again involved[6], but the possible sites of plasticity and the underlying physiology are not known, and NMDA-receptor-dependent plasticity has not yet been correlated with extinction. Moreover, it has been suggested that there are also NMDA-receptor-independent mechanisms of extinction[7].

Marsicano *et al.*[2] now propose just such a mechanism, which involves the endocannabinoids anandamide and 2-arachidonylglycerol, and their CB1 receptors. These receptors are some of the most abundant neuromodulatory receptors in the central nervous system and are expressed at high levels in the limbic system, cerebellum and basal ganglia[8]. The classical behavioural effects of exogenous cannabinoids — such as sedation and memory changes — have been correlated with the presence of CB1 receptors in the limbic system and striatum.

It has been difficult, however, to pin down the physiological role of endocannabinoids and how they are released in these regions. In studies that were the first to reveal such a role, the depolarization of neurons by repetitive activity led to the release of endocannabinoids[9], which diffused to the terminals of other neurons and inhibited neurotransmitter release. This effect was transient in the hippocampus and cerebellum[9] and long lasting in the striatum[10]. Yet these changes in neurotransmission have not been connected to any specific behavioural effects. So the study by Marsicano *et al.*[2] represents a leap forward in two areas of neurobiology, in that it clearly implicates the release of endocannabinoids in a well-known, simple learning task. It also links endocannabinoid release to synaptic plasticity.

After engineering mice to lack the CB1 receptor, Marsicano *et al.* first showed that although these animals could learn and later recall the association of a tone with a foot shock, they could not extinguish the memory. A drug that antagonizes the CB1 receptor similarly prevented extinction in wild-type mice. The authors then found that during the extinction protocol (exposure to the tone alone), the levels of both anandamide and 2-arachidonylglycerol were raised in the basolateral amygdala in mutant and normal mice. This implies that a process involving activation of the CB1 receptors by endocannabinoids is essential in the extinction of conditioned fear.

Next, in experiments with slices of normal mouse brains, the authors looked at neurons in the basolateral amygdala that can release GABA (an inhibitory neurotransmitter). They found that low-frequency stimulation of these neurons leads to a long-term reduction in the release of GABA, which in turn leads to less inhibition of the connecting 'pyramidal' neurons. This long-term 'depression' — a type of synaptic plasticity — was completely blocked by the CB1-receptor antagonist, and absent in CB1-deficient mice. These findings suggest that the endocannabinoids reduce GABA release in the basolateral amygdala, thereby helping to extinguish the fear-conditioned response. In mammals, the neurons that release GABA are largely interneurons, which can be divided into several populations on the basis of their expression of certain proteins and peptides (such as cholecystokinin). The role of endocannabinoids in reducing GABA release fits with the finding that CB1 receptors in the basolateral amygdala are present on the terminals of cholecystokinin-containing interneurons[11,12].

This is an entirely new cellular and molecular mechanism for extinction. But how does it tie in with the NMDA receptors? There seems little doubt that activation of these glutamate receptors in the basolateral amygdala is somehow required for extinction[6]. But Marsicano *et al.*'s brain-slice experiments were performed with blocked glutamate receptors, showing that the endocannabinoid-mediated synaptic plasticity they report does not need the NMDA receptors. So we have yet to find out how these receptors are involved in extinction.

It has been argued that the neuronal circuitry underlying fear conditioning has similarities to that responsible for fear-related clinical conditions, such as post-traumatic stress disorder[4]. Behavioural therapies for these conditions — including systematic desensitization and imagery therapies — share features with extinction. The finding that the endocannabinoids contribute to extinction raises the possibility that drugs that target these molecules and their receptors could be useful new treatments for anxiety disorders. Finally, there is much anecdotal evidence of patients using cannabis heavily in the early stages of psychiatric illness. This has often been thought to contribute to acute illness. But it seems possible that it may instead be a form of self-medication for the sometimes extreme anxiety that these people experience. ■

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Earth science

Core values

John Brodholt and Francis Nimmo

Calculating the age of the Earth's solid inner core has proved to be a tricky business. But the suggestion that there is more potassium in the core than had been thought could help to reconcile differing estimates.

Potassium is a relatively insignificant element in the Earth, languishing in sixteenth place in the league table of chemical abundance. But, right now, radioactive decay of a potassium isotope, ^{40}K, is responsible for about 10% of the heat lost by the Earth. As ^{40}K has a half-life of 1.25 billion years, its decay would have produced much more heat in the past — just after the Earth formed, 4.6 billion years ago, daily decay of ^{40}K would have produced more heat than the present total daily heat loss of the Earth. Heat within the Earth drives processes such as convection in the mantle layer and the generation of the planet's magnetic field. So knowing how potassium and other radioactive elements are concentrated in different parts of the Earth is fundamental to understanding these processes.

There is a large concentration of potassium in the Earth's crust, and a significant proportion remains in the mantle below. What is not known is how much is in the Earth's core. Although experimental results have been ambiguous, it has generally been thought that, because of the relatively large radius of potassium ions, not much of this element could be absorbed in the core. But new results from Gessman and Wood[1], reported in *Earth and Planetary Science Letters*, show that the amount of potassium in the core depends on the core's sulphur and oxygen content, and on the structure of the coexisting silicate melt. Their findings help to explain some of the ambiguities in the earlier data, and also enable them to estimate the maximum concentration of potassium in the Earth's core — a number that has important bearing on the age of both the inner core and the Earth's magnetic field.

Although the magnetic field is generated by fluid flow in the liquid outer core, it is generally accepted that the solid inner core also plays a fundamental role. This is because a large part of the energy needed to drive this magnetic dynamo is thought to come either from the latent heat of crystallization of the inner core, or from convection due to the separation of a light chemical component during freezing[2,3].

Driving a dynamo without an inner core is extremely difficult as that would require the heat flux to be high enough to provide the necessary convection, but not so high that the core solidifies. At the July meeting on 'Study of the Earth's Deep Interior' (SEDI), D. Gubbins (Univ. Leeds) argued that it is pretty much impossible for the Earth to have established a geomagnetic dynamo without an inner core; D. Stevenson (Caltech) suggested that it might be possible to sustain a dynamo without an inner core if the core was initially superheated, perhaps by 1,000 K. But this seems unlikely, as then the core would probably have been hot enough to melt the overlying mantle.

So if an inner core is necessary for the dynamo, and given that there is clear evidence for a geomagnetic field in rocks as old as 3.5 billion years, the logical assumption is that the Earth's solid inner core must be at least that old. The problem, however, is that models of core evolution have difficulty simulating an inner core that is older than about 1 billion years[4]; the core seems to be growing too quickly. But Gessman and Wood's results[1] may help to reconcile these two incompatible views.

If the inner core has grown to its present size at a constant rate over 4.6 billion years, the heat of crystallization would provide 0.5 TW (1 TW $= 10^{12}$ W) of the total core heat flux. Estimating the total core heat flux is difficult, but by assuming that in the lowest 250 km of the mantle heat is transported by conduction only, the answer comes out at about 7 TW. Convective upwellings from the core–mantle boundary (mantle plumes) may increase this figure to 10 TW. In the absence of internal heat sources, the difference between these estimates and the heat from crystallization must be accounted for by heat released through cooling. This would require a core-cooling rate of 120–200 K every billion years, a rate that is considered rather too high. So either the core is much younger than 4.6 billion years, or there is another internal heat source — such as radioactive heating. Using similar arguments, Labrosse *et al.*[4] estimated that, if the inner core is as old as 4.6 billion years, around 4 TW must be released through radioactive heating.

Gessman and Wood's high-temperature, high-pressure experiments[1] show that, in the presence of sulphur and oxygen, potassium alloys with liquid iron, and that in the Earth's core a concentration of up to 250 p.p.m. could be expected. That much potassium would produce only about 1.7 TW of heat, somewhat less than the 4 TW required for an inner core whose age matches the Earth's. But it may be enough to push back the core age to about 2.5 billion years. Rama Murthy and colleagues (personal communication), however, suspect that there might be even more potassium in the core than Gessman and Wood suggest. And if the core-forming liquid equilibrated with the mantle at lower pressures than assumed by Gessman and Wood, the concentration of potassium in the core could be higher still. If the abundance of other radioactive elements, such as uranium and thorium, in the iron-rich liquid of the core is also affected by the presence of sulphur, that again would push back the age of the core.

At this point, although the experiments performed by Gessman and Wood help, they do not fully resolve the problem of the age of the Earth's inner core and dynamo. If the core really can store significant quantities of potassium, geochemical arguments regarding stratification of the mantle will also have to be revisited[5]. Clearly, more theoretical and experimental work is needed. It is worth noting, however, that Gessman and Wood's results apply to other planetary cores. The inner core of Mars formed at lower pressure and is thought to have a high sulphur content, so it could also have very high concentrations of potassium: radioactive decay may have provided the energy for an early magnetic dynamo on Mars. ■

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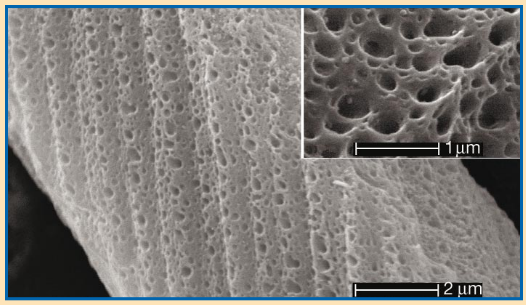
Materials

Zeolites branch out

Wood, with applications ranging from construction to cabinet-making, has just notched up another use. As they describe in *Advanced Materials*, Angang Dong and colleagues (*Adv. Mater.* **14,** 926–929; 2002) have used it as a template for creating zeolites.



Zeolites are porous structures of crystalline aluminosilicate, made on templates that define the size of the pores and their interconnectivity. They can be designed for specific applications; for example, the pore size can be chosen to set the rate at which other molecules will diffuse through the zeolitic structure.

Templates such as shells have already been used to synthesize inorganic analogues of biological materials. As the structural organization of such materials cannot be finely controlled, some of the advantages of rationally designed synthetic templates are lost. But other properties make biological templates attractive: they can be cheap, abundant, renewable, and so commercially viable; and they are also environmentally benign.

Dong *et al.* report the synthesis of a zeolitic material possessing a porosity inherited from its wood templates — bamboo (a grass with woody stems) and cedar (a conifer). Further advantages of wood are its intrinsically complex and hierarchical pore structure, and the abundance of tree species — and so morphologies.

To make a zeolite, the authors used a 'seeded growth' technique. First they treated the wood templates with a polyelectrolyte, and dispersed pre-formed zeolite nanocrystals through the templates. Then they washed the nanocrystal-coated wood slices and immersed them in zeolite solution for a day. The zeolite–wood composite was heated in air to remove the wood, leaving a free-standing zeolite composed of thin, uniform, continuous membranes.

Using X-ray diffraction on both the bamboo and the cedar templates, Dong *et al.* verified that the resulting materials were purely zeolitic. Scanning-electron-microscope images revealed that the synthetic strategy had not destroyed the skeleton of the original tissue. Instead, the zeolite nanocrystals had completely penetrated the wood, faithfully replicating the wood's cellular structure in fine detail. The cedar-template zeolite (shown above) was composed of interconnected bundles of micrometre-scale hollow vessels, with some fibres having features such as pits (which originally connected adjacent cells) and helical stripes. The bamboo zeolite showed rings and spine-like structures.

Applications of zeolites formed from wood templates are still some way off. But Dong *et al.* predict that they could ultimately be useful in catalytic and adsorption technologies. **Rosamund Daw**