will come. For 2-cm marks, or larger, as in Close's recent 1987–97 portraits (see cover, this issue) that distance is at least 2 m, which most viewers cross as they approach. Some forms of camouflage, like a tiger's stripes, may break up the animal's shape only when seen from very near. Most perception textbooks show a spotted Dalmatian, initially lost in a background of spotty shadows, but which usually appears quickly and never goes away (like Harmon's description of seeing Lincoln with small blocks) (*10*). I find that the Dalmatian, like a block portrait, does break up reliably into mere flat spots when enlarged (or approached) to make the spot spacing exceed 0.3°.

Testing a wide range of sizes revealed that the division between seeing a block portrait as flat or solid occurs at a critical mark size of 0.3° (which is independent of the number of marks per face). This refutes the size invariance of shape perception and Harmon and Julesz's critical-band theory of the block-portrait effect. It seems that the blocks (or their edges) (*11*) compete with the face to capture the visual shape-from-shading process. The size and type of the marks determine their power of attraction. This competition is bottom-up, determined by the stimulus, not top-down, controlled by the observer. Close concedes that, painting at arm's length, even he cannot see the face unless he backs away (*2*).

One might suppose that Close was a naïve artist, obsessed by grids, who innocently produced the coarsely gridded paintings that we use here to reveal the size dependence of shape perception. In fact, Close has devoted his career to studying just that: *"The self portrait from 1967–68 is the first portrait head that I painted. . . . The idea was to make something that was so large that it could not be readily seen as a whole and force the viewer to scan the image in a Brobdingnagian way, as if they were Gulliver's Lilliputians crawling over the surface of the face, falling into a nostril and tripping over a mustache hair"* (*2*). He was more thorough than his scientific colleagues; the size of the marks in his block portraits increased by 15% per year from 1973 (0.4 cm) to 1997 (9 cm). He made sure that exhibitions of his work would convey the idea, canceling a retrospective that could not provide long viewing distances. So credit Chuck Close with discovering this size-dependent breakdown of our ability to extract shape from shading, well within the bounds of our visual field and acuity.

References and Notes

1. In 1886, Ernst Mach wrote, "Some forty years ago, in a society of physicists and physiologists, I proposed for discussion the question, why geometrically similar figures were also optically [visually] similar. I remember quite well the attitude taken with regard to this question, which was accounted not only superfluous, but even ludicrous" [*The Analysis of Sensations*, translated by C. M. Williams and S. Waterlow (Routledge/Thoemes, London, 1996), p. 109].
2. Chuck Close exhibition organized by Robert Storr, Museum of Modern Art, New York City, 26 February to 26 May 1998. The exhibition is at the Hayward Gallery, London, 22 July to 19 September, 1999. All relevant paintings, except *Maggie*, are reproduced in the catalog [R. Storr, *Chuck Close* (Museum of Modern Art, New York, 1998)]. The Close quote is from recorded narration provided at the exhibition.
3. "Beauty depends on size and order; hence an extremely minute creature could not be beautiful, for our vision becomes blurred as it approaches the point of imperceptibility, nor could an utterly huge creature be beautiful, for, unable to take it in all at once, the viewer finds that its unity and wholeness have escaped his field of vision" [*Aristotle's Poetics*, translated by J. Hutton (Norton, New York, 1982), chapter 7].
4. E. E. Cooper, I. Biederman, J. E. Hummel, *Can. J. Psychol.* **46**, 191 (1992). Unlike identification, judging whether one has seen a particular object before is size-specific. For discussion of the size question, see www.visionscience.com/mail/cvnet/1998/0307.html.
5. L. D. Harmon and B. Julesz, *Science* **180**, 1194 (1973); L. D. Harmon, *Sci. Am.* **229** (no. 5), 71 (1973); in O. J. Grusser and R. K. Klinke (Eds.), *Pattern Recognition in Biological and Technical Systems* (Springer-Verlag, New York, 1971), pp. 196–219.
6. *Keith/1,280*, exhibited at the Bykert Gallery, New York City, 20 October to 15 November 1973.
7. Harmon (1971) includes a face with 0.4-cm squares. The blocks are 0.4 cm in Harmon and Julesz's (1973) Lincoln (cover of *Science*), 0.8 cm in Harmon's (1973) George Washington (cover of *Scientific American*), and 1.0 cm in his Mona Lisa. Close's *Keith/1,280* (1973) is made up of dots on a 0.4-cm grid.
8. E. C. Keuls [*Plato and Greek Painting* (Brill, Leiden, Netherlands, 1978)], on the basis of texts by Plato and Aristotle.
9. F. W. Campbell and R. W. Gubisch, *J. Physiol.* **186**, 558 (1966).
10. Dalmatian photo by R. C. James, in R. L. Gregory, *The Intelligent Eye* (McGraw-Hill, New York, 1973), p. 14.
11. M. C. Morrone, D. C. Burr, J. Ross, *Nature* **305**, 226 (1983).

12. I thank S. Bernardete for Greek citations and D. R. Williams for suggesting the artificial pupil. Supported by the National Eye Institute.

PERSPECTIVES: GEOPHYSICS

Hawaiian Plume Dynamics

John Lassiter

The Hawaiian Islands have long shaped geologists' views about Earth's interior. The apparently fixed position of the Hawaiian "hot spot" led to the theory that deep-seated plumes of hot, buoyant mantle were responsible for ocean island volcanism at Hawaii and many other ocean island chains (*1*). Chemical and isotopic differences between ocean island basalts and mid-ocean ridge basalts have long been used by geochemists to constrain models of mantle convection and the chemical evolution of Earth (*2–4*). In this issue, Blichert-Toft *et al.* (*5*) present evidence from hafnium isotopes suggesting that ancient deep ocean (pelagic) sediments are present in the source of some Hawaiian lavas. Important in its own right, this result also suggests that combined geochemical and seismologic study of the Hawaiian "plume" may help resolve one of the most important and long-standing questions in earth science: whether convection of Earth's mantle is layered.

Evidence for layered mantle convection comes primarily from geochemistry. Mass balance appears to require that a substantial portion of Earth's mantle is less depleted in elements concentrated in the continental crust [such as large-ion lithophile (LIL) elements] than the highly depleted upper mantle sampled at mid-ocean ridges (*2, 4*). Rare gas isotope distributions, especially for Ar and He, also suggest that part of Earth's mantle retains a large fraction of its primordial gas budget, as well as a large fraction of the ^{40}Ar produced by the decay of ^{40}K (*3, 4*). To have preserved this reservoir for the age of the Earth, the reservoir must remain convectively isolated from the upper mantle, where the processes of crust formation at mid-ocean ridges and island arcs have stripped a large fraction of the initial rare gas and LIL elements. A reasonable location for this gas- and LIL-rich reservoir is therefore the lower mantle. The change in mantle mineralogy that occurs at a depth of 660 km, indicated by a seismic discontinuity, was long believed to act as a barrier to convection, blocking transfer of cold downwelling slabs or hot upwelling plumes. The 660-km discontinuity was therefore thought to mark the boundary between a depleted upper mantle and a more primitive lower mantle (*6, 7*).

This model is not consistent with recent seismic tomographic images, which are widely interpreted as indicating that many subducting slabs do not stop at the 660-km discontinuity, but continue to descend deep into Earth's interior (*8, 9*). If a substantial fraction of subducted slabs have penetrated into the lower mantle for much of Earth history, significant long-lived chemical layering is difficult to preserve (*10*). However, seismic tomography can only provide a snapshot of the current thermal structure of the mantle. Earth has been slowly cooling for the past 4.5 billion years, and there is no a priori reason why mantle convection could not have been layered for most of the geologic past even if today such layering appears to have broken down (*4*).

The mounting evidence for ancient recycled crust and sediments in the Hawaiian plume suggests how seismologists and geochemists can combine forces to constrain the

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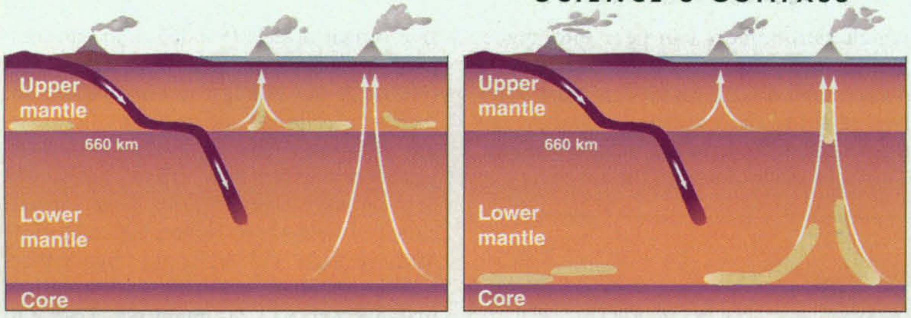

Models of mantle convection. (Left) In a two-layer convection model, the 660-km discontinuity serves as a barrier for convection. **(Right)** Alternatively, subduction of crustal material can reach the lower mantle before being transported upward again in a plume.

mechanism of mantle convection, at present and far back in Earth history. As discussed by Blichert-Toft, *et al.* (*5*), hafnium and neodymium isotopes are well correlated in most oceanic basalts. But some Hawaiian lavas have unusually radiogenic Hf isotopes given their Nd isotopic composition. Similar features are found in modern pelagic sediments, but not in most other types of crustal or mantle rocks. Blichert-Toft *et al.* also show that the lavas with the most unusual Hf isotopes derive from a source with a much higher Pb:Hf ratio than other Hawaiian lavas. This higher ratio is characteristic of crustal-derived sediments. These data strengthen previous suggestions for a recycled component in Hawaiian lavas (*11–13*). Blichert-Toft *et al.* further suggest that the low $^{207}Pb/^{204}Pb$ values in the recycled sediment compared with most modern sediments require that this sediment is ancient, perhaps as old as 3 billion years. It is not clear how robust this age estimate is, although other estimates using different assumptions or isotopic systems have also yielded ages greater than 1 billion years (*13*).

Depending on the depth at which the Hawaiian plume originates, the presence of old recycled crust in the plume suggests two different models of mantle convection. If the Hawaiian plume derives from the 660-km discontinuity, the presence of ancient recycled crust in the plume would suggest that this region of the mantle has acted as a slab "graveyard" for much of Earth history. This would strengthen suggestions that whole-mantle convection began recently (*4*). In contrast, if the Hawaiian plume derives from the core-mantle boundary, the presence of ancient crust in this plume would require such recycled material to be present in the lower mantle. This would in turn require that slabs penetrated the 660-km discontinuity at 1 to 3 billion years ago, much as they do today.

How can we determine the depth from which the Hawaiian plume originates? Geochemistry can provide only indirect evidence. Brandon *et al.* (*14*) recently argued that anomalous abundances of an osmium isotope, ^{186}Os, in some Hawaiian lavas reflect incorporation of a small quantity of core material. Blichert-Toft *et al.* argue that the Hf-Nd isotope trend in Hawaiian lavas precludes melting of depleted upper mantle. The lack of an upper-mantle signature in Hawaiian basalts may indirectly suggest that the Hawaiian plume originated at greater depth.

Seismological studies can potentially provide a stronger constraint on the Hawaiian plume's depth of origin. Recent seismological studies have shown that the Iceland plume extends through the upper/lower mantle transition zone (*15*) to the core/mantle boundary (*16*), providing the most direct evidence to date for some mantle plumes deriving from the core/mantle boundary. No comparable study has yet been performed for Hawaii. An extensive array of ocean-bottom seismometers will be necessary for detecting a hot, narrow plume in the deep mantle beneath Hawaii, if such a plume exists. Such a study, combined with the increasingly robust evidence for ancient recycled crust in the Hawaiian plume, may finally answer the question whether mantle convection is, or has been, substantially layered.

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PERSPECTIVES: PLANETARY SCIENCE & ASTRONOMY

Extrasolar Giant Planets and Brown Dwarfs

Adam Burrows

Until just 5 years ago, the census of stars in our galaxy did not extend much below one-tenth of a solar mass ($M_\odot$). An object of less than ~0.08 $M_\odot$ cannot sustain itself by thermonuclear burning against the inevitable radiation losses from its surface. Such substellar objects, nicknamed brown dwarfs, should thus radiate and cool over eons of astronomical time like hot coals plucked from a fire. These objects were expected to resemble large, hot planets such as Jupiter, but planetary scientists had only been able to detect and study planets in our solar system. That left a yawning gap between the mass of Jupiter (M_J), ~0.001 $M_\odot$ or 1 M_J, and that of small stellar objects with ~0.1 $M_\odot$, a gap of two orders of magnitude in mass in the distribution of known objects. Be they extrasolar planets formed in protostellar disks around bright and massive stars or substellar-mass brown dwarfs formed directly by the same processes that give rise to stars, they remained undetected, their existence in doubt, their importance debated, their properties unknown.

This situation has changed dramatically as recent surveys in the solar neighborhood, in young stellar clusters, and around nearby stars are turning up scores of giant planets and brown dwarfs. The optical brightness of stars like our sun makes it obvious that they at least are prevalent in the galaxy, but in the solar neighborhood, there may be more brown dwarfs than sunlike stars (*1*). Substellar objects are far less luminous and emit the bulk of their luminosity in the infrared. Direct photometric and spectroscopic measurements of brown dwarfs—previously beyond the powers of technology—are now writing a new chapter in stellar astronomy. The brown dwarf Gliese 229B (*2*) was the first in a series of discoveries. Since then,

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