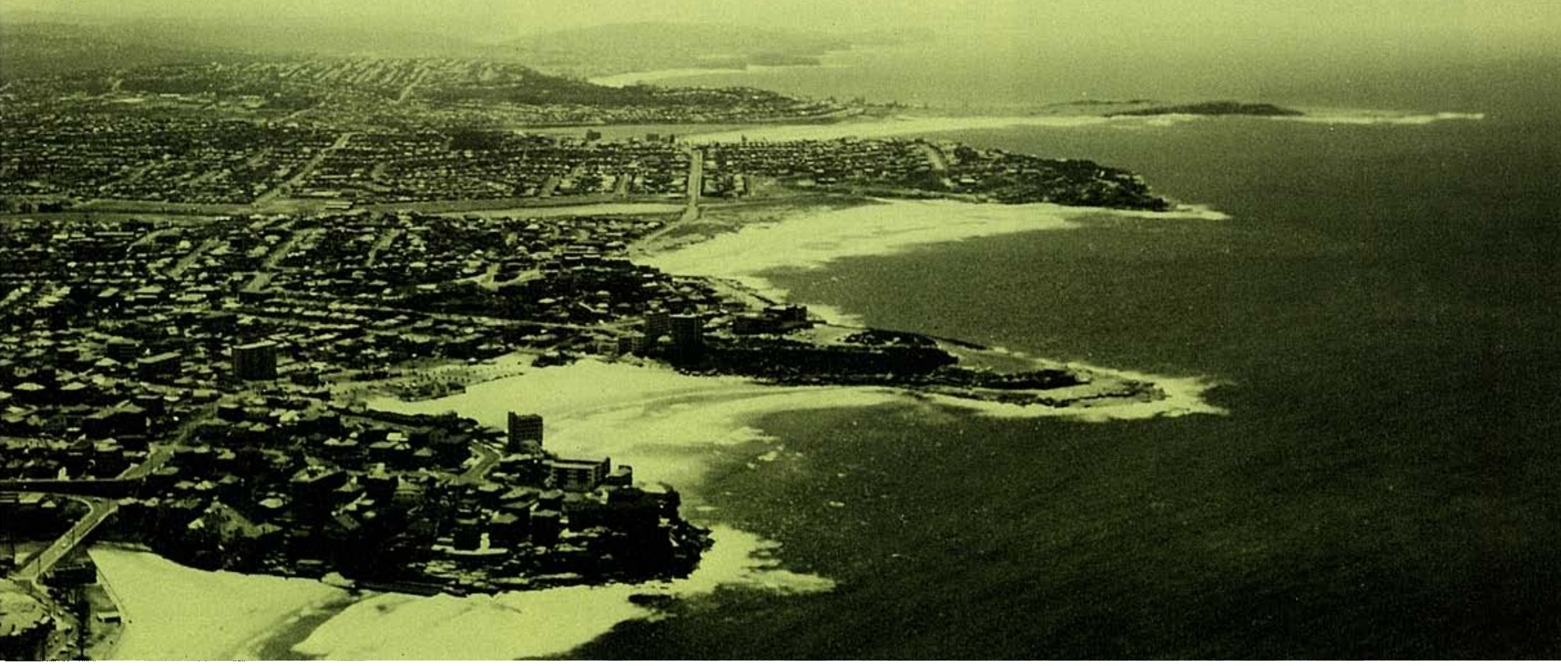
Fossil magnets: clues to the past

If you wander about the coast of New South Wales — anywhere between Newcastle, say, and the Victorian border — looking at the landscape with a geologist's eye, you'll identify the local rocks as old underwater sediments laid down in Palaeozoic and Triassic times. You'll see no sign of anything younger.



Yet a group of scientists has come to the conclusion that this entire coastal strip once lay buried under more than a kilometre of younger rock. The sites of modern Sydney, Wollongong, Jervis Bay, and Nadgee Nature Reserve were, the researchers say, blanketed by later sediments that accumulated in the Jurassic and Cretaceous ages. In places these deposits, now vanished, may have been at least 4 km deep.

The evidence comes from examining magnetism locked millions of years ago into grains of iron compounds in the rocks. The study of this 'palaeomagnetism' has already filled some gaps in our knowledge of the tortuous path followed by this and other continents as they have drifted over the earth's surface, and it is providing mineral companies with new tools for prospecting; but palaeomagnetism is now being used to reconstruct an eroded landscape.

To appreciate how scientists can learn so much from 'fossil magnetism', we must understand how rocks become magnetized in the first place. We are not talking about visible magnets, but about tiny crystal grains of iron oxides such as magnetite and haematite or compounds containing titanium (titano-magnetites). In certain circumstances the magnetic structure of these grains may alter under the influence of the earth's magnetic field.

If the grains are to tell their story to a 20th Century scientist, their magnetization must somehow become fixed in position, aligned with the earth's magnetic field. Both igneous and sedimentary rocks may come to contain such palaeomagnets.

Igneous rocks form from hot volcanic lava or magma welling up from below the earth's crust. At these high temperatures, grains of iron compounds cannot act as magnets, but as the rocks cool, the grains reach their Curie temperature — the temperature below which they become strongly magnetic. Each compound has its own Curie temperature; magnetite's, for example, is 580°C.

At a lower temperature, known as the blocking temperature, the magnetism is 'frozen' into the grains, so by the time they have cooled to normal ground temperatures the grains have preserved a record of the earth's field at the time and in the place where the rock hardened.

Some sedimentary rocks become magnetized while the original deposit is being packed down by the weight of overlying material. The developing rock contains tiny crevices into which water penetrates, giving grains a somewhat fluid medium in which they can line up with the earth's field. As the rock matures, it fixes the grains in their magnetized orientation.

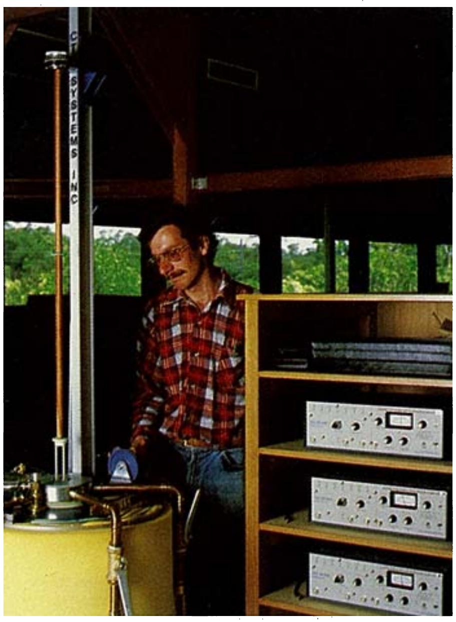
Tiny grains in the rock preserve a record of the earth's magnetic field.

Other sedimentary rocks, and some igneous ones too, acquire palaeomagnets when crystals such as haematite grow in iron-rich water percolating through the rock. As it grows, each of these crystals responds to the earth's field until it enlarges beyond a critical volume, above which its magnetism remains fixed.

A rock may become magnetized more than once in its history. An igneous rock, for instance, already holding a record of the earth's field at the time the rock cooled, may weather and acquire new magnetic crystals in the presence of percolating groundwater.

Degree of latitude

What can a scientist learn from this magnetism? One important answer is: how far away from the equator the rock was when it became magnetized. This is because the magnetized grains behave as tiny compass



A researcher using the rock magnetometer to measure a specimen's magnetism.

needles that not only point towards the north as it appears on a map, but tilt as well, pointing up into the sky if they are in the Southern Hemisphere and down into the ground in the Northern Hemisphere. Only near the equator do the magnets lie horizontal.

The nearer they are to one of the poles, the more steeply they dip. A simple trigonometrical equation links the angle of inclination of a palaeomagnet to its geographical latitude when it became magnetized.

Palaeomagnetism has therefore become a valuable weapon in the armoury of a student of continental drift. If you know the age of a particular rock, its palaeomagnetism can tell you its latitude at that time. If you can find enough rocks of different ages, you can build up a picture of the continent's north–south movements over hundreds of millions of years. And from the horizontal component of the magnetism you can determine how far the continent has rotated, like an extremely slow merry-go-round.

Unfortunately you cannot infer the rock's longitude from its magnetism, and you must turn to other clues for information on the east–west positions of the continent at different times in its history.

The theory may sound simple. Actual measurement of the direction of the palaeomagnetism in a rock, however, turns out to be much more complicated. Since a scientist is interested in the direction of the rock's magnetism, he must measure the orientation of his specimen before he removes it from its site. He must also allow for any disturbances that may have tilted the rock from the original plane in which it lay when it became magnetized; he does this by measuring the angle of the bedding plane of the rock outcrop. With this information he can reconstruct the original orientation of the rock sample.

In the laboratory, the scientist extracts from the sample a cylinder of rock, 2·5 cm in diameter and 2·2 cm long, and puts it into a rock magnetometer to determine its direction of magnetization.

The magnetism of a rock is so faint that scientists can measure it only in an environment in which they can control all other magnetic influences. With suitable apparatus they can cancel the earth's magnetic field around an experiment, but measurements would be impracticable in a laboratory filled with the magnetic 'noise' created by electric motors and other sources of magnetic disturbance.

Measurements of palaeomagnetism therefore require special surroundings. The rock magnetism laboratory of the CSIRO Division of Mineral Physics in Sydney has no iron components. It was built using unreinforced concrete, limestone aggregate, and even copper nails. The air-conditioning motor is in the garden, well away from the experimental area. Without this laboratory, one of only two of its kind in Australia, the Division's palaeomagnetism studies, carried out by Dr Brian Embleton, Dr Phil Schmidt, and Mr Dave Clark, would have been impossible.

Drifting Matilda

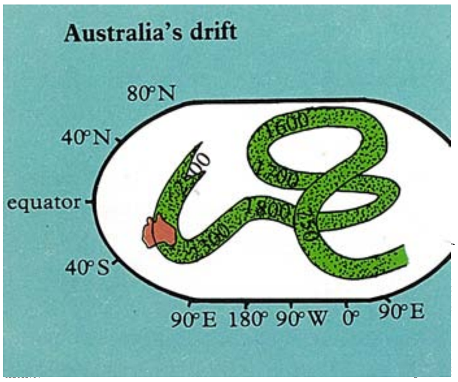
The most spectacular story to emerge from these studies must surely be the history of Australia's movements as the continent drifted about over the earth's surface. Palaeomagnetism did not provide the first evidence for this drift, but it has supplied much of the detail, although the picture remains far from complete.

The CSIRO rock magnetism laboratory has no iron components.

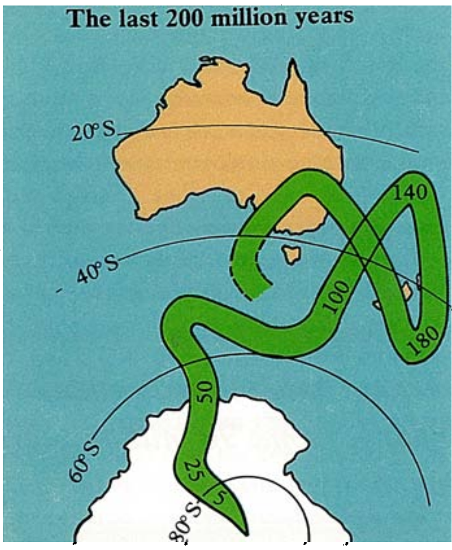
Of course, palaeomagnetism studies tell us the latitudes through which Australia has travelled relative to the magnetic poles, not the geographic poles. The geographic poles are the ones from which lines of longitude radiate on maps, and they mark the ends of the axis about which the planet rotates. The magnetic poles move about relative to the geographic poles; the South magnetic pole at present lies at about latitude 66°S, right outside Antarctica and, indeed, relatively close to Australia.

However, on average the magnetic pole spends as much time to one side of the geographic pole as it does to the other, and over a period of about 10 000 years — not much longer than a nod or a wink to a geologist — the average positions of the two poles coincide. Scientists choose their samples in such a way that the average magnetization of the samples provides a satisfactory estimate of the average magnetic field during the period over which the rock was forming.

Scientists drilling for rock samples.



A map of the South Pole's apparent movements, as seen from Australia, between 2500 and 750 million years ago. In reality the Pole stayed still and the Australian continent drifted.



How the South Pole seems to have moved during the Mesozoic and Cainozoic eras. The dates are in millions of years.

When a researcher determines Australia's historical latitude from the palaeomagnetism of a rock sample, therefore, he can confidently mark that latitude on a map as if magnetic and geographic poles were one.

Although it seems logical to regard Australia as moving relative to the South Pole, scientists find it convenient to think of the continent as staying in one place while the pole has moved about. They have therefore produced diagrams of the 'apparent polar wander', showing how the South Pole would have appeared, to an Australian observer gifted with both long life and long sight, to have drifted to and fro.

The older Australian coals derive from plants that grew in a cold climate.

From this viewpoint, the South Pole seems to have been in Australia about 2400 million years ago, before setting off eastwards and then looping north well up into the Arctic Circle. In practice, this means that Australia was performing the 'mirror image' of these movements — passing close to the North Pole 1500–1600 million years ago.

Scientists have compiled several alternative itineraries to account for the palaeomagnetism measurements from Palaeozoic rocks, but they agree that an atlas published at the start of the Mesozoic era, some 230 million years ago, would have shown the South Pole more or less on the Queensland–New South Wales border. From there the pole seemed to loop beyond New Zealand and back, passing close to south-eastern Australia about 120 million years ago, then heading southwards, as Australia in reality drifted north.

Australia did not travel independently all this time. At one stage the land mass formed part of a federation of continents that we call Gondwanaland; then this grouping gradually came apart and for a while Australia and Antarctica remained together. This aspect of the history, so important to palaeontologists, was described in *Ecos* 24.

The scientists have now accumulated so much information on the palaeolatitudes through which Australia passed, particularly during the Mesozoic era, that they can often date a rock from its palaeomagnetism. But they have to be careful, for the date at which a rock became magnetized is not necessarily the date of that rock's formation.

Cold coals

One intriguing implication of mapping Australia's drift concerns coal. To many people the idea of coal formation conjures up an image of forests whose dead trees were somehow prevented from being completely decomposed. Certainly all coal does derive from the incomplete decay of organic plant matter, but the plants need not have been trees.

Much of Australia's abundant coal was laid down during the Permian period, when, according to the evidence from palaeomagnetism, the South Pole occupied a position near Tasmania, before crossing the southern coast of the mainland and moving north into New South Wales. In other words, the great coal-mining districts of eastern Australia endured a polar climate in those days, and seem unlikely to have supported forests.

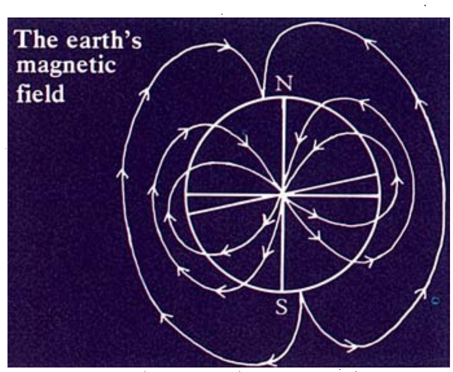
This notion fits neatly with quite separate evidence that the older Australian coals derive from plants that grew in a cold climate, forming communities something like the tundra of modern Siberia and northern Canada. Palaeobotanists have found that these plants belonged to relatively few species and attained no great size, and the rocks surrounding coal deposits often show signs of glaciation.

In addition, Ms Michelle Smyth of the CSIRO Division of Fossil Fuels has deduced from her petrographic studies that much Australian coal (from the Lower Permian, for example — say 250–270 million years old) was a long time in the making, and must have lain on or near the surface without fully decomposing for an extensive period. This indicates permafrost conditions.

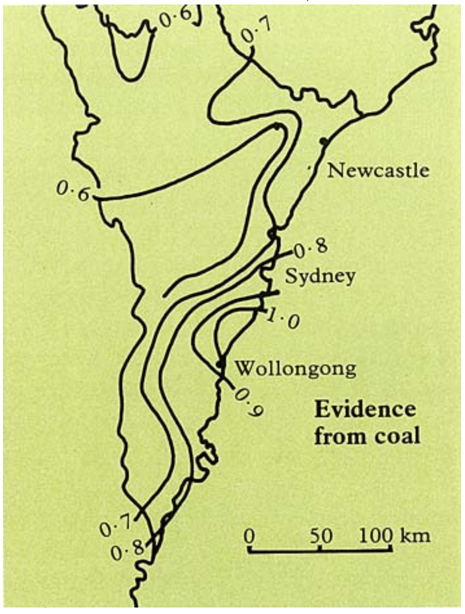
'Fossil magnetism' not only reveals details of Australia's peripatetic past, it also tells us something of the temperatures to which rocks have been subjected during their history. Scientists can obtain this information by reversing the process by which a rock originally became magnetized: for example, they can heat the rock and gradually destroy its magnetism.

In practice, the researchers heat a specimen of the rock to successively higher temperatures, typically in the range 100–600°C, cooling it between heatings and remeasuring its magnetism each time. In this way they monitor changes in the rock's magnetism as the specimen is progressively raised to higher temperatures. From the temperature at which the rock loses magnetism, the scientists can deduce the temperatures at which it originally became magnetized.

For these experiments, the scientists use a special furnace kept magnetically shielded, or, as the researchers put it, in a zero field.



During the earth's history, the magnetic poles have seldom coincided with the geographic poles (N, S). Magnets align themselves with the lines of force. North of the magnetic equator they dip; south of it they tilt up.



A map of the vitrinite reflectance ('shine') of surface coals in the Sydney Basin supports the idea that much erosion has occurred. Coals with the highest values must have been most deeply buried in the past.

Sydney buried

Experiments of this kind enabled the CSIRO team to confirm what some other studies had already suggested, namely that Australia's eastern coast once lay under deep Jurassic and Cretaceous deposits. They examined rock samples from nine sites in the region known to geologists as the Sydney Basin, roughly from Newcastle to Wollongong, and found that all nine contained, in addition to their original high-temperature magnetization, an 'overprint' of low-temperature magnetization acquired much later.

By progressively demagnetizing samples from these sites, the scientists concluded that the rocks that now make up the surface landscape along the coast of the Sydney Basin must have been heated to about 220°C some 90 million years ago.

From magnetic and other evidence, the scientists believe the Sydney Basin rocks must have been kept hot for something like 5–10 million years. Clearly the rocks could not have been exposed to the atmosphere. They must have been well buried: just how deep is a little hard to say, as the calculation involves, among other things, making assumptions about the geothermal gradient — that is, the rate at which the temperature changed with depth. But the researchers confidently assert that more than 1 km of sediment must have lain over the modern surface rocks, and that the covering in places was several times that thick — perhaps more than 4 km deep.

These conclusions find strong support in some quite different observations that had previously been unexplained anomalies. One such line of evidence involves fission tracks in apatites.

Apatites are naturally occurring crystals of calcium phosphate (hydroxyapatite makes up much of our teeth). Trapped inside some crystals lie traces of radioactive minerals, which emit *alpha* particles as they decay. These fission products leave tracks as they pass through the crystal, and a scientist can, millions of years later, measure the density of the tracks under a microscope and so arrive at an estimate of the crystal's age. The older the crystal, the more tracks there will be to count.

But there is a catch. If an apatite crystal for any reason heats up above 65°C, its fission tracks begin to disappear; at 125°C all the tracks are erased. The density of these tracks therefore tells a scientist not the age necessarily of the crystal, but rather how much time has elapsed since the crystal was last warmed up to 65°C or higher.

Well inland from the eastern coast of New South Wales, dating rocks by the fission tracks in apatites gives the same results as dating by other means, but for some time scientists at the University of Melbourne have been perplexed by the observation that towards the coast apatites seem too young for their rocks. The nearer you approach the coast, the greater the discrepancy you find. In Palaeozoic granites, for example, apatite fission tracks give ages ranging from 360 million years 100 km inland to 80 million years along the coast.

The CSIRO group can relate this anomaly to their palaeomagnetic detective work. The nearer apatites are to the coast, the higher the temperature to which they were raised (and the more thoroughly, therefore, their fission tracks were erased) during that subterranean 'heat wave' about 90 million years ago.

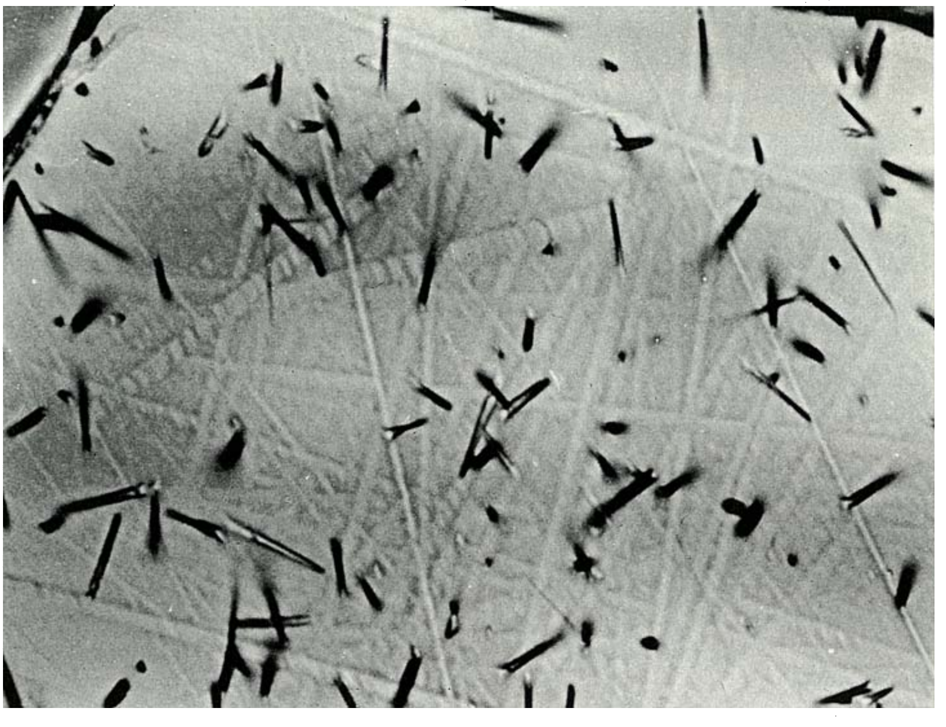
Shiny coals

The same geological phenomenon would account for another curious observation, this time involving coal. A cut, polished surface of coal shines, and scientists have accumulated much information on the shininess of coals from collieries in the Sydney Basin. This property, technically known as vitrinite reflectance, indicates the depth of burial of the coal and how much it has been heated.

When the reflectance values for coals at the surface are plotted on a map, they form concentric contour lines centred on a coastal point between Sydney and Wollongong, where the highest values occur. Once again, the palaeomagnetism work

What caused these dramatic changes some 90 million years ago?

Fossil radioactive fission tracks in a crystal of apatite from a granite on King Island in Bass Strait. The tracks, photographed by Dr Andrew Gleadow of the University of Melbourne, measure up to 16 μm. The long, faint lines are polishing scratches.



Geological time

era	period	time since start of period (million years)
Cainozoic	Quaternary	2
	Tertiary	65
Mesozoic	Cretaceous	130
	Jurassic	195
	Triassic	240
Palaeozoic	Permian	290
	Carboniferous	350
	Devonian	400
	Silurian	435
	Ordovician	500
	Cambrian	575

ties in well. The more the coal shines, the higher the temperature to which it has been raised, and the more deeply it must therefore have been buried at some time in the past.

Where coal with the highest reflectance value occurs near the surface, therefore, the greatest erosion must have occurred. In other words, the evidence from coal supports the tale told by palaeomagnetism: that a considerable depth of rocks has been eroded from the Sydney Basin — particularly near the coast.

One other clue that younger rocks once covered the present surface deserves a mention. Although Jurassic sediments do not make up any of the landscape that we see in the Sydney district, they do occur in some of the local breccia — a composite rock, made up of magma and volcanic fragments, formed by the rapid 'boiling' of steam and hot gases in a narrow vent. The violent activity plucks pieces of rock from the sides of the vent and deposits some of them at a deeper level.

Much of the breccia around Sydney has long since disappeared, but some Jurassic fragments fell deep enough to avoid erosion. Scientists have dated these fragments from the traces of pollen and spores they contain.

All of which leaves the question: what caused these dramatic changes some 90 million years ago? Geologists, who routinely study such huge phenomena and such vast periods of time that their explanations smack to everybody else of understatement, say there must have been an 'event', presumably associated with the processes that separated Australia from New Zealand and Lord Howe Island.

A considerable depth of rock has been eroded from the Sydney Basin — particularly near the coast.

This separation resulted from the creation of new sea floor as magma oozed out of a long crack in the earth's crust and spread sideways. All this must have followed millions of years of geological drama relatively near the surface. Theoretical modelling of the way plates of the earth's crust split and the two pieces move apart (more concisely, the way Atlantic-type rift margins form) suggests that high temperatures, uplifting, and erosion must all have taken place on the eastern edge of the Sydney Basin before the plates carrying Australia and New Zealand began to be pushed apart, about — as independent evidence shows — 76 million years ago.

Scientists suspect that the erosion over the Sydney area may have been swift, most of it taking place inside 10 million years. Where has all this displaced sediment gone? Perhaps it washed into the Tasman Sea, where sediments of unknown age reach thicknesses of up to 1 km, or perhaps down a network of rivers into basins (such as the Otway) on the southern margin of the continent, where Jurassic, Cretaceous, and Tertiary deposits have accumulated to depths of 8 km. These deposits contain Australia's main source of hydrocarbons, particularly oil.

The scientists are planning further studies to find out how much of Australia was affected by the 'overprint event'. Various types of evidence already show that rocks were modified along a stretch of the eastern coast from about Newcastle southwards into Victoria, but traces of the 90-million-year-old 'baking' may lie waiting to be discovered as far apart as Tasmania and Queensland.

Scientists can often date a rock from its palaeomagnetism

The coast of Western Australia represents another similar rift margin, and the CSIRO researchers hope to examine rocks in that region before long. About 140 million years ago the plate carrying India drifted away from Australia's western margin, and the scientists will therefore be examining rocks for signs of an 'event' about 140 million years ago. They already know what other Australian rocks of that age 'look' like palaeomagnetically, and should therefore have little trouble spotting any overprint there may be.

Besides unravelling the route of Australia's complex 'driftabout' and throwing new light on the geological history of the eastern coast, palaeomagnetism studies have a significant contribution to make to mineral exploration. By enabling people to understand the magnetic properties of local rocks,the work is helping to achieve better interpretation of both aerial and ground magnetic surveys. Since many economically important minerals occur in association with ores containing iron, accurate interpretation of the magnetic 'profiles' of surveyed rocks should lead prospectors faster — and more cheaply — to valuable discoveries.

John Seymour

More about the topic

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