required to discriminate between two cladogenetic events occurring in any given time interval.

The result is a plot of number of the variable sites against time. The plot is a hyperbola — well-spaced cladogenetic events are easily resolved with relatively little data, but the number of variable sites required rises steeply as intervals shorten. With 200 variable sites of 18S rRNA, resolution is no better than 140 million years. With 708 variable sites from complete 18S rRNA sequences, as in this study, the limit of the resolution of 18S rRNA sequence data is 40 million years. Adding the complete sequence of 28S rRNA — to give a total of around 1,500 nucleotides — would permit a resolution of 19 million years. To get down to one million years (very nearly the scale of current palaeontological and stratigraphic sampling) one would require 28,000 variable nucleotides, beyond the limits of present practicality.

The 40-million-year limit on the resolving power of 18S rRNA means that adjacent nodes supported by BPs of less than 95% probably reflect cladogenetic events that occurred within this period. Translated into real animals, this suggests that deuterostomes and protostomes diverged from a primitive triploblastic coelomate ancestor, and underwent considerable subsequent divergence, within a period of 40 million years or less. In other words, the Cambrian explosion. □

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MAGMATISM

Underplating over hotspots

W. Steven Holbrook

MOST of the magmatism that creates the Earth's crust occurs in well-defined tectonic zones: mid-ocean ridges, continental and island arcs, and continental rift zones. In contrast, hotspots — sites where plumes of hot material rise from deep within the Earth's mantle — can occur nearly anywhere, affecting both continental crust (as beneath Yellowstone) and oceanic crust (as beneath Hawaii). But it is difficult to quantify exactly how much magma hotspots deliver, and what that magma is composed of, because of the likelihood that a substantial portion of the material is not erupted but intruded as a deep-crustal 'underplate', where its presence can be inferred only by indirect geophysical methods. On page 600 of this issue[1], Caress *et al.* settle a controversy over the occurrence of crustal underplating, and in so doing raise several fundamental questions about the magmatic processes that link the Earth's crust and mantle. Their paper describes seismic refraction experiments carried out in the Marquesas Islands in the Pacific.

The controversy settled by Caress and his co-authors is whether underplating ever occurs above oceanic hotspots. The only previous modern seismic study in such an environment, conducted more than a decade ago across the Hawaiian island of Oahu, yielded ambiguous results. Although ten Brink and his coworkers interpreted the data as evidence of an underplated layer similar to that beneath the Marquesas[2,3], an alternative view of the same data concluded that no such layer was required[4]. The results of Caress *et al.* confirm the existence of crustal underplating above oceanic hotspots. Moreover, the rapid increase in seismic velocity with depth requires that the composition of the crust changes vertically. Thus neither the volume nor the composition of hotspot magmatism could have been accurately predicted from the surface lavas alone.

Because underplating is defined as magmatic material added to the base of the Earth's crust, one of the main difficulties in quantifying it — indeed in identifying it — has been to distinguish underplating from the pre-existing crust. This problem is particularly acute beneath continents, the crust of which is thick (25–45 km) and laterally heterogeneous. The Marquesas Islands, because they are built on thinner (6–8 km), simpler oceanic crust, offer a natural laboratory in which the structure of the pre-existing crust, and therefore of the underplate, can be confidently determined. Moreover, because the Marquesas hotspot lies within a large tectonic plate, magmatism there is not increased by a mid-ocean-ridge spreading centre, as it is at Iceland for instance.

The surprisingly large volume of magmatism beneath the Marquesas Islands — 950,000 km^3, nearly two-thirds of which resides in the underplated zone — implies that the Marquesas hotspot is about as strong as the Hawaiian hotspot. The thickness of magmatic material emplaced above an intraplate hotspot depends on the strength (flux) of the plume and the speed at which the overlying plate moves past. Because the Hawaiian and Marquesas Islands both lie on the Pacific Plate, the equivalence of magmatic thickness beneath them (about 17 km) implies that the plume fluxes are roughly equal. Previous measures of plume flux, however, based on estimating the amount of buoyant plume material needed to uphold the seafloor swell around volcanic chains, had designated the Hawaiian hotspot as the strongest on Earth, with a flux 1.3–2.5 times that of the Marquesas[5,6].

One way around this conclusion is if the high-velocity material contains a substantial proportion of pre-existing mantle. Velocities of 7.9 km s^{-1} correspond to ultramafic compositions[7] and are usually interpreted as upper mantle[8]. Caress *et al.* assign this zone to the crust because of the strong reflector at its base, which they interpret as the crust–mantle boundary (Moho). If, however, the high-velocity material largely consists of pre-existing mantle material, then the 17-km crustal thickness is an overestimate, and the estimate of Marquesas plume flux decreases accordingly. Such an interpretation, though, provides no ready explanation for the strong Moho reflector.

If the interpretation of Caress and colleagues is correct, it raises the question of why the underplate has such high velocities and, hence, a different composition from the upper crust. Are the upper crust and underplate derived from primary magmas of different compositions, which rise to different levels of neutral buoyancy? Or are the upper and lower crust formed by crustal fractionation of a single primary magma? Other unanswered questions brought to light by the Marquesas study are whether underplating occurs contemporaneously with the extrusive volcanism[1], or during a later episode related to flexural stresses induced by the overlying volcanic load[2]. How is the underplate emplaced — is it as vertical dykes or horizontal sills? And how is the delivery and emplacement of melt affected by a nearby spreading centre?

These questions will surely be the subject of future geological and geophysical investigations. Meanwhile, the seismic results from the Marquesas islands have confirmed the intuition of many geoscientists that the lava erupted from a hotspot volcano is only the tip of the iceberg. □

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