Using the "PSN" seismograph network in southwest Australia to improve earthquake locations in the region

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Abstract

A new seismograph network in south western West Australia is providing extra data which can be used to improve Geoscience Australia earthquake locations in the area. The new data have been used to relocate 32 of the larger earthquakes in the region from July 2012 to August 2013. These solutions suggest the uncertainties in GA locations are normally in the order of 5 – 10 km, but can be significantly higher. They also suggest that most earthquake clusters in the region are more tightly grouped than the GA catalogue suggests. The solutions presented are also consistent with the hypothesis that all events in the region have shallow (< 5 km) focal depths. In order to improve locations in the region in general, more seismographs and a better velocity-depth model are needed.

1 Introduction

Geoscience Australia (GA) routinely locates earthquakes in Australia, including southwest Australia (SWA), using stations in the Australian National Seismograph Network (ANSN). In SWA, stations are at Mundaring, Kellerberrin, Ballidu, Narrogin, Rocky Gully and Morawa (purple diamonds in fig 1). Figure 1 also shows earthquake epicentres in the region (blue circles, diameter proportional to magnitude), located by GA between 1/7/2012 and 1/7/2013, and with magnitude (ML) ≥ 2.5.

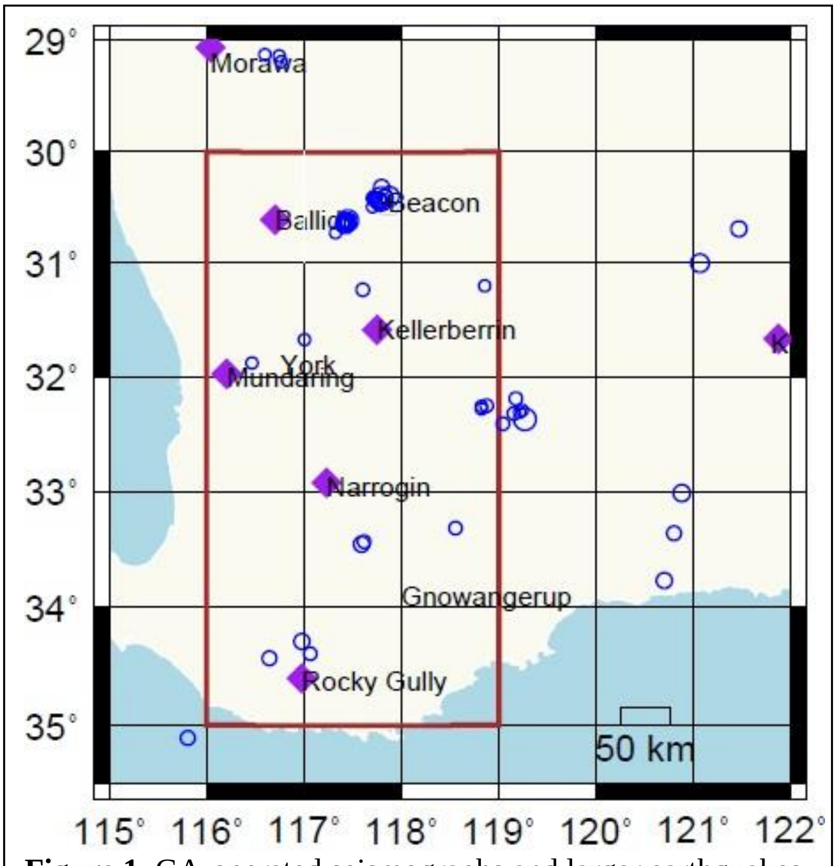

Figure 1. GA-operated seismographs and larger earthquakes (ML ≥ 2.5) in SWA, 1/7/2012 – 1/7/2013. Box shows region selected for study.

The earthquakes are often about 100 km from the nearest ANSN station, which means that location errors can be large.

From 2006, a non-governmental ("Public Seismic Network" or PSN) network has been developing across regions in Australia, including the SWA region (Dent et al., 2010). The term “PSN” was coined by Edward Cranswick in the USA in the 1980s, and was taken up by a group of enthusiasts, including Larry Cochrane, developing their own equipment. The initiative was prompted by the Loma Prieta (San Francisco) earthquake of 1989. PSN now generally refers to ”independent” seismic stations which use software and hardware marketed by Larry Cochrane (Redwood City, Ca., USA). All data are available on request, but format and delivery time can be very variable. In Australia, our stations are connected via the internet to a data centre operated by the Australian Centre for Geomechanics (ACG).

The PSN stations operate at a higher sampling rate than the ANSN stations (usually 200 s/s), and clear phase arrivals can generally be picked. However, the stations are not well calibrated, and reliable magnitudes are not generally obtained.

PSN seismographs in the SWA region are frequently closer to active epicentral subzones (e.g., points A-M in Dent, 2012) than the ANSN stations, and consequently, the data from the PSN stations can be particularly useful in improving locations in the area (though GA has not used the data).

The previous configuration of the PSN network was described by Dent et al. (2010). Several important changes were made to the network configuration in 2013, increasing its sensitivity in key areas. Specifically, new stations at Koorda, Pingelly and Kulin replaced closed or insensitive stations at Beacon, Pinjarra and Lake Grace.

In this paper, some of the recently acquired PSN data are added to GA phase data, to create a small new data set of improved earthquake locations in SWA.

2 A review of seismicity in the southwest seismic zone, July 2012-July 2013

Within SWA exists a generally accepted, but poorly defined, region of elevated seismicity, known as the southwest seismic zone (SWSZ). Several proposed boundaries for this region of higher seismicity have been used in the literature (e.g. Everingham, 1965; Michael-Leiba, 1987; Gaull et al., 1990; Leonard 2008). In this study, a simple rectangular area, as used by Dent (2011a), and shown in Figure 1, is used to approximate the SWSZ.

In this region, in the 12 months from July 2012 to July 2013, there were 267 events located by GA, of which 177 were of ML 2.0 and above, and 4 above ML 3.0. The largest event was ML 3.5, west of Beacon. This degree of seismicity could be considered relatively low for the SWSZ, though it is fairly typical of activity since the significant Beacon swarm in early 2009 (Dent, 2009).

To enlarge the relocation data-set, the time frame considered was extended to the end of August 2013.Within this region and timeframe, there are 44 GA-located events of ML $\geq$ 2.5. 15 of these events were not relocated because the PSN stations did not provide significant new phase data. To the relocation data set were added three events northeast of Hyden, which were just outside the zone boundary as originally defined. The events which have been relocated are listed (with an identifying serial number) in Table 1.

Table 1. Geoscience Australia's locations of events chosen for relocation

Serial#	Date	Time UTC	GA location		depth	RMS	Comment	ML
1	18/07/2012	0920	117.794	-30.429	2	0.71	Beacon 1	3.5
2	18/07/2012	1635	117.880	-30.405	3	1.21	Beacon 2	3.2
3	09/08/2012	0420	117.770	-30.436	4	1.08	Beacon 3	2.8
4	09/08/2012	0433	117.836	-30.411	6	1.05	Beacon 4	2.8
8	14/08/2012	1659	116.467	-31.877	0	0.99	W of York	2.5
9	27/08/2012	0456	117.325	-30.731	10C	0.86	Koorda 1	2.5
10	28/08/2012	0432	117.736	-30.427	5	0.8	Beacon 5	2.7
11	28/08/2012	1942	117.773	-30.438	0	0.33	Beacon 6	2.8
13	06/09/2012	1256	118.561	-33.320	0	0.98	Pingrup	2.6
14	21/09/2012	0853	117.705	-30.425	0	0.75	Beacon 7	2.6
16	09/12/2012	0741	117.608	-31.232	0	0.91	Wyalkatchem	2.6
17	12/12/2012	2048	118.824	-32.261	10C	0.99	Hyden #1	2.5
18	31/01/2013	2024	118.829	-32.281	10C	1.03	Hyden #2	2.5
25	25/04/2013	1213	118.859	-31.198	6	0.89	Westonia	2.5
26	17/05/2013	1511	117.456	-30.619	4	0.7	Koorda 2	3.3
27	22/05/2013	1047	117.066	-34.396	0	1.87	Kojonup 1	2.6
30	03/06/2013	1327	117.430	-30.630	0	0.44	Koorda 3	2.6
32	03/06/2013	2009	116.646	-34.435	10C	1.72	Kojonup 2	2.7
33	03/06/2013	2025	116.977	-34.292	0	1.37	Kojonup 3	2.9
34	13/06/2013	1530	117.439	-30.628	5	0.27	Koorda 4	2.8
35	16/06/2013	1047	117.398	-30.660	7	0.52	Koorda 5	2.6
36	05/07/2013	0153	117.591	-33.458	5	1.0	Katanning#1	2.9
37	05/07/2013	0319	117.618	-33.437	2	0.92	Katanning#2	2.6
38	09/07/2013	1609	117.004	-31.674	2	0.77	Meckering	2.5
40	20/07/2013	1524	117.702	-33.541	5	1.52	Katanning#3	2.5
41	23/07/2013	0934	117.905	-30.857	9	0.93	Bencubbin#1	2.8
42	01/08/2013	0416	117.959	-30.913	0	0.80	Bencubbin#2	2.9
43	15/08/2013	0529	118.906	-30.361	10C	1.02	Bonnie Rock	2.6
44	21/08/2013	1102	117.655	-33.449	0	0.85	Katanning#4	2.9
A	03/03/2013	1325	119.248	-32.292	10C	0.99	Hyden #3	2.5
B	03/03/2013	2136	119.276	-32.375	1	0.52	Hyden #4	3.4
C	29/06/2013	1511	119.220	-32.312	10C	1.2	Hyden #5	2.5

The majority of these events originated from three significant clusters, one about 12 km west of Beacon (2 events of ML 3.0 and above), and the other, about 40 km to the southwest, or about 20 km north of Koorda (also with 2 events ML ≥ 3.0). The Koorda site appears to be the same location as an important swarm in 2005 (point F in Dent, 2012). The west Beacon location seems to be new.

The third cluster occurred on the eastern boundary of the zone, north of Hyden, and contained at least 28 events with 2.0 ≤ ML ≤ 3.4. These events are quite scattered (figure 1), but the events are relatively poorly located, being outside of the network of seismographs in the region.

3 Earthquake location methods

Earthquakes in the region are initially located by GA. GA switched its earthquake location method from EQLOCL (developed by Gary Gibson and others) to Antelope (Boulder Real

Time Technologies) in mid-2009. In this semi-automatic location procedure, it is difficult to incorporate data from external sources and GA has not generally used S phase arrivals in its solutions.

In this paper, seismic events are located using EQLOCL. Other differences from the GA method include putting greater weight on close stations, and very little weight (or none at all) on more distant stations. Also, S arrivals are given very little weighting, except if the stations are close (< ~ 50 km), and the S arrivals are demonstrably clear, and can be read with reasonable precision. Focal depths are very difficult to determine without quality data. No studies of SWA earthquakes, using high quality and near-field data (e.g. Allen et al., 2006) have found focal depths greater than 5 km. In these relocations, if the EQLOCL program does not find an acceptable depth for the event (i.e. between 0 and 5 km), focal depths have been constrained to either 5 km or 1 km.

New data from the PSN stations in the area have been added, and the weightings of the ANSN arrivals have been modified where considered appropriate. Frequently, phase arrivals from distant stations (~ 200 km) which were used in the GA solutions, have been omitted from the relocation process here.

Some variations between the GA location and the new location can be attributed solely to the change in assigned depth from 10 km to 1 km.

3.1 Crustal structure model used

The crustal structure model used in the relocations was WA2. This 2-layer model was developed (Dent, 1990) to replace the old, single layer model used at the Mundaring Observatory (WA1). A derivative of this model is still used by GA for Antelope locations of West Australian events. It is generally considered that the model needs updating, and in particular, a low-velocity layer near the surface is needed (e.g. Somerville & Ni, 2010).

3.2 Focal depths used

In the relocation process, the EQLOCL program is initially allowed to find its own optimum depth. Quite often, however, the focal depths tend to become negative – in this case, the focal depths are constrained at 1 km depth. The trend of the focal depths to become negative is interpreted as indicating the model is not wholly valid in this region.

Less frequently, the program finds greater depths for an event, ~10km or sometimes more. In these instances the focal depth has been constrained to 5 km, because this is the approximate depth suggested by well-constrained events in the region. Restraining the focal depths usually causes very little change to the standard deviation (SD) of the residuals. More often, it exposes a suspect phase arrival, which has then been deferred from the location procedure.

4 Results

Twenty nine earthquakes have been relocated. Data from the original GA solution are shown in Table 1, and from the new solutions in Table 2.The distance between the GA location and the new location is also shown in Table 2. Because the new locations generally use more data, and closer data than the GA locations, and the RMSs are lower, they are considered to be better than the GA locations. The new locations have been assigned a subjective accuracy code, from A to C. The discrepancies between the GA locations and the relocations range from 1 km to ~ 40 km, with an average value of 10 km, and a median value of 7 km.

The original locations, and the relocations, are plotted on Figure 2, and will now be discussed in more detail. Because the events are clustered, this discussion will consider the relocations in cluster-groups.

Table 2. Relocations of events listed in Table 1

Ser #	Long	Lat	Comment	ML	Depth	Phases	Stns	SD	Diff (km)	Qual
1	117.76	-30.45	Beacon 1	3.5	3.5	7	4	0.122	4	A
2	117.76	-30.38	Beacon 2	3.2	1 C	5	3	0.074	12	C
3	117.75	-30.44	Beacon 3	2.8	1 C	5	4	0.133	2	B
4	117.78	-30.37	Beacon 4	2.8	1 C	5	3	0.073	7	C
8	116.45	-31.91	West of York	2.5	1.4	8	5	0.367	4	B
9	117.46	-30.60	Koorda 1	2.5	1 C	6	3	0.22	0	B
10	117.79	-30.39	Beacon 5	2.7	3.4	7	5	0.188	6	A
11	117.82	-30.36	Beacon 6	2.8	3.7	5	3	0.119	12	C
13	118.53	-33.34	Pingrup	2.6	5 C	5	4	0.48	4	C
14	117.74	-30.41	Beacon 7	2.6	2.8	4	3	0.0	4	A
16	117.67	-31.26	Wyalkatchem	2.6	1 C	5	4	0.252	7	C
17	119.01	-32.24	Hyden	2.5	5 C	6	4	0.127	19	A
18	118.93	-32.30	Hyden	2.5	1 C	5	3	0.429	10	C
25	118.78	-31.20	Westonia	2.5	5C	5	4	0.187	8	C
26	117.42	-30.65	Koorda 2	3.3	1 C	5	4	0.226	5	C
27	117.07	-34.42	Kojonup 1	2.6	5 C	6	6	0.334	2	C
30	117.40	-30.6	Koorda 3	2.6	5 C	4	3	0.162	4	C
32	117.07	-34.34	Kojonup 2	2.7	5 C	5	3	0.333	43	C
33	117.01	-34.30	Kojonup 3	2.9	1 C	5	4	0.126	3	B
34	117.44	-30.64	Koorda 4	2.8	1 C	5	3	0.12	1	B
35	117.42	-30.62	Koorda 5	2.6	5 C	5	3	0.835	5	C
36	117.68	-33.45	Katanning #1	2.9	5 C	7	6	0.249	9	A
37	117.70	-33.46	Katanning #2	2.6	1 C	7	5	0.165	9	A
38	117.05	-31.68	Meckering	2.5	5 C	8	6	0.921	5	A
40	117.74	-33.45	Katanning #3	2.5	5 C	6	5	0.13	10	B
41	117.91	-30.98	Bencubbin#1	2.8	5 C	5	4	0.148	12	B
42	117.85	-30.96	Bencubbin#2	2.9	5 C	7	7	0.505	12	C
43	118.61	-30.39	Bonnie Rock	2.6	5 C	7	6	0.200	44	C
44	117.72	-33.45	Katanning #4	2.9	5 C	6	6	0.071	7	B
A	118.99	-32.39	Hyden	2.5	5 C	5	5	0.143	28	A
B	119.18	-32.44	Hyden	3.4	5 C	6	5	5.4	12	C
C	119.21	-32.35	Hyden	2.5	5 C	5	4	0.306	4	B

4.1 Clustered earthquakes

4.1.1 North of Hyden

There were ~30 events of ML ≥ 2.0 in this region during the life of the cluster, i.e. between Dec. 2011 and June 2012, of which 10 were of ML ≥ 2.5. Only two of these (#17, 18) are inside the area defined in Figure 1 and have been relocated. Three large events just east of the zone boundary, including the largest of the cluster (ML 3.4) have also been relocated, and are labelled A, B and C in Table 1. The PSN station at Kulin, installed in February 2013, was the closest to the earthquakes, but events in the cluster are still hard to locate well because the seismographs (other than Kambalda, KMBL) are all to the west of the events. Relocations of #17 and #18 do not use new data at all, but have been relocated because they are plotted on the extremities of the cluster, and are anomalously deep (i.e. 10 km). The epicentre plot of Figure 2 suggests two possible event sources about 30 km apart, but the likelihood is that there is only one source zone, which is indistinct because of the poor locations.

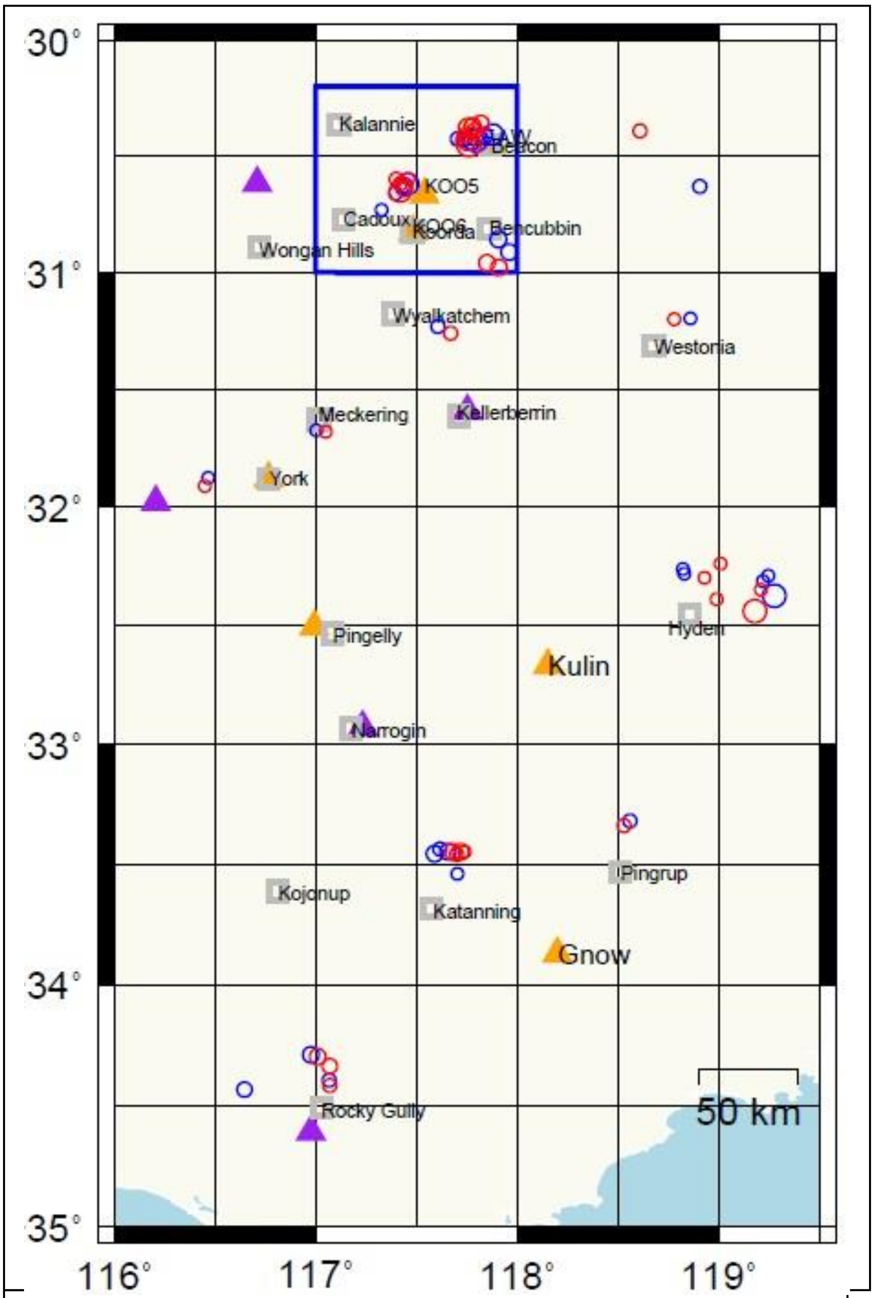

Figure 2_ Map showing GA and new locations. Original GA locations – blue circles. Relocations – red circles PSN seismograph locations – orange triangles. Grey squares – towns. The area in the blue rectangle is enlarged in Figure 3.

This cluster may well be at the same location as a cluster which occurred north of Hyden in September 2006. The largest event in that cluster was magnitude (ML) 2.5.

4.1.2 South of Kojonup

The GA locations suggest three events in May and June 2013, spread over about 30 km. Event #32 has been relocated by ~ 40 km to be close to event #33, about 20 minutes later. All three events are probably from the same location.

4.1.3 North of Katanning

The GA locations of these four events are relatively close (~ 20 km) – however the relocations bring them still closer (within ~ 5 km of each other).

4.1.4 North of Koorda

The Koorda/Beacon region is shown in detail in Figure 3. Approximately 120 events above ML 1.5 were located there from mid-2012 to late 2013.The PSN station KOO6 (opened in February 2013) is about 20 km south of this cluster, and is important in constraining the locations. A station KOO5 operated about 10 km east of the epicentres in September and October 2012, and recorded some small cluster events. The S-P times of these events at KOO5 are all close to 1.3 secs. This S-P has been notionally applied to one of the relocated events (event #34) and the resulting solution is considered to be close to representing the true location of most of the events in this cluster. This location is close to (~ 3 km) the location assigned to a significant cluster in 2005 (point F, -30.64, 117.47, Dent 2012), and it is possible, even probable, that they originated from the same location. The location presented here should be preferred as it uses better (closer) data than were used in the 2005 locations.

4.1.5 West of Beacon

This seismic cluster was active throughout much of 2012, and approximately 90 events over ML 1.5 were located by GA .The PSN station at Beacon (closed December 2012) recorded the majority of these events, as well as many smaller ones, too small for GA to locate. The S-P's of the Beacon recordings show a very narrow range (1.3-1.5 secs), indicating that the events are in reality very tightly grouped.

Six earthquakes have been relocated using Beacon PSN phase data, but in general, arrival time residuals are still greater than desired. It would be hoped that most computed P phases would be within ~ 0.1 sec of observed times, and S arrivals within ~ 0.5 secs, but this in general has not been achieved.

Event #14 is considered very well located (i.e. quality "A") as it uses the S-P time from a temporary station (BEAW) which was sited about 1 km from the epicentre. It is probable that this location more closely represents the true location of the majority of the events in this cluster. The very short S-P time (0.37 secs.) indicates a maximum focal depth of ~ 3 km for the event.

The inability of the computer solutions to reduce to a well-defined point is probably due to inadequacies in the velocity-depth model used (WA2 – Dent, 1990). This model has a 2 layer crust, the upper layer having a P velocity of 6.13 km/s, and the lower layer 7.1 km/s. It is generally accepted that a thin surface layer with a relatively low velocity exists (e.g. Somerville and Ni, 2010), and the absence of such layer in the WA2 model may explain much of the mismatch between computed and observed travel times.

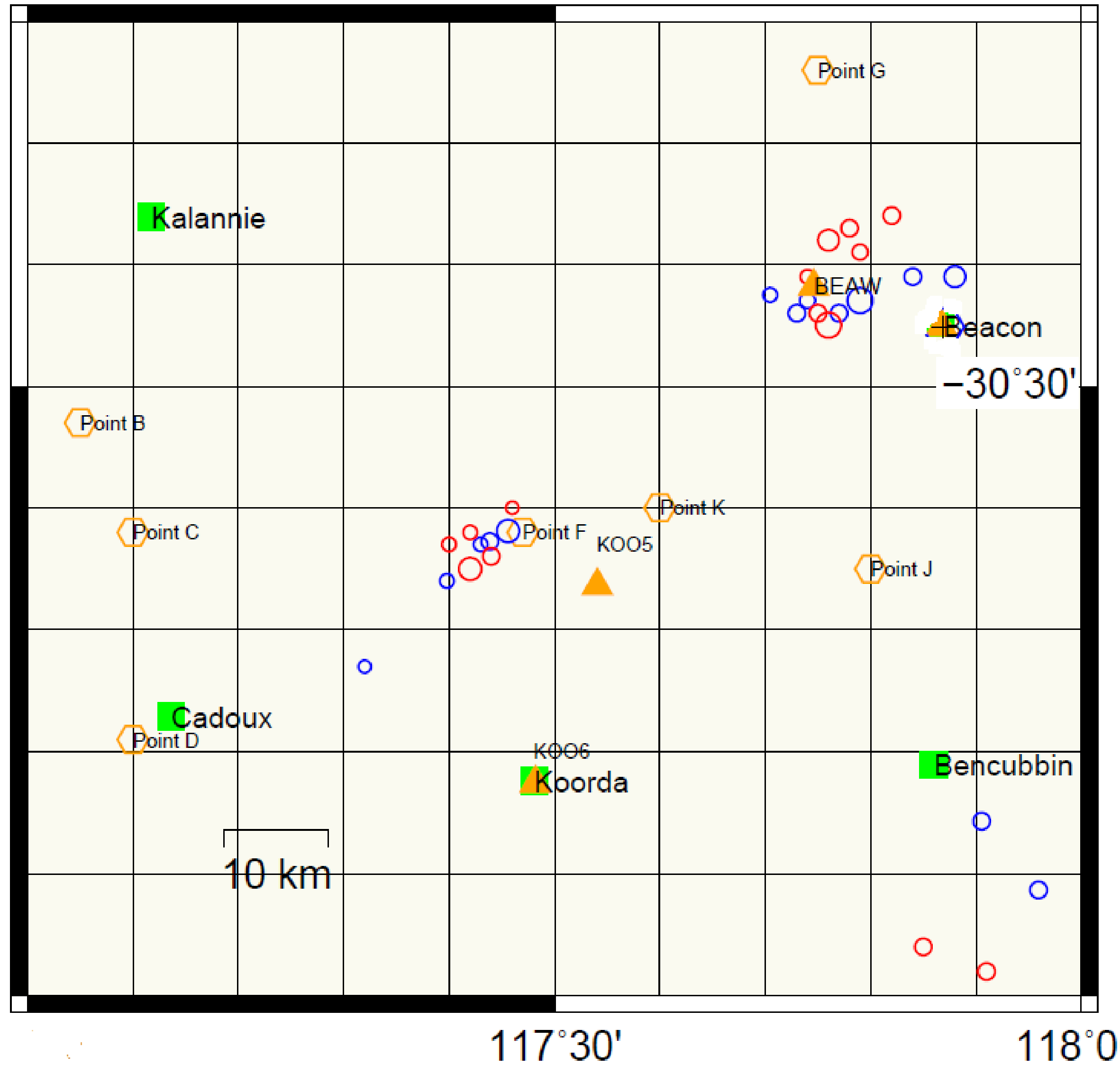

Figure 3. West Beacon and Koorda relocations in greater detail. Blue circles =original GA locations: Red circles = relocations: Orange triangles = PSN seismograph locations: Yellow hexagons = well-located cluster sources, from Dent (2012)

4.1.6 South of Bencubbin

Two events of close to the same size (events # 41 and #42, ML 2.8 and ML 2.9) occurred south of Bencubbin, about a week apart. Relocating the events brings them closer together, but their position, on the edge of the seismograph network, means that the locations have relatively large uncertainties.

4.2 Non-clustered earthquakes

Apparently non-clustered events occurred near, York, Pingrup, Wyalkatchem, Westonia, Meckering and Bonnie Rock, although the York event was accompanied by one smaller located event on the same day.

The Wyalkatchem event is close to the assumed centre of a swarm that occurred in September-October 2011 (point I, -31.25, 117.45, Dent, 2012). Clusters have been recorded previously near Pingrup, and perhaps Westonia. Meckering was the source of thousands of events following the Magnitude 6.7 event there in October 1968 (Gordon & Lewis, 1980).

5 Factors contributing to poor locations

Other than the probability that the earth model does not match the actual conditions, contributing to a poor location, the following possibilities seem to account for some of the poor locations.

1. One or more of the normal ANSN network stations in the region is not supplying data
2. Two seismic events arriving almost simultaneously obscure phase arrivals
3. The events are near the boundaries of the local seismograph network

Only events of ML ≥ 2.5 have been considered here. The more numerous smaller events can be considered overall to be even less accurately located than these events, because there will be fewer phase arrivals available to locate the events, and the phases are also likely to be harder to read accurately.

Looking at meta-data provided with event locations, it is not necessarily easy to identify events of poor precision – often the SD of residuals is similar to that for better located events. Also, while the number of stations and phases used is noted, it does not tell if a “critical” close station was not operating at the time.

6 Discussion

Accurate locations are needed to determine if events are in the same location, or just close to, important historic seismicity. They could also be useful in looking for correlations between seismicity and local geology (faults) and/or topographic features. GA locations of larger events in SWA are probably within 5 to 10 km of the correct earthquake location. Poorly located earthquakes could affect event-declustering algorithms used in earthquake hazard studies.

Increasing the number of seismic stations is likely to lead to better locations, so the new PSN network is useful in contributing to this. In addition, because the network lowers the earthquake magnitude detection threshold, the network is potentially useful for verifying assumptions on the magnitude-completeness level of the GA earthquake catalogue in this region. Leonard (2008) has stated that the GA catalogue is complete for events of ML > 1.5 in SWA since 1990, but a frequency-magnitude plot of events in the Beacon swarm of 2009 (Dent 2009) suggests many events between ML 1.6 and ML 1.9 have gone unlocated.

The relocations presented here still have much room for improvement. Consideration needs to be given to more innovative ways of earthquake location, such as the Double Difference method (Waldhauser and Ellsworth, 2000).

More field data are available from temporary deployments around the west Beacon and Koorda clusters, and when they are processed, a better idea of the swarm locations should be achieved.

6.1 Focal depths of swarm events

All swarms so far studied in the SWSZ in any detail, have been shown to have, or probably have, shallow focal depths (< ~ 4 km). These include Burakin (2002-2003, Allen et al., 2006), Yorkrakine (1996-1998, Dent, 2011b), and Lake Mollerin (Dent, 2011, 2012). S-P times extracted from very close (< ~ 2km) stations to the 2012 west Beacon swarm suggest a maximum focal depth of ~ 2km. There are insufficient data to constrain focal depths for the Koorda (2012-2013) swarm, but the data that are available are consistent with shallow focal depths for events in that swarm too.

7 Conclusions

Factors limiting the accurate location of earthquakes in SWA, and which are partially remedied by using PSN data include 1) insufficient seismograph coverage, and 2) data 3399sampling rate not high enough. Other factors that need to be addressed to improve locations include 3) an inaccurate velocity model, 4) inadequacies in the capabilities of the location program itself, 5) lack of expertise in determining which arrivals to use and the weighting given to them, 6) invalid focal depth assumptions, and 7) incorrect phase identification.

Relocations of earthquakes using additional data from PSN stations have resulted in the earthquakes in clusters becoming more tightly grouped. However, an accurate assessment of hypocentre distribution within clusters has not yet been obtained.

8 Acknowledgements

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