A slow divorce: tectonic signals in an ancient continent

Australia is a continent of ancient cratonic rocks, at least two-thirds of which formed more than 1400 million years ago. Australia is also the lowest and flattest of all the continents and is largely remote from active plate boundaries. So it is easy to see why Australia is often viewed as the most stable of continents.

Of course, earthquakes such as the Newcastle (magnitude 5.6) earthquake on 28 December 1989, which led to 13 deaths and an estimated $4 billion total damage bill, indicate that Australia is not totally immune from tectonic activity. But it still comes as a surprise that, with an average of about 80 earthquakes of magnitude 3 or higher each year and one magnitude 6 or higher quake occurring about every 20 years, Australia releases significantly more earthquake energy — on an area-normalised basis — than comparable cratonic regions in Canada, Brazil, northern Europe, and much of Africa.

While the great majority of these earthquakes are natural, Australia also has an unusual preponderance of human-induced earthquakes. These are mostly associated with filling of large reservoirs, such as the 25 September 1996 quake associated with the Thompson Reservoir, east of Melbourne, which at magnitude 5 was Victoria's largest earthquake in the last 30 years. Globally only about 2% of large reservoirs have induced significant quakes. In Australia, five of the six largest dams have done so.

Australia has a quite extraordinary historical record of surface fault ruptures. Surface ruptures accompanied three powerful earthquakes ranging from 6.3 to 6.7 in magnitude that occurred at Tennant Creek in the Northern Territory in 1987 and the 1968 Meckering earthquake in Western Australia. These ruptures created fault scarps up to 35 kilometres long with a maximum displacement of over one metre. Surface rupturing has also accompanied at least five other quakes in recorded history. However, until recently there has been little understanding that the record of seismicity in Australia is also significantly expressed in its longer-term landscape evolution.

The October 1968 Meckering earthquake was Western Australia's most significant in terms of damage and cultural upheaval. It resulted in a ground rupture almost 40km long, some of which is still visible. Image courtesy Geoscience Australia.

A slow divorce

Newer research indicates that there are literally hundreds of older neo-tectonic features, as now compiled by Dan Clark at Geoscience Australia. And the significance is not to be sneezed at! For example, strata deposited just a few kilometres from Adelaide as (geologically) recently as 30 million years ago are now overturned. Elsewhere in the Flinders Ranges and in the Snowy Mountains, there are numerous outcrops showing ancient basement rocks thrust several metres over river gravels and hill screes less than 100 000 years ago. Such features would not be out of place in the most active of mountain ranges.

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This slow, ongoing tectonic activity can be understood in the context of the evolution of the Indo-Australian Plate, one of the most dynamic and highly stressed of the major tectonic plates. In fact, Australian earthquakes are just part of much broader distribution of intraplate earthquakes throughout the interior of our plate. They reflect the gradual buildup of tectonic stress over the last five to 10 million years due to changes in the forces along the distant plate boundaries that both drive and resist our plate's northward motion.

In tectonic terms, these quakes provide evidence that our plate is breaking up under progressively rising levels of stress. In effect, our 43-million-year-long dalliance with India is coming to an end in a kind of grand plate-tectonic 'divorce'. In a few million years, Australia and India will again be separate plates going their different ways as they were prior to 45 million years ago.

But there is an even more intriguing picture of active tectonics that is beginning to emerge from studies of the Australian landscape. As it moves north, the continent is tilting, warping and bobbing up and down by several hundred metres.

A striking asymmetry

We see this most emphatically in the striking asymmetry in young marine sediments around the continental margin. For example, the southern onshore margin is literally plastered with young limestones, often extending hundreds of kilometres inland. The Nullarbor Plain is the most striking example — a 2000-km-long relict submarine plain, exposed as seas retreated from the southern margin around 15 million years ago. In contrast, the onshore northern margin is virtually devoid of marine deposits of such age. Why is there no Nullarbor equivalent along the northern margin of the continent?

The exposure of the Nullarbor can be attributed in part to eustatic processes which have seen the global sea levels fall by around 100 metres over the last 15 million years or so. However, in the western, inland part of the Nullarbor, Eocene and Miocene palaeo-shorelines show seas extended to elevations now more than 250 metres above sea level, indicating the continent has actually risen by at least 150 metres since then. Moreover, these same shorelines can be traced to elevations more than 150 metres lower across the Nullarbor, implying a significant tilting of the Nullarbor since then. The absence of onshore marine deposits of comparable age along Australia's northern coastline implies that the seas are now as high as at any time during the last 65 million years. So the northern coastline must be sinking at least as fast as the long-term eustatic fall in sea level. The pattern of exposure in inundation reveals an extraordinary continental scale tilting. As it moves northward, the Australian continent is tilting, north side down, south-west side up and has been doing so at a rate of around 20 metres every million years for the last 15 million years.

The pattern of young vertical motion is more complex than this simple tilting, as demonstrated by the profound enigma of Lake Eyre. The lowest point of Lake Eyre is some 15 metres beneath sea level, begging the question of how any part of a stable continent can remain below sea level without filling up with sediment. The answer is that it can't, and that Lake Eyre has not been at such a low point for more than few million years. We know this because we can see the remnants of an older, precursory palaeolake, equally as big as the modern Lake Eyre, now some 140 metres above Lake Eyre along its drainage divide with Lake Torrens.

Today, the floor of the vast salt pan of Lake Eyre has a southerly tilt several metres lower in the south than the north — with the lake floor seemingly acting as a kind of giant tilt meter!

While we don't know the exact age of this palaeo-lake — termed lake Billa Kalina — it implies this landscape is going up and down by over 100 metres, gradually changing the position of the depocentre of the Eyre basin, on timescales of a few million to a few tens of million years. Today, the floor of Lake Eyre, and other large lake salt lakes of South Australia, has a southerly tilt several metres lower in the south than the north — with the lake floor seemingly acting as a kind of giant tilt meter!

Similar features can be seen around Mt Gambier in south-east South Australia and in western Victoria, where few-million-year-old beach strand lines show the region has risen by 180 metres at a rate of 65 metres per million years. In Tasmania, some beach ridges now 30 metres above sea level have been dated at only 120 000 years old. If correct, parts of Tasmania would appear to be literally rocketing out of the sea!

The underlying issue

The question becomes, what is causing this tilting, warping and bobbing up and down of our continent over the last few tens of millions of years? Most likely it is a response to the complex flow in the mantle hundreds of kilometres below the continent.

At the largest scale, mantle flows as part of the circulation that accommodates subduction. Wherever there is vertical flow in the mantle, it pulls or pushes on the plates above. For example, the upward flow in the rising plume beneath Africa explains the unusual elevation of much of that continent. In a similar way, as continents move into the realms of subduction, they get pulled downwards by the descending mantle flow. That is exactly what appears to be happening in northern Australia, as it encroaches on the Indonesian and Melanesian subduction realms.

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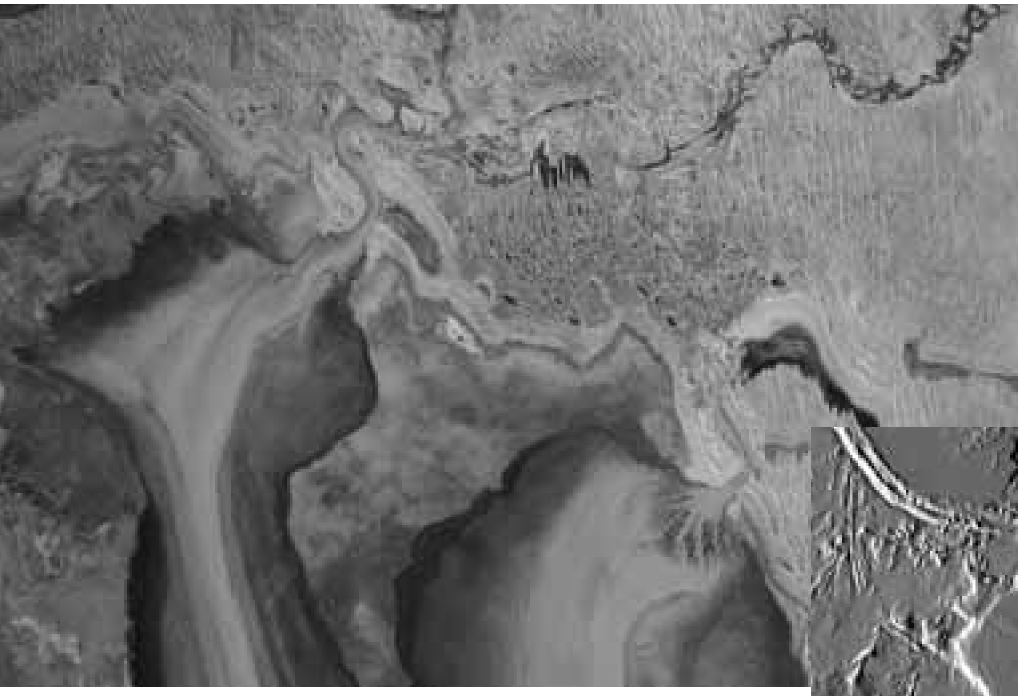
But what about the Lake Eyre and southern margin undulations? Can these be related to generation of smaller scale flow in the uppermost mantle, where drips and eddies form due to differential flow between the plate and the mantle beneath? If so, it presents the exciting possibility that we might be able to see which way the mantle is flowing relative to the plate above.

Such flow instabilities would certainly help explain the strange coincidence of young basaltic volcanoes along the uplifting southern edge of Victoria, and south-east South Australia. Such instabilities would be consistent with the continent moving north across the mantle beneath, generating instabilities along its trailing edge. Such an interpretation may also provide a neat explanation for the apparent tilt on the floor of Lake Eyre and other salt lakes in South Australia — with the depocentre tracking a transient mantle instability sweeping southwards relative to the continent.

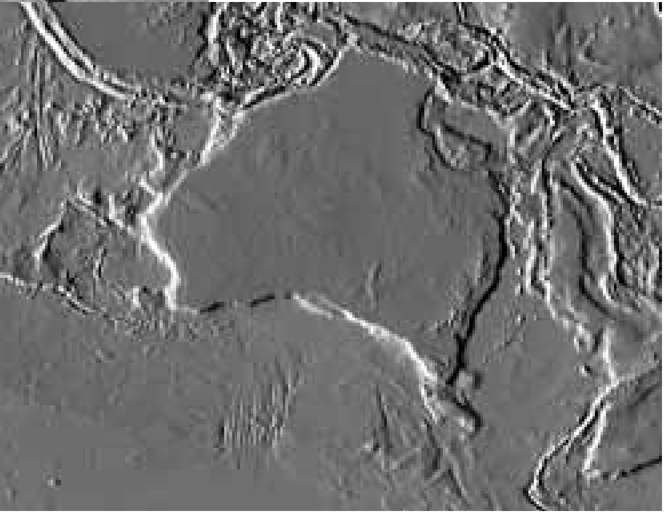
This is certainly my working hypothesis, with the transient nature of features such as Lake Eyre reflecting the growth of instabilities in the flow at the base of the lithosphere, gently pulling on the plate as it moves northward across the mantle beneath. When such instabilities detach from the plate above, the downward pull is released and the landscape above gently inverts leaving features such as Lake Billa Kalina improbably stranded on the present-day drainage divide.

The Nullarbor Plain is a 2000-km-long relict submarine plane, exposed as seas retreated from the southern margin of the continent around 15 million years ago. In contrast, the onshore northern margin is virtually devoid of marine deposits of such age. Image courtesy Brian Voon Yee Yap.



LEFT: Lake Eyre from the Landsat satellite after heavy flooding in May 2009. The lowest point of Lake Eyre is some 15 metres beneath sea level, begging the question of how any part of a stable continent can remain below sea level without filling up with sediment. Image courtesy NASA/Jesse Allen, using Landsat data provided by the United States Geological Survey.

BELOW: Topographic map of the Australian continent and surrounding margins. No other continent provides such an insight into the direction of mantle flow beneath the continents. Image courtesy Mike Sandiford.



In fact, by virtue of its flat landscapes, arid climate and its speed — Australia is the current speed champion of the continents, travelling at around 6–7 cm/year northwards — Australia appears to preserve a unique record of the way the mantle flows deep beneath the continent. Nowhere else on any other continent can we get such an insight into the direction of flow beneath the continents.

Far from being an inert continent irrelevant to active tectonic studies, we now understand that Australia has special attributes that preserves unique tectonic signals not available elsewhere. As a fast, flat and dry continent, it is helping us elucidate subtle surface responses that track change in distant plate boundary forces and the flow in the mantle deep beneath. In addition to these fundamental insights, this understanding is also important for a number of emerging, pragmatic issues.

For example, understanding earthquakes and controlling them is becoming an increasingly important issue as we seek to deal with emerging energy issues, such as making enhanced geothermal system deliver significant, GW-scale, zero-emission electricity power, or for storing CO_2 in the subsurface. The issue is not trivial, since perturbing pore-fluid pressures in the crust are a key to inducing seismicity and can be easily done, as is testified by the Thompson Dam quake.

Similarly, tracking the response of ancient drainage systems to subtle undulations helps provide one of the key controls on the dispersal and concentration of placer deposits such as uranium through time, and the dispersal and evolution of our freshwater faunas in our inland rivers systems. The suggestion that these systems must have changed significantly through time, at least in some parts of the continent, is crucial to efficient exploration-targetting strategies and may be fundamental to understanding the biodiversity in our inland river systems.

This work has been the subject of an ARC-funded research project including a professorial fellowship, during the period 2005–2009. The work has involved many collaborations — those with Mark Quigley and Dan Clark are particularly worthy of mention.

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FURTHER DISCUSSION OF THESE ISSUES CAN BE FOUND IN THE FOLLOWING PAPERS.

Sandiford, M, 2003, in Hillis, RR, and Muller, D, (Eds) Evolution and dynamics of the Australian Plate, *GSA Special Publication* 22, p 101–113.

Celerier, J, *et al*, 2005, *Tectonics* 24, TC6006, doi:10.029/2004&C001679

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