A study of NW Australian Earthquakes and Stress Regime

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Abstract

A 3-year deployment of a temporary seismic network in NW Australia recorded 28 regional seismic events with a precision which allowed the reliable calculation of focal mechanisms. These focal mechanisms provided sufficiently accurate information for the inversion of the deviatoric stress tensor.

The study of the misfit between individual focal mechanisms and the stress tensor shows that the micro earthquakes in NW Australia sample the seismogenic crust, and that they are not biased by stress reorientation due to near-surface or other local features.

Introduction

The Australian continent sits on the Indo-Australian plate. The continent itself is old and commonly regarded as seismically quiet and stable (Johnston *et al.*, 1994; Leonard *et al.*, 2007). Tregoning (2003) used GPS data to show that the velocity residuals of 12 stations on the Australian Plate were statistically indistinghuisable from zero, with a standard deviation of about 0.6 mm/year. This is the equivalent of a strain rate smaller than $6.4 \cdot 10^{-18} s^{-1}$ (Leonard, 2008), a value at the lower end of the spectrum typical for intraplate rates (Mazzotti, 2007). Tregoning's 2003 conclusion that the Australian continent does not measurably change its dimensions still stands.

Nevertheless, intracontinental earthquakes do happen, and on a regular basis. Leonard (2008) presents a total of 27000 recorded events (with the first record going back to 1788), 17000 of which are considered to be main shocks. The catalogue is reasonably complete for events with magnitude 5.0 and above from 1910 onwards and for magnitude 3.5 and above from 1975 onwards. This database leads to a calculated recurrence rate of 1.1 magnitude 5 or larger events per year, which is similar to the McCue (1990) estimate of a 5 year recurrence of magnitude 6 events. On a regional scale, northwestern Australia has the highest rate for the continent, with a magnitude 5 or larger event every 1.2 years (Leonard *et al.*, 2007).

Western Australia makes up about one third of the Australian continent and is geologically remarkable for containing two Archean cratons: the Yilgarn and Pilbara cratons (Myers *et al.*, 1996) (see Figure 1). The Pilbara Craton in the north is separated by the Paleoproterozoic Capricorn Orogen from the Yilgarn Craton to the south. To the west these two cratons and the intervening Capricorn Orogen are separated from the Indian Ocean by the Neoproterozoic Pinjarra Orogen (Myers *et al.*, 1996)(Figure 1). The Pinjarra Orogen now forms part of a passive margin, a continental remnant of the rift which formed in the Mesozoic with the separation of India from Australia (Myers *et al.*, 1996; Fitzsimons, 2003).

These tectonic elements are separated by various fault systems, including the very large Darling Fault which separates the Pinjarra Orogen over almost its entire extent from the rest of the continent to its east (see Figure 1). The Darling Fault is traceable over more than 1500 km with a downthrow in some places of up to 10 km (Matur, 1974; Dentith & Featherstone, 2003). The fault has a long and complex history but is currently inactive and aseismic (Harris, 1994). The tectonic elements themselves also host large numbers of faults, some of which are substantial and extend for hundreds of kilometers (Myers & Hocking, 1998).

Studies of the stress field of the Australian continent use a variety of stress indicators. Hillis & Reynolds (2003) compiled a database in which focal mechanisms account for just over 7% of the data. Western Australia is described by 58 stress indicators. Only 6 of these are focal mechanisms: 2 from the Canning Basin and 4 from the Perth region.

Studies of focal mechanisms by Clark & Leonard (2003) and Spassov (1998) were limited to larger events which are necessarily few. For Western Australia, this limitation left 5 events around Meckering in the southwest and 5 events scattered over the Kimberley area in the northeast of the State (see Figure 1).

Here, I summarise the results of a study of micro earthquakes in NW Australia reported by Revets *et al.* (2009), in which I calculated focal mechanisms and inverted these solutions to calculate the deviatoric stress tensor.

Data and Data Processing

We deployed a temporary network of eight stations over a 3-year period with Guralp CMG-40T seismometers and Reftek 72A-07 recorders along the northwestern margin of Western Australia. The data from these stations was supplemented by data recorded by stations of the Australian National Seismological Network (AU) which is managed by Geoscience Australia, as well as from the Global Seismic Network (GSN) stations at Marble Bar and Narrogin (see Figure 1 for location details of the stations). We obtained digital waveforms of the events recorded by

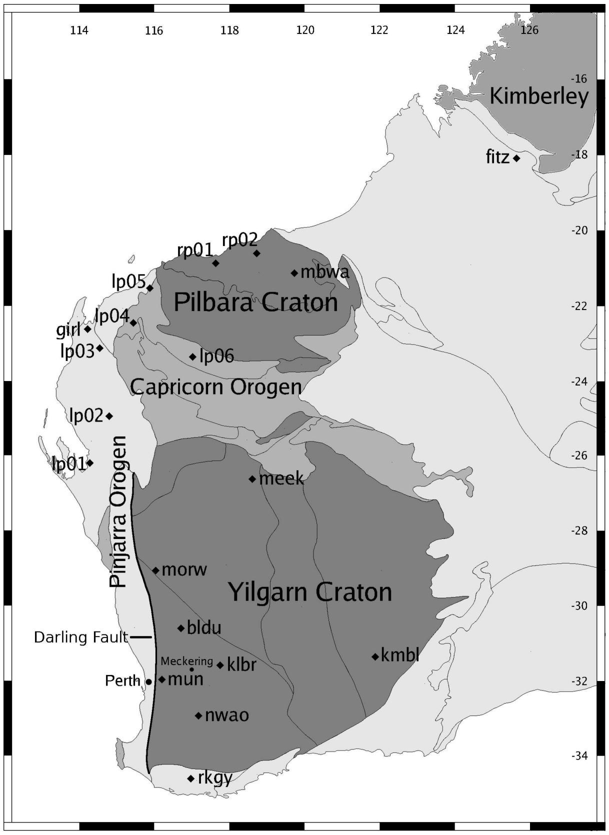

Figure 1: Tectonic elements of Western Australia (after Myers & Hocking, 1998) with location of the stations

the stations of the ANSN through the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS, available on-line on www.iris.edu).

Over the deployment period, 28 events occurred in the area between 20° and 30°S and between 112° and 120°E (1). Two events out of the 28 were too small to be analysed.

Data processing included the use of GSAC (Herrmann & Ammon, 2007), HYPOELLIPSE (Lahr, 1999) and the FPFIT program (Reasenberg & Oppenheimer, 1985), as well as some digital filters written especially to deal with issues of the correct reading of the polarity of the first arrival.

The deviatoric stress tensor can be inverted from focal mechanisms with the method proposed by Gephart & Forsyth (1984) and Gephart (1990a). Gephart (1990b) demonstrates how the method is based on minimizing the smallest angle between the observed fault geometry and any fault geometry consistent with the principal stress directions.

Technical details can be found in Revets *et al.* (2009); Revets (2009, 2010).

Focal Mechanisms

The epicenters of the events lie in the vicinity of significant faults mapped by the Geological Survey of Western Australia (see Figure 2) (after Myers & Hocking, 1998). As the confidence limits of the calculated position of the epicenters are usually between 10 and 20 km and those of the depth at least as large (see Table 1), hypocenters may well coincide with known faults. The events studied here are small and occur at depth, and verification of location on the ground is impossible, a common occurrence for most Australian earthquakes (Clark & McCue, 2003). Because the events are small and because of the error margins on the hypocenter locations, the actual earthquake may have happened on adjacent zones of weakness, rather than on the larger known faults.

About two thirds of the focal mechanisms show a significant strike-slip component to displacement, with the other third predominantly either normal or reverse faults, and a single pure dip-slip (event 2) faulting event (Figure 2). The average uncertainty on the calculated strike is 5.8° (standard deviation 4.1°) while that of the calculated dip is 9.2° (standard deviation 8.4°).

Stress Regime

Inversion of the nodal plane orientations from all the focal mechanisms yields stress orientations from the deviatoric stress tensor which are broadly consistent with published results (Table 2). These studies, also based on focal mechanisms (Leonard *et al.*, 2002; Clark & Leonard, 2003; Spassov, 1998) were for Western Australia limited to the Perth area. The orientations we obtain are consistent with the proposed stress model of the entire continent (Hillis & Reynolds, 2003).

The first calculation using all focal mechanisms yielded an average minimum angular misfit of about 9.5°. This is somewhat high, and raises the question of possible heterogeneity of the data set. A Kolmogorov-Smirnov test of normality of all the misfit values yields a probability of 0.06. This probability increases to 0.49 when 6 outliers are removed. There is no correlation between magnitude of an event and the misfit to the modelled stress tensor ($r = -0.12$). Identification of the outliers shows that most refer to events in the Capricorn Orogen.

A plot of the fault plane positions on the Mohr sphere shows that a significant number of the planes are unlikely to fail under the stress regime defined by the stress tensor obtained from all the focal mechanisms (Figure 3). The number of planes for which τ_b is clearly different from zero as well as the number of planes with a negative τ_s invites further scrutiny. Identifying these planes reinforces the earlier indication that the Capricorn Orogen events differ from the other events. We performed a series of inversions using subsets of the focal mechanisms solutions, choosing groups on the basis of the tectonic element in which or along which they happened. Table 3 lists the events included in the various groups.

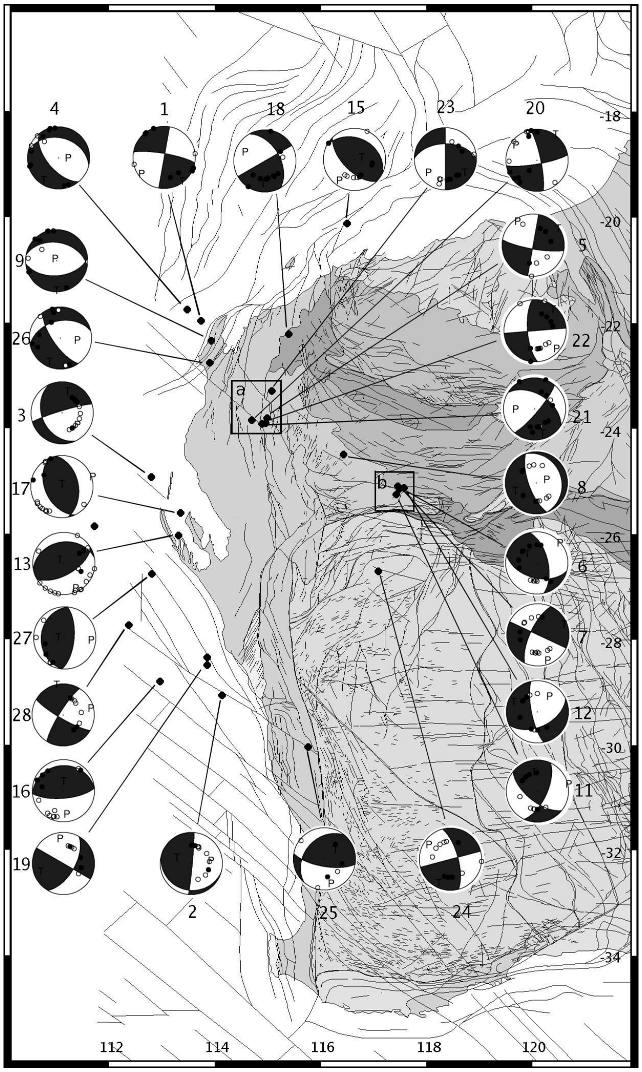

Figure 2: Geological map of Western Australia with mapped faults superimposed (after Myers & Hocking, 1998) and with the results of the focal mechanism calculations. The events are numbered in chronological order, with details in Table 1. The rectangles group clusters of events: (a) contains the Middalya group and (b) the Mount Clere group

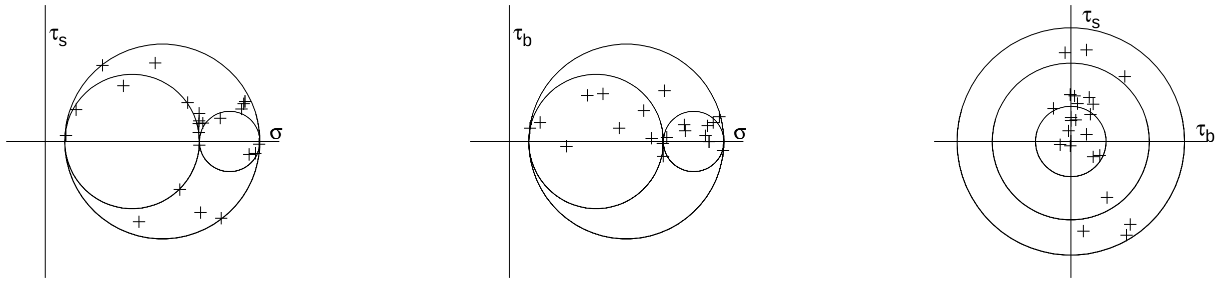

Figure 3: Mohr sphere projections, showing the poles of all the fault planes relative to the stress components defined by the stress tensor obtained from inverting all focal mechanisms

The orientation of the overall stress tensor is consistent with the measurements and modeling of the stress on the Australian continent (Hillis & Reynolds, 2003; Reynolds *et al.*, 2002, 2003). Adding the directions of the main stress component from our calculations (black arrows) to the stress map of Australia yields Figure 4, with the white arrows showing the orientation of the calculated main stress of the various stress provinces by Hillis & Reynolds (2003). The maximum horizontal stress component of the stress tensor for the Pinjarra Orogen (PO), Capricorn Orogen (CO), as well as those of the subgroups Cape Range (CR), Middalya (Mi) are indistinguishable from the Hillis and Reynolds results. The orientation of the maximum horizontal stress from the tensor of the Mount Clere group is slightly different and trending more ESE, while the orientation from the Abrolhos subgroup tensor is significantly different and trends in an almost SE direction. Nevertheless, both are broadly aligned with the overall stress tensor.

Burbidge (2004) proposed an alternative model, using the thin plate spherical finite element modelling technique, in contrast to the previous elastic models (Coblentz *et al.*, 1998; Reynolds *et al.*, 2002). His best fitting model predicts maximum horizontal principal stress directions along the southern half of the Western Australian coast more or less parallel with the coast. The model also predicts that thrust faulting will be the dominant mode of faulting for most of the western three quarters of the continent. The orientation of the stress tensors and the focal mechanisms calculated in this study do not fulfill these predictions.

Discussion

Two thirds of the events used for stress tensor inversion occurred at depths at or below 10 km. The uncertainties on the depth estimates of the hypocenters are substantial (see Table 1). Our attempts at relocation of the events by incorporating the arrival times recorded by our temporary network to

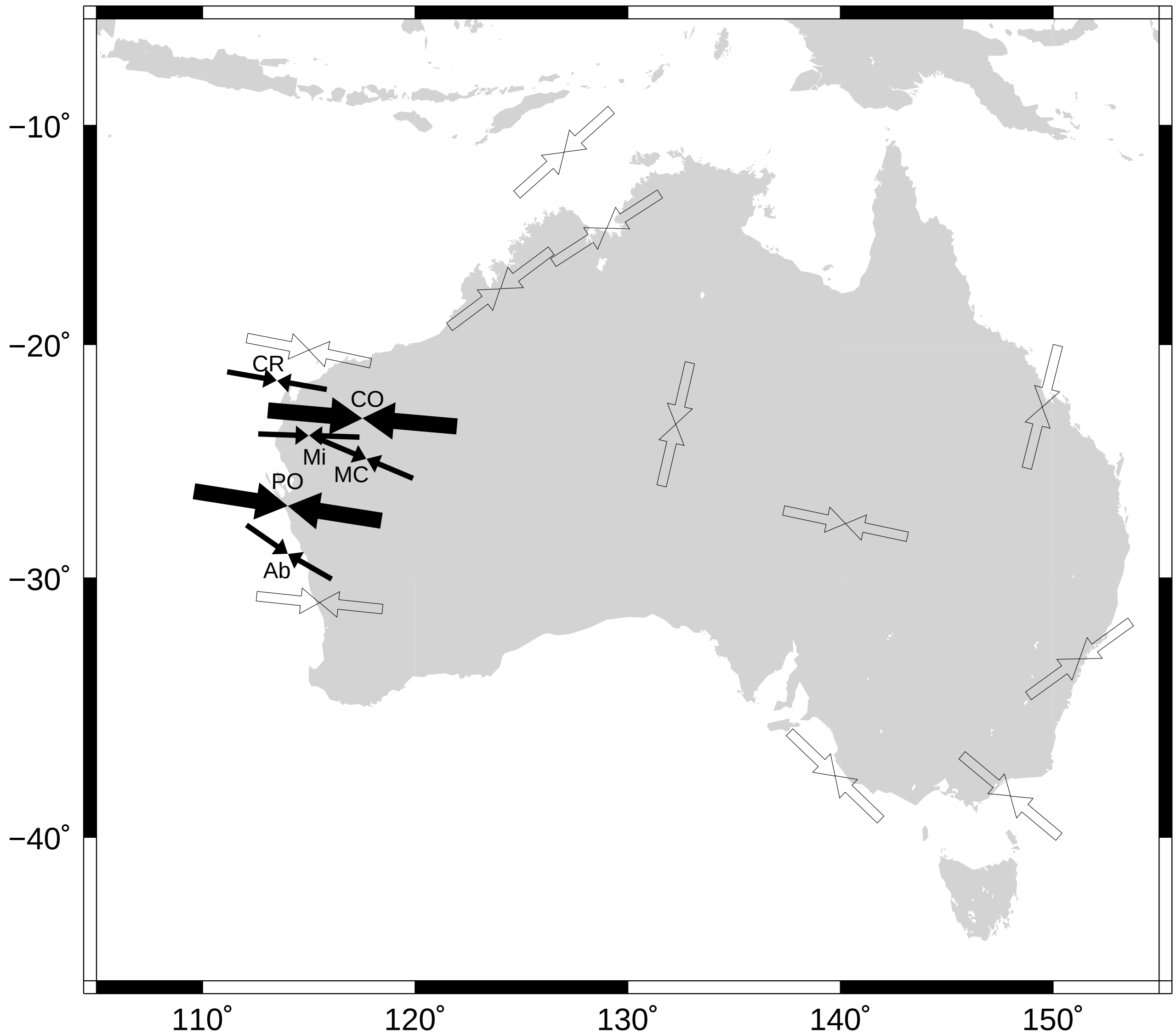

Figure 4: Summary map with σ_1 stress directions from our stress tensor calculations (black arrows) and from Hillis & Reynolds (2003) (white arrows). The thick black arrows show the stress direction for the Pinjarra (PO) and Capricorn (CO) Orogens a whole, while the thinner black arrows show the stress directions for the subgroups of Abrolhos group (Ab), Cape Range group (CR), Middalya group (Mi) and Mount Clere group (MC) (see Table 3)
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the arrival times recorded by the permanent network yielded broadly similar hypocentral depths, which leads us to regard the calculated hypocentral depths as acceptable. These hypocentral depths indicate that the stress regime sampled is that of the seismogenic crust rather than the result of stress reorientation by near surface features. Our data set extends well below that accessible to quarrying activities or normal drilling operations. The consistency between stress directions derived largely from shallower sources of data (Hillis & Reynolds, 2003) and our data set supports the suitability of micro earthquakes as a useful source of information for the determination of the crustal stress field.

The absence of correlation between magnitude or depth of events with minimum angular misfit between fault plane and modelled stress tensor indicates that the micro earthquakes studied are sufficiently unbiassed with regard to local effects to be useful for stress inversion. These correlations are absent for all the groups of events, even when subgroups yielded somewhat different stress tensors.

Sandiford & Egholm (2008) highlight that the Darling Fault, a steep (70°) west dipping, north-trending structure, has no historical record of seismicity, despite being misoriented by only a few 10s of degrees for failure in reverse fault mode. As shown here, σ_1 of the Abrolhos stress tensor has a plunge of 30°, making it virtually normal to the plane of the Darling Fault. This combination of orientations is sufficient to explain seismic quiescence of the Darling Fault as first suggested by Dentith & Featherstone (2003): the stress on the Darling Fault effectively locks it into place.

Conclusions

Micro earthquakes can be used, even with a modest recording network, to calculate focal mechanisms reliably when care is taken with the assessment of first arrival polarity. The deconvolution of the FIR induced acausality from the traces proves to be highly effective.

Focal mechanisms from micro earthquakes can be used to calculate (deviatoric) stress tensors and provide useful and consistent information of the orientation of the seismogenic crustal stress field. Such data has wide ranging applications in areas where in situ data is sparse or absent.

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Table 1: Recorded regional earthquakes

Event	Date	Time	Latitude	Longitude	Depth	Magnitude
1	2005-12-14	11:02:26	-21.889	113.701	21.6	2.6
2	2005-12-20	19:49:26	-29.400	114.102	10.0	3.8
3	2005-12-27	09:32:05	-24.860	112.757	0.0	3.5
4	2006-01-29	09:40:16	-21.676	113.446	22.4	3.4
5	2006-02-05	20:06:29	-23.737	114.959	15.0	2.6
6	2006-06-06	15:34:09	-25.032	117.440	5.5	4.5
7	2006-06-12	22:43:40	-25.061	117.556	1.5	3.9
8	2006-09-02	15:47:39	-24.433	116.413	5.0	3.5
9	2006-10-06	12:06:04	-22.269	113.904	26.1	3.0
10	2006-11-22	14:59:43	-25.788	111.680	138.7	2.5
11	2006-12-07	10:58:18	-25.188	117.411	14.1	3.3
12	2006-12-10	16:34:10	-25.085	117.473	10.0	2.7
13	2007-02-15	15:38:36	-25.967	113.276	18.5	5.3
14	2007-05-30	14:31:07	-28.283	113.822	0.0	2.0
15	2007-06-19	05:25:18	-20.042	116.482	13.6	2.8
16	2007-06-28	16:02:25	-28.741	112.923	15.0	3.2
17	2007-07-17	10:31:25	-25.535	113.319	0.0	2.6
18	2007-08-26	00:34:34	-22.145	115.369	5.7	3.2
19	2007-09-15	04:01:10	-28.430	113.824	16.6	2.2
20	2007-10-25	01:28:14	-23.774	114.667	18.7	3.5
21	2007-11-04	12:19:52	-23.842	114.861	15.0	4.0
22	2007-11-07	19:10:45	-23.833	114.933	0.0	4.4
23	2007-11-27	02:48:16	-23.219	115.047	10.0	3.7
24	2008-01-13	16:16:58	-26.650	117.069	2.5	2.9
25	2008-01-15	12:51:52	-29.990	115.739	10.0	2.3
26	2008-01-28	15:37:13	-22.683	113.872	7.2	3.1
27	2008-02-18	19:18:55	-26.693	112.770	10.0	2.8
28	2008-03-31	08:27:48	-27.666	112.332	17.7	4.4

Table 2: Stress tensor parameters. Stress tensor inversions for various sets of focal mechanisms are listed, with n indicating the number of events included, followed by the average minimum angular misfit, R indicating the relative sizes of the stress components, Φ which fixes the orientation of σ_2 and σ_3 in plane perpendicular to σ_1, then the plunge and azimuth of each stress component and finally the 95% confidence interval on the component directions.

Scope	n	misfit	R	Φ	σ_1		σ_2		σ_3		CI
					Plunge	Az	Plunge	Az	Plunge	Az	
All FPS	26	9.51	0.31	53.3	0	100	53	190	37	10	4.9
Capricorn	11	10.25	0.36	-14.0	15	95	13	1	69	231	8.8
Pinjarra	14	7.66	0.30	53.2	0	99	53	189	37	9	5.7
Cape Range	9	6.01	0.24	55.0	0	100	55	190	35	10	6.0
Middalya	6	2.68	0.80	85.5	85	92	5	268	0	1	3.7
Mount Clere	5	4.36	0.44	4.8	56	113	3	207	34	298	7.1
Abrolhos	9	3.63	0.49	-12.1	30	125	10	29	58	282	3.4

Table 3: List of events included in geographic subgroups

Scope	Included events
Capricorn	5, 6, 7, 8, 11, 12, 20, 21, 22, 23, 24
Pinjarra	1, 2, 3, 4, 9, 13, 16, 17, 19, 20, 25, 26, 27, 28
Cape Range	1, 3, 4, 9, 13, 15, 17, 18, 26
Middalya	5, 8, 20, 21, 22, 23
Mount Clere	6, 7, 8, 11, 12
Abrolhos	2, 3, 13, 16, 17, 19, 25, 27, 28