# Do earthquakes occur on fault-lines?

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## Abstract

The 'Earthquakes happen on fault-lines' paradigm needs to be critically reviewed. While it is clearly true in some places, Australia is not one of them. Australia's earthquake history is limited, but in part we can substitute space for time. There is no known mapped fault in Australia that has regular activity occurring on it. The general pattern of epicentres does not suggest a preference for earthquakes to occur on major mapped faults. Limited cases where accurate hypocentres are available do not support the paradigm. Excavations where historic ruptures have occurred do not suggest repeated events at the same location. This raises questions. What weighting should mapped faulting have in a hazard analysis? To what extent might faults heal over time? Are we too blinkered in our quest to find the weak places? Various sites around the globe are visited to see that many other places, even on plate boundaries, also have this problem.

**Keywords:** earthquake, fault-line, hazard

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## INTRODUCTION

Hazard maps and studies over the last decade have tended to be based on mapped fault-lines as well as measured seismicity. The longer the return period being considered, the more the weighting seems to be on the mapped faults. Furthermore, the faults shown are usually relatively simple lines, paralleling the main geological features, with emphasis on the longest possible rupture. Is this a true indication of reality, or are we going in the wrong direction?

The author hesitates to tackle this question, as he is mostly engaged in managing a network, not studying geology, or even hazard to a great degree. However over the years, he has been unable to ignore the increasing discordance between the earthquake patterns and the continual talk of faults. If we say that earthquakes are concentrated along a particular fault, and that future large earthquakes will occur along that fault, then we are also saying that the earthquake hazard is less in other areas. If we say that we should include current seismicity based on zones and then add seismicity based on rare fault movements, that is dishonest doubling up. We can excuse this on the basis of our uncertainty, but that is a fudge factor which should go into the uncertainty arena.

Does the picture of mapped faults tell us anything about the probable location of earthquakes, and in particular, damaging earthquakes?

## EARTHQUAKE PATTERNS - EXAMPLE AREAS

### Western US

In California it is obvious in figure 1 that earthquakes line up beautifully along the San Andreas fault and many others, particularly along the northern coastal area. Even in the southern coastal area there are clear lineations. Some of these are strike-slip plate boundary faults, where GPS tracking can show their movement from year to year. Other clear lineations generally follow this same trend. But not all of California is like that, and looking into Nevada the pattern does not speak of lineations anywhere.

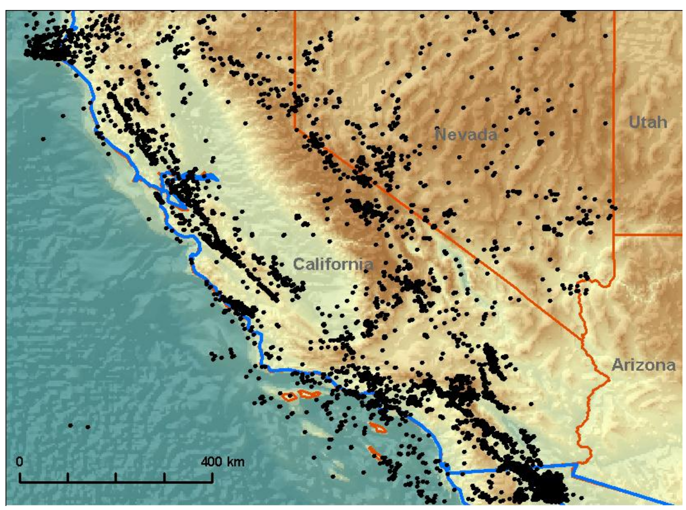


*Figure 1 showing activity along faults in coastal areas, but scattered activity inland.*

### Eastern US

In eastern US (figure 2), while there is much lower seismicity, but also lower epicenter accuracy, we certainly do not see lineations. This has been recognised. From the USGS poster on the Virginia Earthquake (USGS 2011) we read ”Previous seismicity in the Central Virginia Seismic

Zone has not been causally associated with mapped geologic faults....instrumentally recorded earthquakes... have had diverse focal mechanisms and have occurred over an area with length and width of about 120km, rather than being aligned in a pattern that might suggest that they occurred on a single causative fault.” This seems to be a gentle plea to explain the lack of a major fault. Kafka (2000) is more direct. “It seems to me that if we have learned anything at all during the past few decades about earthquake processes in the eastern United States, it’s that there is no simple relationship between faults and earthquakes in this region.” He also notes “if we assume (without scientific justification) that earthquakes are concentrated on a particular fault, then we are saying (without scientific justification) that the hazard is less in other areas.”

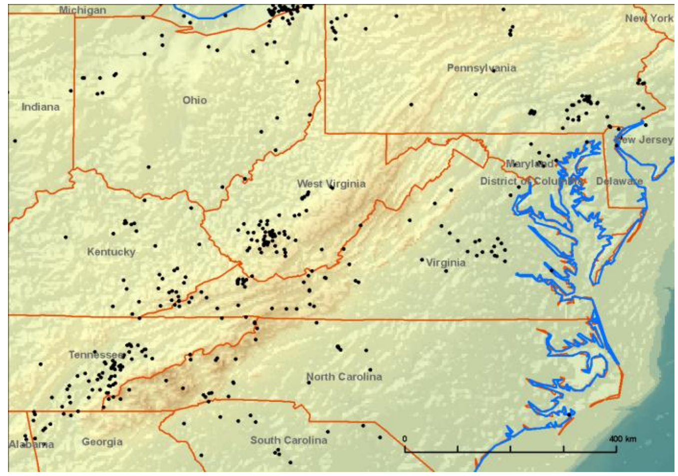


*Figure 2 showing lack of linear features in eastern US.*

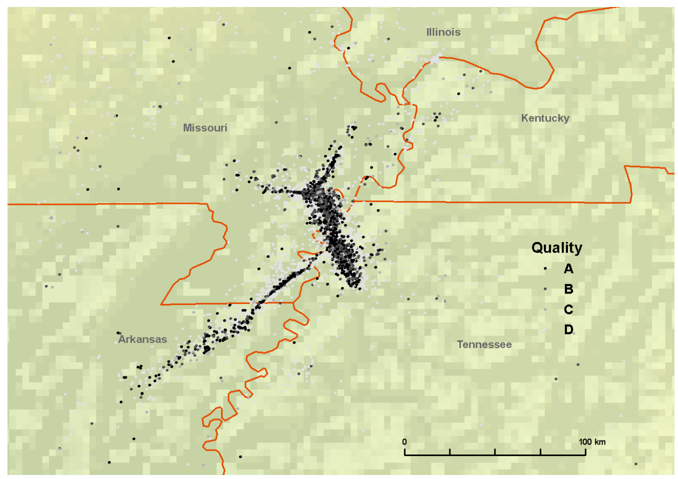


*Figure 3 showing earthquakes closely following faults ruptured in 1811-2.*

## Central US

In the central US, the New Madrid seismic zone (figure 3) is active. Epicentres line up beautifully along a set of faults at different angles. One fault has a shallow dip, and this shows as a wider band. This is not surprising, with aftershock activity continuing since the major events in 1811-12. I would expect if we had monitored Tennant Creek or Meckering in detail for the decades following the major events, we would have found most events following the main fault rupture planes.

## Iceland

Iceland has a long earthquake history, quite detailed mapping, and now excellent monitoring. There is a very active zone, which has many large events. Firstly the major events almost *never* rupture along the same fault as a previous one (figure 4). This fact

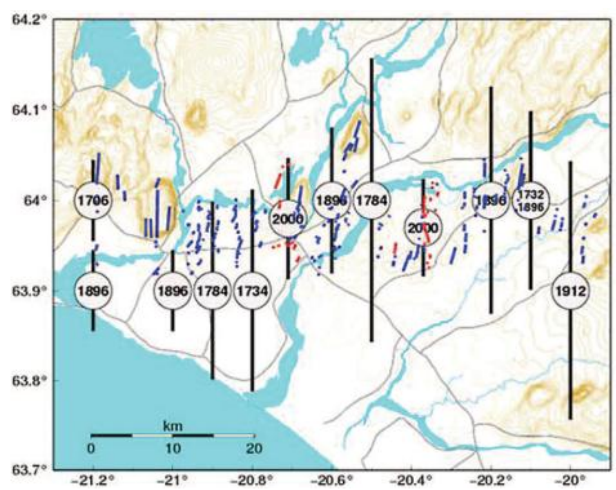


*Figure 4 from Wyss and Steffansson (2006) showing diagrammatically dates and locations of large historic ruptures. Note the lack of repeats in large earthquake ruptures.*

seems incredible, but is the end result of E-W movement across a zone being expressed in N-S segments. This is called bookshelf faulting and shows that variable strength can have a large impact. This also suggests that between events (100yrs?) a stress relief process, fault recovery or stress movement happens, so that after a century the fault is no longer the weakest point. Secondly, it appears that before a major event, the earthquakes sometimes form a volumetric cluster, and after the rupture, they mostly line up beautifully along the rupture. The aftershocks retain linearity for a long time. This strongly suggests that a *volume* is being stressed beyond its limits, and there is some doubt about where the break will be. Thirdly, while the repeated earthquake history does strongly suggest the direction of rupture, we sometimes see conjugate faults and other parallel faults clearly delineated by aftershocks, to defy a simple model (figure 5). Fourthly, history tells that a major event is often closely followed by another similar event further to the west. This has now been clearly seen, courtesy of the good quality monitoring. A major event producing a fault sets off activity in various areas to the west. This suggests that stress transfer in the zone may be much more important than the faults.

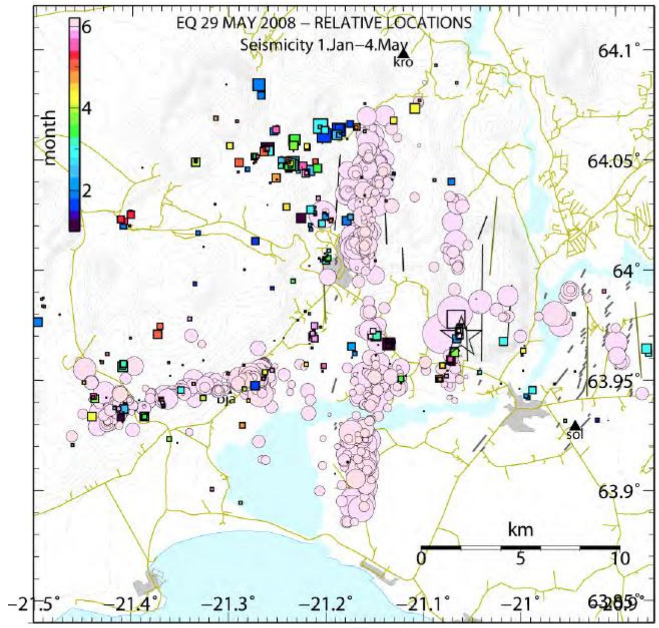


*Figure 5 from Vogfjord et al 2010 showing foreshocks (coloured squares) only partly follow faults,while aftershocks (light circles) define a number of planes.*

Is there a fault healing process? Does it have something to do with the large amount of hot, potent groundwater? While that might seem very different to Australia, when we consider the depths of our earthquakes, heavily mineralised groundwater may be causing healing.

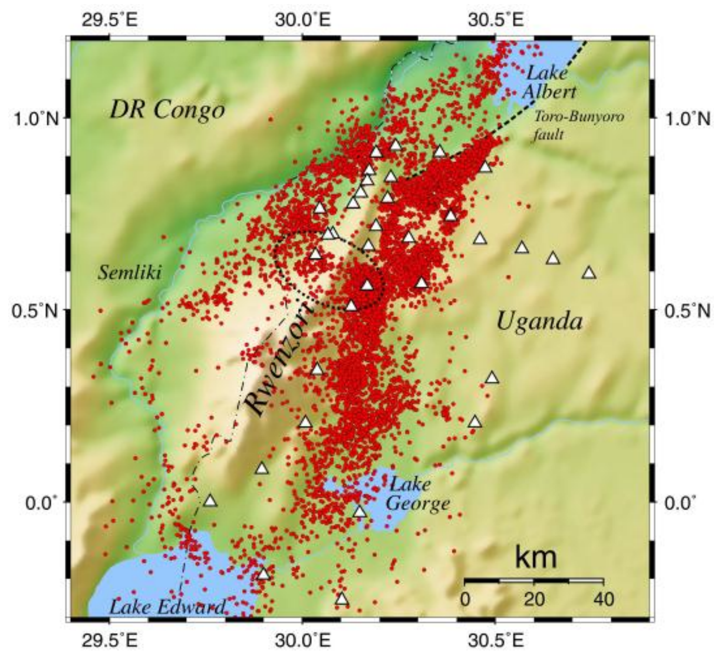


*Figure 6 from Lindenfeld et al (2012) showing epicentral patterns, but not along planes. Seismographs shown as triangles. Rift valley covers most of the low area between Lakes Albert and Edward, and under the Rwenzori Mountains.*

In the Icelandic case, if we applied Occam's Razor, the most important factor would be the earthquake zone, not the individual faults. The value of mapped faults would be in suggesting the direction of the next rupture, and where it would *not* be.

### Uganda

On a trip to Uganda, I heard about a detailed survey of the Rwenzori Mountains, Western Uganda, along part of the rift valley (figure 6). The results of this survey upset me somewhat. In South Australia, I am used to the earthquakes mostly happening in the hilly areas. This survey instead showed earthquakes *avoiding* the 5000m high mountains. Regarding faults, the authors comment ”The majority of these events are grouped in clusters rather than on planar surfaces. Only in a few cases it is possible to associate the epicenter distribution with known faults.” Instead there is discussion of the rift valley and the rift shoulders. Most events occur on the shoulders, from surface to about 30km, while in the rift valley they rarely occur in the top 10 km. When a fault is referred to, it is as a *boundary* between an active and a less active area.

The above cases of Iceland and Uganda have the obvious complexity of strong thermal sources. Thus we can compose acceptable reasons why faulting is not occurring on the main mapped faults. However this does leave open the suggestion that there might be other factors in ‘stable continental’ areas that likewise increase the complexity.

## SURFACE RUPTURES IN AUSTRALIA

### Tennant Creek

The Tennant Creek scarps had not been mapped before the 1988 earthquakes. Subsequent trenching showed no evidence of prehistoric rupturing on two of the three scarps (Crone et al., 1992). The third trench showed significant evidence of previous faulting, but not on the same plane that was ruptured.

There is a gap between the NW scarp and the other two. There is a significant gravity anomaly here. Is the activity related to the presence of this anomaly, rather than the faults?

The 1988 rupturing occurred as three separate earthquakes, not one. It was not all contiguous, and did not follow a simple line.

### Meckering

The Meckering scarp had not been mapped as a fault before the 1968 earthquake. Studies following the earthquake reported “No correlation between geology and faulting was found.” However evidence of previous activity was sought. “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)

The Meckering Fault was not simple, with curvature, a parallel part and offsets. Similarities between the curved scarp and the river course were reported.

The magnetic map shows no features that could be related to the fault.

## Cadoux

The Cadoux rupture 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 be affected by dolerite and quartz dykes. This could have been reactivation, or dykes causing strength variations which affected the rupturing.

## Marryat Creek and Ernabella

The area around the 1986 Marryat Creek scarp had been mapped in detail (Connor, 1978) before the 1986 event which ruptured 13 kms. The scarp did not land on a mapped fault. The northern branch of the fault was within and consistent with a mapped shear zone, and the southern branch was consistent with surrounding fold axes. The nearby creek showed a kink nearby that had some similarity with the fault scarp. Trenching on both branches showed no stratigraphic or structural evidence of previous Quaternary movement (Machette et al., 1993).

It is interesting that the more recent Ernabella scarp (Clark et al, in press) looks surprisingly like the middle portion of the Marryat scarp. Likewise the Ernabella scarp had not previously been mapped as a fault, but that area had not been mapped in detail.

## OTHER AUSTRALIAN EXAMPLES

### Eugowra.

A swarm of earthquakes hit Eugowra in 1994 (Gibson et al 1994). These were accurately located, 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. Figure 7 is the geological map published in 2000 showing faulting in the region, with earthquake epicentres superimposed. It now shows a possible causative fault running along the adjacent valley in a NNW direction. 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.

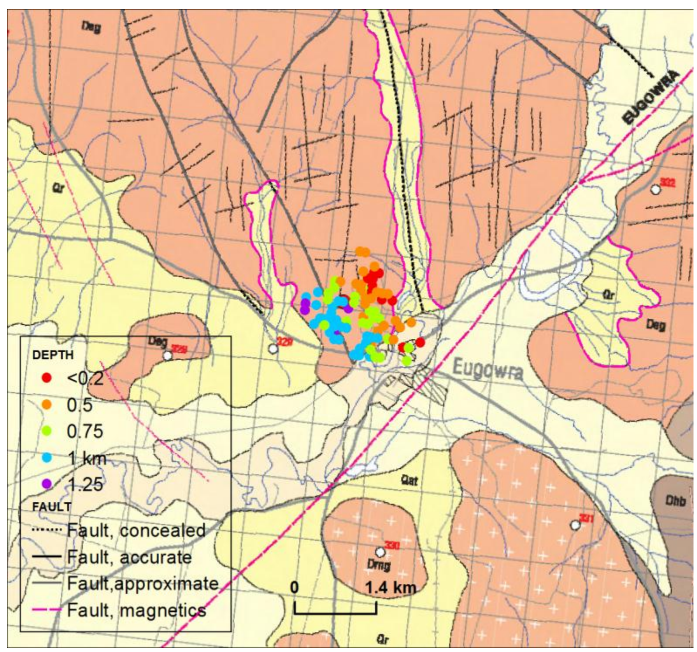


*Figure 7 showing epicentres (coloured by depth) defining a plane that emerges near a concealed fault*

Is it a particular fault that is driving the activity? Is it the intersection of two faults that is driving activity? Is it related to the edge of a basin structure suggested in the wider map showing elevation? Is it some other feature?

**Flinders Ranges**

The Flinders Ranges survey (Love et al., 2006) was one of the most detailed in the country. When less accurate hypocentres were removed, the remaining events showed no obvious planar structures that might be faults. The hypocentres showed 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.

## CHRISTCHURCH

The Christchurch earthquake sequence was not on the plate boundary, and most of the events were over 100 km away. It has some interesting points. The disaster was not from the mainshock, but one of a number of large large shocks following. The ground rupture pattern and aftershock pattern show quite a complex faulting situation. Stirling et al (2002) hazard map (figure 2 in their article) shows more faulting complexity than in many other hazard models, but still not quite that displayed by the Christchurch sequence, nor the actual faults. There are clearly ruptures going in a number of directions, and not rupturing all at once. There still appears to be a gap between the main rupture and later ruptures which seems to be bounded by NE-SW planes. Does this gap represent some structure that has had a major bearing on the whole episode? Does it have some similarity to the Tennant Creek gap?

## DISCUSSION

I have not discussed earthquake data quality much in this paper, and it is important. I believe that the examples used generally have suitable quality for the point in question. Certainly higher quality data is needed from many more areas around Australia. However, I have not let this stop me highlighting the discordance between the faults and the earthquakes.

If we consider the Australian environment, is there a qualitative difference between those faults shown in hazard studies, and what we find with historic surface ruptures? The former generally tend to be straight, and relatively simple. The latter tend to be boomerang, or complex.

The mapping of faults is not easy in most places, given limited outcrop, which is usually only on a near horizontal surface. The estimation of when faulting occurred is usually not straightforward, nor the magnitude of movement. Faults occur at a range of scales, and when looking in detail there are more smaller ones often not far apart. However, are these the dominant features that we should be looking for? Is it possible that river patterns, fault intersections, dykes and stringers, or uplifted blocks might have more value? But these rarely rate a mention in hazard studies.

There is no doubt that plate boundary faults, where GPS measurements show measureable movement now, have a high probability of rupturing. There is little doubt that large ruptures in stable continental areas will have aftershocks along planar structures for many years. But even in and near plate boundary situations there is often complexity so that earthquakes do not repeat on the same faults, and even large events produce unexpected results.

A reigning paradigm is difficult to displace, especially when it works so well in coastal California. With no alternative candidate in sight, it is even more difficult.

If we are going to find the main factors affecting where and when the next damaging earthquake will be, we need to be very forthright about the lack of connection between known faults and earthquakes. We need to proactively look at other scenarios. We need to evaluate what part currently mapped faults should play, if any, in hazard studies of stable continental areas.

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