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Earth science

The slippery slope

George Zandt

Seismic readings suggest that a zone of weak, slippery rocks lies beneath the Pacific northwest coast of the United States. These frail layers might be limiting the violence of earthquakes.

Most of our planet's largest earthquakes and active volcanoes are associated with subduction zones, where one tectonic plate dives under another. As the downgoing plate experiences higher pressures and temperatures, water trapped in its crust and upper mantle is gradually forced out and into the mantle of the overlying plate. At depths of about 100 km, the addition of water lowers the melting temperature of the mantle rocks and initiates partial melting to magma, which rises and erupts in the so-called arc volcanoes that form the 'Ring of Fire' along the Pacific Rim.

Reporting on page 536 of this issue, Bostock and colleagues¹ reveal seismic images of the Cascadia subduction zone, which runs along the Pacific northwest coast of the United States. Using these images, they investigate what happens when water moves into the shallow mantle in front of the volcanic arc (Fig. 1). They show that the forearc mantle, located 40–80 km deep between the coast and the volcanic arc, is largely 'serpentinized'. This means that it has undergone a process that changes the mineralogy of the mantle rocks and their physical properties — a transformation that could have important bearing on the occurrence of earthquakes around subduction zones.

Serpentinization, which can occur when water moves into cool mantle rocks, chemically changes the strong, dry rocks into weak, hydrous rocks — or serpentinite — composed of serpentine minerals, talc and brucite². Chrysotile, the chief source of asbestos, is a serpentine mineral with a fibrous structure. Antigorite, in contrast, is a serpentine mineral that has a plate-like structure and is stable at the temperatures found in the forearc mantle. It is the fibrous or plate-like structures of these minerals that give serpentinites a slippery feel. And although the fibrous nature of asbestos makes it a dangerous health hazard in the environment, slippery serpentinite in subduction zones might be important in limiting the depth at which earthquakes are generated.

Bostock *et al.*¹ located the serpentinite deep under the Cascadia subduction zone when they found an 'inverted Moho' beneath the forearc region. A 'Moho' is the boundary at which the speed of seismic waves rises to a value typical for waves travelling through mantle rocks (around 8 km s^{-1}), and is named after the Croatian Andrija Mohorovičić, who discovered the phenomenon in 1910. Usually, a Moho is associated with a change in chemical composition from crustal to mantle rocks that occurs, on average, at depths of around 40 km under the continents. But Bostock *et al.*, remarkably, have seen an inverted Moho. Under the high Cascade mountains, at a depth of 36 km, the Moho is a normal inter-

face with seismic wave speed increasing with depth. As the authors traced the Moho laterally towards the Pacific Ocean, they saw the interface flip over so that seismic wave speed decreases with depth (Fig. 1).

Bostock *et al.* suggest that this unusual Moho inversion is caused by a major reduction in the wave speed through the mantle — to lower the speed to this extent would require a level of serpentinization of about 50–60%. Much of the water needed for this serpentinization might come from another chemical reaction associated with subduction. As the oceanic crust of the downgoing plate comes under increasing pressure, it transforms into eclogite, a dry high-density rock with seismic wave speeds similar to those in mantle rocks. The seismic images taken by Bostock *et al.* show that the oceanic Moho diminishes, as the crust transforms into eclogite, at a depth of about 45 km, which is consistent with the idea that dehydration of the oceanic crust hydrates the overlying forearc mantle.

Serpentinite is stable to temperatures of 600–700 °C, but at higher temperatures it breaks down into other minerals and water. Bostock *et al.*¹ have devised a thermal model for the Cascadia subduction zone and show that the forearc mantle is sufficiently cold for serpentinite to be stable. But higher mantle temperatures are predicted to exist beneath the volcanic arc, consistent with the reversal of the inverted Moho seen in the seismic image and with the onset of volcanism. If the

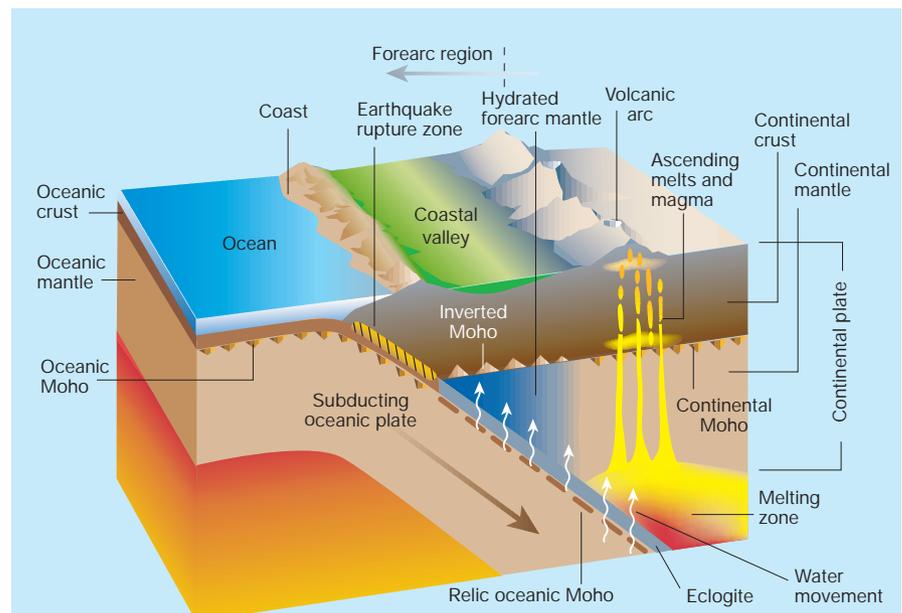


Figure 1 Cross-section through the Cascadia subduction zone on the northwest coast of the United States. Water released from the subducting oceanic crust rises up and hydrates the forearc mantle; water released deeper down causes partial melting of rock to magma that erupts in the arc volcanoes. In the water-altered — or 'serpentinized' — forearc rocks, seismic waves travel more slowly and the usual gradient of wave speed is reversed, producing an effect known as an 'inverted Moho', which has been detected by Bostock *et al.*¹. The slippery nature of the serpentinized forearc mantle limits the seismogenic depth of coupling between the two plates, and so might also limit the impact of earthquakes in the region.

oceanic crust is dry (having given up its water to serpentinization) by the time it reaches the depths at which the mantle melts, then from where does the water to initiate mantle melting come? It could be coming from the mantle of the downgoing slab, or perhaps the lower portion of the serpentinized mantle is being dragged down and is releasing its waters at greater depths³. However, the low density and slippery nature of the serpentine may work against this latter mechanism.

Serpentinized forearc mantle has been found in at least two other subduction zones: Japan and the Central Andes of South America. In the Central Andes, seismic studies have identified a 'blurred' Moho, indicative of hydration⁴, as well as uncovering evidence that dehydration reactions affect earthquakes in the subducting plate^{5,6}. If a fully serpentinized forearc mantle contains about 6% by weight of water⁷, then the total volume of water held there is about 540 km³ per linear km of subduction zone; and if all 37,000 km of the subduction zones on Earth are 50% hydrated, then the total volume of water is 10⁷ km³ — or about one-third of the present volume of water in the Antarctic ice cap. So, if shown to be present globally, the serpentinized forearc mantle could prove to be a substantial water reservoir in the global hydrologic cycle.

One of the most important implications of serpentinization of the forearc mantle is

the possible effect on the termination of large earthquake ruptures². Seismologists have found that these ruptures often terminate near the depth of the continental Moho⁸. The slippery nature of serpentinite may provide a ready explanation for this observation. If these earthquake ruptures occurred deeper in the subduction zone, below the serpentinized layer, they would produce strong shaking over a greater area, threatening a larger proportion of the coastal population centres. Thus, the hydrated forearc mantle may be pivotal in protecting the coastal cities of the US Pacific northwest, as well as other major cities around the Pacific Rim, from greater earthquake danger. ■

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Evolutionary biology

Crowning glories

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The evolutionary trend towards high-crowned teeth in European herbivores during the Miocene was, it seems, driven by the geographically common groups, and not rare ones. That conclusion has broader implications.

The evolution of high-crowned teeth is one of the classic stories of evolutionary biology, but the object lesson of the story might be different from that found in the textbooks. In studying past environments, the rare and more specialized animals often get the most attention. In their paper on page 538 of this issue, however, Jernvall and Fortelius¹ show that a few, common, regionally widespread species can drive major trends, yielding more information than is usually recognized.

Twenty-four million years ago, at the beginning of the Miocene epoch, most herbivorous mammals had low-crowned (brachydont) cheek teeth and a few rare species had high-crowned (hypsodont) teeth. Hypsodont teeth are an adaptation to increased abrasive wear. Although high-crowned teeth are no more mechanically resistant to abrasion than low-crowned ones, the additional height of the tooth

crown means that there is more tooth to wear away over the animal's lifetime. However, these teeth are costly in terms of both the materials needed to produce them and the shape changes that must evolve in the jaws to accommodate them.

Hypsodont teeth have evolved in many herbivorous lineages in response to increased abrasion, whether by the silica secreted by grasses² or by grit in the environment stuck to plant foods^{3,4}. By the end of the Miocene, 5 million years ago, the situation had reversed compared with the beginning of the epoch, with hypsodont forms present at most localities. This change is attributed to increased aridity and the spread of grasslands during this time, which would increase abrasive wear by the spread of more open habitats with higher grit levels, and also by the spread of silica-bearing grasses.

Jernvall and Fortelius¹ examined changes in tooth crown height during the

Miocene in a novel way. They tabulated hypsodonty for 209 European fossil localities by assigning each species a value corresponding to low-, medium- or high-crowned teeth, and then examined the numerical trend in those values for common animals (found in 25% or more of the localities) and rare animals (found in less than 25% of localities). Importantly, they did not compare relative abundances within localities, so that their definition of common does not imply that these animals were the most abundant ones in any given locality, but that they occurred at many localities across the region in each time interval. Rarity was assessed for each interval, so groups that were rare during one time were not necessarily rare at another.

Jernvall and Fortelius examined changes in hypsodonty for species and genera over time, and found similar patterns at both taxonomic levels. In rare genera, tooth crown height stayed relatively constant. In the more geographically widespread ones, however, average hypsodonty began to increase significantly about 11 million years ago. To ensure that this pattern was not driven by particular lineages, the authors selectively removed potentially problematic groups (horses, primates and proboscideans) from the analysis: horses because in the textbook version of events they are the group that were thought to drive the trend of increasing hypsodonty; primates because they have low-crowned teeth and are relatively rare; and proboscideans because they are large and their fossils are usually more likely to be collected than those of small taxa. The pattern was still present in the remaining data.

Brachydont species are often smaller than hypsodont ones, so Jernvall and Fortelius examined the degree of hypsodonty in different crown morphology types. Crown types are characterized by functional properties of the teeth, such as the number, orientation and shape of the cusps⁵, and should be insensitive to size differences among species. The trend of increasing hypsodonty is also found only among geographically common crown types, supporting the view that this trend is not a taxonomic artefact. The proportion of localities that include hypsodont genera and crown types increased significantly after 11 million years ago, whereas the proportion of localities with low-crowned genera and crown types did not. These results imply that drying climatic conditions in Europe, usually associated with the uplift of the Tibetan plateau⁶, allowed ungulates — hooved mammals — with higher tooth crowns to expand their range as more open arid grasslands spread in Europe. Work is needed to see whether the trend in the North American fossil record, which has better temporal resolution, is also driven by common taxa. Examination of the relative abundances of taxa within localities