PLATE TECTONICS

Metamorphic myth

Clear evidence for subduction-induced metamorphism, and thus the operation of plate tectonics on the ancient Earth has been lacking. Theoretical calculations indicate that we may have been looking for something that cannot exist.

Jun Korenaga

Earth's surface is divided into a dozen or so rigid tectonic plates. Movement and subduction of these plates into the mantle governs nearly all geological processes, such as earthquakes, mountain building and even atmospheric composition. However, it is unclear when plate tectonics began. Today, subduction forms blueschist-facies metamorphic rocks — often regarded as the hallmark of plate tectonics. These rocks are found only up to about 800 million years ago[1], and their absence prior to this time has been taken as evidence against plate tectonics on an earlier Earth[2,3]. Writing in *Nature Geoscience*, Palin and White[4] use thermodynamic calculations to show that ancient plate tectonics could not form blueschist-facies rocks to begin with.

There is abundant evidence for plate tectonics during the Phanerozoic, up to 540 million years ago, but prior to this time, the evidence is less clear[5]. The very nature of plate tectonics means that it is difficult to find evidence for its onset. Plates are lost into the mantle at subduction zones, with the loss balanced by plate growth at mid-ocean ridges. Thus, plate tectonics continually rejuvenates Earth's surface on a time scale of about a hundred million years, erasing evidence for its past operation. We must therefore rely on the subtle by-products of plate tectonics that may be preserved on the buoyant continents.

Such by-products include fragments of ancient oceanic crust that have been uplifted and exposed on the continents today, as well as mountain belts, or orogens, formed when two continents collided, presumably after subduction had consumed the seafloor that once existed between them. Many of these by-products of plate tectonics can be traced back to around 3 billion years ago[6]. There is also a suggestion for an even earlier onset of plate tectonics, around 4 billion years ago, based on the mineral chemistry of ancient zircons[7].

One nagging observation that seems to defy an early onset of plate tectonics is the absence of ancient blueschist-facies metamorphic rocks. These rocks owe their name to the predominance of the blue-coloured mineral glaucophane in their makeup. Blueschists form when basaltic rocks, which comprise the oceanic crust, are subject to high pressures and low temperatures at depths of about 15 km in subduction zones[8] (Fig. 1). These metamorphic rocks can be exhumed back to Earth's surface when tectonic plates collide to form orogens. The absence of blueschists in orogens older than 800 million years does not necessarily require the absence of plate tectonics, but begs the question of why something that resurfaced so easily in the recent geologic past failed to resurface in earlier times.

Palin and White[4] have hit this blueschist conundrum from a blind side. Earth's mantle has been cooling over time at a rate of about 100 °C per billion years[9]. A hotter mantle in the past would have produced a thicker oceanic crust more enriched in magnesium compared with the present-day oceanic crust. Using thermodynamic calculations, Palin and White show that the metamorphism of crust with high magnesium content is much less likely to yield glaucophane-bearing mineral assemblages. It is no wonder that we could not find blueschist in those ancient orogens formed when the Earth was much hotter than at present — we may have been looking for rocks that simply could not have been generated.

To preserve blueschist at the surface, the rocks must be rapidly exhumed to Earth's surface without undergoing any further metamorphism[8]. Given this rather intricate scenario required for the surface exposure of once subducted materials, the absence of blueschists does not completely rule out the possibility that blueschist rocks did form on the younger Earth, but were simply not exhumed. However, Palin and White's calculations suggest that the metamorphic products of ancient oceanic crust, though they are not blueschist, can still be identified by their mineral chemistry, so future field studies will provide the ultimate test for their hypothesis.

Palin and White also note that the metamorphism of magnesium-rich crust could have brought more water into the mantle than that of present-day crust, and this prediction is also against the conventional wisdom. The subduction of surface water reduces the volume of oceans and reduces the viscosity of the

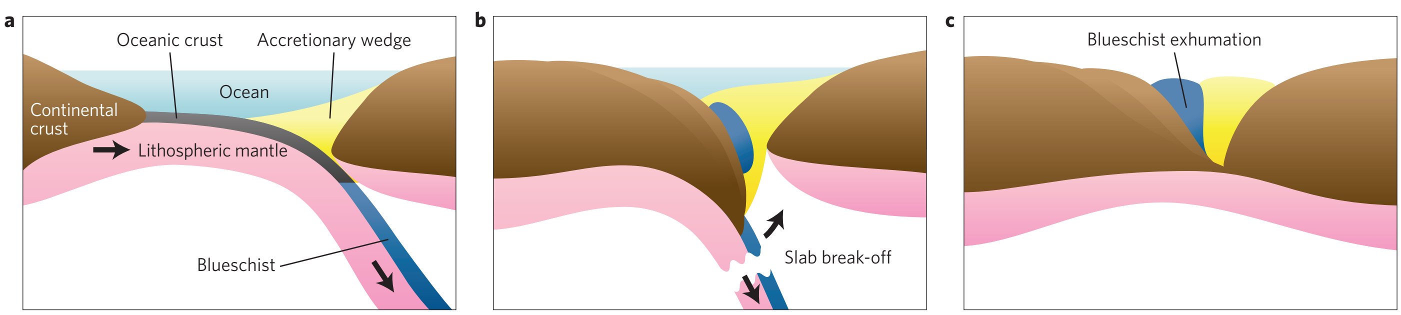

Figure 1 | Schematic illustration of blueschist formation and exhumation. **a**, Blueschist-facies metamorphism occurs when modern oceanic crust is subducted to depths of about 15 km. **b**,**c**, Some blueschists can detach themselves and migrate upward during slab rollback, and when the subducting slab breaks off (**b**), they can be transported further towards Earth's surface and exposed via erosion during continental collision (**c**). Palin and White[4] use thermodynamic calculations to show that blueschist metamorphism would not have occurred in the magnesium-rich oceanic crust that would have characterized the younger, warmer Earth.

convecting mantle. The new thermodynamic calculations therefore have far-reaching implications for the coevolution of the surface environment and the dynamics of Earth's interior[5].

Palin and White's study[4] highlights the importance of understanding the secular evolution of the Earth, as well as the advantage of employing first-principles approaches. The internal state of the planet has been gradually changing, as necessitated by the radioactive decay of heat-producing elements, so we need to have a clear picture of the global setting in which a particular phenomenon of interest takes place. This secular evolution involves not only internal temperature, but also a number of other variables such as chemical composition and material strength. When extrapolating our understanding of contemporary processes to deep time, approaches based on basic physics and chemistry may take precedence over empirical ones. ❐

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PLANETARY SCIENCE

Mars on dry ice

Martian gullies have been seen as evidence for past surface water runoff. However, numerical modelling now suggests that accumulation and sublimation of carbon dioxide ice, rather than overland flow of liquid water, may be driving modern gully formation.

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The search for water has been one of the key threads linking decades of Mars science and exploration. Water is a dynamic geologic agent, and its presence affects subjects ranging from geomorphology to geochemistry to biology. At present, Mars is a cold and dry world, with most of its water locked away as ice in polar caps or below the surface at lower latitudes. However, the discovery of gully landforms less than a million years in age in images from the Mars Global Surveyor orbiter[1] was initially regarded as strong evidence for overland flow of liquid water on Mars in the geologically recent past. Writing in *Nature Geoscience*, Pilorget and Forget[2] challenge a wet origin for the Martian gullies and demonstrate with numerical simulations that the gullies may instead be formed in the present climate due to the sublimation of seasonal CO_2 frost (dry ice).

At first glance, the strong similarity between the morphology of the Martian gullies (Fig. 1) and terrestrial features formed by streams or wet debris flows points to a wet origin. Much of the debate over gully formation has been focused on the source of the putative water. Initially, leading models favoured groundwater discharge[1], but this is inconsistent with the occurrence of gullies on sand dunes and isolated peaks[3]. Other models have proposed melting snow or ground ice during a period when the obliquity of Mars (the tilt of its axis) was higher than today, as expected within the past few million years[3,4]. Whatever the water source, wet models imply the repeated occurrence of thousands of cubic metres of liquid water at each gully[1], which would have profound implications for both climate and possible biology on Mars.

Monitoring of the Martian surface by orbiters over the past two decades has shifted the debate by revealing present-day changes in the morphology of gullies[5]. Successive images show significant changes to gullies, including channel erosion and the deposition of lobate flows[6]. The ongoing activity of Martian gullies is perplexing because the present-day climate on Mars is too cold at these times and locations to support substantial liquid surface water.

However, there is another volatile species that may be the culprit in gully formation. CO_2 frost covers the Martian poles and mid-latitudes every winter. Near the poles, this seasonal cap is around a metre thick, and thins towards the mid-latitudes. The distribution of frost correlates with the regions where gullies are most prominent. Moreover, gully activity appears to be seasonal, with a marked preference for the winter and spring[6,7] — when CO_2 frost is observed on mid-latitude slopes[8]. Thus, CO_2 frost might be responsible for gully formation. This was considered shortly after gullies were discovered[9], but how this process works remains unclear.

CO_2 is the main component of the Martian atmosphere, and condenses wherever the surface temperature drops to its frost point. If the frost anneals to become an impermeable slab of ice, such a layer would be translucent; sunlight can penetrate to the base and induce sublimation[10]. This causes pressure to rise beneath the ice slab, and eventually causes the slab to lift and break apart, rapidly expelling both gas and entrained regolith material[10]. Transient dark spots that are widespread at high latitudes every Martian spring[10] — including in some gully channels[9] and in gully-like features on sand dunes[11] — have been attributed to this process.

Pilorget and Forget[2] propose that gully activity can be attributed to sublimation beneath CO_2 ice and that this process is common, even in lower-latitude gullies. They conduct a detailed numerical study of the condensation of frost on slopes at a range of latitudes and orientations where gullies are common. In addition, they model temperatures to determine where and when CO_2 will condense on the Martian surface and analyse conditions for the build-up of gas pressure and eventual venting. They find that the predicted latitudes and slopes match the general distribution of gullies, which have a marked tendency to face the poles at lower latitudes. Pilorget and Forget find that the debris flows should readily occur at the latitudes and slopes where gully