GEOCHEMISTRY

The Leaking Mantle

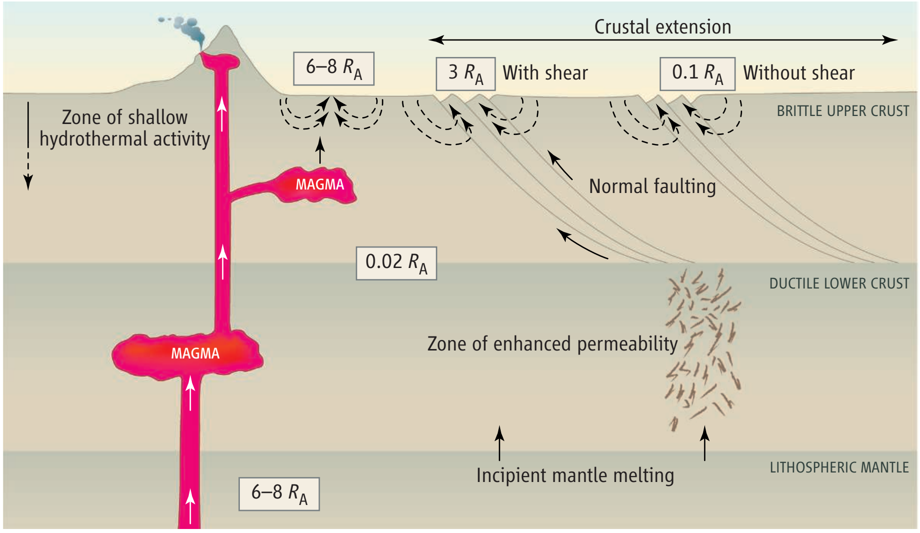
David R. Hilton

The flow of mantle fluids through Earth's crust reveals fundamental geophysical processes and may help pinpoint sources of geothermal energy.

Earth's mantle (the massive silicate shell located between the crust and core) is an important reservoir for volatiles such as water, carbon dioxide, and the noble gases. It combines volatiles captured during Earth's formation with those added later by nuclear reactions or by recycling from the surface. Consequently, mantle-derived volatiles provide a key means to learn about Earth's early history and its continuing evolution (*1*). Although Earth's crustal carapace limits access to the mantle, sampling its volatiles has been pretty straightforward: Researchers target regions where mantle-derived melts (magmas) invade the crust, such as mid-ocean ridges, volcanic arcs, and hot spots. But can volatiles escape the mantle without the help of magma? On page 1433 of this issue, Kennedy and van Soest (*2*) show that the Basin and Range province (which covers much of the southwestern continental United States) is leaking mantle volatiles over a wide area, despite little magmatic activity. Moreover, they propose that the lower crust, usually considered a barrier to volatiles, shows an enhanced permeability caused by the Pacific and North American plates sliding past one another. These observations, and their proposed explanation, have far-reaching implications for the origins of earthquakes and finding new geothermal resources.

Researchers trace mantle volatiles by analyzing the isotopic composition of the lightest noble gas, helium (*3*). Both isotopes, ^{3}He and ^{4}He, are produced in the crust at a ratio of ~0.02 R_A (where R_A is the ^{3}He/^{4}He ratio in air). Higher values indicate the presence of helium from a reservoir enriched in ^{3}He. The only viable possibility is the mantle, which stores ^{3}He captured during planetary accretion. Hence, ^{3}He/^{4}He values between 0.1 and 3 R_A throughout the Basin and Range signify mantle-derived volatiles. What is so unusual about this finding is the lack of magmatic activity in the Basin and Range, except at the westernmost transition to the Cascades magmatic arc. How can mantle volatiles traverse the ductile lower crust and brittle upper crust without melts?

Maps of the deformation dynamics of the western United States may provide the answer (*4*). Plate motion between the Pacific and North American plates drives east-west extension of the Basin and Range province across most of the Central Nevada Seismic Belt (east of 242°E) at rates between 3 and 4 mm year^{-1}. In this region, ^{3}He/^{4}He ratios define minimum (baseline) values of ~0.1 to 0.2 R_A. West of 242°E, strain rates and corresponding flow velocities increase sharply (up to 13 to 14 mm year^{-1}), their direction changes to the northwest, and baseline ^{3}He/^{4}He values also increase to as high as 3 R_A. The increase in ^{3}He/^{4}He values must reflect increased flow of mantle-derived volatiles through the crust. Therefore, the pattern of increasing baseline ^{3}He/^{4}He values toward the west is tracking the increase in permeability of the crust, including the ductile lower crust and its transition to the source of the high ^{3}He/^{4}He values: the lithospheric mantle.



Escape routes. Schematic cross section of continental crust, showing escape routes of mantle volatiles to the surface. Zones of enhanced permeability in the ductile lower crust, formed as a result of shear stresses imposed on areas of crustal extension, may provide an additional connection to the mantle to supplement that provided by volcanic and magma-driven hydrothermal activity. Helium isotope ratios are in boxes.

Two ingredients are required to explain this enhanced permeability. First, fractures that can act as conduits for the mantle volatiles must be present. Kennedy and van Soest suggest that the shear force twisting the regional strain to the northwest generates vertical faults that link the brittle upper crust with the ductile lower crust. Extension alone produces normal faults that are refracted to near-horizontal positions at the brittle-ductile transition (see the figure). Second, these pathways must remain open, at least for part of the time, to maintain a connection between the surface and the mantle source of the high ^{3}He/^{4}He values. Therefore, fluid pressures within the conduits must be extremely high. Continuous connection from the surface to the mantle is not required: Changes in fluid pressure may facilitate growth or sealing of fractures so that the flow could be episodic rather than steady-state.

The realization that helium isotopes can identify zones of enhanced crustal permeability may open new lines of inquiry. For example, Kennedy and van Soest point to ^{3}He/^{4}He anomalies in the Basin and Range (areas where the ^{3}He/^{4}He values are much greater than the baseline) as areas of enhanced geothermal potential. They argue that high helium isotope ratios mark localities such as Dixie Valley, Nevada (*5*), as possessing the enhanced crustal permeability and deep fluid production necessary for geothermal energy development. Mapping helium isotope ratios may thus be a valuable tool for finding new geothermal energy sources.

Another prospect concerns earthquakes. Nonvolcanic tremor (quasicontinuous ground vibration) has been detected in southwest Japan (*6*) and beneath the San Andreas Fault (*7*). The former case reflects movement of aqueous fluids through the mantle (*8*); in the latter, such events may reveal the presence of fluids below the seismogenic zone (i.e., brittle upper crust where earthquakes occur) (*7*). The role of deep fluid movement in changing

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stresses in the upper crust and triggering earthquakes remains unclear, yet these two very different tectonic regimes share a common feature: $^{3}He/^{4}He$ ratios much higher than expected for regions virtually devoid of mantle melting (*8*, *9*). Looking more closely at the helium isotope characteristics of such regions—spatially and temporally—may provide evidence coupling the leaking mantle to one of our greatest natural hazards.

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GENETICS

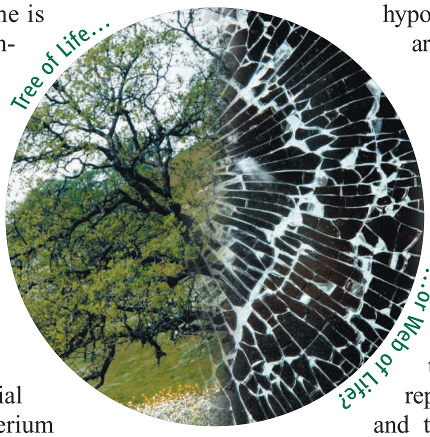
Paradigm for Life

Lateral gene transfer may have spurred microbial evolution, producing a pattern of evolution that resembles a network, rather than a tree.

James O. McInerney and Davide Pisani

It has been known for more than 60 years that prokaryotes can swap their DNA through the processes of conjugation, transformation, and transduction (*1*). This acquisition of foreign genes is generally referred to as horizontal gene transfer (as opposed to vertical inheritance, in which an organism receives DNA from an ancestor). The consequence is that each prokaryotic chromosome is a mosaic of vertically inherited and horizontally acquired genes (*2*). On page 1449 of this issue, Sorek *et al.* (*3*) report the first large-scale empirical analysis of the transferability of genes by analyzing the introduction of almost a quarter of a million genes from other eubacterial and archaebacterial species into the eubacterium *Escherichia coli.* The findings provide insight into the likely evolutionary history of prokaryotes and indicate that interspecies gene transfer is not restricted to special categories of genes, nor are there categories of genes that cannot be transferred.

The role of horizontal gene transfer in evolution has raised fierce debate about the relevance of the Tree of Life, a long-accepted representation of the interrelatedness of living things through evolutionary time, based primarily on the sequence of the genes that encode the small subunit of ribosomal RNA (*4*). The question is whether this depiction should be replaced with a network, or Web of Life (*5*) (see the figure). Whereas a tree reflects evolution as a process in which new species arise, or branch, from specific ancestors, a web may more accurately portray microbial evolution based on the rise of variation (and new species) through the lateral transfer of genetic information between distantly related species.



Tree or Web? There is an ongoing debate about whether the genetic relationship of life on the planet should be depicted as a Tree or Web of Life.

PHOTO CREDIT: JUPITER IMAGES

Using phylogenetic methods, it has been proposed under the complexity hypothesis that not all genes are equally affected by horizontal gene transfer (*6*). Two classes of genes have been identified. Informational genes—those involved in DNA replication, transcription, and translation—are part of more complex protein-interaction networks and are thus less likely to be involved in horizontal gene transfer. So-called operational genes—those involved in day-to-day processes of cell maintenance, such as genes that control energy metabolism and the biosynthesis of nucleotides and amino acids—may be more prone to transfer (*6*). This has led to the notion that a core of nontransferred or rarely transferred genes might have kept track of the clonal history of prokaryotes. If this prediction were true, the Tree of Life hypothesis would hold, even in the presence of rampant horizontal gene transfer (*5*).

Up to now, a major obstacle to understanding the role of horizontal gene transfer in evolution was the lack of large-scale experimental evidence that might corroborate or reject the existence of a core set of genes. Sorek *et al.* have gone a considerable way in providing data to test this idea. The authors found that among 246,045 genes from 79 different species of prokaryotes, there was no single gene that, along with all its prokaryotic homologs, resisted transfer by way of a plasmid (thus, gene transfer by transduction) into *E. coli.* However, whereas all gene families could be cloned into *E. coli*, some genes were not easily transferred. Members of informational gene families represent a substantial fraction of those resilient to cloning, lending more weight to the complexity hypothesis (*6*). And even though 1402 genes were impossible to transfer, favoring the existence of core genes, transferable orthologs of these genes were found, thus opposing the core hypothesis.

There are currently almost 6000 accepted prokaryotic species, but the analysis by Sorek *et al.* could only deal with *E. coli*, because adequate data are currently available only for this species. It is possible that if a different host was used, a different set of untransferable genes might have been identified.

Sorek *et al.* also report that genes from prokaryotic genomes enriched in the nucleotide bases guanine (G) and cytosine (C) are more transferable, consistent with the observation that the synonymous usage pattern of codons (triplets of nucleotide bases that encode amino acids) in recently acquired genes in *E. coli* is different from that of native genes (*2*). The explanation might be that promoter regions (DNA sequences that control the transcription of a gene) in the *E. coli* genome are GC-poor; hence, GC-rich promoters might not work well and would result in nontranscription. It is thought that one of the most important ways to introduce foreign DNA into an organism is by stealth: repressing the expression of the introduced gene until

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