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# Twenty years of earthquakes near Burakin in the Western Australian Wheatbelt: A timeline of events in the Burakin seismic cluster of 2001 – 2002 and subsequent seismicity in the region

V. F. Dent[1], C.D.N. Collins [2] & R. Murdie[3]

1. University Associate, Curtin University, Perth, W.A.; Honorary Research Associate, The UWA Institute of Agriculture, UWA, Perth: Email: vic_dent@yahoo.com
2. G.P.O. Box 2972 Canberra ACT 2601: Email: cdncollins@iinet.net.au
3. Geological Survey of WA: Email: ruth.murdie@dmirs.wa.gov.au

## Abstract

The Burakin earthquake sequence of 2001-2002 in southwest Western Australia represents one of the most significant sequences in Australia since the Tennant Creek events of 1988. The sequence included three magnitude ML 5 events, and an estimated 18,000 smaller events. Elevated levels of seismicity continued into 2005, with occasional events still occurring in 2021. The seismicity from September 2001 to August 2002 is reviewed here. It is suggested that all three ML 5 events may have come from within 5 km of an active location previously identified by Leonard (2002). Events in April 2002 defined new areas of activity just to the north and south of this location, and during 2004-2005, to the southwest. All focal depths seem to be shallow (< 5 km). A connection with an arcuate N-S feature on the geomagnetic anomaly map is suggested. Further analysis of data recorded in 2002 may provide improved focal depths and a better local earth model.

**Keywords:** Earthquakes, Clusters, Seismicity, Burakin, Southwest Western Australia

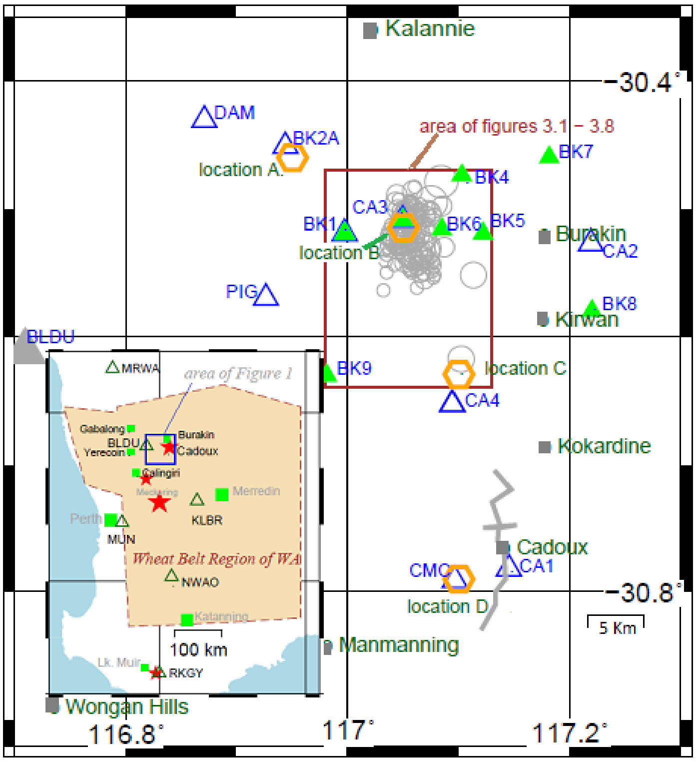
## 1 Introduction

After the occurrence of a large earthquake it is desirable to deploy temporary field stations to record any aftershocks. This enables the location of earthquakes with better precision, and one of the desired outcomes, not necessarily achievable, is the determination of focal depths and the delineation of the causative fault(s). Another aim is to provide insights into the attenuation of strong ground motion, and thus the hazard posed by earthquakes in the region. How well this is achieved depends on the number of stations deployed, their distribution, and the quality of the data recorded. Field deployments around the 1988 Tennant Creek events (Bowman et al., 1990) were able to delineate two fault planes. However, deployments around the aftershock zone of the 2010 Kalgoorlie ML 5.0 earthquake (Bathgate et al., 2010, Dent, 2015), and around the Lake Muir events of 2018 (Clark et al., 2020, Dent et al., 2019) were unable to clearly define a fault plane.

The initial, and usually the largest events, for which there will be less data, will probably be poorly located compared to subsequent, usually smaller, events. This difference in precision is often not apparent in epicentral plots from the subsequent database and may make interpretation of the distribution of the seismicity difficult or misleading.

The Burakin sequence of 2001-2002 was one of the best monitored sequences in Western Australia, and possibly Australia, because of the relatively large number of field recorders deployed after the sequence started. However, the data acquired have not been described in detail. This report is a small step towards understanding this sequence better.

Burakin is a small village situated about 150 km NE of Perth in the north of a region known as the WA Wheatbelt (Figure 1). The intense seismicity which occurred west of Burakin from September 2000 to mid-2002 was described by Leonard (2003) as "the highest level of seismic activity experienced in Australia since the 1988 Tennant Creek M6.7 earthquake". There were ~ 20 events of ML > 3.5 between 28 September 2001 and 30 June 2002 (including three events of ML 5.0 +) and thousands of smaller events. This is a similar number to the 22 ML > 3.5 events recorded after the nearby ML 6.3 Cadoux event of 1979 (Lewis et al., 1981; Denham et al., 1987; Bowman et al., 1990) and significantly more than the six that occurred during the recent Lake Muir sequence in the southern wheatbelt (Clark et al., 2020, Dent et al., 2019). The seismicity of these major events in southwest WA is compared in Table 1.




Legend: Circles = GA earthquake location (Sept 2001- Aug 2002, ML 2.5 or above). Yellow hexagon = earthquake cluster, see Table 2. Triangle = seismograph (filled green if opened after March 2002). Grey square = farm or minor village. INSERT: Red star = earthquake ML 5.3 or above since 1967. Triangle = (permanent) seismograph. Cream filled area = wheatbelt region of WA

*Figure1.Location of seismicity in southwest WA*

About 570 events were located near Burakin by Geoscience Australia (GA), and just under half of these were small (ML < 2.0). However, this is only a small proportion of the estimated 18.000 events detected by field stations installed by GA (Leonard, 2003). The sequence was well monitored with field stations deployed at about 15 sites over the course of the seismicity. The peak of the deployment was just after the third of the three ML 5 events, but even at this stage there were only about five seismographs within 30 km of the seismicity.

## *1.1 Permanent Stations*

The region of the northern Wheatbelt was monitored at the time by five permanent stations

*Table 1 Comparison of major seismic events in southwest WA*

| | Gabalong | Meckering | Cadoux | Burakin | Lk. Muir |
|---|---|---|---|---|---|
| **Start/End dates** | 01/01/1949-01/01/1957 | 01/10/1968-31/01/1969 | 01/06/1979 - 31/12/1979 | **01/09/2001-31/08/2002** | 01/08/2018-31/01/2019 |
| **Largest events (ML)** | 5.8, 5.3 | 6.9, 5.7 | 5.5, 6.2 | **5.2, 5.2** | 5.7, 5.4 |
| **ML ≥5.0** | 4 | 2 | 5 | **3** | 2 |
| **ML ≥3.5** | | 44 | 19 | **21** | 6 |
| **ML ≥2.0** | 11 | 228 | 220 | **288** | 61 |
| **Total located** | 11 | 228 | 220 | **540** | 783 |

(Figure 1): MRWA to the northwest, BLDU to the west, MUN to the southwest, NWAO to the south and KLBR to the southeast. The north to eastern quadrant was lacking in any permanent stations to constrain the errors in location in this direction.

## *1.2 Field station deployments by Geoscience Australia*

Following a significant cluster of earthquakes near Kirwan, south of Burakin (Figure 1), in September and October 2000, four triggered digital seismographs (CA1-4) were deployed in the Burakin-Cadoux region (Figure 1). While recording this cluster, a small group of seven events (largest ML 3.6) was also recorded about 11km west of Burakin.

These stations were decommissioned after initial (Kirwan) earthquake activity reduced. They were re-occupied however following the ML 5.2 event in September 2001, the first stations providing data ~ 14 hours after that event. More temporary stations were deployed after the two ML 5 events on March 5 and 30, 2002. Data recorded by the aftershock deployments were used to derive ground motion attenuation relations for the region; these are used to estimate the earthquake hazard (Allen et al., 2006).

## *1.3 Previous Work*

The initial reference to Burakin activity was in a report on the Kirwan (September 2000) activity, by Leonard & Boldra (2001). Their report noted four sources of activity (A-D, see Table 2), but focussed on the Kirwan activity (Location C), where they estimated some 1,700 events occurred (largest ML 3.5). Location B, west of Burakin was considered a site of minor activity (seven events, largest ML 3.6). The two other locations identified in that report (A and D) were also considered sites of relatively minor activity.

*Table 2 Defined cluster locations. A-D are from Leonard & Boldra (2002)*

| | **Area (Location)** | **Location** | **Max ML** | **Comments** |
|---|---|---|---|---|
| A | NW of Burakin | -30.46<br>116.95 | 1.2 | Very minor. Further activity has not been observed from this location |
| B | W of Burakin | -30.52<br>117.05 | 3.6 | Precursory activity at location of September 2001-April 2002 activity, when three ML 5 events occurred at this location |
| C | SW of Kirwan | -30.63<br>117.10 | 3.5 | A broad area with a NE trend mostly September-October 2000. Also April 2002 |
| D | SW of Cadoux | -30.79<br>117.10 | 2.7 | Related to activity on the Cadoux fault? |
| E | ~ 11 km WNW of Burakin | -30.50<br>117.05 | 5.0 | Active March 2002 (period 4) & April 2002 (period 6) |
| F | ~ 11 km SW of Burakin | -30.54<br>117.06 | 3.8 | Active April 2002 (period 6) |
| G | ~20 km SW of Burakin | -30.56<br>117.00 | 4.5 | Active 2003 – 2005 (period 8) |

Location A was a site NW of Burakin, and Location D was a site close to the Cadoux Fault, about 25 km S of Burakin. Activity at these four locations is summarised in Table 2.

This current report suggests three more earthquake sources (E, F and G) and these are summarised in Table 2 and shown in Figure 3. The initial report focussing on Burakin seismicity was presented by Leonard (2002) and, as the cluster events were still in progress at the time of the report's publication, it was more of a statement of the anticipated research directions, rather than an interpretation of the data then available. In their compilation of Australian fault plane solutions, Leonard et al. (2002) presented solutions for 7 of the larger events in the Burakin sequence. Detailed interpretations were not given, but the initial ML 5.2 event was interpreted as a strike slip event, and most of the remaining were thrust events. The solutions, and preliminary interpretations are presented later in this report

Leonard (2003) discussed Omori decay rates in the Burakin sequence, and he suggested that most of the seismicity could be regarded as separate aftershock sequences for each of

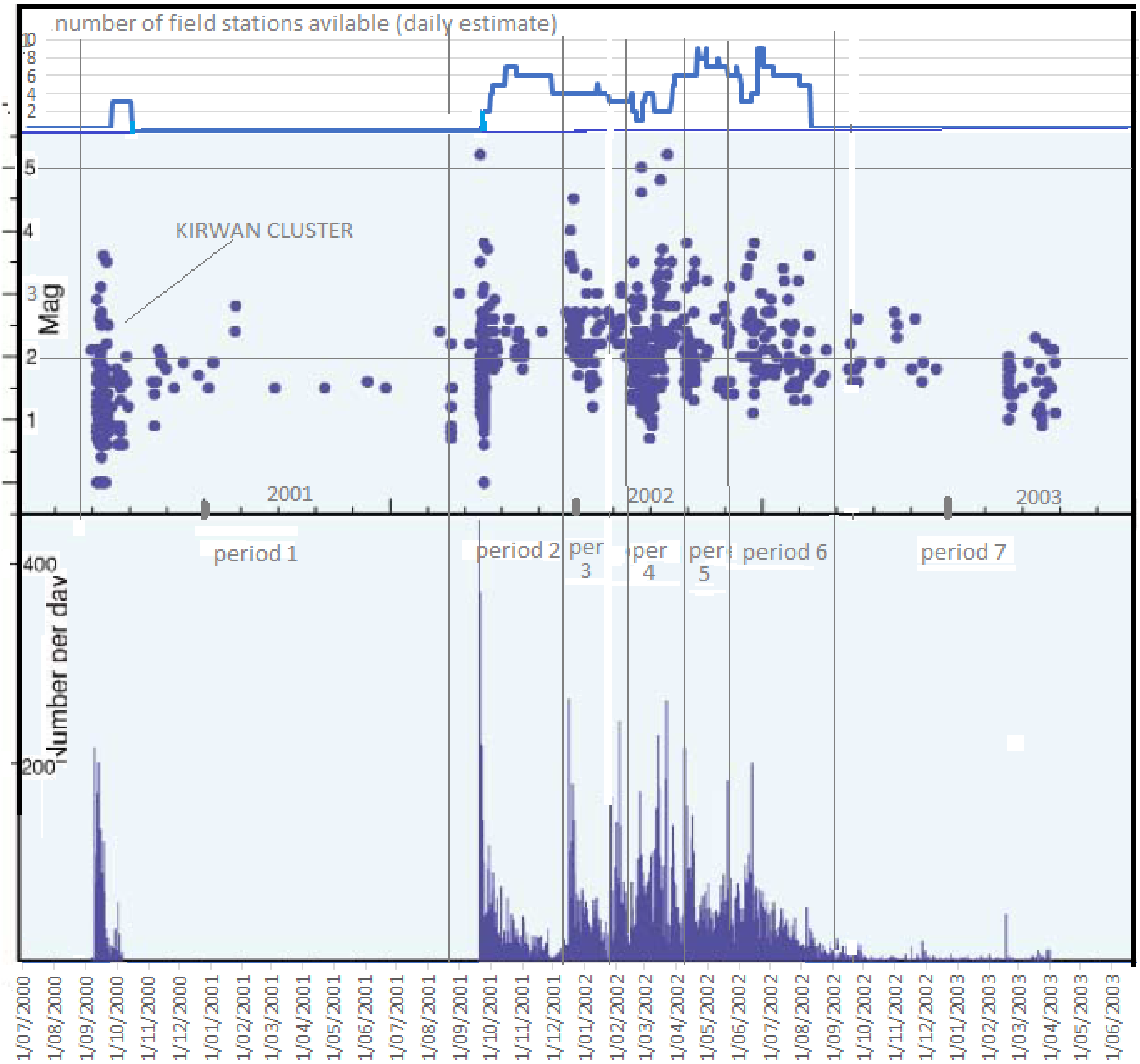



*Figure 2. Field Station availability, & Frequency/magnitude plot - modified from Leonard (2003)*

the four largest events in the September 2001 - March 2002 sequence (the fourth event on 23 March is noted in his article as ML 5.1, but in the GA catalogue is listed as ML 4.8). Figure 2 shows the frequency/magnitude plot presented in Leonard (2003). The numbers seen per day suggests this plot includes small events that have not been listed in the GA catalogue.

In a previous report, Dent & Collins (2020) reviewed the events in the Burakin cluster during March 2002, a relatively short but intense period of the Burakin seismicity. This period contained the last two of the three ML 5 events in the sequence. Dent & Collins (2020) presented relocations for about 20 events in that month and suggested that the events in the cluster were, in general, much closer to field station CA3 (Figure 1) than implied by the GA published epicentres. There appeared to be a concentration of events about 2 km south of CA3, and possibly about 2 km north of CA3 as well.

In this current report, the full sequence, i.e., from September 2001 to August 2002 is reviewed, and subsequent activity through to 2020 is also discussed briefly. GA has kindly assisted by providing much archival data. Epicentral locations after August 2002 are relatively poor as the field network had been withdrawn by then, and locations are based on limited data from the permanent Australian National Seismic Network (ANSN).

### *1.4 Earthquake locations and relocations*

Earthquake locations prior to 2009 were made by GA using the EQLOCL location program (© SRC, Melbourne) and using the WA2 earth model (Dent, 1989). After 2009, GA locations were derived using the Antelope system (© BRTT, Colorado), and the WA2 earth model was used. After 2013 GA started using the IASPEI 91 earth model (Kennett & Engdahl, 1991) rather than WA2 as it was suspected the WA2 velocities were too high. Since 2019, GA has been using SEISCOMP3 for locations.

As detailed in Dent & Collins (2020), GA has used all available phase data for its locations, and significantly, has applied equal weighting to all the phases. This frequently results in the close stations (with relatively high-quality arrivals) having unacceptably large residuals (frequently > 0.5 secs). The relocations presented in this report (Appendix A) have given maximum weighting to the close field station data, resulting in revised locations which can be up to 7 km different from the original GA location. Note that even a small shift in location (~ 1 kilometre) can make a difference in correctly interpreting possible lineation trends in the earthquake epicentres.

Appendix A lists all GA located events of ML 3.5 or more and their relocations, and some events of lesser magnitude. These smaller events were selected for relocation because their remoteness from other contemporaneous events raised suspicions as to their accuracy. The WA2 earth model is suspected to have deficiencies – its velocities may be too high, and the relocations presented here may be modified at some future date if a better earth model can be established. The WA2 earth model was used for the relocations presented here, despite suspected high velocities, as alternative local earth models have yet to be developed.

## 2 Geographical distribution vs time

The period January 2000 – December 2020 has been divided into eight time periods, as shown in Table 3, based partly on the occurrence of the largest events, and partly on event density. These roughly correlate with active periods noted by Leonard (2003). The divisions are intended to include the main events, and their foreshocks and aftershocks.

The locations and relocations of events in these periods are plotted in the 8 sections of Figure 3 and are listed in Appendix A.

*Table 3. Temporal divisions used here*

| | Period duration | Max ML | Comments |
|---|---|---|---|
| 1 | Jan 2000 – Aug 2001 | 3.6 | Includes ML 3.6 precursory event on 22 Sep 2000 |
| 2 | 01 Sep – 20 Dec 01 | 5.2 | Foreshocks and aftershocks of the ML 5.2 event on 28 Sep |
| 3 | 21 Dec – 23 Feb 02 | 4.5 | Resurgence of activity after 21 Dec 2001 |
| 4 | 24 Feb – 19 Mar 02 | 5.0 | Includes ML 5.0 event of 05 Mar 2002 |
| 5 | 20 Mar – 14 Apr 02 | 5.2 | Includes ML 5.2 event on 30 Mar and aftershocks |
| 6 | 15 Apr – 31 Aug 02 | 3.8 | Includes two groups N and S of station CA3 |
| 7 | 01 Sep 02 – 31 Jul 04 | 3.2 | Incudes clusters in Feb-Mar 2003 |
| 8 | Aug 2004 – Dec 2020 | 4.5 | Includes clustered events Aug 2004 – June 2005 |

## *2.1 Period 1: January 2000 – August 2001 (Figure 3.1)*

There were seven events near Burakin in this period, all foreshocks and aftershocks of an ML 3.6 event on 22 September 2000. They were contemporaneous with the “Kirwan” swarm (Leonard & Boldra, 2001), about 12 km SSE (Location C, Figure 1 & Figure 3.1). Approximately 120 events were located during the Kirwan swarm, although a further 1,700 events from the cluster were recorded at the Ballidu station (BLDU), about 40 km to the west of Kirwan (Leonard & Boldra, 2001). Leonard & Boldra (2001) noted four sources of seismicity (Locations A-D) in the area in late 2000. The Burakin location was Location B, and the more significant Kirwan location (at the time) was Location C.

Four field stations (CA1 – 4) were deployed on 21 September 2000, four days after the ML 3.6 Kirwan event, although Leonard & Boldra (2002) note that one of them (CA1?) recorded only a small amount of data. These stations also recorded the events west of Burakin, allowing reasonably well determined locations to be made. They were decommissioned after the Kirwan activity died down (December 2000?), and there was no further significant activity in the region until September 2001, when the main Burakin sequence began.

## *2.2 Period 2: September 2001 – 20 December 2001 (Figure 3.2)*

Approximately 150 events were located in this period, most (128) between 28 September and 7 October 2001 (Figure 3.2), and over half of these (88) were below ML 2.0. From October onwards however, almost no small (ML < 2.0) events were located.

This period includes the first of the ML 5 events (ML 5.2 on 28 September), but as the first field stations were not installed until ~ 14 hours after the event, its location (and others in this period) is poor. Because the data are poor, a relocation for this event is not presented.

The renewed activity commenced on 7 September with the first of two foreshocks (ML 3.0 and ML 2.2) of the main event. The largest aftershocks were ML 3.5 and 3.8, both within three days of the ML 5.2 event. The GA location of the main event is about 3 km south of most of the aftershocks, but there is little close arrival data for this event. A review and relocation of the epicentre (Appendix A) moves it about 2 km west. Its focal mechanism (see beach-ball, Fig 3.2) has been interpreted (Leonard et al., 2002) as being strike-slip (strike 103$^{o}$, dip 84$^{o}$)

Relocations of two relatively large events east of the main group (28 September, ML 3.5, and 1 October, ML 3.8) move them 4 to 5 km back to the main group. The relocations cluster around Location B, with a possible N-S trend.

## 2.3 Period 3: 21 December 2001–23 February 2002 (Figure 3.3)

After very few events in late November and early December 2001, an increase in activity begins with an ML 2.7 event on 21 December 2001. Then four days later major activity recommenced with 10 events on 25 December (including an ML 4.0 event, and an ML 3.6 event). Relocations (Appendix A) of the larger events (ML 3.5 and above) shows a distinct NS trend over about 4 km. However, if the most southerly of these is ignored, it could be suggested that they group around Location B.

Leonard et al. (2002) computed focal mechanisms for two events in this period (the ML 4.0 event on 25 December and ML 4.5 event on 28 December – see beach-balls on Fig 3.3), and both were interpreted as over-thrust events, with similar strike and dip (average strike 192$^o$, average dip 75$^o$).

Note that even though December 2001 was quite seismically active, no locations of events of ML < 2.0 were derived. It seems likely that GA considered there were insufficient data to obtain satisfactory locations for them. Activity continued at a relatively low level between 10 January and 22 February 2002, except for a minor increase between 11 and 13 February (the largest event ML 3.1).

## 2.4 Period 4: 24 February 2002 – 19 March 2002 (Figure 3.4)

Significant activity resumed on 24$^{th}$ February 2002 with an ML 2.9 event, and an ML 3.5 event the next day. This activity leads in to the second of three ML 5 events recorded at Burakin, the ML 5.0 event on 5 March 2002. The seismicity of this period is partly discussed (i.e., 1 March -19 March) in Dent & Collins (2020). Focal mechanisms were computed (Leonard et al., 2002) for the ML 5.0 event, and the ML 4.6 aftershock, about 2 hours later (beach-balls, Fig 3.4). Both were interpreted as overthrust events.

There were 143 located events in the period, of which 98 were less than ML 2.0. However, GA's location policy may have changed as there were very few such small events located after 15 March 2002.

CA3 and BK1 stations were the only field stations operating for most of this period, and locations in this period can be considered relatively poor. Most of the Burakin field stations were not deployed until early April 2002. The GA locations of the two largest events (ML 5.0, ML 4.6, on 5 March) lie well to the east of the majority of epicentres; however, when relocated, join the group around Location B.

Most of the locations for this period appear to be about 1 to 2 km to the north and northeast of station CA3, or about 3 km north of Location B; it is here suggested that they define a new location (Location E). The approximate centre of the activity is at 30.50$^o$S 117.05$^o$E (Table 2). The events may all be foreshocks/aftershocks of the ML 5.0 event. The ML 4.6 event is poorly located and is probably a part of this group. This group north of CA3 was noted by Dent & Collins (2020).

**Legend for Figure 3 (1-4):**
*Circle* = GA earthquake location (magnitudes as indicated on figure). *Magenta diamond* = relocation of a GA epicentre (lines join original with relocation for larger events). *Yellow hexagon* = location of earthquake cluster as per Table 2. *Triangle* = field seismograph (filled if operational in that period). *Grey square* = farm or minor village.

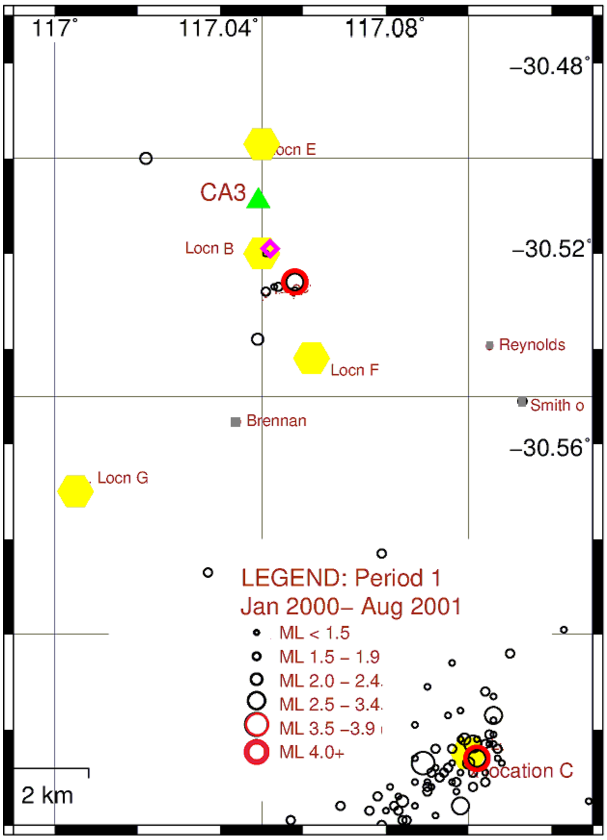



Figure 3.1 Period 1, Jan 2000 – Aug 2001

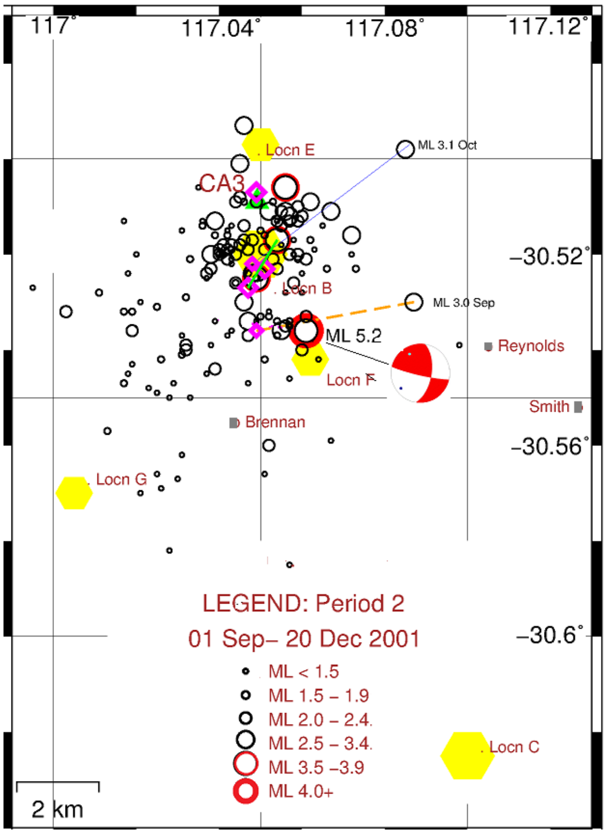



Figure 3.2 Period 2, 01 Sep 2001 – 20 Dec 2001

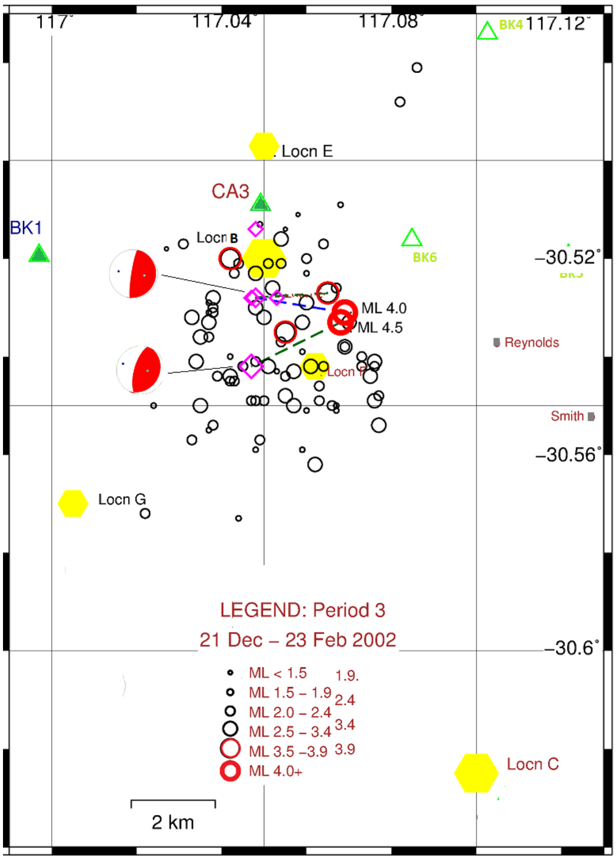



Figure 3.3 Period 3, 21 Dec 2001 – 23 Feb 2002

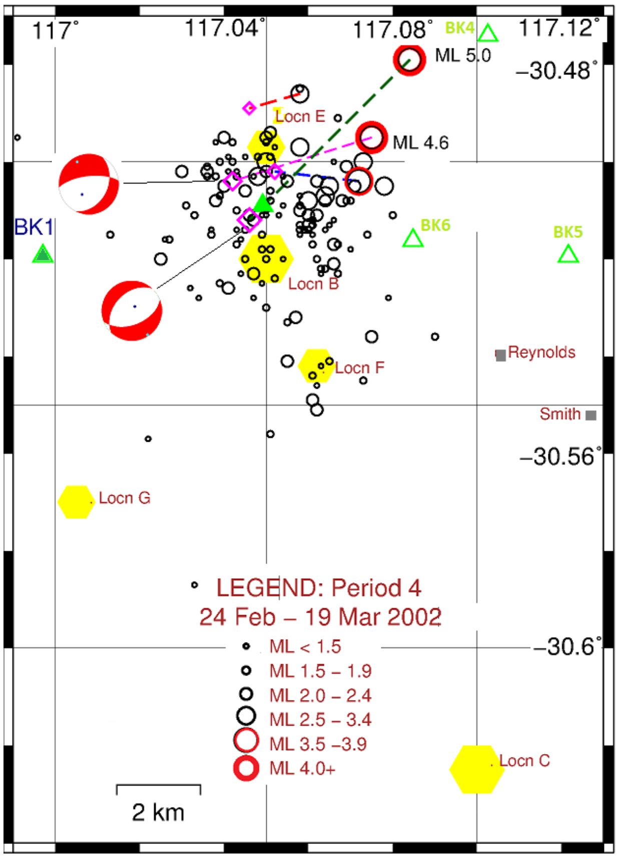



Figure 3.4 Period 4, 24 Feb – 19 Mar 2002

## 2.5 Period 5: 20 March 2002 – 14 April 2002 (Figure 3.5)

This period begins on 20 March and leads to the ML 5.2 event of 30 March. There are five events of ML 3.5+ in this period, and the second largest was ML 4.8 on 23 March. The GA location of the ML 5.2 event places it virtually on Location B, and the relocation also places it there. A relocation of the ML 4.8 event moves it about 2km westwards, also bringing it to Location B.

Focal mechanisms were computed by Leonard et al. (2002) for both the ML 4.8 event and ML 5.2 event. Both were interpreted as being overthrust events, but with quite different strikes (285$^o$ and 27$^o$ respectively).

There were only 14 located events between 27 March and 14 April (smallest ML 2.2), but the field recorders triggered on over a thousand events in this period, which included the ML 5.2 event. As many of the smaller events could be at least roughly located, these data suggest there is a basis for much future research on this period.

## 2.6 Period 6: 15 April –31 August 2002 (Figure 3.6)

In this period, significant seismicity south of Location B is seen for the first time. It began with an ML 2.6 event on 15 April. There are about 130 events located in the period, including five of ML 3.5 or greater. Events in this period up until 4 August generally have good GA locations, as there were multiple field stations providing data. Later events from 5 to 31 August, have less-well constrained locations, and are shown as grey-filled circles on Figure 3.6. In particular, an ML 3.6 event on 16 August plots well to the east of most epicentres and has an anomalous depth (11 km). A relocation of this event (Appendix A) moves it approximately 5 km westwards towards the other epicentres.

During Period 6 there was a brief but significant increase in activity between 18 to 19 April, the largest event being ML 3.8 at a location about 4 km southeast of Location B, a location not previously active. The approximate centre of this activity is at 30.54$^o$S, 117.06$^o$E, and it is here called Location F (Table 2). Activity returned to Location F between 21 and 30 May (largest event ML 3.1 on 30 May), and again between 22 June and early July (largest event ML 3.8 on 23 June).

From about 25 April, activity returned to Location E, i.e., about 2 km north of CA3 and the probable location of the ML 5.0 event of 5 March. The largest event was ML 3.3.

Locations of events in Period 6 are probably better than those of previous periods because of the increased number of temporary recorders.

Period 6 also saw a brief resumption of activity from 26 to 29 April at the location of the Kirwan swarm of September - October 2000, i.e., at Location C (Table 3), about 15 km SSE of Location B. The first, and largest, was ML 3.5.

**Legend for Figure 3 (5-8):**
*Circle* = GA earthquake location (magnitudes as indicated on figure). *Magenta diamond* = relocation of a GA epicentre (lines join original with relocation for larger events). *Yellow hexagon* = location of earthquake cluster as per Table 2. *Triangle* = field seismograph (filled if operational in that period). *Grey square* = farm or minor village.

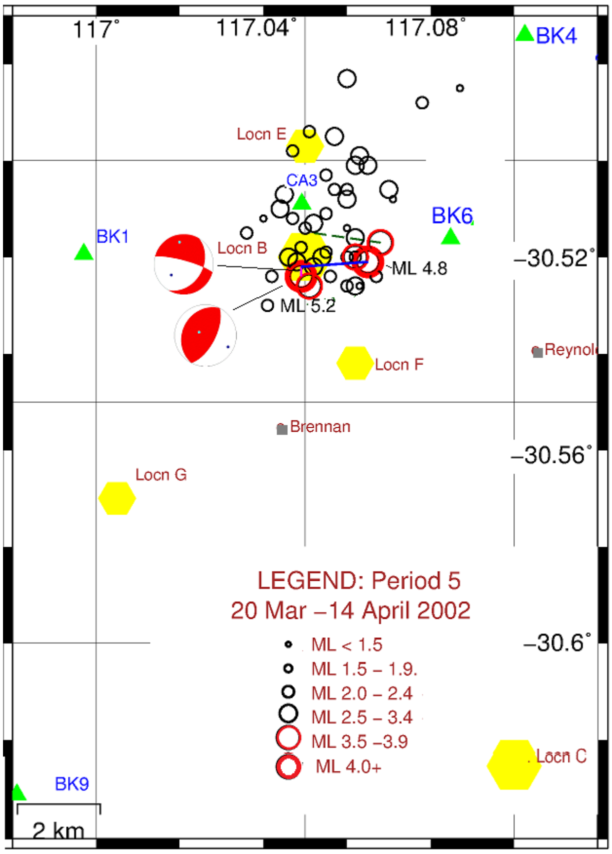



*Fig 3.5 Period 5, 20 Mar – 14 Apr 2002*

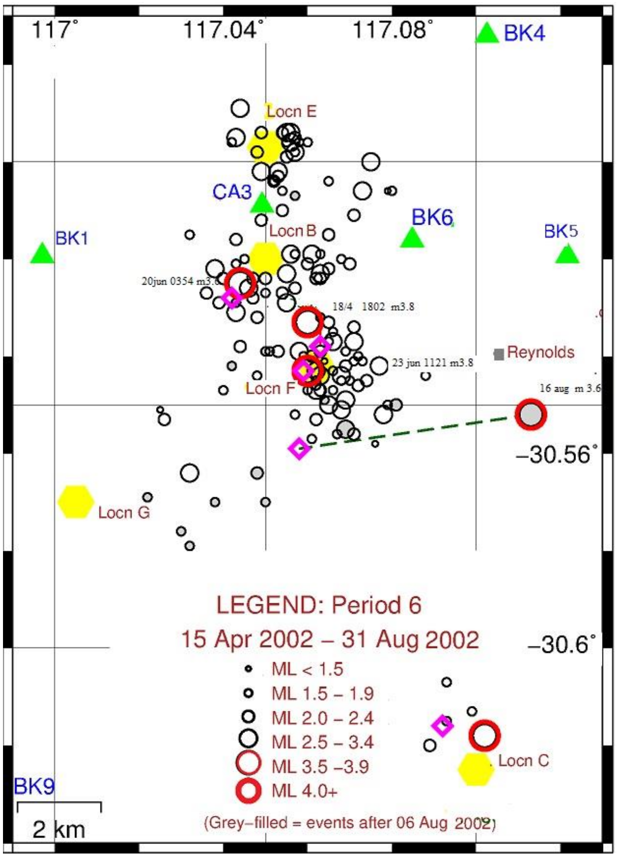



*Fig 3.6 Period 6, 15 Apr – 31 Aug 2002*

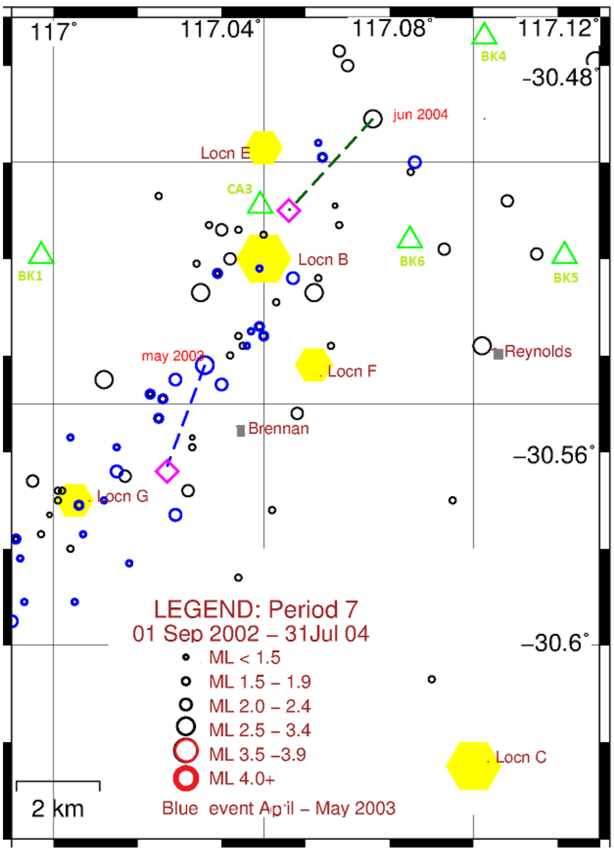



*Fig 3.7 Period 7, 01 Sep 2002 – 31 Jul 2004*

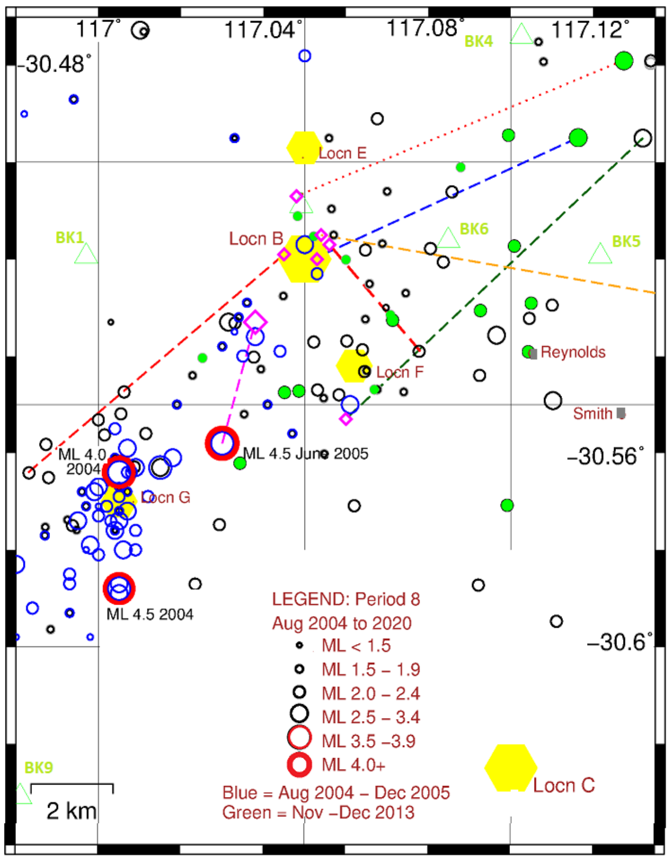



*Fig 3.8 Period 8, Aug 2004 – Dec 2020*

### *2.7 Period 7: September 2002 – July 2004 (Figure 3.7)*

Events in this period of nearly two years are plotted on Figure 3.7. These events are not well located because the field stations had been withdrawn, and locations depend on data from the much sparser ANSN network.

A high proportion of the seismicity, including the largest event (ML 3.2) was in April and May of 2003 (shown in Blue on Figure 3.7). The epicentres display a distinct NE–SW trend but it is suspected that this trend is not real and is introduced by limited phase data combined with poor station distribution (see Dent 2010). The NE-SW trend passes through the location active in 2002 (Location B), but it also passes through a new active location southwest of Location B, which is described in the next period (Period 8).

### *2.8 Period 8: 01 August 2004 – December 2020 (Figure 3.8)*

Events during this sixteen-year period are fairly scattered, but the locations are less precise because only stations from the ANSN network contributed data. However, some relatively good relocations from about 2013 on are presented in Appendix A. These relocations include phase data from stations of the Australian Centre for Geomechanics (ACG) network (Dent, 2013), the most significant of which, in the context of this report, is at the Cadoux General store (CADX – opened late 2014).

There were at least four periods of higher activity, although other periods could be defined depending on the criteria used.

*Period 8.1,* began around 31 August 2004, to the southwest of the main Burakin zone. The events show the same NE-SW trend as events of the previous two years, but there is now a strong concentration in the SW of the active zone. Three large events (ML 3.5+) occurred between April and June 2005 (largest ML 4.5), and it is suggested that they form a new centre of activity (Table 2, Location G).

*Period 8.2,* from November 2013 - March 2014, contained approximately 40 events, the largest being an ML 2.6 event on 7 December 2013. Relocations of the two largest events bring them close to Location B, but the estimated uncertainty remains at ~ +/- 5 km

*Period 8.3*, from 18 - 20 August 2018, hosted four events, the largest being ML 2.9. Relocating this event brings it closer to Location B.

*Period 8.4*, from January - May 2020, contained a group of events, the largest of which (ML 2.5 on 20 January) was located by GA outside of our plot area. However, its relocation brings it closer to location B, and six other smaller events.

The conclusion from this section is that, while a distinct grouping occurred to the SW of location B in 2004, much of the seismicity, right up to 2020, is probably associated with the most important seismicity source of 2001-2002, i.e., Location B.

# 3 Relationship to geology & geophysics

The Burakin area is in the western region of the Archean Yilgarn Craton. The bedrock geology comprises granites of the amphibolite- to granulite-facies crustal Domain 2 (Quentin de Gromard et al., 2021) within the Youanmi Terrane. An E-W trending mafic dyke of the Widgiemooltha suite is mapped within the area, but about 10 km south of most of the epicentres (Figure 4). Dentith & Featherstone (2003) suggested that the narrow NW trending zone of seismicity (approximately 60km x 500km in southwest WA, including Burakin, Cadoux and Meckering) could be due to a “zone of weakness” at a terrane boundary which dips shallowly to the northeast. However, recent revision of the terrane boundaries in the Yilgarn has removed any boundaries in the Burakin-Cadoux region (Quentin de Gromard, 2021; Martin et al., 2021) and the most recent GA earthquake catalogue that includes more events suggests the seismic zone is probably more diffuse and localised.

While the seismicity does not appear to correlate with any of the known geological features, when the events are plotted on the total magnetic intensity (TMI) (Brett, 2020) (Figure 4), a possible correlation with a significant arcuate NS fault, a couple of kilometres to the east of the events, becomes apparent. The fault was interpreted from the magnetic images only, and the dip is unknown, but the curvature suggests it may be west dipping. If this is true, we could be seeing the swarms of earthquakes as stress relief in the hanging wall of the fault. The seismicity seems to nestle in the arc in a similar manner to that noticed by Dentith et al. (2009) for the Meckering M6.5 event of 1968 (Gordon & Lewis, 1980). Dentith et al. (2009) attributed the relative locations of the events and scarps associated with the Meckering sequence to the interaction of east-west compression with northwest-southeast and northeast-southwest trending weaknesses resulting in an apparent arcuate fault.

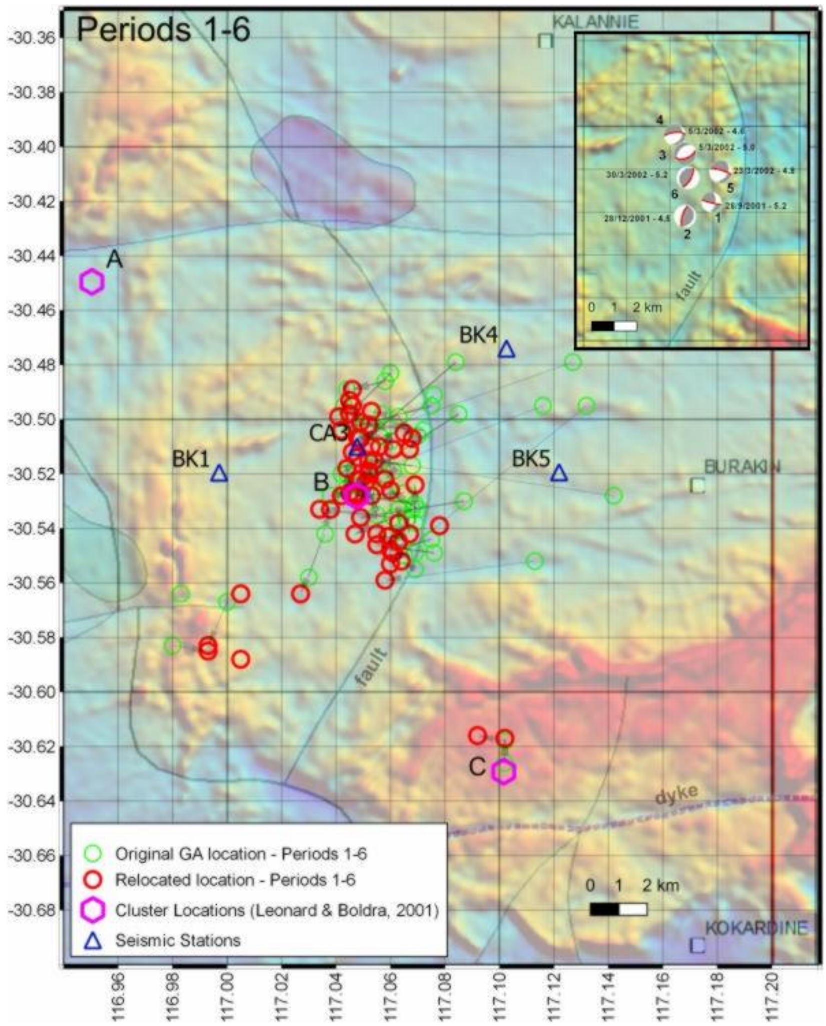



*Figure 4. Relocated earthquakes on total magnetic intensity. Also shown are interpreted faults and dykes. Inset: Focal mechanisms of the largest six events from Leonard et al. (2002) and Clark (2004, unpublished).*

Clark (2004, unpublished) made a preliminary attempt to understand the Burakin sequence by examining the focal mechanisms published by Leonard et al. (2002), and their relation to possible structural lineaments deduced from the total magnetic intensity image (inset, Figure 4). As three of the events he considered have now been relocated, his conclusions relating to the lineaments at the original locations no longer hold. However, his general observation remains, that stress transfer following each event within this structurally complex area is reflected in the diversity of the focal mechanisms. He concluded that the Burakin activity was possibly linked to the terrane boundary between the Murchison and Southern Cross Terranes. However, this boundary is no longer considered to be a terrane boundary (Martin et al., 2021) and the events lie well within the Youanmi Terrane.

# 4 Discussion

The epicentral plots presented here suggest that the “amorphous blob” of epicentres west of Burakin, seen in Figure 1 can be simplified into periods of higher seismicity at four distinct locations (i.e., Locations B, E, F and G). These trends are supported by relocations of the more significant (i.e., larger) events. Relocations of events in 2000 involved increasing the weighting for the field recorders. Relocations in later periods involved the inclusion of new phase data from stations of the ACG network.

Reference to the Time Vs Magnitude plot (Figure 2) suggests that many hundreds of small events (ML 1.5-1.9) have passed unreported – this is particularly noticeable in March and April of 2002. Note also that some of the recorders seem to have had relatively insensitive trigger settings, meaning that these recorders only triggered on relatively large events.

Activity at Location B tailed off after August 2002, but never completely stopped. A new active centre, about 7 km SW of Location B is noted between April and June 2005 (Location G). However, it should be noted that locations after August 2002 are poor because the field stations had been withdrawn, and locations reverted to being reliant on the much sparser permanent network.

Periods of relatively dispersed activity, but which may well have emanated from Location B are noted all the way up to 2020.

Leonard (2003) suggests that the seismicity SSW of Location B, mainly in September and October 2000 (here called the “Kirwan” seismicity) may form a kind of “bridge” linking the Burakin seismicity to the historic 1978 Cadoux fault line, only about 30 km to the SSE. However, this suggestion should be regarded as speculative until supporting features, other than mere proximity, are found.

While focal depths are not accurately determined, the suggestion is that all events appear to be less than 3 km deep. Because there is little depth range, they cannot be used to define a fault plane. Thus, Burakin events join the Kalgoorlie (2010) and Lake Muir (2018) sequences, where a clear three-dimensional fault plane is yet to be defined. This may reflect that the stress released in these events is on a range of smaller structures in the hanging wall of the main arcuate structure.

It is difficult to correlate the fault plane solutions with the observed geology or geophysics, but it must be kept in mind that the input first-motion data is poor, and accurate fault-plane solutions are not likely.

The 2001-2002 Burakin activity seems to resemble that of an active period in 1949-1956 in the Yericoin/Gabalong region, about 70 km southwest of Burakin. During that time period, when the only seismograph was a low-gain recorder in Perth, three ML 5 events (largest ML 5.8), and many smaller events were recorded and felt (Everingham, 1968; Everingham et al., 1982; Dent, 2011).

The authors have noticed that, when smaller events in April 2002 are plotted (i.e., ML $< 2.5$) a thin band of earthquakes, about 3 km long, is seen extending eastwards from location B, and this would seem to be consistent with the strike of 285° noted for the ML 4.8 event of 23 March 2002. Further investigation is planned for this area.

# 5 Conclusions

Some events precursory to the seismicity of 2001-2002 occurred in September 2000. Seismicity of the 2001-2002 sequence reached a maximum in March 2002 and had basically ended by August 2002. Some periods of lesser seismicity have been noted up to 2020 and will probably continue into the future.

The relative uncertainty of the locations of epicentres after August 2002 makes it difficult to correlate earthquakes with the suggested source location. The three ML 5 events of 2001-02 may be closer to each other than GA solutions suggest. Activity in April 2002 is noted at two new locations, just to the N and S of the presumed main location, and this may suggest a NNW-SSE oriented fault plane. This may be supported by a feature noted on the aeromagnetic anomaly map. No clear geological controls are evident.

The relocations presented here conspicuously occur immediately to the west of a prominent aeromagnetic lineament interpreted to be a fault (Quentin de Gromard, 2021). A diverse mix of focal mechanisms derived for the larger events (Clarke, 2004, unpublished) suggests that the events considered here did not occur on this fault plane. However, the close spatial proximity of epicentres to the west of the fault allow that the fault controls seismicity in some way. However, no surface ruptures were available to confirm either hypothesis.

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## *Appendix A. Geoscience Australia epicentral locations, and relocations (this paper)*

| | Date/time | ML | GA location | | Dep, rms, stns/phases (GA) | Relocation | | Dep, rms, stns/phases(Reloc) | Close Stn | Shift (km) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2000-09-22 06:04 | 3.6 | 117.058 | -30.526 | 1.1km 0.23s 12/22 | 117.052 | -30.519 | 1.9km 0.024s 4/7 | CA3 | 0.9 |
| 2 | 2000-09-25 1550 | 3.5 | 117.102 | -30.626 | 0.6km 0.13s 8/15 | 117.104 | -30.620 | 3.6km 0.049s 5/8 | CA3 | 0.6 |
| 3 | 2001-09-07 17:42 | 3.0 | 117.087 | -30.530 | 4.0km 0.66s 6/11 | 117.049 | -30.536 | 3.6km 0.126s 4/6 | BLDU | 3.8 |
| 4 | 2001-09-28 02:54 | 5.2 | 117.061 | -30.536 | 2.4km 0.52s 10/14 | Not relocated | | (poor data) | CMC | |
| 5 | 2001-09-28 03:00 | 3.5 | 117.054 | -30.517 | 0.6km 0.12s 4/7 | 117.047 | -30.527 | 0.8km 0.108s 3/5 | CMC | 1.2 |
| 6 | 2001-09-30 04:02 | 3.0 | 117.045 | -30.501 | 0.1km 0.65s 12/23 | 117.053 | -30.510 | 2.1km 0.045s 6/10 | PIG | 1.2 |
| 7 | 2001-10-01 04:52 | 3.8 | 117.049 | -30.525 | 0.4km 0.28s 11/20 | 117.051 | -30.523 | 3.5km 0.053s 6/10 | CA4 | 0.3 |
| 8 | 2001-10-01 1352 | 3.1 | 117.085 | -30.498 | 0.5km 0.41s 7/12 | 117.048 | -30.522 | 5.1km 0.075s 4/7 | CA4 | 4.4 |
| 9 | 2001-10-05 14:55 | 3.7 | 117.056 | -30.506 | 0.8km 0.28s 12/20 | 117.049 | -30.507 | -0.8km 0.350s 6/11 | CA3 | 0.7 |
| 10 | 2001-11-04 2329 | 2.4 | 117.044 | -30.520 | 0.2km 0.21s 9/17 | 117.044 | -30.518 | 1.9km 0.025s 6/10 | CA3 | 0.2 |
| 11 | 2001-12-25 00:56 | 4.0 | 117.069 | -30.531 | 1.2km 0.47s 15/26 | 117.048 | -30.528 | 4.4km 0.054s 6/8 | BK1 | 2.1 |
| 12 | 2001-12-25 0506 | 3.5 | 117.055 | -30.535 | -0.2km 0.24s 12/20 | 117.053 | -30.528 | 2.1km 0.059s 7/13 | BK1 | 0.7 |
| 13 | 2001-12-25 0510 | 3.6 | 117.065 | -30.527 | 1.1km 0.33s 12/19 | 117.047 | -30.528 | 4.1km 0.130s 7/9 | BK1 | 1.8 |
| 14 | 2001-12-26 1858 | 3.5 | 117.042 | -30.520 | 1.3km 0.37s 12/21 | 117.048 | -30.514 | 1.8km 0.084s 7/10 | BAL | 0.8 |
| 15 | 2001-12-28 1631 | 4.5 | 117.068 | -30.533 | 2.4km 0.37s 17/25 | 117.047 | -30.542 | 4.4km 0.037s 6/9 | BK1 | 2.3 |
| 16 | 2001-12-30 14:57 | 2.5 | 117.076 | -30.549 | 1.1km 0.35s 8/15 | 117.055 | -30.546 | 2.1km 0.081s 5/9 | BK1 | 2.1 |
| 17 | 2002-01-10 15:19 | 3.3 | 117.070 | -30.533 | 1.4km 0.37s 14/27 | 117.060 | -30.526 | 2.1km 0.054s 7/14 | CA3 | 1.2 |
| 18 | 2002-01-10 19:17 | 3.0 | 117.069 | -30.538 | 0.8km 0.33s 13/24 | 117.069 | -30.524 | 3.4km 0.031s 7/11 | CA3 | 1.4 |
| 19 | 2002-01-21 19:34 | 3.0 | 117.075 | -30.544 | 0.1km 0.46s 11/20 | 117.060 | -30.548 | 2.0km 0.028s 4/7 | BK1 | 1.6 |
| 20 | 2002-02-13 00:32 | 3.0 | 117.038 | -30.528 | 2G 0.52s 9/16 | 117.045 | -30.527 | 2.0km 0.084s 5/8 | CA3 | 0.7 |
| 21 | 2002-02-24 2028 | 2.9 | 117.065 | -30.505 | 1.4km 0.41s 11/21 | 117.053 | -30.522 | 1.1km 0.178s 7/14 | CA3 | 2.1 |
| 22 | 2002-02-25 17:37 | 3.5 | 117.072 | -30.504 | 1.5km 0.49s 12/24 | 117.052 | -30.502 | 0.9km 0.107s 6/9 | CA3 | 2.0 |
| 23 | 2002-03-01 18:47 | 3.1 | 117.058 | -30.486 | 0.3km 0.35s 13/24 | 117.046 | -30.489 | 0.6km 0.110s 6/9 | CA3 | 1.2 |
| 24 | 2002-03-05 01:47 | 5.0 | 117.084 | -30.479 | 0.5km 0.48s 14/25 | 117.046 | -30.512 | 1.8km 0.154s 4/6 | CA3 | 5.0 |
| 25 | 2002-03-05 03:29 | 4.6 | 117.075 | -30.495 | 0.4km 0.64s 14/22 | 117.042 | -30.504 | 1.3km 0.150 s 6/9 | BK1 | 3.4 |
| 26 | 2002-03-20 11:47 | 3.2 | 117.060 | -30.508 | 0.5km 0.31s 10/18 | 117.061 | -30.511 | 1.9km 0.074s 4/6 | CA3 | 0.3 |
| 27 | 2002-03-21 0510 | 2.8 | 117.060 | -30.483 | 2.1km 0.52s 9/18 | 117.045 | -30.498 | 4.9km 0.053s 4/6 | BK1 | 2.1 |
| 28 | 2002-03-22 03:24 | 3.3 | 117.070 | -30.506 | 1.3km 0.33s 12/21 | 117.067 | -30.511 | 2.0km 0.038s 4/7 | CA3 | 0.6 |
| 29 | 2002-03-22 03:25 | 3.1 | 117.063 | -30.499 | 0.6km 0.18s 6/10 | 117.068 | -30.507 | 2.1km 0.024s 3/6 | CA3 | 0.9 |
| 30 | 2002-03-25 0544 | 3.7 | 117.068 | -30.517 | 1.6km 0.34s 14/25 | 117.052 | -30.515 | 1.2km 0.020s 7/10 | CA3 | 1.6 |
| 31 | 2002-03-30 21:15 | 5.2 | 117.049 | -30.524 | 0.8km 0.43s 18/29 | 117.049 | -30.522 | 2.1km 0.520s 5/7 | CA3 | 0.2 |
| 32 | 2002-04-03 1206 | 3.5 | 117.051 | -30.526 | 1.8km 0.17s 16/27 | 117.049 | -30.522 | 1.6km 0.019s 8/11 | CA3 | 0.4 |
| 33 | 2002-04-18 14:14 | 3.1 | 117.066 | -30.537 | 1.3km 0.21s 17/27 | 117.067 | -30.542 | 2.0km 0.028s 9/15 | BK6 | 0.5 |
| 34 | 2002-04-18 18:02 | 3.8 | 117.063 | -30.533 | 2.4km 0.37s 19/33 | 117.063 | -30.538 | 2.2km 0.031s 8/14 | CA3 | 0.5 |
| 35 | 2002-04-18 19:06 | 3.1 | 117.063 | -30.544 | 0.3km 0.34s 15/26 | 117.063 | -30.545 | 2.2km 0.013s 6/10 | BK6 | 0.1 |
| 36 | 2002-04-25 16:50 | 3.3 | 117.057 | -30.498 | 0.6km 0.22s 16/31 | 117.053 | -30.497 | 1.9km 0.037s 8/15 | CA3 | 0.4 |
| 37 | 2002-04-25 17:47 | 3.2 | 117.049 | -30.502 | 0.9km 0.44s 19/35 | 117.046 | -30.495 | 1.8km 0.028s 8/13 | CA3 | 0.8 |
| 38 | 2002-04-26 06:43 | 3.5 | 117.102 | -30.618 | 3.7km 0.34s 21/35 | 117.092 | -30.616 | 5.3km 0.039s 9/14 | BK5 | 1.0 |
| 39 | 2002-05-08 11:18 | 3.2 | 117.043 | -30.495 | 0.6km 0.20s 16/30 | 117.041 | -30.499 | 1.9km 0.060s 9/14 | CA3 | 0.4 |
| 40 | 2002-05-30 17:10 | 3.1 | 117.069 | -30.549 | 3.2km 0.47s 14/23 | 117.055 | -30.542 | 1.5km 0.041s 7/10 | CA3 | 1.6 |
| 41 | 2002-06-16 02:59 | 3.3 | 117.044 | -30.489 | 0.3km 0.23s 17/33 | 117.045 | -30.493 | 1.9km 0.037s 9/16 | CA3 | 0.4 |
| 42 | 2002-06-20 03:54 | 3.6 | 117.044 | -30.525 | 1.6km 0.21s 17/21 | 117.042 | -30.528 | 2.0km 0.031s 9/16 | CA3 | 0.4 |
| 43 | 2002-06-23 11:21 | 3.8 | 117.060 | -30.543 | 0.5km 0.18s 15/27 | 117.059 | -30.543 | 2.1km 0.036s 8/14 | BK6 | 0.1 |
| 44 | 2002-06-30 05:26 | 3.0 | 117.053 | -30.502 | 1.4km 0.18s 12/22 | 117.049 | -30.501 | 2.2km 0.038s 6/11 | BK6 | 0.4 |
| 45 | 2002-07-22 19:38 | 3.4 | 117.065 | -30.550 | 2.5km 0.34s 16/28 | 117.061 | -30.549 | 2.4km 0.056s 7/13 | BK6 | 0.4 |
| 46 | 2002-07-23 16:09 | 3.2 | 117.061 | -30.519 | 2.5km 0.28s 18/30 | 117.058 | -30.522 | 2.6km 0.022s 6/10 | BK6 | 0.4 |
| 47 | 2002-08-06 05:49 | 3.2 | 117.069 | -30.555 | 1.7km 0.29s 15/27 | 117.064 | -30.552 | 2.3km 0.033s 8/14 | BK6 | 0.6 |
| 48 | 2002-08-16 09:47 | 3.6 | 117.113 | -30.552 | 11km 0.34s 7/13 | 117.058 | -30.559 | 3.1km 0.059s 4/7 | KLB | 5.5 |
| 49 | 2003-05-11 1830 | 3.2 | 117.036 | -30.542 | 2.1km 0.23s 7/12 | 117.032 | -30.549 | 1.7km 0.109s 4/7 | BLDU | 0.4 |
| 50 | 2003-08-18 1756 | 2.8 | 117.129 | -30.479 | 0G 0.32s 4/9 | Not relocated | | (poor data) | BLDU | |
| 51 | 2004-06-02 1704 | 2.7 | 117.076 | -30.491 | 2.9km 0.54s 6/12 | 117.056 | -30.510 | 0.0km 0.116s 4/7 | BLDU | 2.8 |
| 52 | 2005-04-12 1159 | 3.5 | 117.005 | -30.588 | 2N 0.23s 5/8 | Not relocated | | (poor data) | BLDU | |
| 53 | 2005-04-12 1200 | 4.0 | 117.005 | -30.564 | 0G 0.23s 4/6 | Not relocated | | (poor data) | BLDU | |
| 54 | 2005-04-18 0902 | 3.2 | 117.000 | -30.567 | 0G 0.29s 4/8 | 116.993 | -30.583 | 1.9km 0.074s 4/6 | BLDU | 1.7 |
| 55 | 2005-05-09 1452 | 3.2 | 116.980 | -30.583 | 0G 0.51s 6/10 | 116.993 | -30.585 | 1.0km 0.100s 4/6 | BLDU | 1.3 |
| 56 | 2005-06-12 2036 | 4.5 | 117.030 | -30.558 | 7.6km 0.41s 6/12 | 117.038 | -30.533 | 2.1km 0.171s 5/9 | BLDU | 2.6 |
| 57 | 2008-08-01 1727 | 3.1 | 117.132 | -30.495 | 0G 0.42s 5/8 | 117.060 | -30.553 | 7.0km 0.240s 3/5 | KLBR | 9.2 |
| 58 | 2013-12-06 1414 | 2.5 | 117.127 | -30.479 | 10km 0.99s 8/16 | 117.048 | -30.507 | 1C 0.303s 6/8 | BLDU | 8.4 |
| 59 | 2013-12-07 0625 | 2.6 | 117.116 | -30.495 | 9.0km 0.88s 8/16 | 117.061 | -30.473 | -0.4km 0.128s 5/5 | BLDU | 6.9 |
| 60 | 2018-08-20 2253 | 2.3 | 117.078 | -30.539 | 10km 1.2s 7/13 | 117.056 | -30.517 | 1.7km 0.131s 5/8 | BLDU | 3.1 |
| 61 | 2018-08-20 2330 | 2.9 | 117.142 | -30.528 | 10km 0.99s 9/13 | 117.054 | -30.515 | 1.4km 0.093s 6/9 | BLDU | 8.9 |
| 62 | 2020-03-16 1419 | 2.3 | 116.983 | -30.564 | 10km 0.68s 8/11 | 117.045 | -30.519 | 1.1km 0.100s 7/11 | BLDU | 7.7 |