Whittington *et al.*[1] demonstrate, this may even lead to melting inside the shear zone, causing further localization of the deformation within the shear zone. But this result should be interpreted with caution, as strain heating depends strongly on the evolution of stress within the zone, which itself depends on the assumed deformation mechanism and is currently the subject of much debate[2]. Enhanced strain heating could also explain the formation of larger than expected volumes of granitic magmas produced by partial melting of deep crustal rocks[3]. This process, referred to as anatexis, is observed in many mountain ranges, most notably in the granitic belts associated with the Main Central Thrust fault in the Himalayas.

A recent and vigorously debated model for the evolution of large, hot mountain belts, such as the Himalayan–Tibetan system[4], relies on the formation of a ductile, partially molten lower crust that may be extruded at Earth's surface in regions of high precipitation and thus surface erosion. The high-temperature conditions necessary for partial melting of the lower crust are thought to be achieved by increased heat production due to radioactivity, resulting from a thickened crust and/or shear heating. A reduced conductivity in the lower crust would significantly reduce the time necessary for such radiogenic heating to take place, and would potentially lead to higher crustal temperatures. This hypothesis, and many others concerning the dynamics of mountain belts, should now be revisited in view of Whittington and colleagues' new measurements[1] of thermal conductivity.

Also in need of reassessment are most quantitative models of Earth's dynamical behaviour, because heat transport is such an important process inside the Earth. For example, a reduced crustal conductivity would also imply a higher mean temperature in the underlying mantle, especially during the early, 'hotter' stages of the planet's evolution. This, in turn, has direct implications for our understanding of the early Earth's differentiation and the distribution of elements in its various reservoirs (the crust, mantle and core). ■

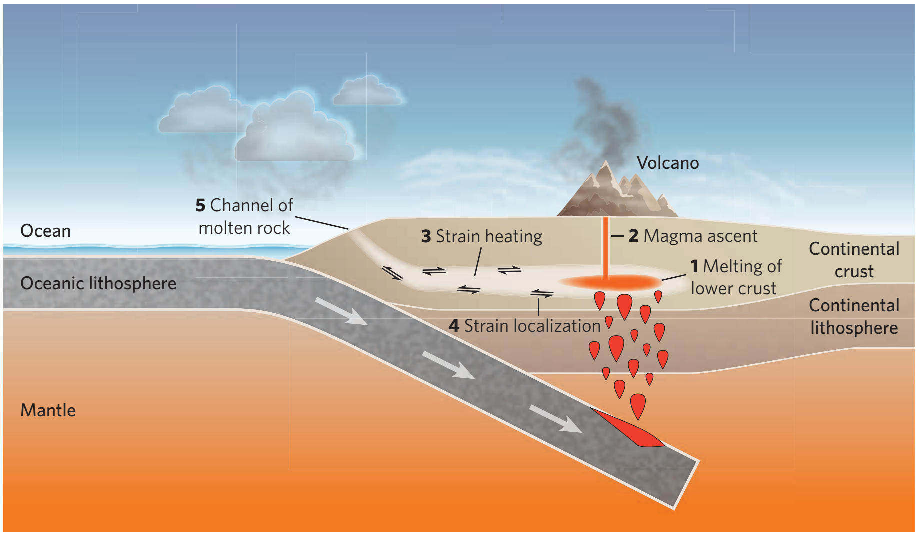

Figure 2 | Implications of a lower crust that is warmer than expected. Whittington and colleagues' observation[1] that the lower crust is a good thermal insulator and is thus warmer than previously recognized has many consequences for magmatic and tectonic processes in convergent plate settings such as subduction zones: **1,** more efficient melting and mixing of the lower crust following mantle-derived basaltic intrusion; **2,** more rapid and efficient ascent of the resulting magma through the crust; **3,** enhanced strain heating during tectonically driven deformation of the lower crust; **4,** enhanced strain localization; **5,** quicker development of a lower-crust channel of molten rock that may be extruded at Earth's surface in regions of high precipitation and thus surface erosion.

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DINOSAURS

Fuzzy origins for feathers

Lawrence M. Witmer

Cretaceous fossil deposits in China are famous for their feathered dinosaurs. But the surprising discovery of a herbivorous dinosaur with a filamentous coat raises fresh questions about the evolution of feathers.

Liaoning Province in northeastern China is renowned for the fossils that document, in often vivid detail, virtually the entire biota that lived over a period of several million years during the Early Cretaceous (about 125 million years ago)[1]. Although exquisite fossils of diverse vertebrates, invertebrates and plants have been recovered, it's the spectacular feathered dinosaurs that have received most attention[2–4] and caused much controversy[5,6]. On page 333 of this issue, Zheng and colleagues[7] present the discovery of a small dinosaur, *Tianyulong confuciusi*, from the Yixian Formation of Liaoning, that promises to send the debate on dinosaur feathers in a totally new direction — and a confusing direction, at that.

Even without preservation of portions of its skin, *Tianyulong* would be a notable find, because its genealogical ties are to a group of herbivorous dinosaurs, called heterodontosaurids, that had undergone their evolutionary radiation 70 million years earlier, making *Tianyulong* a 'living fossil' in its own time. Heterodontosaurids used to be regarded as a fairly obscure group, related to the more famous duck-billed hadrosaurs. But recently, heterodontosaurids have taken centre stage as the most evolutionarily basal branch of the entire great radiation of herbivorous dinosaurs, the Ornithischia (Fig. 1, overleaf), that included not only hadrosaurs but also *Triceratops, Stegosaurus* and a host of related animals[8]. Were it not for its skin, *Tianyulong* would be important as a late-surviving twig of this branch of the ornithischian family tree, and the first of its kind known from Asia. But the fossils of *Tianyulong*, splayed on a stone slab, reveal three patches of long filaments reminiscent of structures thought to be the evolutionary progenitors of feathers. The only problem is that *Tianyulong* isn't supposed to have anything like feathers.

Before the 1990s, life was simple: feathers were thought to be an exclusively avian attribute, found in all birds today and extending back to the iconic *Archaeopteryx* in the Late Jurassic, some 150 million years ago. The discovery of very bird-like feathers, complete with shaft and vanes (pennaceous feathers), in some of the predatory theropod dinosaurs found in Liaoning (such as *Caudipteryx* and *Microraptor*) rocked the scientific world[2,4,9], because the feathered dinosaurs were outside the evolutionary group of acknowledged birds. Still, it wasn't completely unexpected, in that these dinosaurs are representatives of the theropod

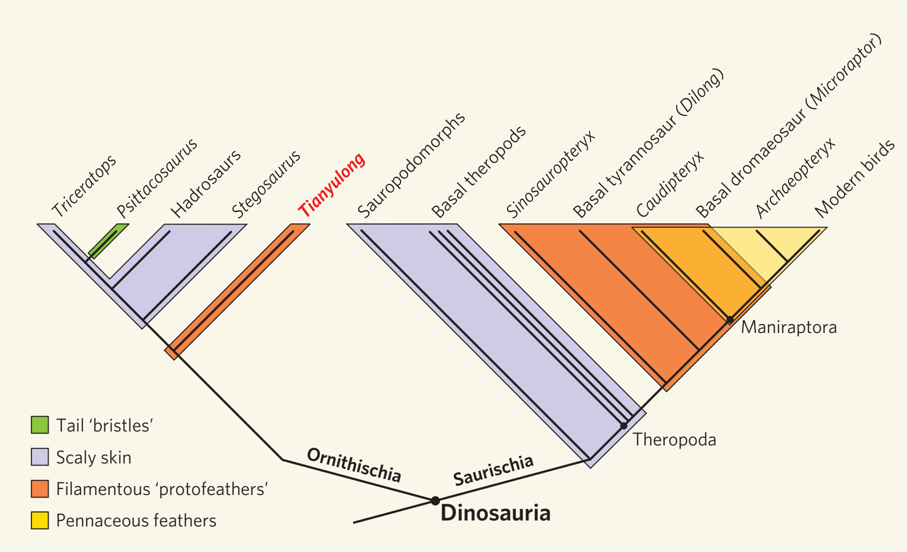


Figure 1 | Dinosaur relationships and skin characteristics. The dichotomy between feathered birds and scaly reptiles was demolished by the discovery of true pennaceous feathers in the non-avian maniraptoran dinosaurs thought to be closest to birds. More controversial have been the filamentous skin structures, variously regarded as external 'protofeathers' or internal structural fibres. Zheng and colleagues' discovery[7] of filamentous structures in *Tianyulong* further complicates the picture, in that this is an ornithischian dinosaur far removed from the ancestry of birds. Many other dinosaurs, such as other ornithischians and basal saurischians, had reptilian, scaly skin. So, were the ancestral dinosaurs fuzzy animals cloaked in 'protofeathers', which were subsequently lost multiple times in later groups? Or were dinosaurs primitively scaled, and did later groups independently evolve wispy, feather-like or even bristly skin coverings?

group, Maniraptora, that is skeletally the most bird-like, and from which birds are widely thought to have evolved. Feathers became just one more character showing that link, albeit a compelling one. But *Tianyulong* is not at all closely related to birds and, as a heterodontosaurid ornithischian, is on an entirely separate branch of the dinosaur family tree (Fig. 1).

And indeed, *Tianyulong* doesn't have true pennaceous feathers. It has long filaments, very similar to what have been called 'protofeathers' or, more non-committally, 'dinofuzz'. These filaments are evident in some theropods such as *Caudipteryx* that have true pennaceous feathers, but are also found in a range of other theropods that lack definitive feathers, such as the basal coelurosaur *Sinosauropteryx*, the therizinosauroid *Beipiaosaurus* and the basal tyrannosauroid *Dilong*[3,4,10].

Herein lies the controversy. No one disputes that these filaments are integumentary (in the skin). The question is, from what part of the skin do they come — the outside or the inside? Many[3,4,10,11] have regarded them as epidermal (that is, as projecting, external appendages that are somehow evolutionarily related to feathers). Others[5,6] have regarded them as dermal (that is, as the remains of collagen fibres below the skin's surface). In this context, the difference between epidermal and dermal is huge. If they are epidermal, then they bear not only on feather evolution and avian origins, but also on metabolic physiology, behavioural display and flight. If they are dermal, then they're ultimately structural in function and have little bearing on those other issues. Unfortunately, the rhetoric of this debate has overshadowed the scientific evaluation of evidence[9]. If the integumentary filaments of *Tianyulong* are dermal (collagen fibres), then they become interesting but not of monumental importance. However, if they are epidermal, then they take on great significance.

Given the position of *Tianyulong* near the evolutionary base of ornithischian dinosaurs, the presence of epidermal, filamentous, feather-like structures could mean that the ancestral dinosaur was a fuzzy (though maybe not cuddly) animal. Of course, that would also mean that a fuzzy coat of protofeathers was lost many times in dinosaur evolution, because lots of dinosaur groups on both great branches of the dinosaur family tree are known to have scaly, reptilian skin (Fig. 1). But, before complicated scenarios for feather evolution are concocted, the fundamental question to be answered is whether the filaments of *Tianyulong* are on the outside or inside of the skin's surface.

That seemingly simple question is surprisingly hard to answer. The obvious test would be a biochemical or molecular assay to find out if the filaments are composed of the feather protein keratin or the collagen protein, but the mode of fossil preservation may not

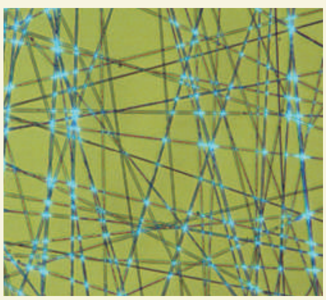
CHEMISTRY

Thinking outside the flask

The present credit crunch is forcing everyone to save money, and chemists are no exception. A good cost-cutting measure is to perform reactions on a small scale, thereby reducing the outlay on raw materials and minimizing the energy required to drive the reactions. Reporting in *Nature Chemistry*, Anzenbacher and Palacios describe the ultimate in miniature reaction vessels — junctions formed when two polymer nanofibres are fused together (P. Anzenbacher Jr & M. A. Palacios *Nature Chem.* doi:10.1038/nchem.125; 2009).

The authors prepared nanofibres — each hundreds of times narrower than a human hair — from readily available polymers, and loaded them with various chemical reactants. They then laid fibres containing different reactants across each other and exposed them to either heat or solvent vapour. This caused the fibres to fuse together, forming junctions that defined discrete chemical reactors with attolitre-scale volumes (1 attolitre is 10^{-18} litres). The junctions contained as few as 1,500 molecules of each reactant.

To illustrate the principle of their ultra-small reactors, Anzenbacher and Palacios doped fibres with two non-fluorescent compounds that form a fluorescent product when they react. When the two types of fibres were overlapped to form



a random mat and then heated, fluorescence at the fused junctions clearly indicated the formation of the reaction product (pictured).

The authors showed that several types of reactions can be performed in their attoreactors, including those in which one of the reactants is polymeric (although reactions with two polymeric reactants are expected to be problematic, because polymers can't easily diffuse through the nanofibre matrix). Furthermore, the products can be analysed directly within the junctions using fluorescence measurements or mass spectrometry.

Several applications for these attoreactors suggest themselves. For example, libraries of nanofibres could be prepared in which each nanofibre is loaded with a different compound from the same chemical class. Selected libraries could then be reacted with each other, as in combinatorial chemistry, to prepare many different products quickly and easily. If the products could be screened directly for biological activity, this would be useful for the high-throughput preparation and testing of compounds in drug-discovery programmes.

Stephen Davey

permit a meaningful test. That leaves observable structure, and here the best indicator would be whether the filaments are tubular or solid in cross-section. Feathers are hollow, tubular structures, and developmental models predict that 'protofeather' filaments should also be hollow[11]. By contrast, collagenous filaments should be essentially solid.

Zheng and colleagues[7] interpret the filaments of *Tianyulong* as being hollow, although it's fair to question their evidence (longitudinal stripes on the filaments). But other attributes of the filaments are also highly suggestive of their being epidermal. For example, the filaments associated with the base of the tail are extremely long, and, given that the tail is already reinforced internally with stiffening rods of ossified tendons, it is possible that these filaments indeed project outside the skin's surface. Even if they can be shown to be definitively epidermal, the ultimate question is whether they are part of the evolutionary lineage of true feathers or an independent evolution of projecting epidermal appendages. Certainly, the finding of very differently structured, projecting, hollow 'bristles' on the tail of another Yixian ornithischian, *Psittacosaurus* (a basal horned dinosaur)[12], raises the possibility that there may be a range of filamentous epidermal structures in dinosaurs, and that not all such structures may be related evolutionarily to feathers[13].

Perhaps the only clear conclusion that can be drawn from the foregoing is that little *Tianyulong* has made an already confusing picture of feather origins even fuzzier. Such an outcome is common in palaeontology. But the prospects of new fossils, new molecular and imaging techniques (such as synchrotron tomography), and even new ideas, offer the hope of bringing the evolutionary picture into sharper focus — and that picture may well end up being of fuzzy dinosaurs. ■

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GLOBAL CHANGE

West-side story of Antarctic ice

Philippe Huybrechts

During the past five million years, the West Antarctic ice sheet has waxed and waned in size. A two-pronged reconstruction of that history provides clues to the ice sheet's future behaviour.

For human societies, the prospect of sea-level rise is probably the most serious long-term threat from unabated climate warming. Both the Greenland ice sheet and the West Antarctic ice sheet are believed to be vulnerable to warming at the levels projected for the coming centuries. Sustaining those levels for many more centuries or millennia could ultimately cause the demise of both ice sheets — producing a worldwide rise in sea level of about 12 metres compared with today's levels, of which some 5 metres would derive from West Antarctica[1].

The past can be a guide to the future. But the late Quaternary (the past 0.5 million to 1 million years), for which we have the most data, was generally colder than today, and so is not an ideal analogue for the future. The twin papers by Naish *et al.*[2] and Pollard and DeConto[3], published in this issue, now present a step towards filling this gap in data and understanding. In their reconstruction of Antarctica's glacial history, the authors concentrate on the early to middle Pliocene, an interval of time between 5 million and 3 million years ago, when planetary temperatures were more in the range of those projected for the coming centuries.

The suspected vulnerability of the West Antarctic ice sheet stems from its particular setting. It is grounded mostly below sea level and is surrounded by large floating ice shelves (Fig. 1). These floating extensions are in direct contact with the ocean and are widely believed to have a crucial role in keeping the grounded ice sheet in place. At present, Antarctic temperatures are too low to generate significant surface melting during the summer, and this will remain so even with moderate warming. Some combination of sea-level changes and changes in sub-ice-shelf melting must therefore be a key process by which variations in global climate control changes in the West Antarctic ice sheet. A long-standing debate among glaciologists has been the mechanism by which changes to the ice shelf are transmitted inland to grounded ice sheets across their common boundary, the 'grounding line'[4] (Fig. 1), and how effective this mechanism might be.

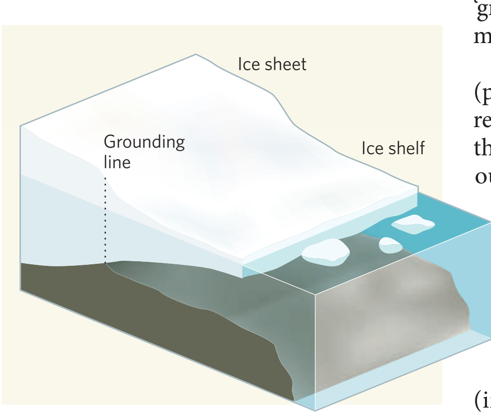

Figure 1 | The West Antarctic ice sheet. This much simplified depiction shows, to the left, the grounded marine ice, which sits upon bedrock or sediment on the sea floor. To the right, separated by the 'grounding line', is the floating ice shelf, which is thought to buttress the grounded ice sheet. The new observational study[2] and modelling work[3] identify a 40,000-year cycle in which the grounding line moves back and forth across the sea floor between glacial and interglacial states, punctuated by periodic ice-sheet collapses with more or less open-ocean conditions during super-interglacials.

Naish and colleagues' observational evidence (page 322)[2] comes from a new sediment core recovered from beneath the Ross Ice Shelf near the current ice-shelf margin. The site turned out to be a strategic location. The range of sediments and rock types and other features seen in the core allowed the authors to distinguish between a cyclical succession of conditions at the drill location: open ocean with little or no summer sea-ice (super-interglacial conditions warmer than those of today); coverage by a floating ice shelf (interglacial conditions much like today's); and overriding by an ice sheet grounded on the sea floor (glacial conditions). Moreover, unlike many other glacial records in which each glaciation has erased the evidence of the previous one, this record stands out in having large sections without such hiatuses because tectonic forces have produced a favourable rate of bedrock sinking.

Dating of undisturbed sections along the core enabled Naish *et al.* to identify 40 sedimentary cycles, each of about 40,000 years' duration, during the Pliocene (up to 1.8 million years ago). These results are in good accordance with the same cyclicity seen in marine-isotope records of global ice volume and mean deep-sea temperatures[5], and are in phase with summer half-year insolation caused by variations of the Earth's tilt at the same periodicity.