Evidence for a linear aftershock distribution from a survey near Myrtle Springs, SA, December 1994

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Abstract. An array of temporary seismographs was deployed by PIRSA to record events in an important earthquake cluster in the northern Flinders Ranges of South Australia in Dec 1994-Jan 1995. Earthquakes relocated using data from this survey occurred in a narrow zone about 3 km long, trending to the northwest. Focal depths are estimated to be between 3 and 5 km. The northwest trend approximates that of the Norwest Fault, a short distance to the northeast of the epicentres. However, this fault is believed to dip to the northeast, and so these events were apparently not on this fault, although a splinter fault is a possibility.

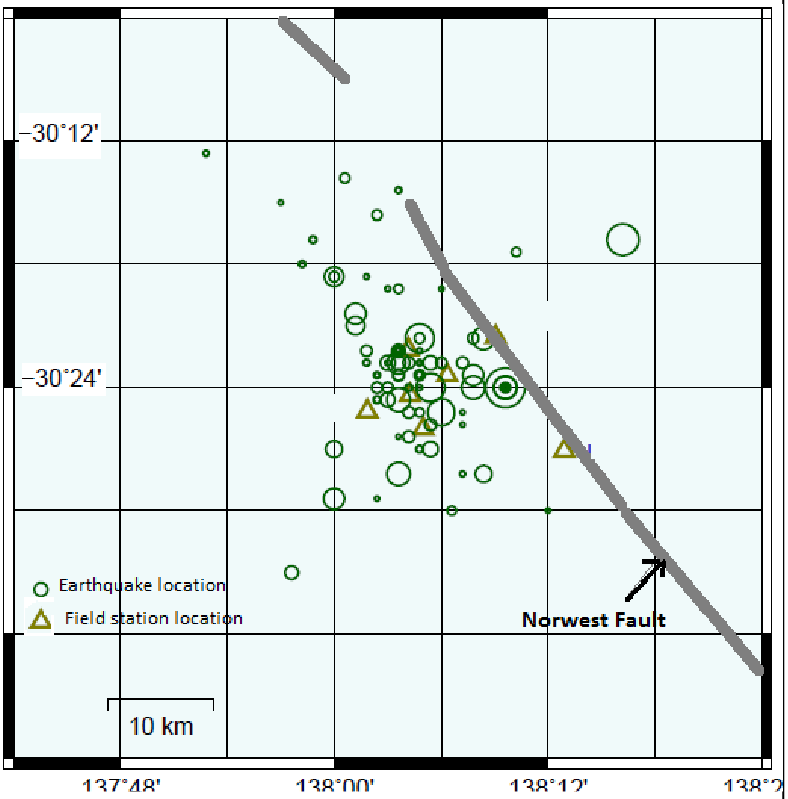
1 Introduction

A magnitude 4.2 earthquake occurred northwest of Leigh Creek, in the Flinders Ranges, about 450 km north of Adelaide, on 29th November 1994 and was followed by a sequence of hundreds more events over the next couple of weeks. This region, in the northern Flinders Ranges, is noted for its elevated seismic activity, and falls within the “Adelaide Geosyncline” seismic zone as defined by Gaull et al. (1990), zone 16 of 29 zones encompassing most Australian seismicity. The event was the largest in South Australia since 1990. A later event (5th December at 2049 UTC) is listed in the Geoscience Australia (GA) catalogue as having a

Figure 1: Geoscience Australia locations of major earthquakes (1991 – December 2011)

magnitude (M_L) of 4.6, but data from the Primary Industry & Resources of SA (PIRSA) regional network suggests this is an over-estimate, and they assigned an M_L of 3.6 to this event. It was not until March 1997 that a larger event occurred (Burra, M_L 5.0). GA locations of major SA events (1991 – December 2011) are shown in Figure 1.

Figure 2. PIRSA locations of Myrtle Springs events



PIRSA locations of events in the Myrtle Springs sequence are plotted on Figure 2, and the largest events are listed in Table 1. The distribution of events with time is shown on Figure 3. After an initial burst of activity on 29th-30th November 1994 there was a brief lull until 5th December, from which day on there were about four days of high activity. Seismic activity increased again in late January 1995, and occasional events continued until mid 1995.

A review of the PIRSA earthquake catalogue data suggests some precursory activity, as early as 28 August 1994. Many of the larger events in the cluster were felt strongly at the Myrtle Springs homestead, approximately 20 km ESE of the activity.

Figure 3 Distribution of events with time

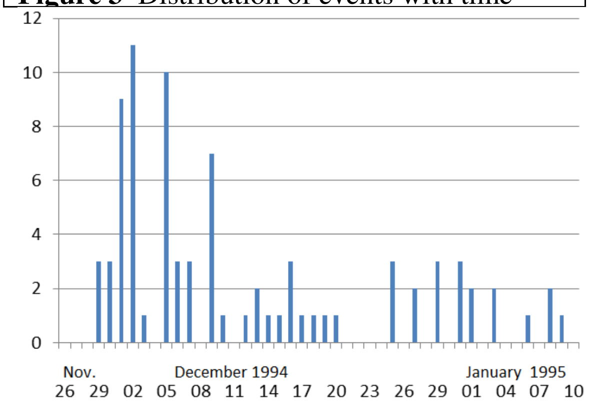


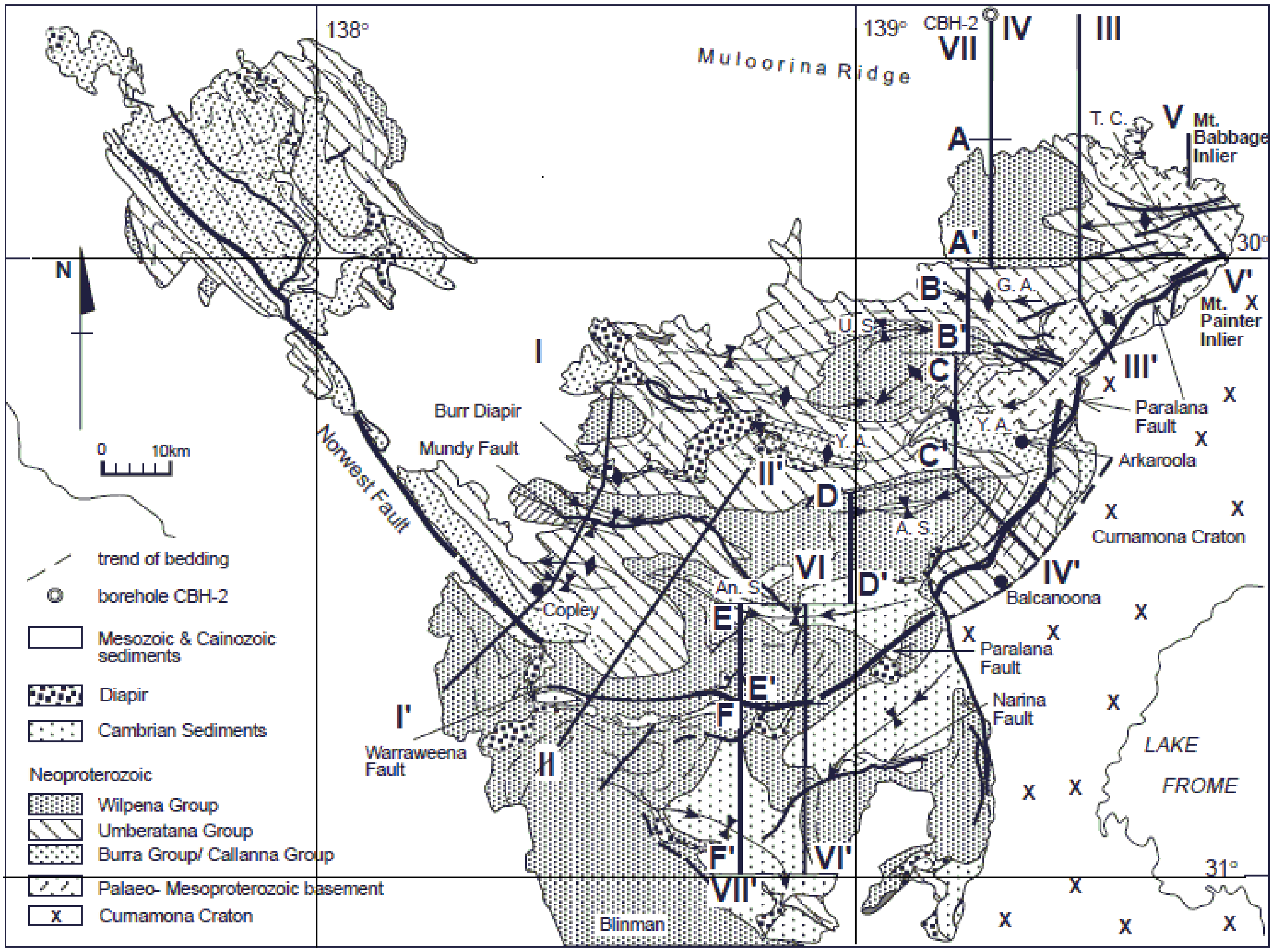
Table 1 PIRSA locations of Myrtle Springs events (M_L ≥3.0)

Date	UTC	M_l	Lat.	Long.	Dep	acc	Comment
30 Nov	1953	4.0	-30.40	138.16	5.1	C	GA M_l 4.2 reloc to acc B
30 Nov	2014	3.0	-30.40	138.16	5 G	D	Analyst constrain depth
30 Nov	2023	3.1	-30.40	138.16	5 G	E	Analyst consttrain depth
01 Dec	1809	3.0	-30.36	138.14	5.2	D	
05 Dec	1946	3.3	-30.41	138.06	6	D	
05 Dec	1957	3.0	-30.38	138.06	11	D	
05 Dec	2029	3.1	-30.47	138.06	5 G	D	relocated to accuracy C
05 Dec	2049	3.6	-30.28	138.27	12	D	GA M_L **4.6,** Reloc. to C
05 Dec	2102	3.4	-30.40	138.09	8	D	
05 Dec	2116	3.4	-30.36	138.08	1.3	D	relocated to accuracy.C
07 Dec	0532	3.3	-30.42	138.10	8	D	
09 Dec	1553	3.1	-30.40	138.13	5	D	relocated to accuracy A
12 Dec	0203	3.1	-30.34	138.02	13	C	relocated to accuracy A
23 Jan	1744	3.2	-30.49	138.00	8	C	
27 Mar	0444	3.3	-30.39	138.13	6	C	

1.1 Regional Geology

The geology of the northwest Flinders Ranges (from Paull et al., 1999) is shown in Figure 4. Although composed of Precambrian rocks, the Flinders Ranges are believed to be a relatively young topographic feature, and continue to build relief today (e.g. Sandiford, 2003; Quigley et al., 2007). The earthquakes occurred proximal to the significant "Norwest" fault, which trends NW-SE and dips to the northeast. This fault forms the southern boundary of a prominent northwest trending range. Figure 4 indicates that rocks forming the range are thrust over the rocks to the southwest.

Figure 4. Geology of the Northern Flinders Ranges (from Paull et al., 1999)



2 – Seismograph deployment

The first PIRSA instruments to be installed were a seismograph and accelerograph, at the Myrtle Springs homestead (code MYS0) on the 5th December 1994, which were connected by telephone to Adelaide. Other seismographs were installed closer to the epicentral zone on 8th /9th December. All instruments were "Kelunji Classics" sampling at 200 samples/sec, and with Omega timing. Data from the instruments were reviewed on 10th December, resulting in MYS2 being moved to MYS7, and MYS6 to MYS8

The stations were serviced on 16th December. MYS0 was closed on 4th January 1995 and the rest on 9th January.

Stations MYS3, 5 and 6 were close to the epicentres, and so good locations with some depth control are possible

Table 2 Station coordinates and Operational Periods

Stn	Lat	Long	opened	closed	Remarks
MYS0	-30.4513	138.2154	05th Dec 94	4th Jan 1995	+accelerograph?
MYS2	-30.3591	138.1513	08th 0631	11th Jan 0054	+accelerograph?
MYS3	-30.4334	138.0835	09th 0439	10th Jan 0015	
MYS4	-30.3690	138.0693	09th 0734	17 Jan 0344	
MYS5	-30.4193	138.0308	09th 0626	09th Jan 2303	
MYS6	-30.4063	138.0709	08th 0734	11th Dec 0141	
MYS7	-30.4063	138.0709	11th 0200~	10th Jan 0149	Replaces MYS6
MYS8	-30.3900	138.1055	11th Dec	17th Jan 0417	

when data from those stations are available. MYS8 malfunctioned, and only P phase arrivals can be confidently determined from it. Considering the era of digital field seismographs was only just beginning at the time, the Myrtle Springs cluster was extremely well monitored. Operational dates and locations of the field instruments are listed in Table 2, and the locations are plotted on Figure 2.

3. Myrtle Springs earthquake locations

3.1.1 Accuracy Codes

Table 3 shows the codes used by PIRSA to assign uncertainties to their locations of regional seismic events. Events in Table 1 are not considered well located, and have accuracies ranging between "C" and "E". For this study, where some very accurate epicentres have been obtained, a new category, A! (i.e. location uncertainties < ~1 km) has been introduced.

Table 3 - PIRSA codes for location uncertainties

Code	Uncert-ainty	Remarks
A!	< 1 k	This rept.
A	< 2 k	
B	2 – 5 k	
C	5 -10 k	
D	10-50	
E	>50 k	

3.1.2 Notes on earthquake location procedures

Up to six portable seismographs were deployed by PIRSA in the epicentral zone between 5th December 1994 and 10th January 1995, enabling some events to be located to accuracies A and A! Much data were collected by this survey, and only data from the larger events have been examined in this report.

Locations for events in any cluster are not unique, because they depend on the velocity model chosen, and the phase-arrival data set used. Thus there are usually small differences between PIRSA and GA locations for the located events of the Myrtle Springs swarm. Solutions presented here should be preferred to solutions which may be found in GA or PIRSA catalogues, because of the extra precision that close arrival-time data (recorded at high sample rates) provide.

Larger events in the cluster (M_L > ~ 2.5) were located by PIRSA shortly after their occurrence, using the EQLOCL location program together with data from "regional" seismographs. The PIRSA stations were all over 150 km from the epicentres, so most locations were assigned a low accuracy (D, i.e. +/- 10-50km).

In this study, some of the previously located events have been relocated. However the field instruments have also allowed good locations to be made for small events which were not detected by the PIRSA regional seismic network.

The velocity-depth model used by PIRSA for their routine locations is SA1A, a simple model, and assuming a single-layered crust. This model, and others discussed in this paper are summarised in Table 4.

Table 4. Synopsis of Velocity-Depth Models

Model = SA1A			**Model = VIC5A**			**Model = TESTM**			**Model SH01**	
Depth	P vel	S vel	**depth**	P vel	S vel	**depth**	P vel	S vel	**depth**	P vel
0-38	6.23	3.58	0-3.63	5.12	3.13	0-5.15	4.00	2.60	0-18	5.94
> 38 k	8.05	4.60	8.46	6.01	3.57	6.72	6.00	3.52	18-39	6.46
			17.17	6.04	3.59	17.17	6.04	3.59	> 39 k	7.97
			35.61	6.45	3.69	35.61	6.45	3.69		
			> 36 k	7.81	4.46	> 36 k	7.81	4.46		

The first relocations of Myrtle Springs events using survey data were made in 1995 and a multi-layered model, VIC5A, was used. This is the model usually used for Victorian earthquakes, and has lower velocities than the SA1A model. This model was found to give better results (lower S.D. of residuals) than the SA1A model. A test model was also constructed at that time (MYS5A), and was used in some trial locations.

P wave arrivals are usually sharp and relatively easy to pick accurately. However S wave arrivals are often more emergent, and consequently have larger uncertainties. Thus it is acceptable for S wave arrivals to have larger "residuals" than P waves. The best-located events can be expected to be those where close seismographs surround the events.

3.2 New earthquake locations using field-station data

Considering the points above, a limited set of locations considered to be of high quality is shown in Table 5 and plotted on Figure 5. The table only contains events from December 9th because the full set of seismographs was not in place until then. December 9th was the last day on which numerous swarm events of magnitude > 2.0 occurred.

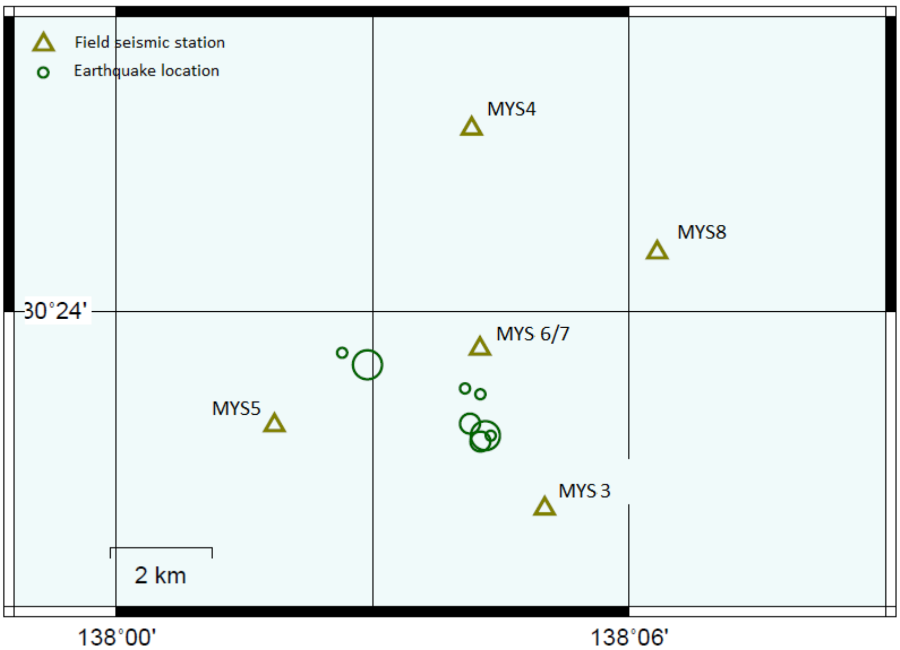
The criteria for an event to be listed in Table 5 are that it must have been recorded at MYS3, MYS5, and MYS6 (or its replacement, MYS7), which were close stations surrounding most of the events, and at least one of the slightly more distant stations, MYS2, MYS4 or MYS8. The plot of good locations (Figure 5) suggests a linear epicentral zone about three km. long which trends SE-NW, and with the majority of events at the south-eastern end of the zone. However, it must be remembered that the well-located events all occurred several days after the largest events, and may not represent the cluster as a whole.

Table 5. Events located to Accuracy "A"

DEC '94 Dy HrMn	**Mag** (M_L)	**Stations** (in order*)	**Longit.**	**Latitude**	**Depth** VIC5A	**Depth** TESTM	Acc	Remark
09,0959	--	6,5,3,2,0	138.059	-30.411	3.4	5.9		new
09,1527	1.4	6=3,5,4,(2)	138.073	-30.421	3.0	5.1	A	
09,1531	--	6,3,5,2	138.076	-30.420	3.5	5.9		new
09,1550	2.1	6,3,5,4,(2)	138.071	-30.422	2.8	4.8	A	
09,1553	3.1	6,3,5,4,(2)	138.072	-30.421	3.2	5.2	A	big
09,1841	--	6,3,5,4,(2)	138.069	-30.419	2.7			
09,1930	2.0	6,3,5,4,2	138.071	-30.420	1.5	4.6		new
12,0203	2.9	5=7,3,4,8	138.049	-30.409	3.4	4.7	A	big
12,0303	--	7,3,5,8,4	138.068	-30.413	2.6	3.8	A	
12,0606		7,3,5,8	138.073	-30.421	2.5		A	
12,0636	--	3,4,5,7,8	138.071	-30.414	2.5	3.6	A	
12,1538	--	6,3=5,8,4	138.061	-30.415	2.7	4.2	A	
13,1907	1.5	5,7,3,4	138.045	-30.408	2.8	4.7	A	

- Equal (=) sign is used where two arrivals are at the same time

Figure 5. Myrtle Springs events, accuracy "A" locations.



The locations in Table 5 have been made using P arrivals because of the relative uncertainty of the S wave arrivals. The S arrivals did not fit the solutions well, and this is probably because the earth model used does not accurately reflect the local geological conditions. However the VIC5A model, with slower velocities near the surface, is more likely to match the local geology, considering the alluvial sand cover in the area and the relatively shallow focal depths of the events. When future research produces a better model for the area, observed S wave arrivals will probably agree more closely with theoretical values.

3.3 Location Accuracy

The accuracy of a location can be gauged from the standard deviation (S.D.) of the residuals. Good solutions have a low S.D. Location accuracy is also influenced by the number of recording stations and seismic phases used, the closeness of the stations, and their azimuthal distribution around the earthquake. If all stations are to one side of an event, then the "gap" angle will be > 180 degrees and a less-well constrained solution results.

Table 6. S-P times and S wave residuals (Vic5A and TESTM models)

Event dy,hhmm	Stat-ion	**S –P** secs.	Epic dist	Resid **VIC5A**	Resid. **TESTM**
09,1553	MYS6	blocky	1.7k		
	MYS5	0.9(e*)	4.0k	.30	-.01
	MYS4	1.10(e)	5.8k	.33	.05
13,1907	MYS5	0.70		.30	.01
	MYS3	1.07		.43	.16
	MYS4	1.09		.43	.16
09,0550	MYS3	0.54	1.8k	.15	-.16
12, 0203	MYS7	??	2.1k	.23	.08
	MYS5	0.73	2.1k	.17	.02
	MYS3	1.02	4.3k	.26	
	MYS4	1.09	4.8k	.27	.17
	MYS8	Blocky	5.8k		
12, 0303	MYS7	0.57	0.8k	.25	.03
	MYS3	0.71	2.7k	.28	.06
	MYS8	0.72	4.4k	.13	-.07
12, 0636	MYS7	0.57	0.8k	.25	.06

*e = emergent arrivals

3.4 Focal depths and Velocity models.

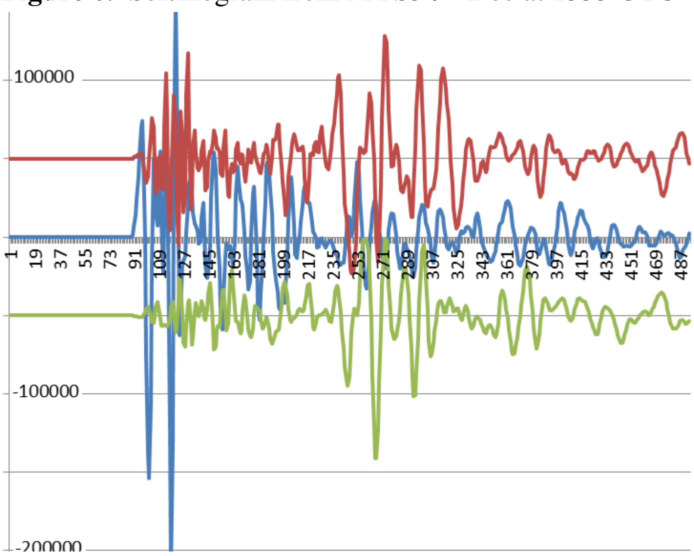
Because computed focal depths are relatively sensitive to the velocity-depth model used, it is important to discuss the models used here in some detail. The most recently published velocity model in the South Australian region is the Shackleford-Sutton model (SH01 – Collins 1988). It was constructed using data from field surveys in the region of the Adelaide Geosyncline. The SH01 model has a mid-crustal discontinuity at 18 km, with the P velocity above being 5.94 km/s, and below being 6.46 km/s. An S wave velocity was not determined. The SH01 model was used for locations in a major survey of the seismicity in the southern Flinders Ranges between 2003-2004.

The SA1A model as used by PIRSA is an apparent simplification of the Shackleford-Sutton model in that is a single-layer model, with a P velocity close to the average of these two P velocities in the SH01 model (i.e. 6.23 km/sec).

Where temporary stations surround the Myrtle Springs events, changing the velocity model will not greatly affect the latitude and longitude of the locations, but will affect the focal depths. A model with faster P velocities will produce solutions with a shallower focal depth.

Using the VIC5A model, the positive residuals for the S phases (i.e. arriving later than predicted) suggest longer hypocentral distances, which means slightly greater focal depths. Table 6 shows observed S-P times and S wave residuals for some of the located events. Figure 6 shows a typical waveform (MYS3, 9th December @ 1553 (2.4 secs. of data)).

Figure 6. Seismogram from MYS3 9th Dec at 1553 UTC



Refraction surveys undertaken in the region by PIRSA (Taylor, 1988) suggest basement P wave velocities may be as low as 4.0 km/sec in some places, below an alluvial cover between 70 and 270 m thick. This is about 20% less than that used by the VIC5A model. A P velocity of 4.0 km/sec was applied in a new model, "TESTM" (Table 4), and locations using this model have produced slightly deeper focal depths than the other models, and also give close agreement between calculated and observed S wave arrivals (Table 6).

3.5 Relocations of lesser precision

There are two other groups of events for which relocations can be made, but to a lesser degree of accuracy than the events listed in Table 5.

Group 1). In this group of events, the only additional data are from the relatively more remote (~20 km) station MYS0. This set of events is earlier in the sequence and the events are usually larger than the events in Table 5. They were located by PIRSA using standard network data in 1994-95, but with addition of MYS0 phase data, considerably more constraint on the epicentres has been achieved. This allows an estimate of the uncertainty in conventional earthquake locations in this area.

Table 7 Relocated earthquakes with accuracy ratings of "B" and "C".

Date	**Ml**	Original (PIRSA) location				Relocation					
Dec. 1994		**Longitude**	**Latitude**	**depth**	**Acc.**	**Longit**	**Latitude**	**Dep.**	**Stns**	**Comment**	**Acc**
		(SA1A model)		km				km	&order		
05,1937	2.1	138.058	-30.388	12.1	D	138.063	-30.385	4.9	MYS0	Little change	C
05,1957	3.0	138.062	-30.383	11.6	D	138.095	-30.376	9.2	MYS0	Little change	C
05,2029	3.1	138.056	-30.466	5G *	D	138.075	-30.456	5G	MYS0	Little change	C
05,2049	**3.6**	138.269	-30.277	12.2	D	138.050	-30.395	4.2	MYS0	Big move	C
05, 2102	3.4	138.094	-30.398	7.7	D				MYS0		
05,2116	3.4	138.080	-30.364	1.3	D	139.049	-30.345	5.4	MYS0	Little change	C
07,0259	2.3	137.957	-30.548	8.5	D	138.070	-30.376	2.7	MYS0	Big move	C
07,0532?	3.3	138.102	-30.423	7.7	D	138.102	-30.423	7.8	MYS0	No change	C
08,1555		Not PIRSA located				138.074	-30.421	3.4	6,2,0		
09,0635	2.0	138.011	-30.228	9.1	E	138.071	-30.412	2.5	6,3,2,0		
09,0959		Not PIRSA located				138.059	-30.411	3.4	6,5,3,2		B
09,1205		Not PIRSA located				138.075	-30.420	3.4	6,3,5	New event	B
09,1531		Not PIRSA located				138.076	-30.420	3.5	6,3,5,2		B
09,1930	2.0	138.079	-30.363	7.2	C	138.071	-30.420	1.5	6,3,5,4		A
10, 0613	1.9	138.168	-30.292	5G	D				3,6,5		
14,0458	1.3	138.508	-30.972	8.0	E						
16,0640	1.4	137.951	-30.254	9.8	E	138.037	-30.406	4.4	5,4,3,0		B
23,1845		Not PIRSA located				138.012	-30.432	0.8	7,5,8	New event	B
25,1125	2.4	138.031	-30.370	9.9	D	138.062	-30.412	2.1	4,5,7,8		B
25,1229	1.7	137.982	-30.279	12.2	C	138.064	-30.421	3.7	4,5,7,8		B
28, 1444	1.6	137.968	-30.301	10.5	E	138.054	-30.406	1.1	4,5,7,8		B
28,1512	1.7	138.157	-30.402	5G	F	138.056	-30.411	1.9	4,5,7,8		B
29,1803	2.5	138.049	-30.382	10.9	C	138.074	-30.434	4.0	4,5,7,8		B
06/1/ 1833	1.5	137.883	-30.213	8.3	E	138.012	-30.432	4.4	7,5,4		B
• G indicates depth was constrained by the analyst											

The MYS0 station recorded the second-largest event of the cluster on 5th December, (GA M_L 4.6, PIRSA M_L 3.6). Both GA and PIRSA locations place this event considerably northeast of the main grouping of events, but using MYS0 data to produce a new solution brings the event back close to the main grouping of events. The SA1A model was retained for relocations using MYS0, to retain consistency with the original PIRSA locations.

Group 2). The network of temporary stations close to the epicentral zone has also allowed the location of other small events which did not quite meet the stringent criteria for an event to qualify to be included in Table 5. The VIC5A model was used for these locations and they are mostly assigned accuracy "B".

Figure 7 Relocated Myrtle Springs events of lesser accuracy

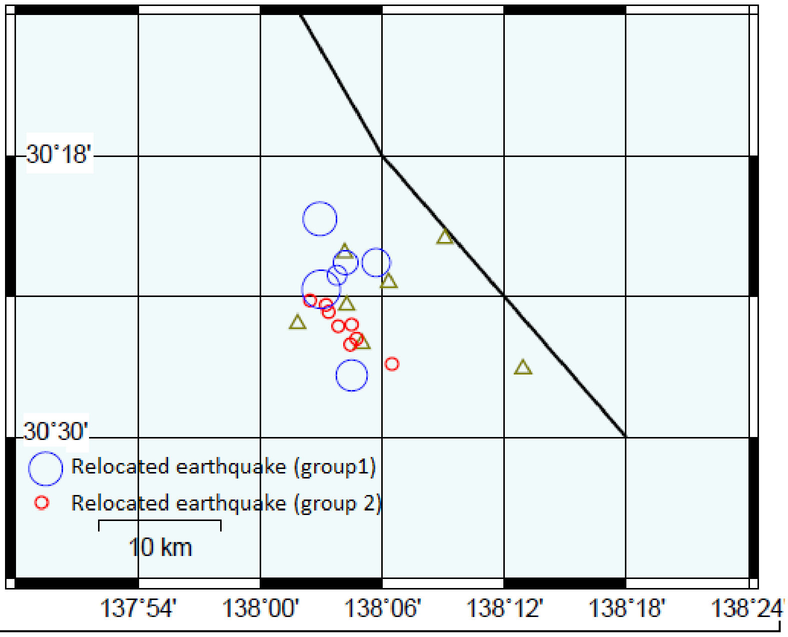


Table 7 shows the events and their relocations, and they are plotted on Figure 7. All of the focal depths are significantly less than the PIRSA depths. The new depths probably more closely reflect real depths, although the uncertainties are still high.

The relocated PIRSA epicentres (i.e. group 1 above) are more concentrated around the epicentral region than they were initially, but are still somewhat scattered. Accuracy "B" locations, which use data from the temporary network are approximately linear (NW-SE) and follow the trend of the accuracy "A" locations.

Using well located events presented here, it may be possible in the future to "invert" the data to construct a better velocity-depth model for the region. If such a model is constructed and applied, it is possible that there may be even more convergence of the epicentres towards the epicentral zone described above.

4 – Discussion and conclusions

The best-located events (accuracies A and B) suggest a NW-SE trending zone, with a greater density of events at the southeast end of the zone. GA and PIRSA locations of mostly earlier and larger events are not accurate enough to display this zonation.

The epicentres define a lineation rather than a plane. The uncertainties in depths are too great to permit interpretation of a three-dimensional feature.

The epicentres are offset from the mapped position of the Norwest Fault, but appear to be parallel to it. Positive correlation of seismicity with specific faults is relatively uncommon in Australia, but the possibility of a connection in this case seems fairly real. In this region of the Flinders Ranges, the Norwest fault is largely concealed by Quaternary alluvium, and there may be some inaccuracy in its mapped location. When the fault reappears above the alluvium to the northwest, the map suggests a small change in its orientation. The Myrtle Springs events may have occurred on a splay or a splinter fault associated with the Norwest fault. The data suggest that the depths of the best located events are between 3 and 5 km, and probably at the deeper end of the range. It will be difficult to reduce the uncertainty until the velocity-depth model is better constrained.

Further processing of the field data would allow many more events to be located, but not necessarily to a high degree of accuracy. Focal mechanisms for the better-located events may be determined at some future date.

The new and improved locations give a unique opportunity to gauge the uncertainties in the routine earthquake location procedure using the permanent PIRSA network. Relocations using data from close stations shows that routine locations are normally within 10 km of the epicentres, but may be up to 20 km out.

4.1 Swarm-like characteristics, and comparison with some other recent seismic clusters.

Considering that a magnitude of 4.6 assigned to the event on 5th December is probably an over-estimate, the Myrtle Springs cluster becomes more like a typical main-shock/aftershock sequence than an earthquake swarm. However, the cluster was included in a discussion of about 30 earthquake swarms, Australia-wide, which occurred between 1983 and 2007 (Dent 2008). In Table 8 some of the pertinent features of the Myrtle Springs cluster are compared against some other recent important Australian earthquake clusters, although some descriptors used (e.g. "duration of main phase") are fairly subjective. The Burakin cluster of 2001-2003 (Leonard 2002) in the southwest seismic zone of WA (SWSZ) is by far the most significant, and the Beacon 2009 (SWSZ) sequence (Dent 2009) was also significant. The Myrtle Springs cluster seems similar to the Yorkrakine 1996 (SWSZ) sequence (Dent 2011), although the Yorkrakine sequence had a much longer duration.

Table 8 - Comparison of some important recent seismic clusters

Feature	**Myrtle Springs 1994 - 1995**	**Burakin 2001-2003**	**Beacon 2009**	**Yorkrakine 1996-1998**
M_L of Max. event	4.2	5.1	4.8	4.6
M_L of 2nd event	3.6	5.0	4.3	4.2
Duration of main phase	29 Nov 1994 - 9 Dec 1994	25 Feb -3 Apr 2002	30 Jan 2009 - 26 Feb 2009	30 Aug – 12 Sep 1997
# events $M_L \geq 4$	1	7	6	2
# events $M_L \geq 3$	15	52	50	23

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