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A review of aftershock data for the ML 5.0 Kalgoorlie event, April 2010

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ABSTRACT: An ML 5.0 earthquake occurred in the Kalgoorlie-Boulder area on 20th April 2010. An aftershock survey conducted by Geoscience Australia provided locations for about 300 aftershocks which occurred from 3 to ~ 45 days after the event, and a north-south oriented zone possibly correlating with the Boulder-Lefroy Fault was suggested by Bathgate et al. (2010). Nearly 40 of the aftershocks detected by GA have been relocated here using the program EQLOCL and data provided by GA. Two models were used, which were similar to those used by Bathgate et al., and extra data from a nearby seismograph have been used where available. Relocations of events with extreme focal depths (~ 0 km and > 2.5 km) have suggested they have more "normal" depths, of around 1.5 km. The new locations suggest a degree of clustering of aftershocks in 3 areas, all within an epicentral zone about 1.5 km wide, but no depth trends are evident. More research is needed to determine the best earth model for the region. Focal depths are dependent on the earth model applied, and a new model may suggest slightly deeper focal depths. Data from ACG stations indicate that many of the larger aftershocks which occurred before, or after, the survey are much closer to the epicentral zone than published solutions suggest.

1 Introduction

The Kalgoorlie-Kambalda region of Western Australia is a recognised area of above average seismicity. It was labelled Source Zone 7 in Gaull et al. (1990), and they characterised the seismicity as "mainly resulting from rock burst in mines in Kalgoorlie". Magnitude 4 events in the area are a relatively common occurrence (six events since 1960). However, the ML 5.0 earthquake on 20th April 2010, about 0.5 km south of Boulder, and 1 km west of the Kalgoorlie Consolidated Gold Mines (KCGM) super pit (Figure 1) was the first of this size in the region. It caused significant damage in the Boulder town area (Edwards et al. 2010), and the estimated damage was just under $10 million (J.E. Daniell pers. comm. 2015).

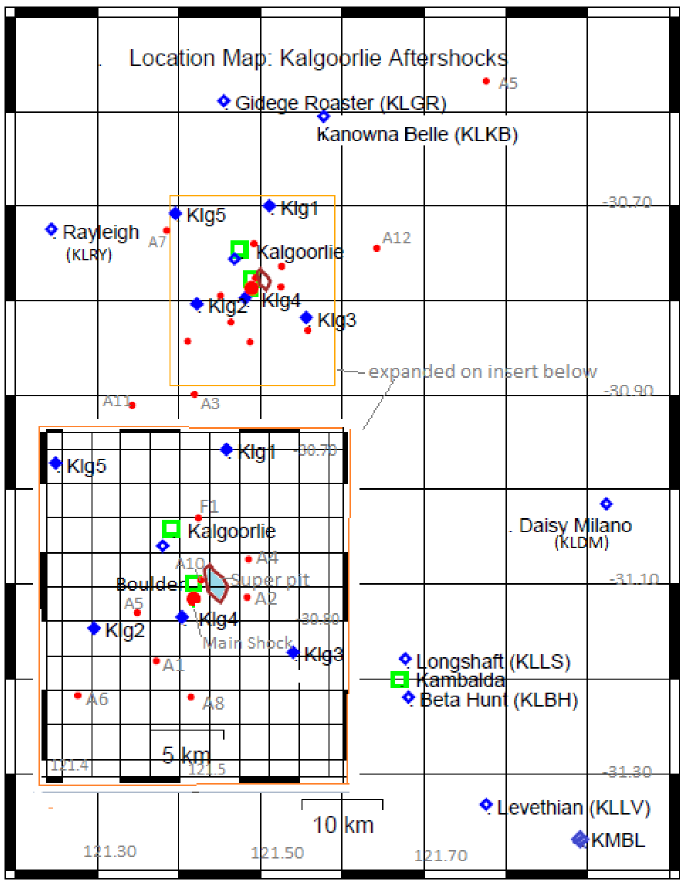


Figure 1 Location map, Kalgoorlie Aftershocks. Red circles= foreshock (F) & aftershocks (A) of ML 5.0 event of 20th April 2010. Diamonds = seismic stations, open = ACG operated, closed = GA operated.

In the Geoscience Australia (GA) database there are 12 probable aftershocks of the event (until 19th Sept. 2010), labelled A1 to A12 on Figure 1, with a magnitude range between ML 2.0 and ML 2.9. GA locations are normally made using data from the Australian National Seismograph Network (ANSN), and the nearest station to this event was at Kambalda (KMBL), some 70 km south. The next nearest station is ~ 400 km to the west, at Kellerberrin. This sparse network means that normally locations in the region are not very precise. For the 20th April event however, several mining companies in the area provided phase data from the Australian Centre for Geomechanics (ACG) network, allowing a relatively good location to be made. An aftershock survey consisting of 5 field instruments (KLG1 – KLG5, Figure 1), was conducted by GA following the event (Bathgate et al. 2010) and was in place by 23rd April, or 3 days after the main Kalgoorlie event. The stations were deployed over a six week field season (to 8th June 2010), and resulted in 544 new seismic event locations. It is estimated that about a half of these were aftershocks of the 20th April event, and the remainder were blasts relating to nearby mining activity.

The closest survey station to the aftershocks was KLG4, which was about 1 to 2 km south of most of the events. A close station is required to get good depth control for the relocations. The survey data was collected at 100 samples/sec, which is a relatively low value considering the nearness of the events.

Bathgate et al. (2010) concluded that the aftershocks extended for about 3 km in a north-south direction, in an area just south of Boulder. Most were less than 2 km deep. A small number were between 3 and 4 km deep, and no events were deeper than 4.5 km. GA used the Antelope location program (Boulder Real Time Technologies, Colorado, U.S.A.) to locate the aftershocks. They suggested that the events originated from activity on the westerly dipping Boulder Fault, which, at its closest, is about 0.5 km east of the epicentral zone.

The events were located by GA using two earth models, WA2 and IASPEI91. The IASPEI91 model (Kennett & Engdahl, 1991) has a P wave velocity about 5% lower (5.8 km/sec) than the WA2 model (Dent, 1990). The "preferred" solutions (ie with the lower RMS of residuals) were a mixture of solutions from both models, although the IASPEI91 model solutions comprised the majority. Bathgate et al. (2010) suggested that the IASPEI91 model was better because it supplied the majority of preferred solutions, and in the case of located blasts, the IASPEI locations were closer to blasting sources than the WA2 solutions. Bathgate et al. (2010) did not discuss the location quality in terms of the probable errors in latitude, longitude and depth. Magnitudes were not determined.

Additional data available to supplement the data set.

The Australian Centre for Geomechanics (ACG) operated a network of about 14 low-cost seismographs in the Kalgoorlie-Kambalda region (Dent et al. 2006) at the time of the Kalgoorlie events (Figure 1). Continuous data from eight of these stations have been made available for this review, although because of high noise levels in the vicinity of the mines, only Cheetham St. (KLGC) has provided significant amounts of useful data. KLGC is of particular significance, as it was the nearest of the ACG stations, and only about 3 km north of the epicentral zone. Access to data from the other stations has remained restricted, although phase arrival data have been provided for the main (ML 5.0) event.

This report is divided into a discussion of activity in three periods. Period A discusses the week before the aftershock survey was fully in place (17th to 23rd April), which includes the main shock and two relatively large aftershocks located by the ANSN network. Period B covers the first period of data collection of the aftershock survey (24th April to 6th May). There were two ANSN-located aftershocks in this period and about 200 hundred smaller events were detected by the aftershock survey. GA has made phase data for this period of the survey available for review.

Period C (16th May to the end of the survey, 8th June), is discussed only briefly as data for this period was not supplied. There were three more ANSN-located aftershocks in this period, as well as ~200 more small events detected by the GA survey.

2 Events in Period A (17th to 23rd Apr 2010)

This period commences 3 days before the main event, and includes an ANSN-located ML 2.5 event on 17th April (since determined to be a blast from the Mt Charlotte gold mine). It continues until the start of the aftershock survey (24th April). Three ANSN-located aftershocks (A1-A3, Table 2) occurred in this period.

2.1 Events on 20th April 2010

The main event (ML 5.0) occurred at 00:17 hours GMT on 20th April, and GA located one aftershock on that day (event A1 on Figure 1, ML 2.6 at 22:24 hrs). The GA database solution for the main event is 30.787 S, 121.489 E (Figure 2), at a depth of 2 km. GA used a combination of phase data from the ACG network, and more remote ANSN stations to arrive at this location, but information on the exact stations used, and the model used, is not available.

The author has relocated the ML 5.0 event, using data from the ACG network, and using the EQLOCL program. EQLOCL was routinely used by GA for its earthquake locations until mid-2009. The DAL1A earth model was used as it has similar velocities to the IASPEI91 model in its upper layers. The DAL1A model was used by the Seismology Research Centre, Melbourne, for locating earthquakes near Eugowra, NSW – a granitic area hosting shallow earthquakes (Gibson et al. 1994). The solution arrived at is 30.793 S, 121.476 E (Appendix 1, the "Regional Seismic Network" or "RSN" solution), and a depth of 1.5 km. This solution used P phase arrival data from 5 close stations, and three S phase arrivals and is about 1.5 km southwest of the GA solution. Other data from more distant stations were deferred, as including them in the calculations increased the residuals for the close station data which are considered more reliable than the more distant data.

The uncertainties in location given by EQLOCL are about +/- 2.5 km in latitude and longitude, and +/- 9 km in depth (Appendix 1). These values are very conservative, and it is suggested that the uncertainties are probably about +/- 1.5 km in position, and +/- 2 km in depth, within about a 90% probability.

Table 1 Velocity-Depth models used by EQLOCL in aftershock relocations

WA2			DAL1A			SYD1		
depth	P vel	S vel	depth	P vel	S vel	depth	P vel	S vel
0 – 19 km	6.13	3.62	0 - 10.5	5.8	3.35	0 – 2.0	4.8	3.0
			10.5 - 26.5	6.3	3.64	2 – 7	5.8	3.45
			26.5 -31	6.9	3.98	7-18	6.36	3.74
19 - 36.5	7.14	3.96	31 - 50	7.35	4.24	18-41	6.8	3.93
> 36.5	8.27	4.75	> 50	8.08	4.66	> 41	8.04	4.62

When the WA2 velocity model was used, a solution was obtained which was about mid-way between the RSN solution and the GA solution. However, the RMS of residuals was higher, and the focal depth computed was -0.4 km. The velocity-depth models used in the EQLOCL solutions are summarised in Table 1.

The KLGC seismograph detected many other aftershocks on 20th April, 20 of which are listed in Appendix 2. Approximate magnitudes range from 1.6 to 2.6, but more work is needed to verify these values. These events have not been located as such as there are insufficient data, but the S-P times at KLGC (Appendix 2) indicate that they are aftershocks.

Table 2 Summary of larger (ANSN located) Kalgoorlie events, April – September 2010

Event Date, Time		**Label**	**Magn.**	S-P (sec)	**Survey**	**Period**	**New Location (using survey & ACG data)**					**comment**
Date	**Time (UTC)**	**(Fig 1)**	**(ML)**	at KLGC	**data**		Latitude south	Longit east.	Depth (km)	RMS of resid.	Model used	
17/04/2010	08:57:39	F1	ML 2.5	0.7	no data	A						Mine blast
20/04/2010	**00:17:09**		**ML 5.0**		no data	A						**Main Event**
20/04/2010	18:38:13	A1	ML 2.6	0.43	no data	A						
22/04/2010	22:24:25	A2	ML 2.6	0.40	no data	A	30.793	121.473	1.4			Meertens*
23/04/2010	15:49:37	A3	ML 2.8	0.49	no data	A	30.794	121.485	1.4			Meertens*
25/04/2010	15:40:34	A4	ML 2.8	0.52	ev 046	B	30.788	121.492	1.1	0.015	DAL1A	
30/04/2010	11:48:58	A5	ML 2.7	0.37	ev 181	B	30.779	121.482	1.3	0.015	DAL1A	
9/05/2010	16:55:07	A6	ML 2.8	0.54	no data	C	30.793	121.489	1.5			Meertens*
4/06/2010	10:56:26	A7	ML 2.6	0.57	ev 244	C	30.789	121.490	0.28	0.034	IASPEI	GA soln
6/06/2010	18:29:46	A8	ML 2.5	0.41	ev 264	C	30.784	121.475	0.52	0.045	IASPEI	GA soln
16/06/2010	22:59:32	A9	ML 2.0	0.52	no data							
23/06/2010	03:30:00	A10	ML 2.3	0.57	no data							
26/07/2010	18:38:29	A11	ML 2.9	0.60	no data							
19/09/2010	21:23:14	A12	Ml 2.6		no data							

* = J. Meertens, Pers. Comm., 2015

2.2 Other GA-located events in Period A

The event on 17th April (event F1 on Figure 1) , which occurred near 5 pm local time, has recently been confirmed by mine staff to be a blast from the Mt Charlotte mine. The ANSN locations for the three aftershocks in this period (A3 – A3) are not good, as all the seismographs used to locate them are relatively distant. Event A1 (ML 2.6), plots about 5 km south of the main event. Event A2 (ML 2.6), appears to have originated in the Super Pit, the open cut mine east of the main shock location. However, all mining operations were suspended for some days immediately after the main event. Event A3 (ML 2.8), plots about 30 km south of Kalgoorlie. However, for all three events, the S-P times at KLGC (Table 2 & Appendix 2) indicate that they were 4 km or less from KLGC, and therefore are probable aftershocks, and much closer to the main shock location than the ANSN locations suggest.

Other aftershocks detected by the KLGC station during period A are listed in Appendix 2 (1). It is probable that an in-depth examination of KLGC data would identify many more small aftershocks. High-quality KLGC data (ie three-component data, sampled at 200 s/s) were retrieved for some aftershocks at the time of the events, but unfortunately the hard disk containing the raw data has failed and further data cannot be retrieved.

3 Aftershock locations by GA using survey data (periods B and C)

"Preferred" aftershock locations determined by GA from survey data during periods B and C (24th April to 5th May, and 6th May to 8th June), as presented by Bathgate et al. (2010) are plotted on Figure 2 (~ 300 locations). Many of these solutions have focal depths of 0.0 km. The dataset contains locations made with data from all five field stations, as well locations using as few as three stations.

The four largest of these events were earlier located by GA (A4, ML 2.8 A5, ML 2.7 A7, ML 2.6, and A8, ML 2.5). These events are indicated on Figure 2. A4 and A7 are near GA's main-shock location, but A5 and A8 are about 1 km to the northwest.

In Figure 3, an attempt has been made to plot only the probable better locations. Subset 1 contains only events which used at least 7 phases in the location. From this subset, subset 2 (coded according to depth in Figure 3) contains events where the RMS is < 0.04 secs. This plot of "better" locations has shed most of the events outside of the suggested epicentral zone.

Figure 2 Geoscience Australia locations (by depth)

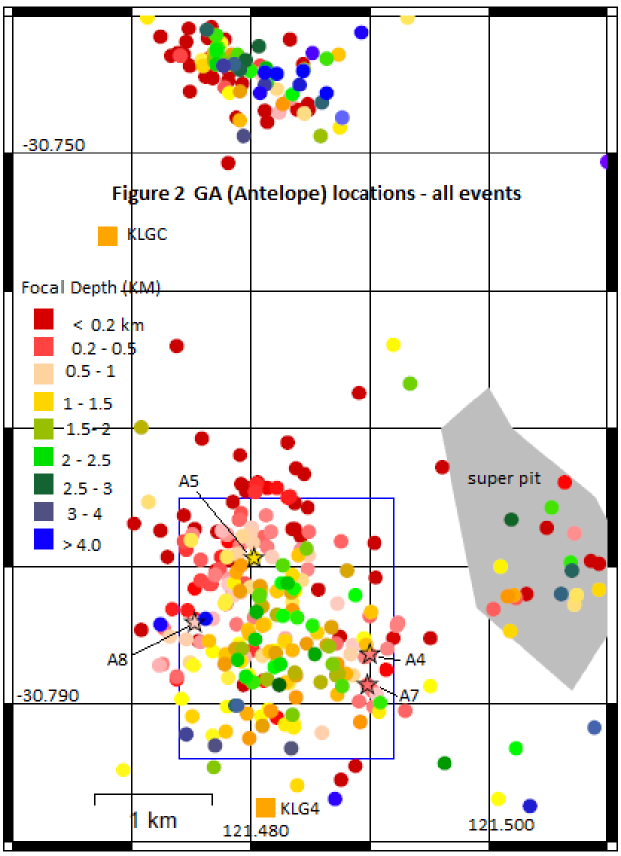
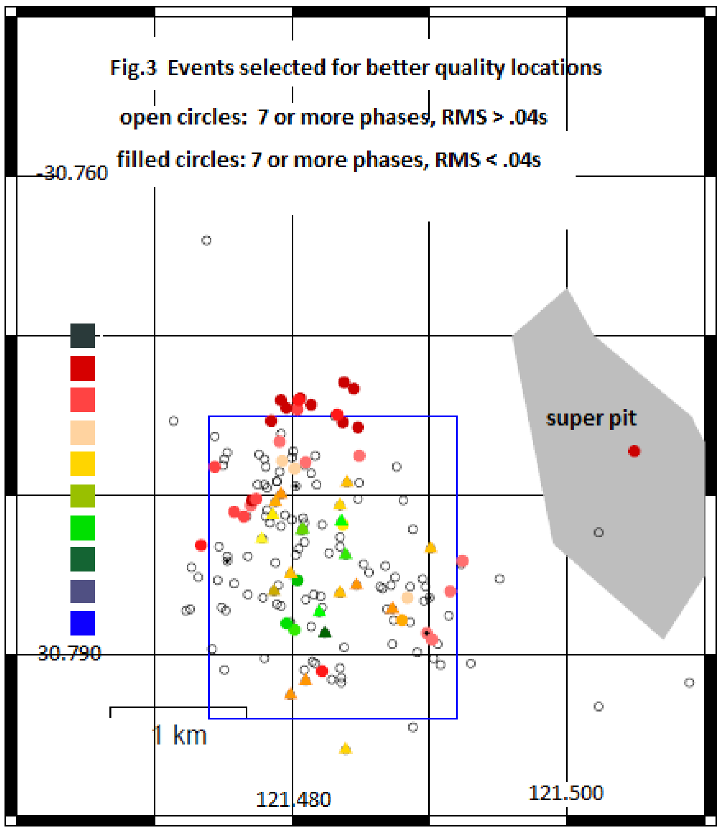


Figure 3 Suggested better locations from **Figure 2**



3.1 Relocations of selected events in Period B using EQLOCL

Period B is the first period of the aftershock survey – the period for which phase data is available. From the collection of ~ 300 located aftershock locations provided by GA, a limited number (~45) have been chosen for relocation using EQLOCL. These have been selected to represent various groups of events – i.e. deep events (> 2.5 km), very shallow events (depth ~ 0.0 km), and events with a large RMS of residuals (i.e. > .06 sec). Also selected for relocation were events for which "Hi Quality" data (i.e. 3 component data at 200 s/sec.) from the nearby Cheetham St. seismograph were available, and also events which were well recorded on all five stations of the GA field network.

Each event was relocated twice, first using the WA2 model and then with the DAL1A model. The result has been that events which GA located at > 3.0 km depth are now less than 2 km, and, for a lesser number of events, relocation has brought them from less than 2 km, to just over 2 km in depth (see Table 3).

The original GA locations for the ~45 relocated events are shown in Figure 4 A, and the new solutions are plotted in Figures 4B (WA2 model) and 4C (DAL1A model), and listed in Appendix 3. The events are color-coded according to focal depth. In the relocations, some S phase arrivals were deferred for some events as they appeared to be poor picks. Unfortunately the original data could not be examined. S phase arrivals are often difficult to pick accurately.

Figure 4 (A) Antelope locations by depth

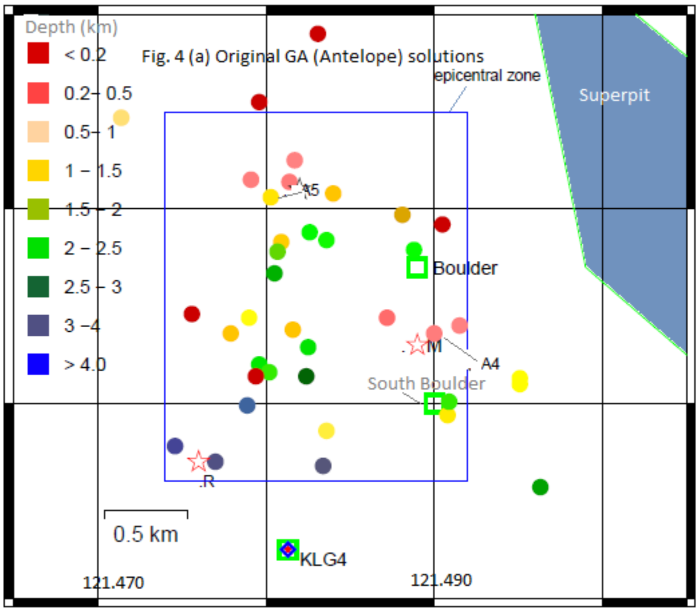


Figure 4 (B) Relocations using WA2 model

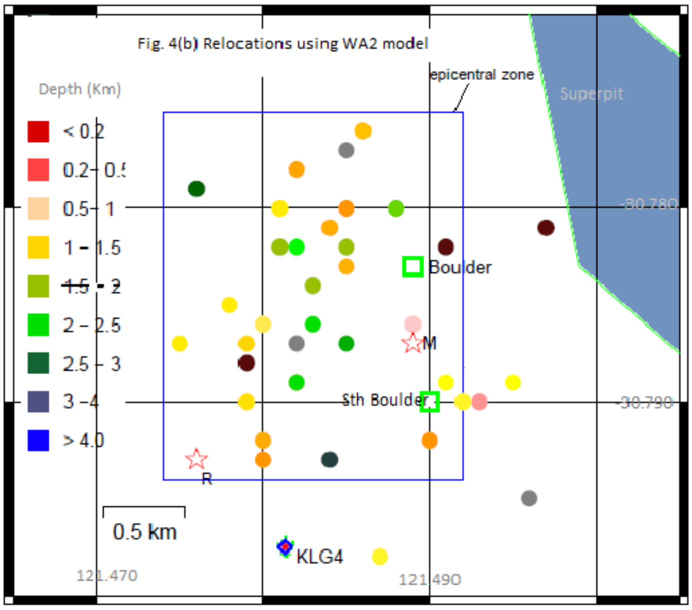


Figure 4 (C) relocations using DAL1A model

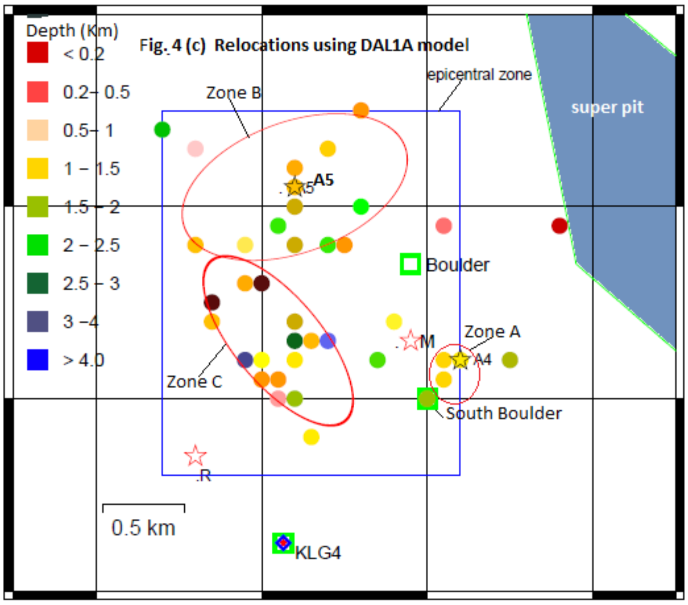
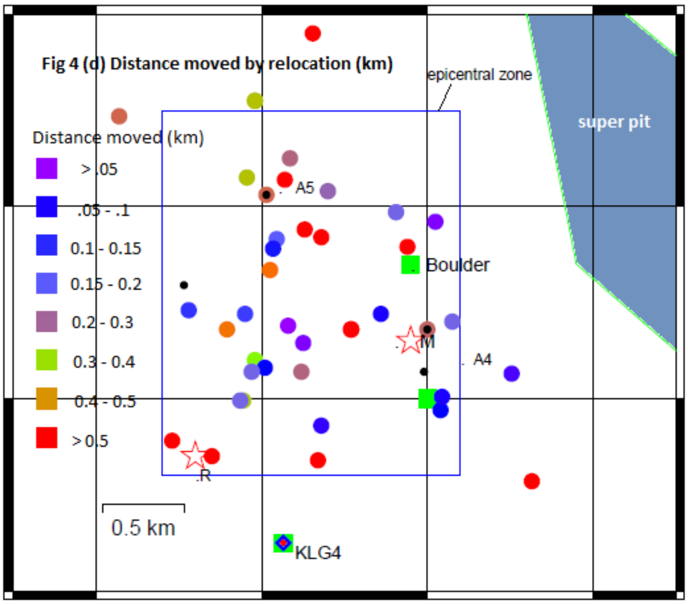


Figure 4 (D) Antelope locations showing distance moved (km) by relocation using DAL1A model



Legend Figure 4 (a-d). Circles = earthquakes; Diamond = seismic station; Square = town centre; M= Main shock location (GA); R= main shock location (RSN); A4 = relocation of aftershock A4; A5 = relocation of aftershock A5

Figure 4D shows the original GA locations, coded according to how far they have been moved by relocation. In some cases, relocation has resulted in relatively insignificant changes in latitude, longitude and depth – i.e. less than 200m. In other cases the shift is significantly larger – this is generally found where focal depths had been anomalously deep or shallow, and have now returned to a more "central" position. Sometimes significant changes (improvements?) in location are made by simply deferring an "errant" S phase arrival.

Table 3 Summary of location/relocation data for important events (deep, shallow, or large magnitude)

Date & time		Geoscience Australia Location					EQLOCL relocation				Comment
	event #	# phas	RMS	model	depth		RMS	phases	model	depth	
27/04_1233	ev098	6	0.024	IASPEI	3.2		0.022	5p 1s	DAL1A	1.3	Becomes shallower
03/05_0858	ev267	5	0.003	IASPEI	3.1		0.024	5p 1s	DAL1A	1.5	Becomes shallower
02/05_0012	ev243	5	0.013	IASPEI	3.1		0.023	4p 0s	DAL1A	-0.33	Becomes shallower poor q.
19/05_1258	ev047	5	0.003	WA2A	4.6		0.012		IASPEI	1.93	GA "non-preferred" soln
16/05_1500	ev006	6	0.032	WA2A	3.5		0.034		IASPEI	0	GA "non-preferred" soln
26/04_0920	ev069	9	0.052	IASPEI	0.71		0.04	5p 3s	DAL1A	2.2	Becomes deeper
29/04_1059	ev154	5	0.002	WA2A	2.7		0.0	4p 0s	DAL1A	3.15	Becomes deeper poor q.
04/05_1328	ev287	8	0.037	IASPEI	0			6p 2s	DAL1A	2.04	Becomes deeper
24/04_1231	ev023	7	0.013	WA2A	2.51		0.0	4p 0s	DAL1A	0.99	Poor quality
24/04_1756	ev026	6	0.039	WA2A	2.09		0.012	5p 1s	DAL1A	2.5	stays deep
25/04_1540	ev046	9	0.049	IASPEI	0.33		0.015	5p 3s	DAL1A	1.0	Event A4 **Ml 2.8**
30/04_1148	ev181	8	0.047	WA2A	1.13		0.053	4p 2s	DAL1A	0.9	Event A5 **Ml 2.7** poor quality

3.2 Events in Period C (16th May 2010 – 8th June 2010)

This period marks the second phase of the GA survey. About 120 aftershocks were located by GA in this period, but these events are not re-examined here. Two of the larger aftershocks (A7 & A8 in Figure 1), originally up to 15 km to the southwest of the main event, were relocated by GA using the survey data (events 244 and 264), and the revised locations are now within the epicentral zone (far east, and far west respectively).

4 Focal depths of aftershocks

From their locations using survey data, Bathgate et al. 2010 concluded that the depths of aftershocks did not exceed 4.5 km, and that the deeper aftershocks were concentrated to the west of the Boulder fault, reflecting the westerly dip of that fault. Their Figure 3 (C and D) showed 12 events of depth 2-3 km west of the main shock, and 6 events of depth 3.0 km +, south and west of the main shock.

A summary of relocation data for five of the "deep" events of Bathgate et al. 2010, is given Table 3. Three of the deepest (depth > 3.0 km), relocated using the DAL1A model, now have depths of 1.5 km or less. The other two events could not be relocated, but the alternative ("non-preferred") solutions determined by GA had depths of 1.9 km and 0 km. Both of these solutions used the IASPEI model. Note that some of these events are difficult to locate accurately because there are only 4 or 5 phases recorded.

Relocation of some events which GA located at less than 2 km (events 69, 153 and 28) has brought them to just over 2 km in depth (see Table 3).

The computed focal depths are very model dependant. Somerville and Ni (2010) observed that a shallow low velocity layer should be incorporated in models used for earthquake locations in the WA cratons. Test locations made using a model which has such a layer (SYD1, Table 1) have produced locations which are about 0.5 km deeper, with only a small increase in the RMS of residuals.

Further investigation of velocity-depth models is currently being undertaken by J. Meertens of Curtin University.

The results above indicate the large uncertainties that are inherent in depth calculations. They suggest that it cannot be confidently stated that any of the aftershocks have depths greater than ~ 2.5 km. This is with the caveat that locations using a more appropriate model may produce focal depths that are moderately deeper. More work is required before a meaningful interpretation of the location and azimuth of the causative fault (or faults), or its probable dip, can be made.

5 Discussion

5.1 Interpretation of aftershock epicentral distribution

Based on relocations presented here using the DALIA model, as well as relocations of some of the larger (ML > 2.0) aftershocks, it is proposed that there are three groupings of aftershock locations (Figure 4 C). The first group, group A, are close to aftershock A4 (Ml 2.8), and just east of GA's proposed mainshock location. Group B events are in the north of the epicentral zone, and are diffuse, with a possible EW or NE trend. Aftershock A5 (ML 2.7) is in the centre of this grouping. Group C events are in the southwest of the zone, and have a northwest orientation. This orientation is the same as trends in geomagnetic lineations in the area.

5.2 Discussion of focal depths

The conclusions of both the GA study (2010) and this study are that the events are quite shallow. Interestingly, this is not is complete agreement with a preliminary InSAR investigation by GA that suggested that there was no measurable surface deformation caused by the main earthquake (Dawson, pres. Comm., 2015). This might suggest that the main event was relatively deep.

The depths of aftershocks previously identified by GA as being relatively deep (~ 3 km) are strongly questioned, although there is a degree of uncertainty about all focal depth determinations. The focal depths of relocated events do not so far show a convincing trend across the epicentral zone, and this could be at least partially because of inaccuracies in the epicentral determinations. The north-south trend suggested by Bathgate et al. (2010) is not supported by these data. Three cluster groups within a fairly tight epicentral zone are suggested, and two of these may represent orthogonal lineations.

The uncertainties in depths and locations indicate that more stations, particularly at close distances, together with higher sampling rates, are required to achieve the kind of precision in event location needed to define the orientation and dip of the causative fault(s) for earthquakes in this (and other) regions.

An assessment of the quality of GA's location of the main event cannot be made until the sizes of the residuals for the phases used are available. The lack of correlation of the "RSN" solution of the main shock, with the aftershocks, may be due to errors in its location.

The data set of aftershock locations requires further examination, and all events with zero depth or very shallow focal depths should be relocated.

Relocations using the DAL1A model (as a proxy for the IASPEI91 model) seem to on average to produce a better solution than the WA2 model. The depths computed by the DAL1A model range is 0.3 to 2.0 km. A refining of the model may improve locations such that more structure is evident, and will probably also affect the average focal depths.

The phase paths for the events discussed here are only sampling the top few km of the crust, and only the top layer of the models are involved in computing the solutions. This does not necessarily mean that the DAL1A model will be the more suitable model on a regional scale, where most of the phases considered have passed through deeper layers of the crust, or have entered the upper mantle.

6 Conclusions

Aftershock epicentres may be defining three source locations within an area approximately 1.5 km by 1.5 km around the main shock location. Focal depths within the epicentral zone range between ~0 and 2 km deep, but do not show a consistent pattern. The use of unverified velocity-depth models for earthquake locations in the Kalgoorlie region may be hindering the construction of the best possible data set of aftershock locations.

7 Acknowledgements

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Appendix 1 EQLOCL solution for ML 5.0 event, 20th April 2010, using DAL1A model

Appendix 1 "Regional Seismic Network" solution for the main Kalgoorlie event.

Appendix 1 EQLOCL output for ML 5.0 Kalgoorlie event DAL1A model

```
Date            2010-04-20
Origin Time     0017  9.45   +-   0.49
Zone                    51
Easting             354.17   +-   2.70        Longitude     121.476
Northing           6592.34   +-   2.62        Latitude      -30.793
Depth                 1.47   +-   8.86

Arrival times    =  8       S.D. = 0.062        Seismographs =  5
Nearest recorder =  4.2 km  Gap  = 214.6 deg    Accuracy = A
Effects Code     =          Imax =  0           Fault =

   1 km SE (122 deg) of  KLG
WESTERN AUSTRALIA
 550 km  E ( 78 deg) of PERTH
  36 km NE ( 61 deg) of Coolgardie
   5 km  S (173 deg) of KALGOORLIE


No magnitudes known                             Assign ML  5.0
```

DATA USED

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
KLCH	P	10.24	0.02	2.18	10.24	0.01	4.2	349	24.2	24.2
KLCH	S	10.81	0.20	1.24	10.81	-0.00	4.2	349	24.2	24.2
KLGR	P	13.37	0.03	1.80	13.38	-0.01	22.7	354	4.7	4.7
KLKB	P	13.48	0.03	1.80	13.42	0.06	23.0	24	4.7	4.7
KLKB	S	16.17	0.20	1.11	16.32	-0.15	23.0	24	4.7	4.7
KLRY	P	13.57	0.03	1.80	13.50	0.07	23.5	288	4.6	4.6
KLRY	S	16.41	0.20	1.11	16.47	-0.06	23.5	288	4.6	4.6
KLFM	P	14.77	0.03	1.76	14.82	-0.05	31.1	239	3.4	3.4

8 times used, S = 0.062

Deferred Data

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
KLFM	S	18.43	0.50	0.90	18.75	-0.32	31.1	239	3.4	3.4
KLLS	P	17.14	0.03	1.71	17.53	-0.39	46.8	155	2.3	2.3
KLLS	S	22.30	0.50	0.88	23.44	-1.14	46.8	155	2.3	2.3
KLDM	P	17.48	0.03	1.70	17.96	-0.48	49.3	120	2.2	2.2
KLBH	P	17.48	0.03	1.70	18.26	-0.78	51.1	157	2.1	2.1
KLLV	P	20.31	0.03	1.66	20.87	-0.56	66.2	154	1.6	1.6
KMBL	P	21.49	0.10	1.29	22.39	-0.90	75.0	148	1.4	1.4
KMBL	S	30.30	0.50	0.84	31.86	-1.56	75.0	148	1.4	1.4

Appendix 2 - Events recorded by Cheetham St. seismograph (KLGC)

Appendix 2, part1. Period A 17 April – 23 April 2010

Date and Time (UTC)	**ML** (GA)	**M** KLGC	**M** KLLS	**ML** (new)	**S-P (secs)** (KLGC)	**Qual**	**Comment**
17/04/2010 08:57	2.5	1.2		2.1	0.7		Mt. Charlotte (F1)
20/04/2010 00:17	5.0	3.6		**4.5**	0.36	hi	MAIN SHOCK
20/04/2010 01:26		0.7		1.6	0.40	lo	
20/04/2010 01:55		1		1.9	0.437	hi	
20/04/2010 01:56		1.6		2.5	0.39		
20/04/2010 02:16		1.7		2.6	0.45		
20/04/2010 02:31		0.7		1.6	0.404	hi	
20/04/2010 02:40		1.3		2.2	0.54	hi	
20/04/2010 05:43		1.1		2.0	0.58	hi	
20/04/2010 06:03		0.8		1.7	0.45	hi	
20/04/2010 06:41		1.1		2.0	0.42	hi	
20/04/2010 07:11		1.2		2.1	0.71	hi	
20/04/2010 07:15		0.9		1.8	0.374	hi	
20/04/2010 07:17		0.7		1.7	0.56	hi	
20/04/2010 07:51		1.0		1.9	0.68		
20/04/2010 10:45		1.8		2.7	0.5	hi	
20/04/2010 18:38	2.6	1.0	0.3	1.8	0.43		Event A1
21/04/2010 01:07		1.2		2.1	0.43		
21/04/2010 02:03		1.2		2.1	0.42	lo	
21/04/2010 08:33		0.7		1.6	0.38	lo	
21/04/2010 15:11		0.6		1.5	0.51	lo	
22/04/2010 00:39		1.2		2.1	0.43	lo	
22/04/2010 06:55		1.5		2.4	distant		
22/04/2010 07:23		1.2		2.1	0.42	lo	
22/04/2010 14:16		1.9		2.8	0.495	hi	
22/04/2010 22:24	2.6	2.0	1.2	2.7	0.44		Event A2
23/04/2010 12:32		0.1		1.0	0.53		
23/04/2010 15:49	2.8	2.8	1.4	3.2	0.49		Event A3
24/04/2010 09:56		0.9		1.8	0.46	hi	
24/04/2010 11:01				0.9	5.6		remote

Appendix 2, part 2. Period B 24 April – 05 May 2010

Date	ML (GA)	M KLGC	M KLLS	ML (new)	S-P (KLGC.)	Qual	Comment
24/04/2010 11:01				0.9	5.6		
24/04/2010 17:56		0.7		1.6	0.43		ev026
24/04/2010 20:54		-0.3		0.6	0.25		ev028
25/04/2010 07:08		0.2		1.1	0.57		ev038
25/04/2010 08:35		-0.2		0.7	0.243		ev040
25/04/2010 11:38		0.1		1.0	0.53		ev042
25/04/2010 15:03		0.1		1.0	0.43		ev045
25/04/2010 15:40	2.8	1.2		2.1	0.43		ev046 (A4) KLRY M 1.8
25/04/2010 17:19		0		0.9	0.43		ev049
25/04/2010 20:48		-0.2		0.7	0.4		ev050
26/04/2010 00:21		1.1	0.1	1.7	0.53	Hi	ev057
26/04/2010 03:19		1		1.9	0.51		ev061
27/04/2010 10:36		1.7	0.4	2.2	0.51	hi	ev094
27/04/2010 12:33		0.5		1.4	0.41	lo	ev098
30/04/2010 11:48	2.7	2.4	1.4	3.0	0.37	hi	ev181 (A5)
02/05/2010 14:52		0.9		1.8	0.44		ev249

Appendix 2, part3. Period C (05 May 2010 – 08 June 2010) and beyond

Date	ML (GA)	M KLGC	M KLLS	ML (new)	S-P KLGC	Qual	Comment
9/05/2010 09:17		1.1		2.0	0.56	Lo	no survey data
9/05/2010 16:55	2.8	2.0	1.4	2.8			A6 (no survey data)
30/05/2010 02:08		1.9		2.8	0.64		no survey data
02/06/2010 21:46		1.6	0.3	2.1	0.47	Hi	event ID 222
04/06/2010 10:56	2.6	1.7	0.8	2.4	0.57	Hi	event ID 244 (A7)
06/06/2010 18:29	2.5	1.6	1.0	2.5	0.49	Hi	event ID 264 (A8)
16/06/2010 22:59	2.0	1.3	0.5	2.0	0.65	Hi	A9
23/06/2010 03:30	2.3	1.7	0.6	2.3	0.57	Hi	A10
26/07/2010 18:38	2.9	2.9	1.4	3.3	0.65	Hi	A11
16/09/2010 21:23	2.6	1.4	0.6	2.2	0.53	Hi	A12

APPENDIX 3

Latitude, Longitude, Depth and RMS of residuals for GA and EQLOCL aftershock locations

DATE	**TIME** comment	**EVENT**	**GA solution** Longitude	Latitude	**depth** (Km)	**RMS** (sec)	**PHAS**	**model** used	**Move** (Km)#	**EQLOCL solution** Long.	Lat.	**depth** (Km)
24-Apr	09-56-50.4	ev015	121.4854	-30.7864	2.28	0.004	6	wa2a	0.83	121.493	-30.783	1.3
24-Apr	12-31-11.8	ev023	121.4824	-30.7886	2.51	0.013	7	wa2a	0.25	121.48	-30.788	0.99
24-Apr	17-55-59.9	ev026	121.4825	-30.7871	2.09	0.039	6	wa2a	0.05	121.482	-30.787	2.5
24-Apr	20-54-35.5	ev028	121.4859	-30.7487	1.7	0.0004	4	wa2a	0.2	121.484	-30.748	1.1
25-Apr	01-36-14.4	ev033	121.4888	-30.7821	1.99	0.06	9	wa2a	0.93	121.498	-30.78	0
25-Apr	01-47-11.9	ev035	121.4872	-30.7856	0.29	0.045	9	iasp	0.09	121.488	-30.79	0.9
25-Apr	07-08-50.1	ev038	121.4908	-30.7906	1.1	0.058	8	wa2a	0.1	121.49	-30.79	1
25-Apr	11-38-15.1	ev042	121.4836	-30.7914	0.85	0.04	7	wa2a	0.08	121.483	-30.79	1.1
25-Apr	15-03-50.4	ev045	121.484	-30.7792	1.28	0.034	8	wa2a	0.23	121.482	-30.78	1.4
25-Apr	15-40-34.3	ev046	121.4900	-30.7864	0.33	0.049	9	iasp	0.26	121.492	-30.788	1
(**aftershock A4 ML 2.8**)												
25-Apr	17-19-17.1	ev049	121.4831	-30.771	0	0.028	5	iasp	1.1	121.484	-30.78	1.9
25-Apr	20-48-57.0	ev052	121.4836	-30.7816	1.97	0.019	8	wa2a	0.7	121.486	-30.78	1.5
25-Apr	21-56-17.9	ev054	121.4963	-30.7943	2.33	0.015	5	wa2a	1.12	121.487	-30.788	1.85
26-Apr	00-21-45.4	ev057	121.4915	-30.786	0.34	0.029	8	iasp	0.21	121.491	-30.79	1.2
26-Apr	03-19-13.1	ev061	121.4909	-30.7899	1.9	0.021	6	iasp	0.09	121.491	-30.79	1.2
26-Apr	09-20-31.3	ev069	121.4714	-30.7753	0.71	0.052	9	iasp	0.27	121.474	-30.78	2.2
26-Apr	11-25-29.5	ev073	121.4779	-30.7864	1.28	0.051	9	wa2a	0.48	121.476	-30.78	1.3
26-Apr	16-24-47.6	ev075	121.4791	-30.7785	0.33	0.046	9	iasp	0.38	121.482	-30.78	1.6
27-Apr	04-02-16.4	ev083	121.4817	-30.7775	0.34	0.051	9	iasp	0.25	121.482	-30.78	1.6
27-Apr	06-45-28.8	ev089	121.4756	-30.7854	0	0.026	5	iasp	0.15	121.477	-30.79	-0.3
27-Apr	10-36-50.3	ev094	121.4796	-30.788	2.07	0.038	7	iasp	0.31	121.482	-30.79	1.7
27-Apr	12-33-20.0	ev098	121.4746	-30.7922	3.16	0.024	6	iasp	0.66	121.477	-30.79	1.3
27-Apr	12-48-05.5	ev099	121.4789	-30.7901	2.81	0.032	5	iasp	0.37	121.482	-30.788	1.11
28-Apr	00-40-47.4	ev110	121.479	-30.7856	0.97	0.041	8	wa2a	0.16	121.479	-30.78	1.4
28-Apr	06-17-45.7	ev120	121.4816	-30.7862	1.28	0.041	7	wa2a	0.04	121.482	-30.786	1.6
28-Apr	16-47-19.5	ev124	121.4809	-30.7817	1.24	0.062	9	iasp	0.19	121.479	-30.78	0.8
28-Apr	17-34-32.3	ev125	121.4805	-30.7833	2.25	0.076	9	iasp	0.49	121.482	-30.79	2.2
28-Apr	23-20-18.2	ev131	121.4881	-30.7803	1.57	0.04	7	wa2a	0.21	121.486	-30.78	2
28-Apr	23-26-13.5	ev132	121.4802	-30.7884	1.9	0.038	9	iasp	0.1	121.481	-30.79	1.5
29-Apr	10-59-41.5	ev154	121.4787	-30.7901	2.67	0.002	4	iasp	0.21	121.479	-30.788	3.15
	poor quality – 4 P phases only..											
29-Apr	21-21-54.7	ev165	121.4826	-30.7812	2.02	0.01	5	wa2a	0.78	121.476	-30.777	0.5
30-Apr	00-03-26.5	ev168	121.4848	-30.7757	0	0.032	8	iasp	0.15	121.484	-30.777	
	4 p and 4 s none deferred											
30-Apr	11-48-58.6	ev181	121.4803	-30.7794	1.13	0.047	8	wa2a	0.27	121.479	-30.78	0.9
(**aftershock A5 ML 2.7**)												
30-Apr	22-43-57.2	ev192	121.4777	-30.7436	3.2	0.056	6	wa2a	0.16	121.478	-30.74	2.6
30-Apr	23-05-00.8	ev202	121.4812	-30.7441	4.03	0.02	6	wa2a	0.22	121.479	-30.74	3.2
01-May	06-41-51.6	ev218	121.4905	-30.7808	0	0.022	6	iasp	0.05	121.491	-30.78	0.3
01-May	07-05-18.7	ev221	121.4717	-30.8022	2.01	0.103	6	iasp	0.78	121.479	-30.805	0.72
01-May	07-39-30.3	ev222	121.4794	-30.7886	0	0.024	6	iasp	0.21	121.481	-30.79	0.4
01-May	16-49-59.4	ev228	121.4951	-30.7887	1.01	0.003	6	wa2a	0.07	121.495	-30.788	
02-May	00-12-52.2	ev243	121.4834	-30.7932	3.07	0.013	5	iasp	0.98	121.48	-30.784	-0.33
02-May	14-52-57.5	ev252	121.4814	-30.7786	0.32	0.047	9	ias	0.5	121.485	-30.782	1.5
03-May	08-58-04.9	ev267	121.477	-30.793	3.1	0.003	5	iasp	0.5	121.48	-30.79	1.5
	poor quality?	5 p and 1 s and klg5 deferred										
03-May	10-28-45.7	ev273	121.4807	-30.7822	1.81	0.011	7	wa2a	0.12	121.481	-30.781	1.9
04-May	13-28-10.0	ev287	121.4796	-30.7745	0	0.037	8	iasp	0.38	121.481	-30.778	2.04
	poor quality?	4 p 1 s klg5 def, klg4s def										

Notes: # **-** this column shows the distance of the new location from the original survey location by GA