GEOPHYSICS

Earth's evolution explored

A study provides evidence for the unconventional idea that the advent and evolution of plate tectonics on Earth were related to the rise of continents and to sediment accumulation at continental edges and in trenches. See Article p.52

WHITNEY BEHR

Earth is the only planet in the Solar System that shows a form of planetary evolution known as plate tectonics. In this mode of planetary cooling, a convecting mantle conducts heat through a relatively rigid outer shell called the lithosphere. This shell is produced at spreading centres (boundaries between two separating plates), and is recycled back into the mantle at subduction zones (regions in which one plate is being forced underneath another). Why planetary cooling on Earth operates in this mode, and when the current period of plate tectonics began, remain subject to debate[1–3]. On page 52, Sobolev and Brown[4] propose answers to these questions that could have fundamental implications for understanding the connections between internal dynamics and surface processes — including climatic and atmospheric processes — on Earth and other planets.

Subduction is one of the main drivers of plate motion, and therefore of heat loss, on Earth. Fast-moving plates lead to enhanced cooling. By contrast, if plates slow down or are stalled, heat becomes trapped in the mantle and cooling is reduced. The rate at which subduction can proceed depends on a few factors[5,6]. These include the material strength of the descending plate, and the strength of the interface between the descending and overriding plates (Fig. 1).

The interface strength is a parameter that can be particularly sensitive to the composition of the material that is being subducted[7,8]. For example, magnesium- and iron-rich igneous rocks (those formed by the solidification of lava or magma) that characterize the oceanic crust are dry and strong, and therefore lead to low subduction velocities[8]. By contrast, blankets of sediment that are mostly derived from eroding continents and laid down on top of the oceanic crust are wet and weak, and result in accelerated subduction — a process known as sediment lubrication. This process might have influenced the dynamics of several modern subduction zones, including those associated with the Andes[7,9] and the Himalayas[8].

Sobolev and Brown explore the potential role of sediment lubrication in the dynamics of early Earth (about 4.5 billion to 2 billion years ago). They consider global glaciation events — periods in which Earth's surface was mostly covered in ice — that are well established in the geological record. They point out that these events led to enhanced weathering and erosion of emerging continents. Moreover, they hypothesize that the corresponding supply of sediments at continental margins helped to lubricate the interfaces between descending and overriding plates, and therefore facilitated Earth's modern episode of plate tectonics. To support this hypothesis, the authors searched for correlations between the vigour of subduction-dominated plate tectonics and the supply of continent-derived sediments to the oceans through time.

As proxies for subduction rates, Sobolev and Brown compared temporal variations in several existing data sets, including those describing the cumulative length of mountain belts — interpreted by the authors to reflect the frequency of continental collisions — and the occurrences of paired metamorphic belts. Such belts comprise parallel strips of metamorphic rock (that formed from pre-existing rock under extreme heat or pressure) that have a similar age but contrasting mineral assemblages. Paired metamorphic belts have long been considered to be hallmarks of asymmetric subduction[10]. As proxies for sediment delivery to the oceans, the authors focused on the relative influences of crustal material (representing sediments) and mantle material on the geochemistry of both sea water and volcanic rocks.

The strength of Sobolev and Brown's work is that it brings together globally compiled data sets to form a unified hypothesis. Each of these data sets is inherently complex and has disputed implications. But when combined, the data sets seem to coalesce into three broad peaks over geological time. One of these peaks coincides with the emergence of continents above sea level, and all three peaks seem to coincide largely with global glaciation events. The peaks also seem to precede the assembly of continental landmasses known as supercontinents, which was presumably driven by increased plate motion.

Although the concept put forward by Sobolev and Brown is intriguing, there is more work to be done to test it. A key avenue for further exploration is quantifying the feedback between sediment lubrication and mountain building. For example, the development

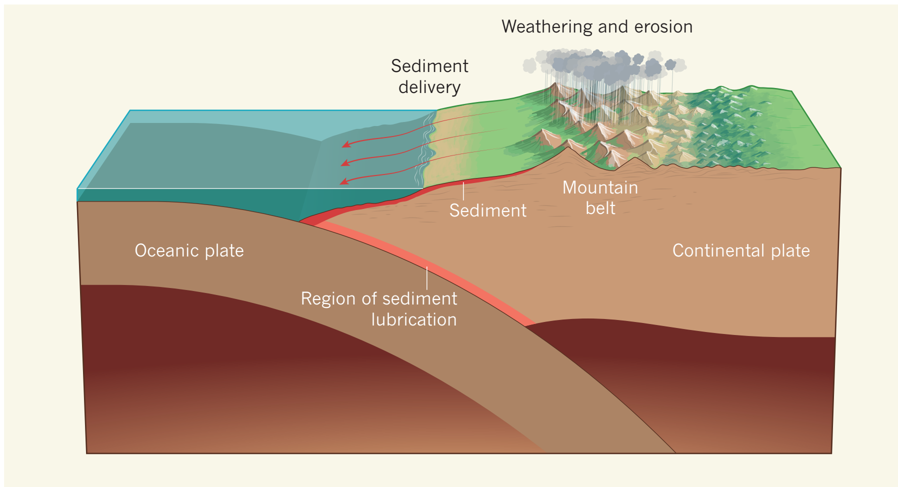

Figure 1 | Sediment lubrication and early Earth's dynamics. Following global glaciation events, in which Earth's surface was mostly covered in ice, continental mountain belts were subjected to enhanced weathering and erosion. Sobolev and Brown[4] hypothesize that the sediment that was produced by these processes was delivered to subduction zones — regions in which one plate is being forced underneath another; in the case shown, these comprise an oceanic plate and a continental plate. The authors suggest that the sediment lubricated the interface between these plates, and therefore helped to initiate the current period of plate tectonics.

of elevated topography in the overriding plate increases the frictional resistance of the plate interface, and therefore reduces plate velocities[11,12]. Yet simultaneously, the growth of mountain ranges induces surface erosion and increases sediment supply. Moreover, volcanic activity and the burial of carbon at subduction zones affect the global climate, and therefore erosion. Which of these processes dominates over specific timescales and how the processes are coupled are poorly understood.

It would also be valuable to assess sediment fluxes and budgets (the differences between inputs and outputs), and the geochemical tracers of these sediments from continental mountain belts to subduction trenches. Such an assessment would need to take into account how Earth's lithosphere and climate at these early times differed from those of today. From the viewpoint of geology, better constraints from natural rocks and experiments on material strength for both the shallow (frictional) and deep (viscous) plate interface are needed to quantify the importance of changes in the physical characteristics of subducted rocks on interface properties. ■

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MATERIALS SCIENCE

The thinnest sheets of metal oxides

2D crystalline membranes are easily made from some materials, but not from those with strong 3D lattices, such as technologically useful perovskite oxides. Free-standing perovskite monolayers have finally been made. SEE LETTER P.87

YORICK A. BIRKHÖLZER & GERTJAN KOSTER

Science often benefits from the discovery of extremes. Once we have proved the existence of an extreme, it can help us to build models that explain scientific phenomena. In the field of materials science, an outstanding experimental goal has been to prepare sheets of technologically useful transition-metal oxides, such as perovskites, at their fundamental minimum thickness. On page 87, Ji *et al.*[1] report the preparation of the first such sheets for the perovskite oxides strontium titanate ($SrTiO_3$) and bismuth ferrite ($BiFeO_3$), and provide a glimpse of their properties.

Many technologically beneficial materials are crystalline, including transition-metal oxides. The atomic or molecular order in a crystal is defined by the unit cell, which is the smallest repeating unit of the crystal structure. In the case of strontium titanate, for example, the unit cell is a cube that has edges about 0.4 nanometres long[2]. This represents the smallest possible length or thickness of the objects (2D sheets, 1D rods or 0D 'dots') that can be made from this material — and is therefore of interest to nanotechnologists, who try to reduce the size of materials in search of previously unseen properties and functions.

Sometimes, nature offers a helping hand to nanotechnologists by producing crystalline materials that are intrinsically layered and which have weak bonding between the layers. 2D sheets can be isolated (exfoliated) more-or-less spontaneously from such materials — as is the case for the most famous 2D material, graphene, which is exfoliated from graphite. Since the Nobel-prizewinning isolation and characterization of graphene in 2004 (ref. 3), hundreds of other 2D materials have been discovered that fascinate scientists and engineers alike. The list encompasses single-element materials as well as compounds, and spans the full range of electrical properties, from metallic conductors to semiconductors and insulators. The vast majority of these 2D materials are derived from parent materials that have weakly bonded layers, including the transition-metal dichalcogenides[4] (a well-characterized class of semiconductor) and certain oxides[5].

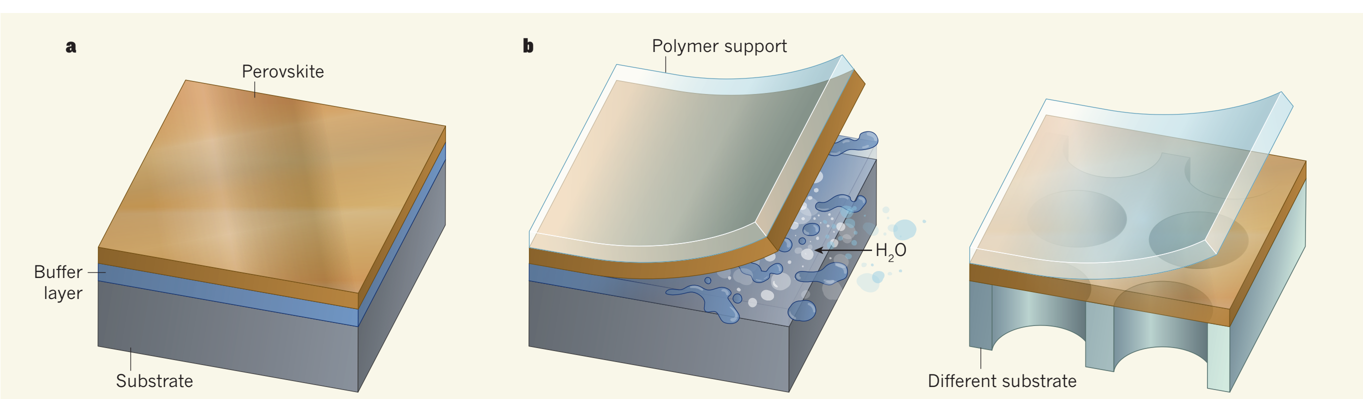

Figure 1 | The synthesis of monolayer perovskite films. a, Ji *et al.*[1] have prepared the thinnest possible free-standing sheets of two perovskite oxide semiconductors, using an established technique called molecular beam epitaxy (MBE) in combination with a previously reported method[9] for separating thin films of materials from substrates. The authors used MBE to 'spray paint' an ultrathin layer of a perovskite oxide semiconductor onto a buffer layer of a water-soluble material on the surface of a crystalline substrate. **b**, Ji and colleagues could release the ultrathin perovskite film by dissolving the buffer layer in water, and, equally remarkably, could use a polymer support to transfer it to other substrates (including some that contain holes, shown). They also imaged its cross-section at atomic resolution (not shown). The findings demonstrate that free-standing monolayers of perovskites can be made, contrary to what had been thought.