206		1 <sup>st</sup> event					
3 Jan 2005	117.479	30.652	3.5	1.5	.264			117.452	30.644	1.4	.097	6
19 Jan “	117.351	30.744	1.7	10G	.407	6	deep	117.440	30.649	1C	.198	5
01 Feb “	117.358	30.735	1.4	11.3	.344		deep	117.406	30.693	1C	.148	5
24 Feb “	117.485	30.629	3.3	2.5	.236			117.464	30.628	1C	.160	7
16 Mar “	117.464	30.639	4.2	2.6	.506	17	KOO1&2	117.449	30.632	31C	.150	10
18 Mar “	117.343	30.717	2.8	9.6	.469	7	deep	117.358	30.677	1C	.100	6
15 May “	117.423	30.689	2.8	10	.618	6	deep	117.502	30.609	1C	.341	5
27 May “	117.447	30.65	3.3	4.2	.767	12		117.434	30.657	3.7	.150	8
27 May “	117.461	30.632	3.0	0G	.311	10						
28 May “	117.401	30.688	2.3	5G	.434	7		117.454	30.630	1C	.169	7
28 May “	117.391	30.700	2.1	5G	.387	6		117.424	30.663	2.4	.126	5
28 May “	117.391	30.704	2.1	5G	.355	6		117.415	30.667	.7	0.00	4
25 Jun “	117.364	30.750	2.2	10G	.441	6	deep	117.448	30.655	1.5	0.00	4
22 Jul “	117.354	30.739	1.2	10.8	.369	6	deep	117.446	30.636	1C	.194	5

## 4.2 Cadoux Zone (30.4 – 31.0° S, 116.8 -117.3° E)

### Previous activity 1 (Feb-Apr 1968)

A significant earthquake (M<sub>L</sub> 4.9) occurred at 30.8°S, 117.3°E, i.e. about 20 km east of Cadoux on 22<sup>nd</sup> Feb, 1968, and a further 8 events of M<sub>L</sub> ≥ 4.0 occurred at the same location between that date and 8<sup>th</sup> Apr 1968. It is possible that this sequence occurred at the same location as the magnitude 6.1 June 1979 event. Because of the very limited distribution of seismographs at that time (the three closest stations were at Mundaring, Kalgoorlie and Meekatharra), the uncertainties in the GA catalogue locations are very large (20 km + at least).

### Previous activity 2 (June 1979 onwards)

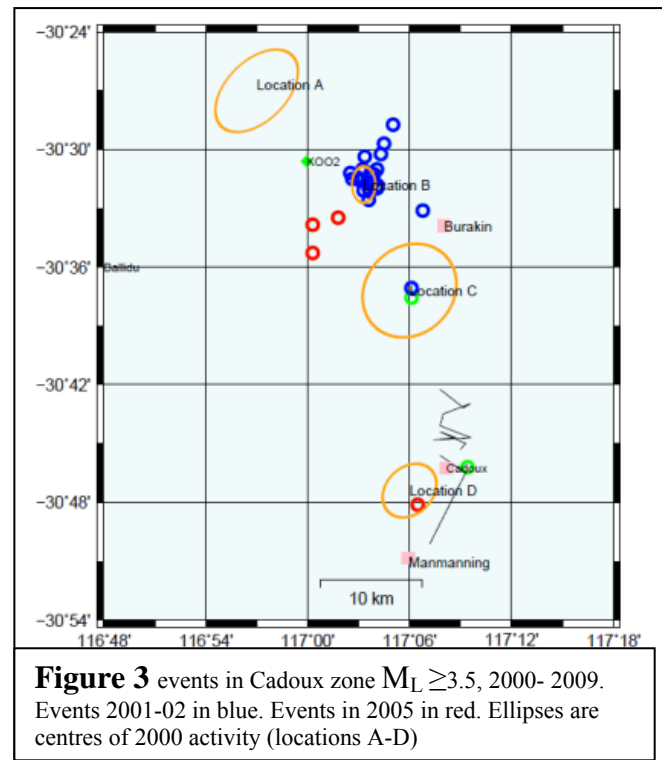
A major (M<sub>S</sub> 6.1) earthquake occurred at 30.827S 117.179E, about 5 km SE of Cadoux in June 1979, with large numbers of aftershocks over the ensuing months (and years). There were two aftershocks and one foreshock with magnitudes ≥ 5.0. This sequence will not be treated in detail here as it has been previously described (Lewis et al., 1981). A simplified representation of the surface fracture from this event is depicted on Figure 3. The seismic activity occurred over a broad area (i.e. at least 20 km x 20 km), but because of the poor seismic network in operation at the time, it is hard to

distinguish trends within this aftershock activity, and much of the scatter may be attributable to poor locations.

### **Previous activity 3 (Sep – Oct 2000)**

The Cadoux region was the centre of intense seismic activity between Sept-Oct 2000, during which period some 1700 events were recorded, and 120 events were located (Leonard & Boldra, 2001). The largest magnitude was  $M_L$  3.6. Much of this activity was recorded by a temporary installation of four seismic stations, resulting in “good” locations for 80 events. Leonard & Boldra defined a “good” location as one where the NS + EW uncertainty was < 30 km.

Leonard & Boldra (2001) defined four source locations for this activity which they labelled A, B, C and D (Table 6), and which they described as having a north-south trend. The locations were not points but circular to ellipsoidal regions, with diameters ranging from about 2 to 10 km and possibly showing vague NE-SE trends (Figure 3). Leonard & Boldra (2001) also raised the possibility they could have been point sources, considering the uncertainties in the locations.



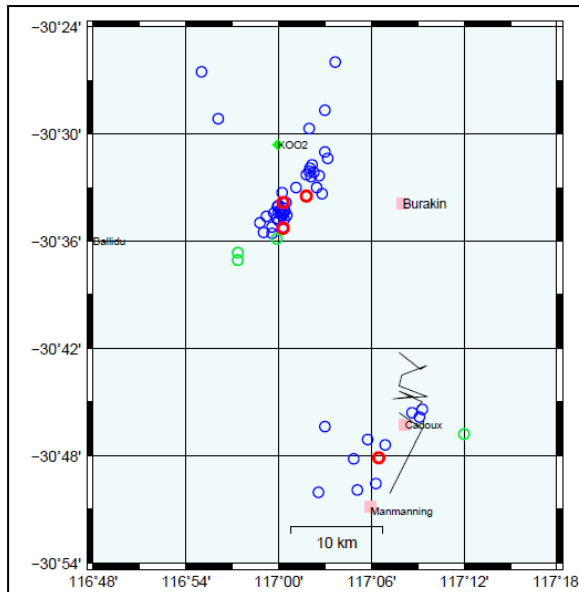
Location C was by far the most active location in 2001, containing 62 of the 80 “accurately located” events, and Leonard & Boldra’s plot of epicentres there showed a distinct north-easterly trend. Towards the end of the active period the seismicity appears to have moved from Location C to locations A and B. Leonard & Boldra (2001) postulated that “rapid stress transfer” was occurring between the locations, and fluid flow or creep in the lower crust were suggested as possible vectors for this stress transfer (Leonard, 2003).

**Table 6. The four source locations defined by Leonard & Boldra (2001)**

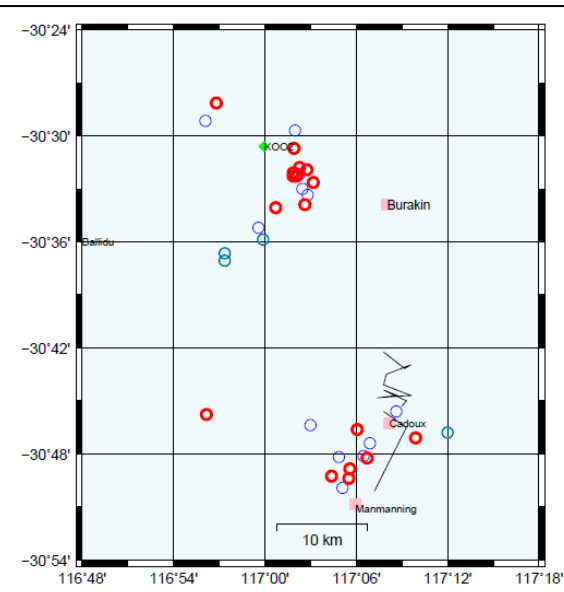
Name	Lon (E)	Lat (S)	shape	Location of zone	Comments
Locn A	116.95	30.45	NE ellipse diam ~10 km	20 km NW of Burakin	Few events
Locn B	117.05	30.53	Diam ~ 2 km	10 km NW of Burakin	
Locn C	117.10	30.62	Diam ~ 10 km	NW of Cadoux	NE trend, many events
Locn D	117.10	30.79	Diam ~ 5 km	Sth of Cadoux	NE trend? Few events

### **Previous activity 4 (Sep 2001 – Aug 2003)**

The Sep – Oct 2000 activity noted above seems to have been a precursor to the much more significant “Burakin swarm” (Leonard, 2002) which began on 28 Sept 2001 with an  $M_L$  5.2 event and included some 18,000 detected events thereafter (Leonard 2003), including two more events of  $M_L \geq 5.0$ . Temporary seismographs were deployed by GA at thirteen different locations in the area to record this activity, and many events were accurately relocated. Allen et al. (2006) presented a table of 67 “good” solutions (between 30 Sep 2001 and 6 Aug 2002) resulting from this survey. The end



**Figure 4A** events in Cadoux region in 2005. Events ML 3.5+ in red. event > 9 km deep in green



**Figure 4B** relocated events in Cadoux region in 2005. Blue circles= original locations, red circles=relocations

of the activity has not been defined, but appears to have continued at declining intensity into 2005. There were minimal events in the area in the years following 2005.

Events in the zone of  $M_L \geq 3.5$  from 2000 to 2009 are plotted on Figure 3. This figure suggests a NNE trend, consistent with the trend seen in the nearby Cadoux earthquake (1979) surface fracture, as seen on Figure 3.

In this review of 2005 activity, this zone will be discussed in two sections, the Burakin subzone, which contains the majority of the 2005 events (and contains the locations “A”, “B” and “C” of Leonard and Boldra 2001), and the much less active region (in 2005) to the south, the Manmanning subzone, (which contains location “D” of Leonard & Boldra, 2001).

## Burakin sub-zone

46 events occurred in the Burakin sub-zone in 2005 and activity, although declining, continued into

**Table 7. Significant events in the Burakin subzone in 2005**

Date	GA location		$M_L$	Depth (km)	SD	# arr	Remarks	Relocation		Depth (km)	SD	# arr	Remarks
	Lon (E)	Lat (S)						Lon (E)	Lat (S)				
4 Jan	117.061	30.433	1.5	2									
<b>12 Apr</b>	<b>117.005</b>	<b>30.564</b>	<b>4.0</b>	<b>0G</b>	.233	6							
<b>12 Jun</b>	<b>117.030</b>	<b>30.558</b>	<b>4.5</b>	<b>7.6</b>	.409	12							
14 Jun	116.956	30.618	1.6	<b>11.8</b>	.313	6	Deep	117.031	30.538	1C	.101	5	
23 Jul*	116.998	30.598	1.2	<b>11.8</b>	.319	6	Deep	117.044	30.565	2.8	.104	7	
26 Jul*	117.033	30.535	1.3	<b>0G</b>	.418	8		117.032	30.512	1C	.277	7	
29 Jul*	116.993	30.587	2.2	0G	.501	9		117.012	30.568	1C	.241	10	16k W
30 Jul*	116.935	30.486	1.0	2G	.344	6	nce?	116.947	30.469	1C	.104	6	Far Nth
1 Aug*	117.047	30.556	1.7	1.02	.126	8		117.053	30.544	1C	.079	9	12k W
2 Aug	116.917	30.442	1.0	0G			nce?	Not relocated, EQLOCL file not found					
10 Au*	116.956	30.611	1.5	<b>11.9</b>	.289	6	Deep	117.031	30.535	1.2	.038	8	13k W
21 Au*	117.041	30.550	1.8	4.9	.547	8		117.035	30.538	1.4	.148	8	13k W
28 Au*	117.033	30.495	1.4	5G	1.10	6	nce?	116.309	30.906	1C	.111	6	moves out
03 Oct	117.050	30.517	2.7	0G	.388	10		117.038	30.530	1.3	.135	7	
01 Dec	117.038	30.536	2.9	2.5	.253	12		117.046	30.532	2.8	.177	9	
	* Uses KOO2 in the solution						nce = non-cluster event						

2007. There were two events of  $M_L \geq 4.0$ , -12 Apr and 12 June (see Table 7), although there is reason to consider that magnitude of the event on 12<sup>th</sup> Apr is too high, as it was only recorded by three stations. Most of the activity in the zone is associated with the magnitude 4.5 event of 12 June. The principal events in the zone in 2005, and also the events which have been relocated (including three “deep” events), are listed in Table 7. Many of the events are close ( $< 5$  km) to the station KOO2, and this has assisted greatly in reducing the hypocentral uncertainties.

The GA locations appear to define a NE to NNE trending zone, consistent with the trend observed from the 2000-2003 epicentres. However, the group of relocated events (Figure 4B) does not show this trend, and the trend should now be considered doubtful.

Location “C” of Leonard & Boldra (2001), which was the most active location during the Sept – Oct 2000 activity, was devoid of activity during 2005.

### Manmanning sub zone

This sub zone was much less active than the Burakin zone in 2005, although it was the centre of activity at the time of the Ms 6.1 earthquake of June 1979. All of the located events which occurred in the zone during 2005 are listed in Table 8. There is only one significant event in this table, an  $M_L$  4.3 event on 12 June at  $30.80^\circ$  S,  $117.11^\circ$  E, which coincides with Location “D” of Leonard &

**Table 8. Events in the Manmanning subzone in 2005**

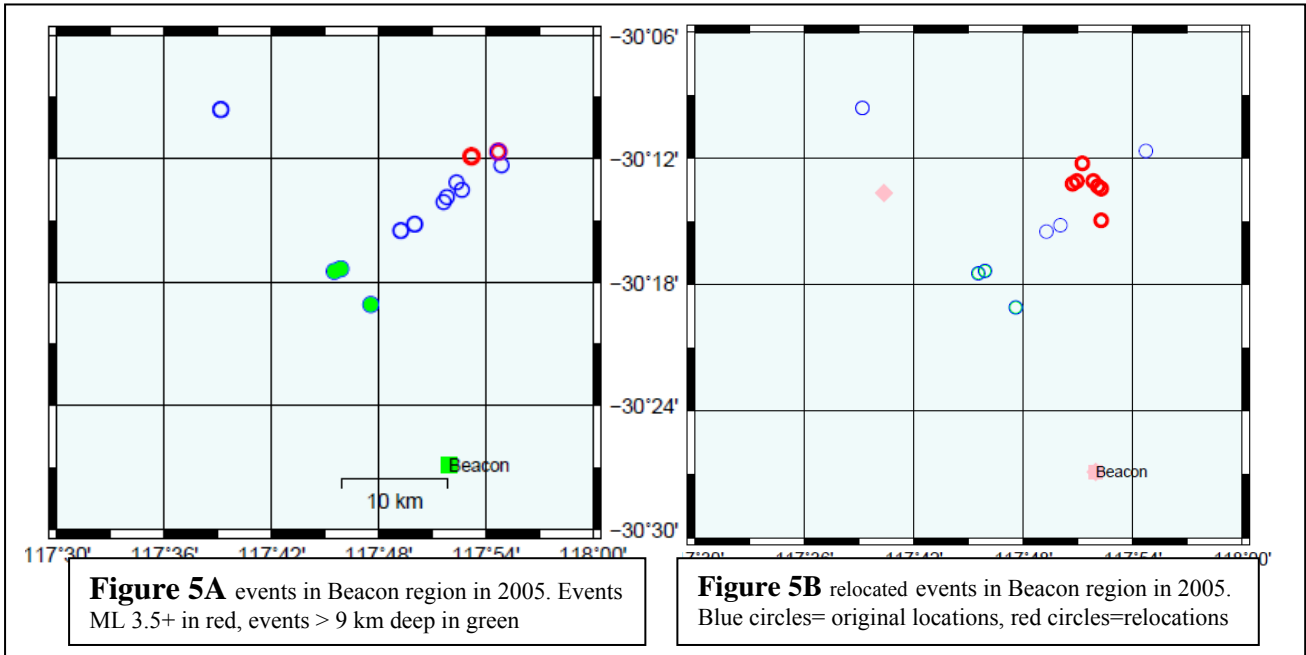
Date	GA location		$M_L$	Depth	SD	#arr	remarks	Relocation		depth	SD	#arr
15 Apr	117.105	30.826	1.7	0G	.345	8						
08 May	117.085	30.832	2.2	0G	.345	8		117.092	30.823		.097	5
11 May	117.043	30.834	1.8	0	.269	6		Cannot improve				
09 Jun	117.050	30.773	2.5	0	.384	7		116.936	30.763	0G	.176	6
<b>12 Jun</b>	<b>117.108</b>	<b>30.802</b>	<b>4.3</b>	2.2	.539	12		117.073	30.821	1C	.157	7
03 Jul	117.155	30.757	1.7	0G	.710	9						
11 Aug	117.081	30.803	1.3	5G	.538	8		117.101	30.777	1.1	.067	6
27 Aug	117.152	30.764	1.5	5G	.544	9						
08 Sep	117.144	30.760	2.9	0G	.552	12		117.112	30.804	0G	.085	7
08 Sep	117.115	30.790	2.4	0G	.746	8		117.093	30.814	0G	.137	5
21 Oct	117.096	30.785	1.7	0G	.371	9						
28 Dec	117.200	30.780	2.2	10G	.342	6	deep	117.165	30.785	1C	.019	5

Boldra, 2001 While there may be some clustering around this point, it is not nearly as pronounced in space and time as the clustering in the other zones. Interestingly, the  $M_L$  4.3 event was only 10 hours before the largest event of the Burakin sub-zone ( $M_L$  4.5). This might be taken as evidence supporting Leonard & Boldra’s proposition of rapid stress transfer in the area. Note that all but one of the events are to the west of the Cadoux fault scarp.

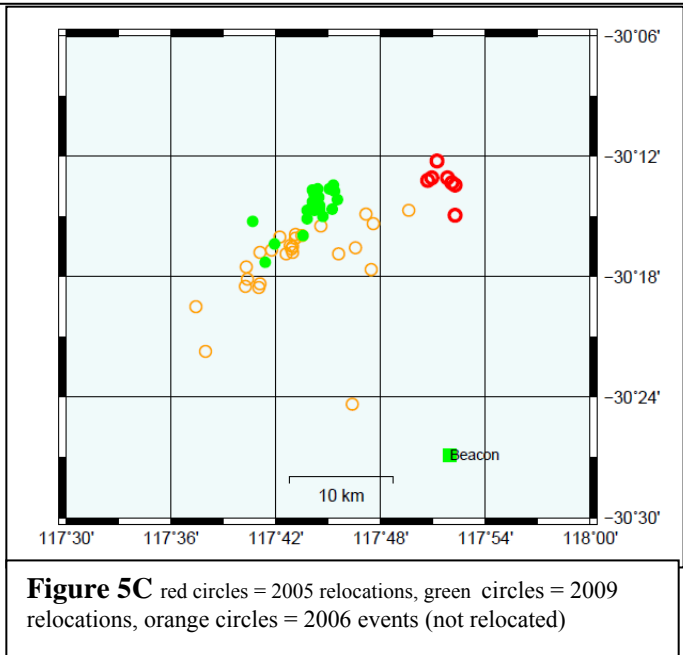
### 4.3 Northwest of Beacon ( $30.0 - 30.4^\circ$ S, $117.5 - 118.0^\circ$ E)

There was no activity in this zone in the 10 years before 2005, and activity appears to have begun there on 22 Apr 2005 (Table 9) with an  $M_L$  3.1 event, followed by an  $M_L$  4.1 event on 1<sup>st</sup> May 2005. There were 13 events in this zone in 2005, and they are plotted on Figure 5. Unfortunately, there were no seismographs close to this activity in 2005, with the closest station (KOO2) being about 50 km to the south





Relatively small events continued into 2006, and to a lesser extent into 2007 and 2008, but relocations for these events are not given here. The 2006 events are plotted on Figure 5C and show a distinct NE trend, but are to the west of the 2005 events. However they correlate well with the major swarm of 2009 (Dent, 2009) – see figure 5C. This apparent migration of the active source by about 10 km to the WSW between 2005 and 2009 warrants further investigation.



**Table 9. Events in the Beacon zone, 2005**

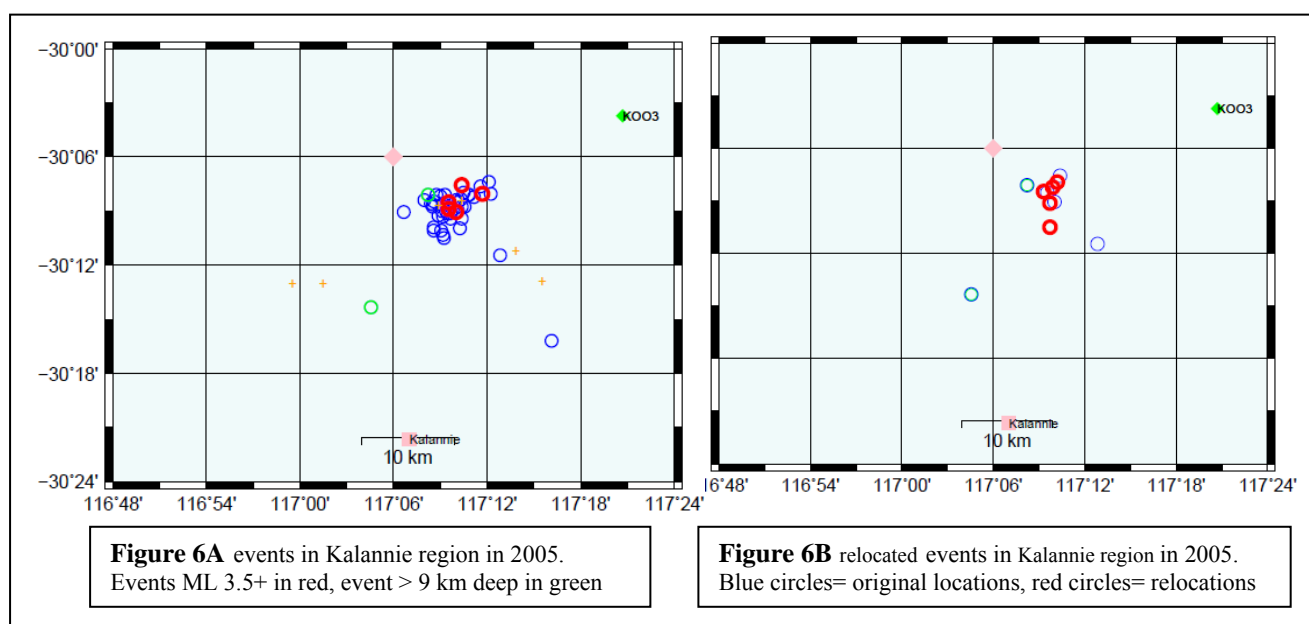
Date	GA location							relocation				
	Long	Lat	M <sub>L</sub>	dep	SD	#arr	remarks	Long	Lat	dep	SD	#Arr
22 Apr	117.861	30.235	3.1	0	.359	8						
01 May	117.912	30.194	4.1	2	.592	15		117.864	30.218	3.0	.264	9
01 May	117.834	30.253	2.0	3G	.391	6		117.868	30.222	1C	.082	5
01 May	117.887	30.198	3.6	0	.651	12						
10 May	117.759	30.291	1.8	13	.293	6	deep	117.849	30.218	1C	.193	5
12 May	117.765	30.289	1.9	13	.326	6	deep	117.845	30.220	1C	.360	5
17 May	117.915	30.205	3.3	0	.443	10						
01 Jun	117.821	30.258	1.8	3.2	.385			117.871	30.224	1C	.126	5
27 Jun	117.873	30.219	2.7	1.2	.478	10						
19 Aug	117.653	30.160	1.3	5G	1.01	5		117.854	30.204	1C	.147	4
22 Oct	117.878	30.225	2.7	2.9	.338	12						
22 Oct	117.864	30.231	2.0	2.2	.260	9						
02 Nov	117.793	30.318	1.3	12.5	.276	6	deep	117.871	30.249	0.5	.061	5
In Depth column, C and G indicate restrained focal depth												

Six events 2005 were relocated (including 3 “deep” events) and are plotted on Figure 5B – the relocations have brought outlying events into main grouping and, as with the Koorda events, the lineation becomes indistinct, and not to be relied on.

#### 4.4 North of Kalannie (30.0 – 30.4° S, 116.8 – 117.5° E)

This zone was the 2<sup>nd</sup> most active of the four zones during 2005, with 48 events, almost all being from 21 Sept on (Figure 6A). Only two small events prior to 20 Sept (i.e. 29 Jan & 14 July) do not belong to the cluster. The more significant of the 2005 events are listed in Table 10.

This seismicity cluster resulted in ground deformation that was detectable by satellite data, and was examined by Dawson et al., (2008). They used the satellite data to identify a deformation zone about 2 km in diameter and produce a highly constrained hypocentre, which they placed at 117.1700° E, 30.1484° S, +/- 120m. They assigned a focal depth of 1.15 km +/- 80m, and elevation change of ~27 mm. They were also able to define the fault parameters, and they concluded that it was a strike slip fault with a minor thrust component. The fault had a strike of 231° (i.e. approx NE-SW) and a dip of 52°. They could not conclude if the deformation was a result of the largest ( $M_L$  4.1) event, or from the combined effect of perhaps the five events of  $M_L \geq 3.5$ .



Robinson (2010) employed a new technique using coda wave data to constrain the locations of multiple close events. This technique can locate events in a relative sense with uncertainties which are an order of magnitude smaller than those from traditional approaches. He was able to conclude that the four largest events of the swarm were separated by distances less than the size of the events themselves, and they probably represent rupturing of overlapping segments of the same fault.

The relocations presented here (Figure 6B) agree with the area of deformation identified by Dawson et al., (2008). Unlike the other clusters described earlier, the GA locations do not display an obvious lineation. A possible northeast trend could be interpreted from Figure 7A, but considering the uncertainties in the locations, it cannot be relied on.

**Table 10 Significant events in the Kalannie zone, 2005**

Date	GA location		M <sub>L</sub>	dep	SD	#Arr	remarks	Relocation		dep	SD	#Arr
29 Jan	117.214	30.191	2.0	0G	.244	9	nce	Can't improve				
14 Jul	117.269	30.270	1.4	5			nce	EQLOCL file not found				
<b>21 Sep</b>	<b>117.159</b>	<b>30.148</b>	<b>4.0</b>	2								
21 Sep	117.167	30.151	3.7	.5	.344			117.162	30.152	3.0	.180	12
<b>22 Sep</b>	<b>117.173</b>	<b>30.126</b>	<b>4.1</b>	3.1	.404	22		117.165	30.137	2.5	.274	11
22 Sep	117.159	30.142	3.9	4.5	.564	16		117.170	30.132	3.3	.143	10
25 Nov	117.195	30.134	3.6	2.2	.333	13						
02 Dec	117.137	30.135	2.2	<b>13.7</b>	.719	10	deep	117.155	30.141	1.2	.109	7
nce = non cluster event												

From the conclusions of Dawson et al. (2008), it would appear that the 2005 Kalannie swarm could have analogies to the Eugowra NSW earthquake swarm of 1994 (Gibson et al., 1994). Using a network of close stations, they were able to show that the faulting occurred on a fault plane of very shallow depth (between 0 km and 1 km), and a dip of 38°. This would suggest that a much denser and more tightly spaced network of stations would be desirable for monitoring future SWSZ clusters, in order to define a potential fault plane.

GA only used data from KOO1 for one of its EQLOCL solutions, but KOO1 data is actually available for several of the larger events, and these data have been used for the relocations shown in Table 10. Relocation of the larger events has had little effect. However, the smaller (outlying) events have been brought into the main grouping.

## 5. Discussion

The vast majority of the 160 epicentres in the study area in 2005 have been found to be associated with four well-defined source locations. Only the 12 events in the Manmanning zone and another 6 from the other zones do not obviously belong to clusters. These events are usually small, and therefore have large uncertainties in their locations. The correlation of possible trends and cluster locations with geology/geophysics will be the subject of another paper.

Events of  $\sim M_L \geq 2.5$  are generally not moved much by relocation, but smaller events can be moved by up to 10 km.

The NE trends originally visible in the Burakin and Beacon clusters appear to be removed, or at least are far less apparent after relocation. However, the NNE trend in Burakin region epicentres, defined by high quality relocations of 2001-2002 events cannot be ignored. Also, the Koorda cluster seems to have retained its NE trend after relocating critical events.

The results of Dawson et al. (2008), suggest that the 2005 Kalannie events are on a NE-SW fault plane, but this cannot be confirmed from the data presented here.

The significant cluster east of Cadoux of Feb-Apr 1968 is poorly located, and could easily have been positioned at the location of the Koorda cluster, or closer to the location of the 1979 M<sub>S</sub> 6.1 Cadoux event.

## 6. Acknowledgements

Thanks to David Burbidge, Rob Dabrowsky and Owen McConnel of GA for facilitating access to Geoscience Australia's Kelunji and EQLOCL data, and to Clive Collins, Kevin McCue, Mike Dentith and Ed Cranswick for critiques of the manuscript.

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