

proton component of cosmic rays, is the two-gamma decay of neutral pions created by multi-TeV protons colliding with molecules such as H_2 and CO . That mechanism would account straightforwardly for the $E^{-2.2}$ falloff of the gamma energy spectrum shown in figure 3. But appraising the contribution of high-energy proton collisions to RX J1713.7–3946's gamma output requires comparing the gamma image with the distribution of molecular clouds in the remnant's vicinity. One problem is that the radio-telescope surveys that trace such clouds by tell-tale molecular transition lines yield only column densities. That is, they cannot easily distinguish clouds at the

shock front from foreground clouds along the line of sight. "It's still a work in progress," says Hofmann.

The shock front's velocity, expressed as β , its fraction of the speed of light, is only about 3%. A charged proton or electron traversing the shock front can acquire a fractional energy gain of about β from the moving magnetic field. That might seem like far too timid a kick to account for TeV cosmic rays. The standard answer is that the very few charged particles that make it to TeV energies not only start out in the high-energy tail of the thermal distribution. They also have to traverse the same shock front hundreds of times. That improbable fate can befall a particle if random

scattering off ambient material reverses its direction often enough without dissipating its accumulating energy.

It's a very slow process. The lucky few typically take thousands of years to reach TeV energies. Supernova shock fronts last for tens of thousands of years before they run out of steam. Perhaps half of their initial energy eventually ends up in cosmic rays.

Bertram Schwarzschild

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New Study Correlates Mantle Melting to Mid-Ocean Ridge Segments

Variations found in the composition along a stretch of exposed mantle on the Arabian peninsula offer fresh evidence for the link between the length scale of ridge segments and Earth's convection process.

The mid-ocean ridge is a 75 000-kilometer network of undersea mountain chains that, like the seam of a baseball, winds around the globe from the Arctic Ocean to the Atlantic, around Africa, Asia, and Australia, under the Pacific, and skirts the west coast of North America. This fundamental feature of Earth's superstructure delimits the intersection of tectonic plates and is the source of 85% of Earth's volcanism. As plates separate and cracks form, the mantle wells up to fill the gap. Partial melting of the solid mantle produces magma that percolates upward through pores and grain boundaries in the rock and then crystallizes into basalt—new layers of

Earth's crust. The process prompted oceanographer Bruce Heezen to characterize the ridge system as "the wound that never heals."

But if the mechanics of tectonic fracture were all that controlled the accretion of crust, one might expect uniform depth everywhere as the plates spread. In fact, the topography of the ridge is rich and varied, with frequent discontinuities and offsets, ranging in length from a few kilometers to hundreds of kilometers, that partition it into segments. Ridge geometry can be complicated, in part because the segments behave like giant, mobile cracks that may lengthen or shorten over time. Never-

theless, they appear to be closely linked to melting in Earth's mantle, based on well-known variations in the petrology, magnetization, and, in some places, the thickness of crust formed beneath the deep oceans along the ridge.

Exactly what accounts for those variations has puzzled researchers for years. Laurent Le Mée, Christophe Monnier, and group leader Jacques Girardeau from the University of Nantes in France have now provided direct evidence for the link between segmentation in ocean ridges and the upwelling process deep underground by studying how the geochemistry of the mantle itself varies along the ridge axis.¹

Rock and magma

The problem of determining how the production and transport of heat and

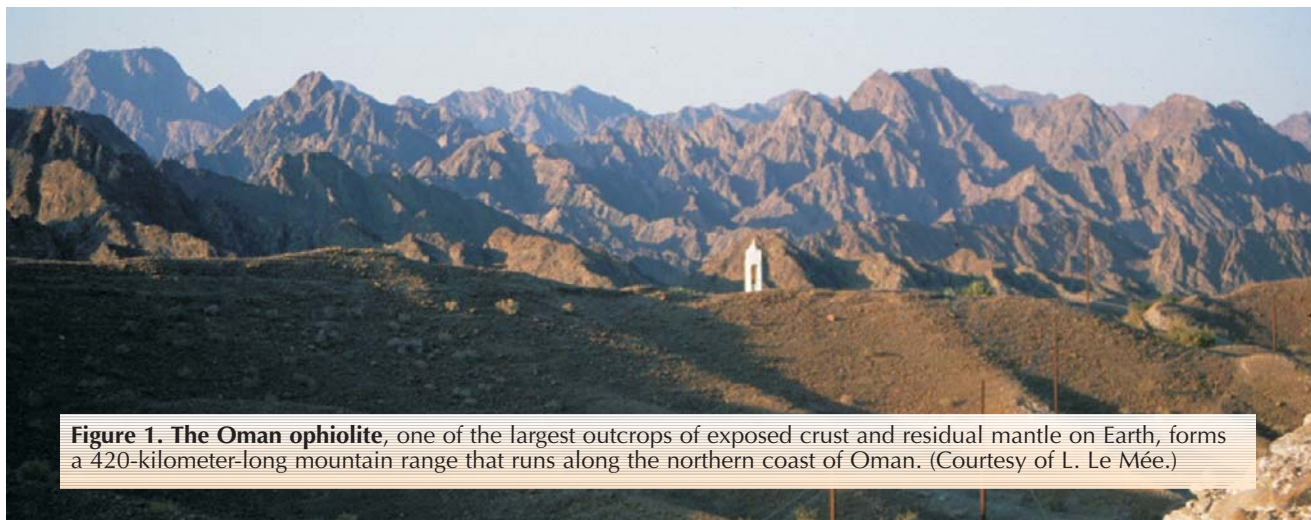


Figure 1. The Oman ophiolite, one of the largest outcrops of exposed crust and residual mantle on Earth, forms a 420-kilometer-long mountain range that runs along the northern coast of Oman. (Courtesy of L. Le Mée.)

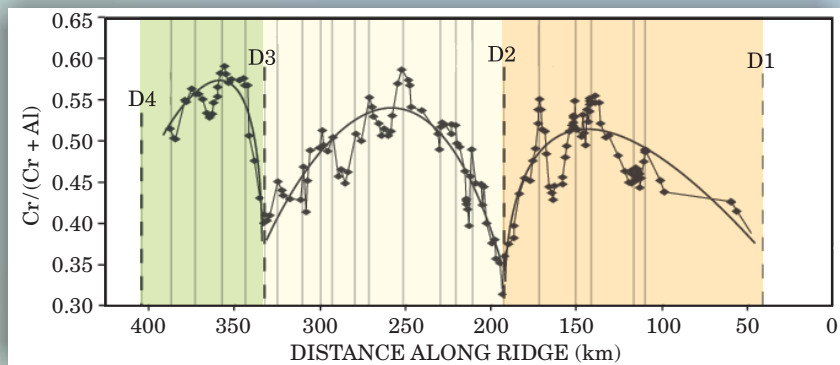
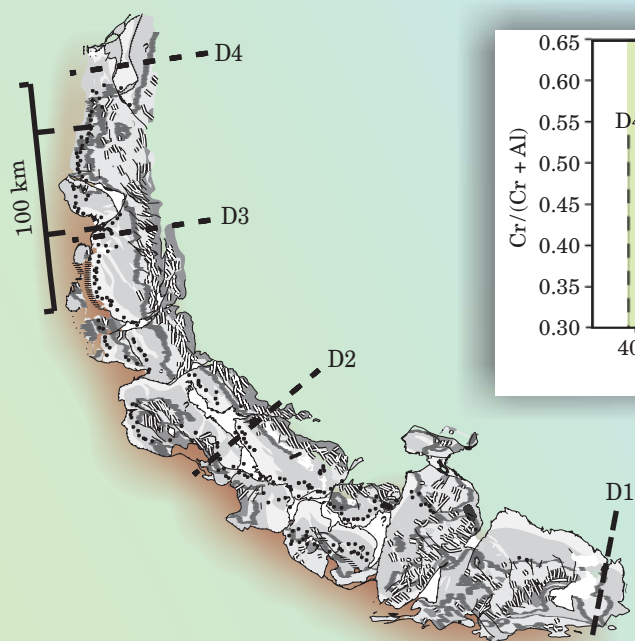


Figure 2. This map of the ophiolite (left) locates the chunks of mantle (black dots) that Laurent Le Mée and colleagues from the University of Nantes in France surveyed and analyzed in their effort to understand how geochemistry varies along the mid-ocean ridge. The gray shadings illustrate the changing depth, with lavas in the topmost layer fed by sheetlike structures that channel the melt and spread the sea floor, and mantle silicates kilometers deeper still. The intrinsic tilt of the outcropping, however, exposes sections of mantle and crust to the surface despite their original location under the ridge. D1–D4 mark the ends of inferred ridge segments. A plot (above) of the extent of melting—indicated by the ratio of chromium to aluminum concentrations—suffered by those mantle samples reveals a trend of highs and lows, defining the location of three distinct segments. (Adapted from ref. 1.)

magma from the mantle influence ridge topography (and vice versa) is not new, but the inaccessibility of Earth's deep interior has limited how researchers could address it. In the deep oceans, kilometers of basaltic crust cover the residual mantle rock that melted to produce the crust. Seismic imaging can remotely determine the amount of molten material below the crust, and thereby indicate the distribution of magma chambers that feed the ridge (see *PHYSICS TODAY*, July 1998, page 17). Rocks coughed out of volcanoes and dredged from the sea floor provide a range in composition data, but only indirect information about the mantle from which they came.

Another approach has been to analyze the topography in the ridge and variations in the geochemistry of basalt that crystallized from the melt and erupted onto the sea floor. The basalt studies have shown a correlation between composition and segmentation in some places but not in others. The melt's percolation to the surface along with fractional crystallization and mixing in magma chambers obscures mantle processes. It's "like looking through layers of frosted glass," explains Ken Macdonald from the University of California, Santa Barbara, of the ambiguity some basalt data can yield.

To study the mantle itself, where melting actually took place, the Nantes team went to one of the geo-

logical wonders of the world: the Oman ophiolite, a mountainous outcropping of exposed oceanic crust and upper mantle located in northern Oman (see figure 1). This 100-million-year-old fossil of what was once the ancient sea floor got pushed onto the neighboring continent, and yet is thought to still preserve a record of the melting and crystallization process similar to what's observed in Earth's active spreading centers.

Since Robert Coleman initiated work in Oman in the 1970s, three decades of groundwork have gone into characterizing the structures there. Adolphe Nicolas and others² inferred the locations of ridge segments on the basis of structural footprints. Below 1000°C, mantle rock no longer deforms, but freezes in the preferred orientation of the flow, which can be evident on the surface.

Cross sections

Silicates of magnesium and iron compose much of Earth's mantle; different constituents of those silicate minerals enter the liquid phase at different temperatures and pressures. Le Mée and colleagues systematically collected 280 chunks of mantle in an effort to map how the composition changed as a result of such partial melting. According to petrologist Georges Ceuleneer (Observatoire Midi-Pyrénées, CNRS), no previous geochemical analysis of the Oman mantle rock has been based on such a

regionally extensive field survey.

In the laboratory, to gauge the extent to which their samples of mantle had melted, Le Mée and coworkers measured the concentrations of chromium and aluminum, two trace elements in the mineral spinel that happen to differ in their melting temperatures. The researchers also did a similar analysis on two other elements in mantle rock, ytterbium and erbium, which also differ in their preference to enter the liquid phase.

The ophiolite comes with its own complications. The Oman outcropping is really a slab of oceanic Earth, inclined 15° to the surface, with ridge segments located along the mountainous right-hand side of the map in figure 2, and eroded mantle rock exposed mainly in the middle and left-hand side of the map. Moving east to west is then equivalent to moving from younger to older parts of the range. The team therefore took pains to confirm that the partial melting composition of mantle rock varied little with depth or lateral distance across the ridge.

Along the ridge, however, the researchers found the chemical composition to vary considerably between samples, with the lowest extent of partial melting near 10% and the greatest extent close to 30%. The range of inferred melt fractions—a factor of three—is similar to what Emily Klein and Charles Langmuir estimated from the composition of

ocean-floor basalts.³ Both estimates could reflect variations in mantle temperature. More striking is the geographic distribution of the data: With data points spread roughly 1.5 km apart and projected along the spine of the roughly 420-km Oman ridge, the variations in composition do not follow a random pattern, but instead reveal the trend of highs and lows shown in figure 2. Indeed, the cross section appears to have minima that coincide with areas where structural evidence suggests the segments end. The data thus form an independent geochemical measure of the segmentation and confirm how the extent of melting is organized.

To appreciate what the results may imply, consider convection in the mantle. In addition to the viscous forces that drag the mantle up as plates spread apart, a more active, buoyancy-driven upwelling could also play a role. The presence of low-density melt causes the hot mantle rock to become more buoyant and rise, a three-dimensional process most pronounced at slow-spreading ridges; magma that percolates out of the rock takes with it heavy iron oxide, leaving the residual mantle less dense. Decompression drives the melting as the mantle rises.

Even though the melting is adiabatic, Girardeau argues that there are still temperature differences—between the hot middle of the segment and the relatively cooler edges—that drive the convection. However, whereas Klein and Langmuir inferred that variation from high to low degrees of melting is gradual over 4000 km of the mid-Atlantic ridge, the distance from highest to lowest in the Le Mée study is only about 50 km. The similarities between lavas and residues are intriguing, but the differences in length scale suggest that the different data sets may reflect different processes, says Peter Kelemen from Columbia University's Lamont-Doherty Earth Observatory.

Girardeau's interpretation is that more upwelling occurs in the central parts of segments, and leads to a greater production of magma there, with less upwelling and melting near the ends, where the crust is typically quite thin. Where ridge segments terminate at large transform faults, explains Kelemen, the ends of the segments are refrigerated by old, cold oceanic crust on the other side of the fault, and that curbs upwelling and melting.

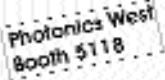
Another question is how to explain

scatter in the data; figure 2 shows a smooth seven-point running average, but large variations in the raw data appear in adjacent samples. "Clearly something besides upwelling is influencing the apparent degree of melting," says Don Forsyth of Brown University. It may not be possible to rule out chemical interactions between the residual mantle and the magma that percolates to the surface, for instance.⁴ Different researchers have different interpretations. But Ceuleneer makes a hopeful assessment: "For the first time, we now have a database to compare mantle composition with basalt composition" along a ridge axis. By that view, the Nantes team's work is likely to inspire geoscientists to go back to Oman, reconsider the basalt data, scratch their heads, and think hard.

Mark Wilson

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