Will the next damaging earthquake in Australia occur on a fault line?

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Abstract

Hazard estimation commonly includes both measured seismic activity and fault studies to produce recurrence estimates. Where long return periods are important, the fault study estimate usually dominates the end result.

We have a limited sample of accurately located moderate to large earthquakes in Australia. A review of ten cases shows that these have mostly occurred away from mapped faults. Studies in two areas of South Australia where earthquakes have been accurately located, show limited correspondence between hypocentres and mapped faults, although there are clearly points of similarity. Significantly, there does not appear to be a major mapped fault in Australia which has regular recorded activity.

There is a concern that removing the fault study component will result in unconservative hazard estimates. This concern is valid, but could be handled by more attention to the quality, quantity and uncertainty in the various data sets. If characteristic earthquakes are invoked, these can have a significant effect on hazard estimates, therefore evidence should be fully presented for careful review. Is the concept of characteristic earthquakes as valid in stable continental areas? If the concept of large events on the fault and small ones in the hanging wall is invoked, it likewise requires evidence.

At this stage, fault source models should not be used in Australian codes.

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Introduction

Hazard estimation commonly includes both measured seismic activity and fault studies to produce recurrence estimates. It is a widely held belief that future large earthquakes will happen on the main faults, and therefore fault studies will result in a better long term risk assessment. The historical catalogue is seen as too limited. Where very low return probabilities are important, the fault study estimate usually dominates the end result. Stable continental areas exacerbate the problem significantly.

In this paper, I review a number of significant Australian onshore earthquakes where hypocentres are accurately or fairly well known. Most of these are larger events (M5.1 and above), although three are smaller. Two areas of activity are also reviewed. Both information type and accuracy vary, and the spread of events across the country is still quite limited. However the results strongly suggest that the next large earthquake will not occur on a fault.

We also question the widely held assumption that earthquakes will repeat at the same location.

Locations of the cases investigated are shown in figure 1 and listed in table 1.

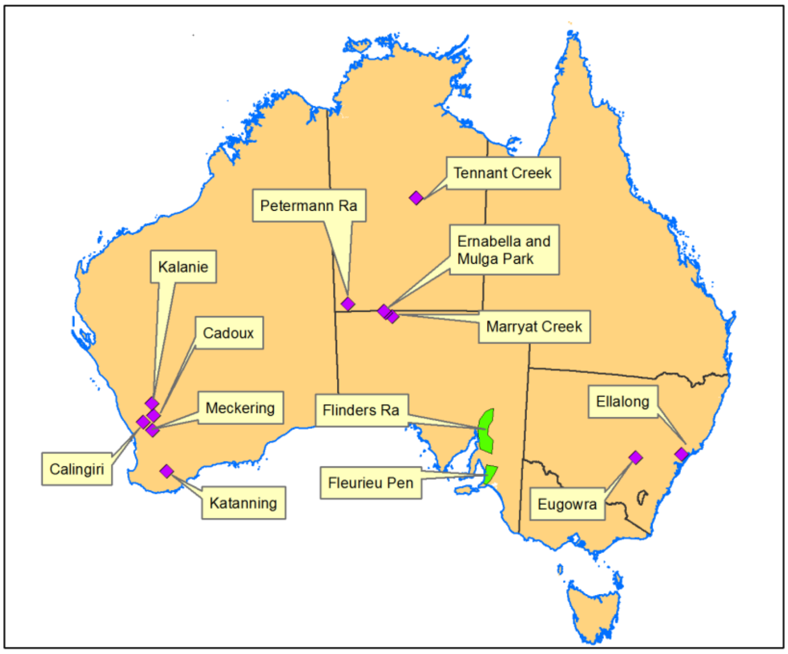

Figure 1 Locations of events and areas of seismicity reviewed in this paper.

Meckering WA	Ms 6.8	14-Oct-1968	Gordon and Lewis 1980
Calingri WA	Ms 5.1	10-Mar-1970	Gordon and Lewis 1980
Cadoux WA	Ms 6.0	2-Jun-1979	Lewis et al 1981
Marryat Creek SA	Ms 5.8	30-Mar-1986	Machette et al 1993
Tennant Creek NT	Ms 6.3	22-Jan-1988	Crone et al 1992
Tennant Creek NT	Ms 6.4	22-Jan-1988	Crone et al 1992
Tennant Creek NT	Ms 6.7	22-Jan-1988	Crone et al 1992
Ellalong NSW	Ml 5.4	6-Aug-1994	Jones et al 1994
Eugowra NSW	Ml 4.1	21-Aug-1994	Gibson et al 1994
Kalannie WA	Mw4.4	21-Sep-2005	Dawson et al 2008
Katanning WA	Mw 4.7	10-Oct-2007	Dawson et al 2008
Ernabella SA	Mw 5.4	23-Mar-2012	Clark et al 2014
Mulga Park SA-NT	Mw 5.6	9-Jun-2013	Clark and McPherson 2013
Petermann Ranges NT	Ms 5.9	20-May-2016	Gibson, this conference

Table 1 Basic details of events reviewed in this paper

Meckering WA

The first large earthquake with an identified surface rupture was associated with the Meckering earthquake in 1968. This 37 km curved scarp was not on a previously mapped fault. Studies following the earthquake reported “No correlation between geology and faulting was found.” However, on detailed investigation evidence of previous activity was found. “At one point compact iron-stained fault breccia was found and in some areas the fault was associated with small quartz reefs and stringers. The fault was also associated with soil containing quartz fragments, and by following such indicators, extensions of small faults could be located.” (Gordon and Lewis, 1980). From this, it was concluded that the fault was likely to be a reactivated older fault. Magnetic maps show features predominantly following two directions. Dentith et al (2009) attempt to show a relation between the features and faulting, but it is not a compelling case where the position of the rupture could have been predicted.

Calingiri WA

This event had a surface rupture of 3.3 km, which was simple in shape when compared to others in this paper. There is no indication of any previously mapped fault or other significant faults with the same orientation, however the land was extensively farmed. After investigation, a band about 20m wide comprising numerous pieces of quartzose rock was found, uphill to the east of the rupture. These were assumed to be from quartz infilling of an old fault. Also test pits suggested a reduction in the soil profile thickness to the east. The surface rupture seems to have no connection to mapped units, there is no gravity anomaly, and there is only a minimal connection with magnetic features.

Cadoux WA

The 14 km Cadoux surface rupture from the 1979 earthquake was a relatively simple plane in the south, becoming complex with conjugate faulting at the northern end. Following the earthquake, a detailed geological map was produced, but it did not show any major fault (Lewis et al., 1981).

The complicated north end of the scarp may have been affected by dolerite and quartz dykes, a few of which are displayed on the 250K scale geology. The magnetic map shows some linear features, probably related to dykes, but not related to prior faulting along the scarp. There is no gravity anomaly. It is hard to envisage this sort of event or composite scarp being proposed or found in a paleoseismic study.

Marryat Creek SA

The area around the 1986 Marryat Creek scarp had been mapped in detail (Conor, 1978) before the 1986 event which ruptured the ground surface in a boomerang shape for 13 km. The scarp did not coincide with a mapped fault. The northern branch of the fault was within and consistent with a mapped shear zone, but the southern branch cut across this zone and was instead consistent with surrounding fold axes. The magnetic coverage is poor, but there is no indication that the scarp is near a significant feature. The nearby creek showed a kink that had some similarity with the fault scarp shape. Trenching on both branches showed no stratigraphic or structural evidence of previous Quaternary movement (Machette et al., 1993). It is interesting to note that another event, only slightly smaller than the mainshock, occurred in the vicinity a few months later, with an almost reversed mechanism. Unfortunately we do not know the exact location.

Tennant Creek NT

The three Tennant Creek scarps had not been mapped before the 1988 earthquakes, and were similar in size to the scarp at Meckering WA in 1968. Subsequent trenching showed no evidence of prehistoric rupturing on two of the three scarps (Crone et al., 1992). The third arm showed significant evidence of previous faulting, but not on the same plane that was ruptured. Magnetic maps show significant detail, and in this case two of the three ruptures align well with high frequency features. There is a gap between the NW scarp and the other two, where a significant gravity anomaly is present. Is the activity related to the presence of this anomaly, rather than the faults, as suggested by Bowman and Dewey (1991)?
The 1988 rupturing followed three separate earthquakes in a 12 hour period, not one. It was not all contiguous, and did not follow a simple line. How does one pick if faulting will all rupture in a single event, separate but closely spaced events, or widely separated events?

Ellalong NSW

This earthquake of magnitude 5.3 happened in 1994, not many years after Newcastle, and it was immediately followed by a quite detailed aftershock survey (Jones et al., 1994). A number of small events were recorded, but as the immediate area is mined for coal, it was unclear if they were aftershocks or mine induced. Intensity reports suggest that the hypocentre was very shallow, and the mainshock was quite well located. The area has been extensively mapped and shows many northerly striking faults, so that it would be hard for the event not to be close to some of them. However, the focal mechanism of the mainshock indicates that a north-westerly striking plane was involved. The mechanism is mainly made up of refracted arrivals, therefore is not of high quality. The authors refer to it as being on an unmapped fault.

Eugowra NSW

A swarm of earthquakes (the largest being magnitude 4.1) hit Eugowra in 1994 (Gibson et al., 1994). These were accurately located in a really high quality monitoring effort, showing a plane which indicated it might be associated with a previous fault, although the authors were not aware of one at the time. The data quality and story are good. The geological map published later shows a possible concealed causative fault under shallow cover, running along an adjacent valley.

However it is clear that there are quite a number of mapped faults in the area, some more major faults interpreted from magnetics that aren't otherwise visible, and certainly other minor faults that are hidden. It is unclear that knowing the location of major faults would have helped in this situation.

Kalannie WA

This earthquake was only magnitude 4.4 and did not rupture the surface, but is included here because the surface deformation was accurately depicted by InSAR (Dawson et al., 2008). It was not reported to be on any fault line, and none are displayed on the 250K geology map. The epicentre occurs in an area with subdued magnetic and gravity signatures.

Katanning WA

This magnitude 4.7 event occurred in an area where no significant activity had been recorded previously. A small surface rupture of 640m length occurred, which was well recorded by InSAR (Dawson et al., 2008). It was not on a previously mapped fault, and is not near any other mapped faults on the 250K geology map. Clark notes that it was approximately 3 km from the end of a previously identified Quaternary scarp, however it is at a significantly different orientation, with an angle of about 80 degrees. The magnetic map is this instance has prominent features in two directions, but neither of them are related to the direction of the surface scarp.

Ernabella SA

This magnitude 5.4 event, when it occurred, was one of the largest for the previous 15 years (Clark et al 2014). It caused a small surface scarp. The boomerang shape is immediately reminiscent of the larger Marryat Creek event. It occurred near a major regional fault, the Woodroffe Thrust, on the upthrown side. Edgoose et al. (2004) report the thrust to be 2-3 km thick in the Northern Territory, while Major and Conor (1993) report the thrust zone to be about 250m wide in South Australia. In either case, the scarp is not on the fault, and is probably about 5 km above it. The rupture shape seems to have little to do with the thrust, however in the absence of either InSAR or a good aftershock survey, the complete shape and extent of the rupture is not known. Clark notes that the east-west arm is in a projected line from a lithological contact, again suggesting that structures other than faults may be important in rupture location.

Mulga Park SA-NT

A year later, another event of similar size occurred nearby. At the time it was considered to be slightly larger, and about 20 km to the north-west, although reported epicentres scattered widely. Clark and McPherson (2013) surveyed the area, and while finding much ground breakage over a well defined narrow area 18 km long, found no sign of a rupture (Figure 2). It is likely, but not certain, that the epicentre is near one of the places of greatest cracking. Leonard reviewed seismograms from the EarthScope USArray and concluded the depth was shallow. The interpreted depth phases on the ISC database scatter from 6 to 19 km. McCue (2013) interpreted a depth of at least 10 km from depth phases interpreted on an Antarctic station. Five stations from the South Australian network, however, suggest a depth of 1.6 to 2 km. In the absence, again, of either InSAR or a good aftershock survey, this event could be considered to be slightly lost! At least five mechanisms were produced for this event (figure 3), but there is considerable variation between them. Only the pressure axis is common. We can be moderately, but not dogmatically sure that the earthquake did not happen on the Woodroffe Thrust.

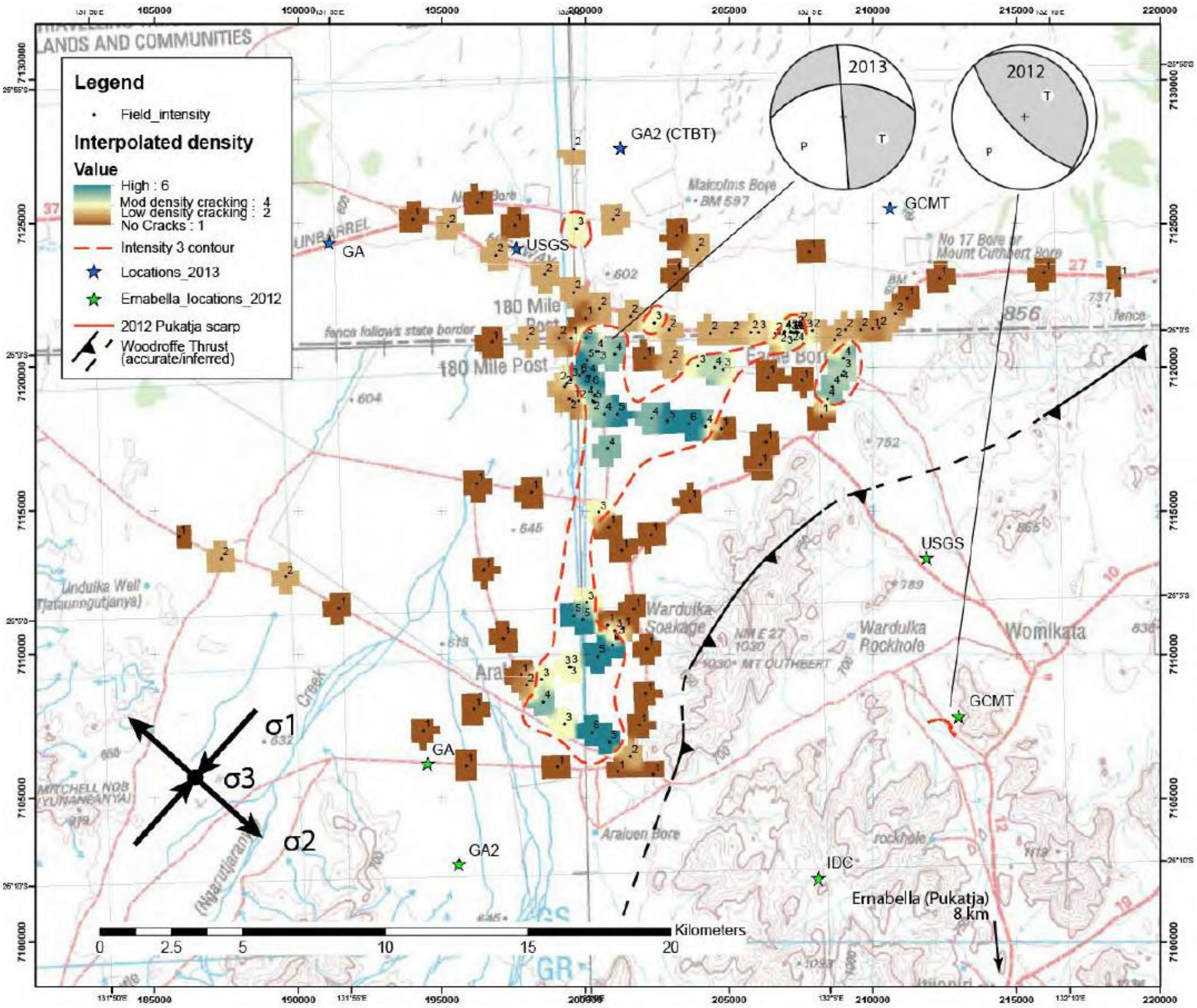

Figure 2 (from Clark and McPherson 2013, figure 3) showing higher density cracking (red dashed area), the Woodroffe Thrust and the previous Ernabella scarp (short red line).

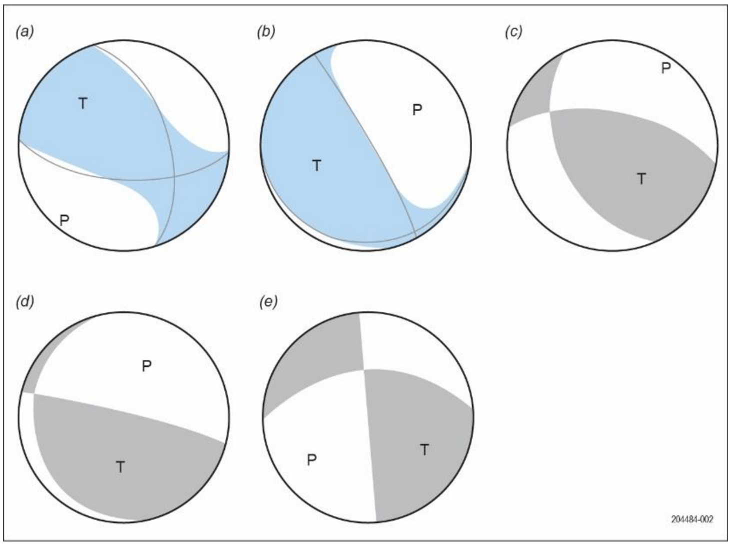

Figure 3 showing five focal mechanisms for the Mulga Park event. (a)USGS final (b) USGS MT initial (c)USGS/SLU (d) Polet (e) De Kool

Petermann Ranges NT

This recent event was definitely near the Woodroffe Thrust, caused a significant surface rupture striking nearly parallel to it, with suitably oriented stress direction, but still did not rupture in the same sense aw the fault zone. The Woodroffe Thrust dips to the south west, while the recent rupture dips to the north north east, probably going through the Woodroffe Thrust. Fortunately, thanks to a number of groups, this event has been well recorded by InSAR, an aftershock survey, and ground observation. Well and truly nailed, this is one earthquake that did not get away.

We now have three earthquakes in only four years, very close to the Woodroffe Thrust, but none of them on the fault, or exhibiting what would be expected from the Woodroffe Thrust.

Unfortunately most of the foregoing surface rupturing events occurred in domains 1 and 3 of Clark et al. (2011). These areas are characterised by very little topographic relief. Two events are in domain 4, in areas of greater height variation, but are not surface rupturing, therefore less compelling. We have no cases of historic surface ruptures in domains 2 and 4. The following two cases examining areas in domain 2 refer to very small events only, and are therefore only tentative, but raise similar questions.

South Flinders Ranges area SA

The Flinders Ranges survey (Love et al., 2006) (Geological Survey of SA, 2016) was quite a detailed earthquake survey in terms of instrument spacing. After less accurate hypocentres were removed, the remaining events showed no obvious planar structures that might be faults. The hypocentres showed some trends, but these had no clear match with topography, or with mapped faults, or with fold axes, although there was a vague similarity with each. This is despite the moderate to excellent geological exposure. Hypocentres occurred from near surface to around 25 km depth.

Fleurieu Peninsula area SA

Improved monitoring since 2010 has resulted in much more accurate hypocentres in part of Fleurieu Peninsula to the east and south of Adelaide (Geological Survey of South Australia, 2016). While recent focal mechanisms show predominantly thrust faulting with a compressional direction favouring range growth (Glanville et al., 2015 and Glanville and Thom, 2016), there is no indication of any preferred plane or planes for the hypocentres to occur on. Major faults are known along the rangefront, and these are usually considered the most likely source for a large event, but the smaller events do not favour these planes. The depths of recent hypocentres range from near surface to about 26 km. The data set is not large, but there is a slight indication of larger events occurring preferentially at greater depth.

Discussion

The first assumption in a fault source model is that earthquakes occur on faults. In this limited study of Australian events we have shown that this appears not to be the case. In the individual event cases, only one earthquake clearly happened on a major mapped fault, but even this happened on the wrong plane. Two more are near the same major fault, but probably not on it, and not with similar focal mechanisms. Another has part of the rupture within a shear zone, the remainder is across the shear zone. Still another may have been on a fault, but the original authors say that it was not. Two cases show some indications of previous activity. Proponents of fault source models must demonstrate that larger earthquakes will occur on larger faults.

The characteristic earthquake model is widely discussed and used. Unfortunately it is hard to find testable cases. Usually there is a large gap in both rate and magnitude between instrumental recording and paleoseismic information (Cowan and Nicol, 1996) so that testing is infeasible. In possibly the only testable case so far, at Parkfield, the method failed (Jackson and Kagan, 2006). The seismic gap model, closely related to the characteristic earthquake model, has also failed to beat random Poisson forecasts (Kagan and Geller, 2012). Should methods based on these failures be used seriously in hazard estimation before they are found to be successful? It is clear that over long time spans, geology markedly changes. What are the likely error bars in such cases for the characteristic earthquake model? While the model is intuitively appealing, we may be impeding earthquake research and hazard mitigation by accepting it.

The modified characteristic earthquake model proposed by Clark et al, (2007) (figure 4) is based on work done on the Cadell Fault in Victoria. This used elevation imaging, seismic profiling, trenching, OSL dating of a small number of samples and expert judgement to interpret at least four large events (M7.0 to M7.3) over a time interval from 80 ka to 20 ka ago. This has been extrapolated to suggest a longer prior time of quiescence, again preceded by another active period. This is extending a simpler characteristic fault model to a more complex active - inactive period model. This becomes exceedingly more difficult to test, and hides many more uncertainties. From the few cases of trenching of historic scarps in Australia, the evidence for repeated movement on the same fault in Quaternary times is slim.

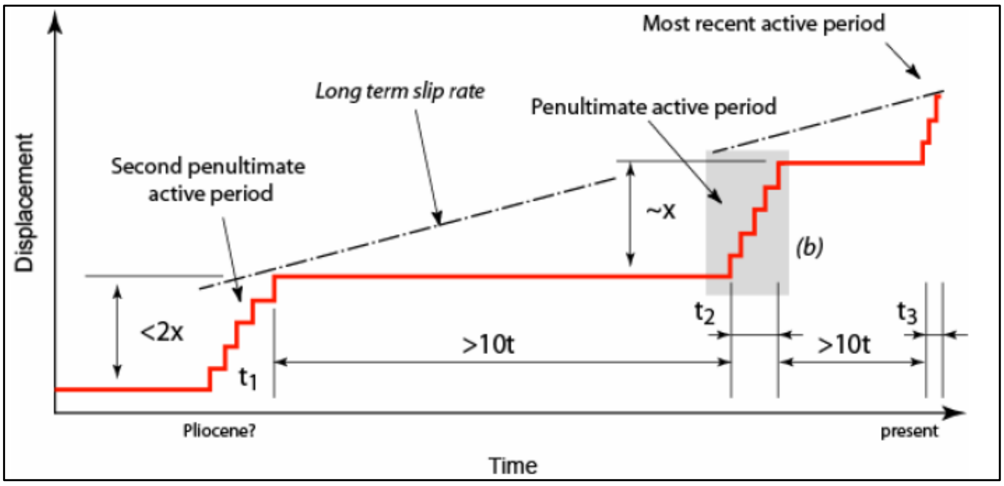

Figure 4 (from Clark et al., 2007) demonstrating the extrapolation of the characteristic earthquake model.

The model of alternating active and inactive periods suggests stages of disequilibrium in various factors (heat flow, groundwater chemistry etc.) which almost certainly will affect fault strength. Even long periods of low level activity suggest that groundwater chemistry can change fault characteristics.

Crone et al. (1992) referring to faults in tectonically stable Precambrain shield areas "suggest that faults in this kind of tectonic setting have long time intervals between surface ruptures. Therefore the concept of recurrence intervals may not be appropriate in describing these faults. Perhaps hazard assessments in stable continental interiors should be based on a random earthquake that can occur at any time on a suitably oriented fault…". The concept of recurrence intervals does not appear to have been seriously questioned.

Another part of the characteristic model is the assumption of similar sized earthquakes. This needs some form of testing to demonstrate that it is applicable. It should not be used in Australian codes until it has passed testing. The concept of characteristic earthquakes is at odds with the relatively well demonstrated Gutenberg-Richter formulation.

For the two area studies there is no clear indication that earthquakes are falling preferentially on any planes, and certainly not on the main mapped faults. This is certainly at variance with many active areas of the globe where small earthquakes clearly show linear and planar structures (e.g.

coastal California). Does this necessarily mean that they should do so in stable continental regions? If they do not, then fault source models do not have the same appeal as the well known Gutenberg-Richter law. We know how far we are extrapolating the Gutenberg-Richter formulation, but do we know how far we are stretching paleoseismic information and judgement?

There have been suggestions that in a compressional regime, most smaller earthquakes will happen in a hanging wall block, with the major events happening on the main thrust fault. To date this has no demonstrated cases in Australia.

In some examples here, the shape of the rupture appears to be affected by factors other than fault position. Lithological contacts, fold axes, and a gravity anomaly have been mentioned. For the next major earthquake we should likewise expect other factors to come into play.

One driver of the fault source model is the belief that using the seismological catalog by itself may be unconservative. This is a valid concern. However there may be other models that can handle this. Using a model that is consistently failing current testing will not take us forward.

Conclusion

While there is a strong belief that the location of fault planes is a vital component in an Australian earthquake hazard study, outweighing the Gutenburg – Richter formulation when important structures are considered, we are left very short of hard evidence. The characteristic earthquake model has not yet succeeded in a testable case. The extrapolation of the model by Clark increases the complexity of the model, making it infeasible to put to the test.

From the examined cases here, it would appear that the next large earthquake is most unlikely to occur on a major mapped fault, but even if it does, it may rupture the wrong plane.

In some more populated areas of Australia there is now a historic catalog of moderate quality going back 150 years or more. When used in conjunction with the well attested Gutenberg-Richter formulation, this surely is becoming a more important part of the hazard analysis, when compared to models that have not yet passed an acid test.

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