Hot Southern Land

BY SANDRA MCLAREN

Rocks unusually enriched in the heat-producing elements uranium, thorium and potassium have profoundly impacted the evolution of our continent and are set to play a key role in Australia's energy future.

As a continent, Australia preserves an extraordinary record of the Earth's evolution over 4 billion years, from events in the earliest years of our planet right through to recent climatic changes. Australian geoscientists have this unique record of the Earth's history to work on, and we can use what we learn from the past to inform the future.

We have known for a long time that the behaviour of rocks is strongly dependent on thermal regime (i.e. how and why temperature varies at depth within the Earth). Because of this important link, understanding thermal regime is fundamental to unravelling many geological processes. Ultimately, it helps to tell us how the Earth works.

The primary tools we have to make inferences on the thermal regime are measurements of surface heat flow. These reflect the heat transferred from the interior of the Earth out through its surface.

Globally, heat flow is highest around the mid-ocean ridge systems, where we have active spreading of plates and molten material from deep inside the Earth brought to the Earth's surface. Heat flow is also generally high in regions of modern and recent volcanic activity, like New Zealand or Iceland.

In the older continental parts of the Earth, such as Australia, heat flow is generally much lower and is largely related to tectonic age. Older parts of the continents have lower surface heat flow than younger parts of the continent.

Natural Sources of Heat

The heat we're measuring is coming from two sources: heat produced from the radiogenic decay of naturally occurring uranium, thorium and potassium, as well as some primordial heat from the conversion of kinetic energy carried by cosmic particles that accreted to form our planet. Due to their long-lived radioactive decay, the heat-producing elements of uranium, thorium and potassium are located mainly within the crust – the outer part of the Earth down to depths of about 30–40 km.

Heat produced from radiogenic decay here, and also deeper within the Earth, is ultimately what makes our planet dynamic – its material is perpetually on the move up, down or sideways. This heat engine is the mechanism driving the movement of tectonic plates and the rock cycle, all processes that are essential for the formation of soil, hydrocarbons and mineral deposits.

What we know about the amount of heat flowing through the surface of the Australian continent is limited because only about 150 measurements have ever been made, mostly in the 1960s and 1970s. Very few new measurements have been made since that time. Compared with other continental regions like Europe or the United States, where the datasets on heat flow contain around 5000 measurements, Australia's heat flow field is not well-defined.

Sandra McLaren amid hot rocks during fieldwork around Mount Painter in the northern Flinders Ranges; a region recording one of the highest surface heat flows in Australia.

Credit: Sandra McLaren

HEAT ZONES

Nonetheless, we can see some very interesting patterns when we look at the continental scale. The average surface heat flow of all continental regions in the world is around 50–60 mW/m^2, but in the central core of the Australian continent – in western Queensland, the Northern Territory and South Australia – measurements of surface heat flow average more than 80 mW/m^2. Some individual measurements in this zone are more than twice the global average and, together with the high average heat flow, define an unusual and striking anomaly regarding continental-scale heat flow.

Some of the high heat flow observed in south-eastern Australia is related to recent volcanic activity (e.g. around Portland in Victoria and Mount Gambier in South Australia). But elsewhere the high surface heat flow is the result of high concentrations of the naturally radioactive elements, uranium, thorium and potassium.

The high concentrations of these elements are mainly contained within early and middle Proterozoic-aged rocks that were formed 1–2 billion years ago, and mainly within granites and other rock types associated with ancient volcanic activity and deep crustal melting. We see these rocks on the surface in places like central Australia, Mount Isa in Queensland and Mount Painter in South Australia, and they are also thought to make up a large part of the sub-surface.

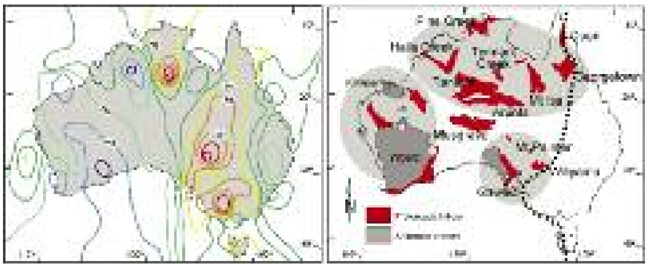
The concentrations of radioactive heat-producing elements in rocks of these terranes, covering a total area of more than 100,000 km^2, are more than twice what we would normally expect and give an average heat production rate of 4.6 μW/m^3. The average heat production rate of granite is only 2–2.5 μW/m^3.

These heat production calculations are measured in microwatts per cubic metre. These rates may seem low but they are in fact about twice the normal rate for granite, which is the highest heat-producing rock type. Most material in the Earth has heat production rates of the order of 0.1 μW/m^3. Australia can produce such high temperatures on geological time scales.

We can identify individual rocks that produce heat at rates more than 10–15 times the global average. The degree of enrichment and the vast area over which we see these enriched rocks means that Australia, in more ways than one, can be justifiably termed the "hot southern continent"!

My own PhD research and subsequent work together with Prof Mike Sandiford have shown that these really hot rocks have played an important role in shaping the long-term history of the Australian continent. Uranium, thorium and potassium like being in the upper part of the crust near the Earth's surface, rather than deeper within the Earth, but the processes that bring them closer to the surface are themselves dependent on temperature.

Essentially, hotter rocks are weaker and more able to melt and deform and undergo geological processing. In turn, these processes redistribute the heat-producing elements, affecting the temperature and strength of the rocks and their capacity to undergo subsequent deformation or magmatism (melting).



Left: Measured surface heat flow in Australia.* Right: major high-heat flow Proterozoic-aged rocks that are 1–2 billion years old. Light-coloured shading shows the three main Proterozoic blocks of the north, south and western cratons, respectively.

***Source: from a compilation of Cull, *Journal of Australian Geology and Geophysics*, 7, p.11–21, 1982.**

Once we recognised these relationships, we could identify an important feedback process that provides profound insight into the geological history of these enriched regions through time. For example, the presence of these high heat-producing rocks can help to account for the generation of many high-grade ore deposits that we find in the central core of the continent. This is because, over long periods, the hot rocks can promote the circulation of hot fluids, which distribute and concentrate precious metals.

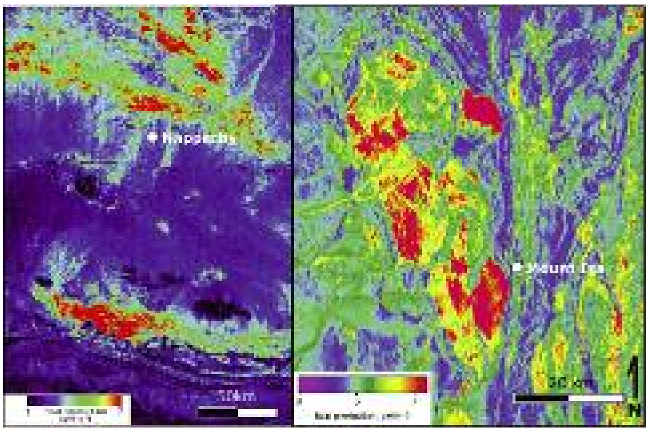
The high heat-producing rocks can also help to explain geological events, such as deformation and mountain-building, that have shaped much of our landscape today. An example of this is known as the Alice Springs Orogenic Event, which occurred around 350 million years ago and was responsible for some of the spectacular landscapes we see today in central Australia.

Our model also helps to explain the factors that have led to the differentiation of the continental crust – that is, why the Earth has organised itself, through time, to have an outer 30–40 km thick layer of silica-rich rocks overlying a much thicker layer of iron- and magnesium-rich rocks. This has been a long-standing problem in understanding our planet's evolution.

In terms of the geological record, we think it's possible that the influence of these high heat-producing rocks continues to the present day. Because the presence of the enriched rocks increases temperatures in the upper part of the Earth, this reduces the strength and long-term stability of the crust and could explain the localisation of earthquake activity (e.g. in the Mount Lofty and Flinders Ranges in South Australia). To explore this more fully, though, we really need to have many more, and more closely spaced, heat flow measurements.

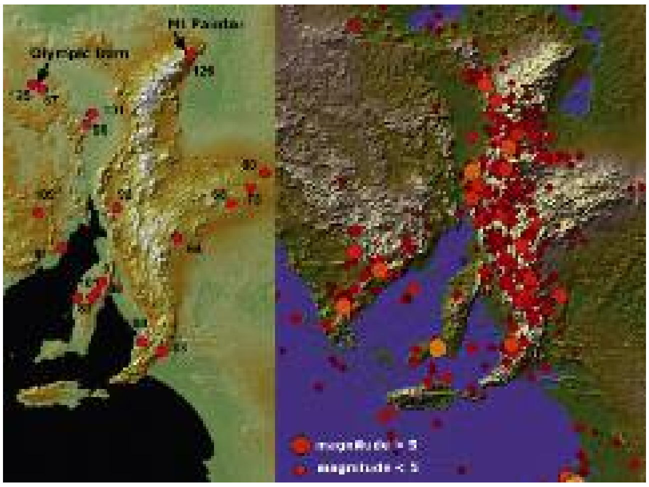
THE POTENTIAL FOR USEABLE ENERGY

As well as the role these enriched rocks have played in our geological past, our work shows they could potentially make a



Examples of mapped heat production rates from the Reynolds and Anmatjira ranges in central Australia (left), and from around the city of Mount Isa (right). On each map the red colours show rocks with heat production rates of 7 μW/m^3 or more. As a consequence of the degree of their enrichment, these granites have a significant impact on the temperature and strength of the crust.

Credit: (Left) Mike Sandiford; (right) Sandra McLaren



Left: topographic image of central South Australia showing surface heat flow measured. Right: locations of historical earthquakes.

Credit: Mike Sandiford (from published data)

huge contribution to our energy future – for both nuclear and geothermal power. These heat-producing element enrichments of Proterozoic-age are the source of Australia's extraordinary uranium reserves and explain our status as one of the most prospective countries in the world for hot-dry-rock geothermal power. To understand this we have the example of the Olympic Dam deposit in South Australia, which is currently the world's richest known uranium resource.

At the surface today Olympic Dam, in terms of its uranium, is energy-dense and highly lucrative on the international market. It provides uranium that is used to generate enormous amounts of power in nuclear reactors around the world. It is no coincidence that the resource is hosted within one of these Proterozoic-aged granite rocks.

However, if we could find a similar uranium enrichment deep within the Earth, it could be a comparably valuable resource of geothermal energy. Geothermal power plants exploit high temperatures at depth within the Earth. They use the high temperatures to heat water to steam which, in turn, drives turbines to generate electricity.

In Iceland or New Zealand, for example, the high temperatures are the result of volcanic activity. In Australia, though, the high concentrations of heat-producing elements have the potential to generate comparably high temperature conditions. This is because the heat produced from the natural radioactive decay means that the rate of change in temperature with depth (the "geothermal gradient") is very high.

So, at 3–4 km depth within the Earth, an Olympic Dam-like resource would push temperatures up to between around 200°C and 400°C, depending on the degree of the uranium enrichment. Temperatures in this range are comparable with the near-surface temperatures we see in conventional geothermal systems, and they are highly prospective for power generation that is both renewable and has low carbon emissions.

Despite the amount of attention given in the media to the emerging geothermal power industry in Australia, it isn't well-appreciated that our potential geothermal resources are intimately linked to our uranium resources. Both energy options are products of exactly the same enrichments in uranium and the other heat-producing elements.

The work we have done in documenting the extent of heat-producing element enrichment shows that our continent has been blessed, geologically-speaking, with an enormous potential resource. The degree of the enrichment throughout the central core of our continent means there are almost certainly more highly lucrative uranium resources yet to be discovered out there. But there are also likely to be potentially lucrative geothermal resources.

Indeed, programs exploring for uranium are equally likely to uncover a key geothermal prospect as they are a new Olympic Dam. Geologically, the difference between the two energy options is the degree of enrichment – whether or not there is sufficient uranium to actually be mined.

Australia has potential for both nuclear as well as hot-dry-rock geothermal power generation, and this potential is huge. If we evaluate our energy future without considering the extraordinary enrichment of heat-producing elements and the potential resources they give us, then we're missing two potentially important options.

The enrichment is a unique, 1.5-billion-year-old legacy of our geological past, and it's up to us to decide how best to exploit it to optimise our energy security into the future.

Dr Sandra McLaren is a Centenary Research Fellow in the School of Earth Sciences at the University of Melbourne. This article is based on her presentation upon winning the 2008 Dorothy Hill Award of the Australian Academy of Science.