(although 1,000 km seems deep to us on Earth, because Earth's atmosphere spans a depth of just 100 km).

So what does this suggest for the larger cousins of these planets, Jupiter and Saturn? They also have strong zonal winds at their cloud tops, but these winds vary much more strongly with latitude than those of Uranus and Neptune. This means that any signature in the structure of their gravitational fields will manifest itself only in the high-order, rapidly varying gravitational moments (J_{10} and higher)[10], which could not be measured during the Voyager fly-bys or in the ongoing Cassini mission.

In 2011, NASA launched its Juno mission, the main goal of which is to accurately measure the high-order gravitational moments of Jupiter from the vantage point of a low-altitude polar orbit. Kaspi and colleagues' approach will enable constraints to be placed on the depth of Jupiter's deep baroclinic flow. This might settle the long-running debate over whether Jupiter's winds are deep-seated or superficial. And

when the Cassini orbiter reaches the end of its mission in 2017, plans are afoot for the spacecraft to enter a low polar orbit around Saturn (before crashing into it) to make the same measurements of the planet's gravitational field as Juno will for Jupiter. By the end of this decade, we may therefore have obtained measurements that constrain the wind-penetration depth for all four gas- and ice-giant planets.

If I were a betting man, my money would be on a shallow penetration depth for the gas giants, given the precedents of their ice-giant cousins. There are several other reasons to expect gas-giant meteorology to be confined to shallow depths[11], one of which is that the fluid interiors of the gas giants become electrically conducting at depths of several thousand kilometres. This allows hydromagnetic forces to disrupt the 'Taylor–Proudman condition', breaking the associated axial coherence of the winds. However, a probe from the Galileo spacecraft found that zonal winds increase with depth near Jupiter's equator[12], so the evidence is

not unequivocal. I await the results from Juno and Cassini with considerable interest. ■

Peter Read *is in the Department of Physics, Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK.*
e-mail: p.read1@physics.ox.ac.uk

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METALLURGY

Iron production electrified

Scientists have long dreamt of converting molten iron oxide to iron and oxygen using electricity. An anode material that withstands the high temperatures and corrosive chemicals involved brings the dream closer to reality. SEE LETTER P.353

DEREK FRAY

In 2011, about one billion tonnes of iron was produced worldwide[1]. Unfortunately, the concomitant generation of carbon dioxide contributed to around 5% of that year's global increase in atmospheric CO_2 (ref. 1). This was not because the amount of CO_2 produced per tonne of iron is high — it is in fact less than that of most metals — but because of the immense quantity of iron produced. In this issue, Allanore *et al.*[2] (page 353) report a discovery that might lead to a more environmentally friendly method for making iron: the reduction of iron ore using an electric current, a process known as electrolysis*.

Iron ore is commonly chemically reduced by carbon in a blast furnace at 1,600 °C to give liquid iron that is saturated with carbon, and a mixture of CO_2 and carbon monoxide[3]. The carbon monoxide is usually burnt to generate heat and more CO_2. However, solidified iron from blast furnaces has few applications because of its inherent brittleness. Useful steel products can be made only by removing most

of the carbon as yet more CO_2 and carbon monoxide, and by removing other impurities that tend to be introduced with the carbon.

An alternative approach is to reduce iron oxides directly with hydrogen. But most hydrogen is obtained by the reaction of methane with

water, or by the electrolysis of water[3]. Either way requires two steps: hydrogen generation and the reduction of the iron oxides. It therefore seems logical to bypass the hydrogen-generation step and use electricity to reduce iron ore directly (Fig. 1). What is more, it would be preferable to use conditions in which both the metal product and the electrolyte (the material in which the iron oxide is dissolved) are liquids, because liquids are generally easier to handle than solids. Another important reason for making a liquid product is that if iron is deposited as a solid from molten electrolyte, it forms as a fine powder that can be easily oxidized, reversing the desired reaction. The overall challenge, therefore, is to devise an electrolytic process that produces carbon-free liquid iron and oxygen.

Iron oxide readily dissolves in metal-oxide melts to form a predominantly ionically conducting mixture in which the iron is present as

Figure 1 | Metal extraction by electrolysis. The interior of an aluminium smelter demonstrates the harsh conditions that must be withstood by the components of electrolytic cells. Allanore *et al.*[2] report materials that could be used as anodes in the electrolytic production of iron.

*This article and the paper under discussion[2] were published online on 8 May 2013.

iron(II) or iron(III) ions. Deposition of liquid metal from the melt is unlikely to be a problem, so the main challenge in developing an electrolytic method for iron production is to find a suitable anode, which must be highly conducting and not be attacked by the melt or by liberated oxygen at 1,600 °C. There are three kinds of material that might be suitable: metals, which are usually highly conducting, but may oxidize; conducting ceramics, which might dissolve in the melt and are not malleable; and cermets, which are mixtures of metals and ceramics[4].

Allanore *et al.* concentrated on metallic alloys that form oxide films on their surfaces during electrolysis — films that do not readily dissolve in the liquid electrolyte. The same group has also reported[5] that iridium is a suitable anode material because its oxide cannot form at above 1,200 °C; the metal therefore remains as a metal during electrolysis, rather than corroding away because of oxidation. However, iridium is much too expensive and scarce to use for industrial iron production.

By examining cheaper chromium–iron alloys, the authors have found these to be resistant to oxidation under the conditions that are necessary for iron oxide reduction in molten electrolyte. Another advantage of these alloys is that any anodic dissolution will not introduce undesirable contaminants into the iron. In fact, traces of chromium could be beneficial, because this metal is commonly added to iron to decrease its oxidation rate.

When an alloy oxidizes, the main components of the film that forms at the surface are usually the oxides of the elements in the alloy. Surprisingly, the oxide layer that formed on the anode during electrolysis in Allanore and colleagues' study consisted of a solid solution of chromium oxide and aluminium oxide. The latter came from the electrolyte, which was a mixture of iron(III) oxide, calcium oxide, aluminium oxide and magnesium oxide. But curiously, when the researchers immersed a chromium–iron anode in the electrolyte without an applied voltage, they observed the formation of an additional mixed layer of calcium oxide and aluminium oxide on top of the chromium oxide–aluminium oxide layer. This observation runs counter to conventional oxidation theory. It may be that, when a voltage is applied, positively charged calcium ions are repelled by the positive potential at the anode, preventing calcium from forming part of the coating.

Allanore and co-workers' results will stimulate further development of affordable alloys for iron oxide electrolysis, and will prompt researchers to consider how to design a large pilot reactor. However, considerable technical development will be required for the authors' discovery to be used commercially. For example, electrolytic reactions invariably take place in two dimensions on electrodes, whereas the chemical reactions in conventional iron-making take place in three dimensions — so it could be difficult to match the space and time yields of conventional smelters in an electrolytic reactor. Electrolytic cells will need to be engineered in which anode-to-cathode distances are short enough to avoid voltage losses in the electrolyte, but not so short that the products (iron and oxygen) formed at each electrode come into contact and react to reform iron oxides. Electrical current densities in the system must also be kept high to maintain a high production rate.

Although there is much to do, a process that is less polluting than existing technology could be developed. This approach could also be applied to the extraction of other metals from their oxides. And there is another exciting potential application: the production of oxygen from metal oxides could be invaluable for space exploration. If the process were carried out on the Moon, for example, the gas could be used in the fuel–oxygen mixture that is needed for rockets and to sustain life[6,7], making human colonization of the Solar System more feasible. ∎

Derek Fray *is in the Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB2 3QZ, UK.*
e-mail: djf25@cam.ac.uk

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EVOLUTION

Stuck between the teeth

A computer model of tooth evolution designed to assess the impact of developmental dynamics on natural selection reveals that complexity reduces the likelihood of maximum fitness being attained. SEE LETTER P.361

P. DAVID POLLY

The evolutionary biologist Leigh Van Valen famously defined evolution as the control of development by ecology[1]. By this, he meant that evolution is governed by the fitness of the phenotype of an organism (its physical form); that fitness depends on the ecological context in which the phenotype exists; and that an individual's phenotype is not a static structure built directly from genes, but a dynamic structure that unfolds sequentially from fertilization to adulthood. The developmental sequence determines and constrains which phenotypes can emerge, such that evolutionary change depends on modifications to development. On page 361 of this issue, Salazar-Ciudad and Marín-Riera[2] present a groundbreakingly realistic computational model of this process. They use their model to demonstrate that developmental complexity often prevents natural selection from reaching optimal fitness when fitness is directly linked to attaining a particular phenotype, but that these 'adaptive peaks' can be reached when fitness is instead linked to functional properties of the phenotype*.

The authors' model revolves around a simulation of the evolution of mammalian tooth development, using well-understood details of molecular developmental biology and functional ecology[3–5]. Mammalian teeth develop from two main tissue types, the mesenchyme and the epithelium. The growth of these tissues helps to shape the tooth germ (the aggregation of cells that eventually form the tooth) as it develops through bud, cap and bell stages (Fig. 1a). A suite of activator and inhibitor molecules controls the rates of cell proliferation, differentiation and death in these tissues[6]. Three-dimensional changes in the developing tissues modulate the distances over which these signals interact, causing local changes in their concentration that result in the formation or loss of signalling centres called enamel knots. The shape into which the dynamically controlled tooth germ folds determines the topography of the crown of the mature tooth and thus its functional properties.

A huge variety of teeth can be produced by this developmental system, ranging from a dog's high-cusped molars to the elaborately ridged molars of some rodents, such as the coypu (Fig. 1b). Tall cusps in mammals are usually associated with the puncturing, shearing and tearing functions of carnivores and insectivores, whereas low cusps, crests and basined surfaces are associated with the grinding and chewing functions of omnivores and herbivores[5].

Salazar-Ciudad and Marín-Riera simulated this developmental system as two sheets of cells, the epithelium and mesenchyme,

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