GEOPHYSICS

Another Nail in the Plume Coffin?

At least one chain of hot-spot volcanoes is not caused by a plume rising up from the core-mantle boundary, calling for a reexamination of the plume hypothesis.

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Scientists love beautiful theories—the kind that are elegant, predictive, and have few free parameters. And they hate it when theories like that prove to be wrong. It is thus with much kicking, dragging, and screaming that geoscientists are being brought to the realization that all might not be well with the concept of mantle plumes.

According to the plume hypothesis, linear chains of volcanoes that form at "hot spots" away from the boundary zones of tectonic plates are caused by hot, buoyant jets that detach from the thermal boundary separating Earth's core from its mantle. The latest attack on this hypothesis comes from Hirano *et al.* on page 1426 of this issue (*1*). The authors describe a small chain of hot-spot volcanoes off the Japanese coast that almost assuredly cannot have been formed by narrow, deep-Earth upwellings.

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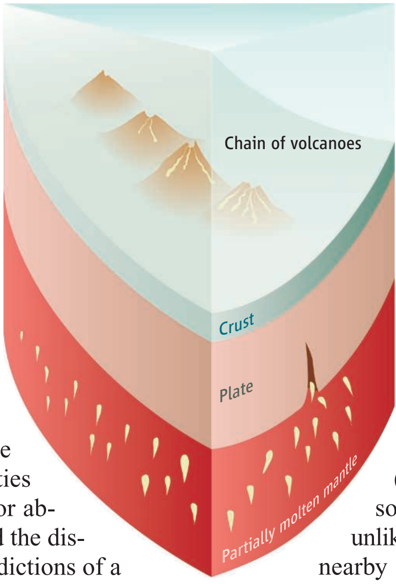
The plume hypothesis was originally proposed by Jason Morgan (*2*), hot on the heels of the plate tectonic revolution. According to the latter theory, most geologic activity—such as volcanic eruptions, earthquakes, and mountain building—is concentrated at the margins of the dozen or so major plates that move together, move apart, or slip past each other on the surface of our planet. Morgan and others noted that island chains such as the Hawaiian Islands and the Canary Islands consist of young volcanoes in the middle of the tectonic plates and therefore cannot be explained by plate tectonics. Moreover, many of these island chains, particularly those on the Pacific plate, show a monotonic increase in age in one direction. Morgan hypothesized that these midplate volcanoes, termed hot spots, are the surface manifestation of mantle plumes that rapidly (to a geologist's way of thinking) rise up from the core-mantle boundary.

Morgan's hypothesis has several attractive features. First, it suggests that the study of hot spots will provide clues to the chemistry and dynamics of Earth's interior, which would otherwise be masked from scrutiny by the rigidity and surface-dominated processes of plate tectonics. Second, the orientation and rate of age progression of hot-spot volcanoes reveal the direction and speed of absolute motion of the tectonic plates, whereas only relative motion could be inferred from the properties of the plates themselves. Scientists therefore immediately started to explore the implications of the plume model for properties of Earth's interior and for absolute plate motions, and the distinction between the predictions of a hypothesis and observed facts quickly became blurred.

But troubling inconsistencies began to emerge. The absolute motions of plates inferred from hot spots on different plates did not agree, prompting the proposal that the plumes "blow in the mantle wind" (*3*). Rocks from hot-spot volcanoes with different ratios of noble-gas isotopes were thought to tap separate reservoirs in the mantle that were isolated from intermixing. Unfortunately, as the number of isotopic tracers grew, additional reservoirs were required (*4*), taxing the ability of geodynamic models to keep them isolated over geologic time scales. Furthermore, because of their small dimensions, plumes proved difficult to detect in tomographic images of the mantle. Advanced techniques do suggest the upwelling of hot material from the lower to the upper mantle beneath some hot spots (*5*), but not beneath others. Are these problems simply the maturing of a valid theory to deal with the complexity of the real planet, or are they the signs of a paradigm in crisis?

Although insignificant in size on a planetary scale, the small seamounts described by Hirano *et al*. are important because they are young hot-spot volcanoes (1 to 8 million years old) that erupt through a very old plate (135 million years old), away from any plate boundaries. Petrologic data confirm that the volcanoes tap a region of the mantle more than 100 km deep that contains very small percentages of melted material. The position of the volcanoes in the flexural trough seaward of the outer rise of the Japan trench suggests that elastic bending of the plate has opened up conduits through which the partial melt can rise to the surface (see the figure). A plume source for these volcanoes is unlikely in any case, because the nearby subduction of the Pacific plate creates widespread downwelling that would block the rise of a mantle plume.



A new kind of volcanism? In this three-dimensional cartoon, a crack in a flexed plate provides a conduit through which buoyant pockets of partial melt in the upper mantle can reach Earth's surface.

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The notion that the upper mantle beneath the plates might contain small amounts of partial melt just about everywhere, and that all it takes is a crack in the plate for that melt to rise to the surface, has been previously proposed as an alternative to the plume hypothesis (*6*). However, prior examples of hot spots used to illustrate this concept were not as compelling, because there was no obvious mechanism for cracking the plate and they were located away from sites of obvious large-scale downwelling.

Does the plate-cracking mechanism proposed by Hirano *et al.* only explain this one small chain of volcanoes, or can it also explain other chains of hot spots? Hirano *et al.* argue that they have found a new and different kind of hot-spot volcano. They base their argument on the observed ratios of isotopes of inert gases. According to plume theory, plumes tap a deep reservoir rich in rare gases, whereas the mid-ocean ridges obtain melt from a reservoir in the upper mantle that is depleted in rare gases. The volcanoes described by Hirano *et al*. have more depleted isotopic ratios, such as those found in mid-ocean ridge basalts; according to plume aficionados, this property would put them in a category different from hot spots such as those in Iceland and Hawaii. However, other interpretations of the rare gas isotopes would not necessarily require distinct mantle sources (*7*).

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