

New Measurements Constrain Models of Mantle Upwelling along a Midocean Ridge

It has long been known that as tectonic plates pull apart along the mid-ocean ridge system, the mantle wells up to fill the gap. Partial melting of the mantle produces magma that percolates upward to the surface and solidifies into new crust within a few kilometers of the ridge. But the details of this process have been a mystery: Over what volume is the mantle melted to form this magma? What is the concentration of the melt? How connected are the pockets of molten material? To answer such questions, an international collaboration designed the Mantle Electromagnetic and Tomography (MELT) experiment, placing seismometers, electrometers and magnetometers on the ocean floor to span the midocean ridge known as the East Pacific Rise (see figure below). After several years of gathering and analyzing data, members of the collaboration presented their results at the Boston meeting of the American Geophysical Union at the end of May.

One aim of the experiment was to distinguish between two models of how the magma is carried to the surface. (The models are described by the same equations but with different parameter ranges.) According to one model, the melt is formed in a narrow zone directly below the midocean ridge and is transported vertically upward by such forces as the buoyancy of the melt and the reduction in mantle density caused by the extraction of the melt to form new crust. This hypothesis is consistent with the observation that the crust forms within a few kilometers of the ridge axis. However, for the melt to have enough buoyancy to rise, the mantle would have to contain relatively high concentrations of melt (equal to several percentage points). The other model calls for lower percentages of melt and for the melt to be present over a much wider area of the mantle around the ridge. Various mechanisms have been proposed that would drive the melt horizontally toward the region beneath the ridge and then upward from there.

Of these two simple models, the MELT collaboration's seismic data¹ favor the one with the wider distribution of melt—at least for the East Pacific Rise. The results indicate that melt concentrations of 1–2% are present as

▶ Magma flowing upward to form fresh crust along the axis of plate spreading does not appear to come exclusively from a narrow zone directly beneath the axis. Rather, molten material is distributed along the ridge in a region more than 100 km wide and over 100 km deep. Moreover, the melt zone is centered to one side of the axis—beneath the faster moving plate.

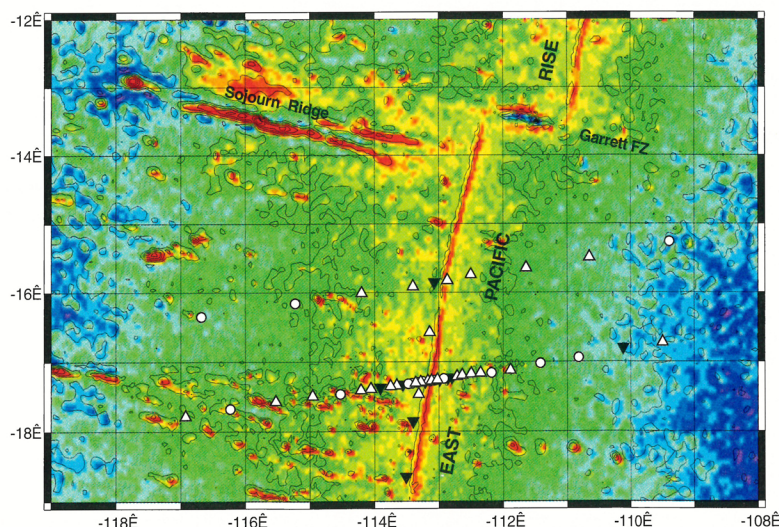
far as a few hundred kilometers to either side of the East Pacific Rise. Those concentrations may extend downward as much as 100 km or more below the ocean floor. A composite sketch of the shape and location of the melt region, inferred from a number of the seismic MELT measurements, is shown in the figure on page 18. Preliminary analysis indicates that the MELT team's electromagnetic measurements are consistent with this picture.

Before the MELT experiment, the East Pacific Rise was known to have certain asymmetries: The Pacific plate to the west of the ridge is moving faster than the Nazca plate to the east. The

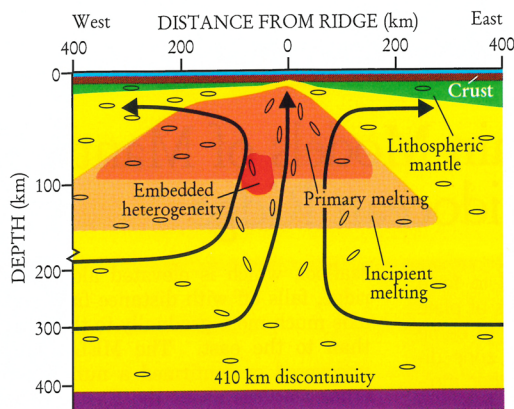
seafloor, which is elevated along the ridge, falls off with distance from the axis much more gradually to the west than to the east. The MELT data uncovered or confirmed a number of other features about the East Pacific Rise that were also asymmetric. Not the least among them was the asymmetry in the distribution of seismic velocities, with the region of slower velocities centered to the west rather than lying directly below the ridge.

Focus of the study

The MELT collaboration focused on collecting both seismic and electromagnetic data. Measurements of the velocities of seismic waves in the upper mantle gave insight into the amount of molten material that is present because the seismic waves travel more slowly through the melt. Detection of electric and magnetic fields provided a measure of the electrical conductivity of the upper mantle: If melt is present and if the pockets of melt are interconnected, one would expect the conductivity to be high. In addition to focusing on seismic velocities and electrical conductivity, the MELT researchers



ARRAYS OF SEISMOMETERS (open triangles) strung along the ocean floor in two lines spanning the East Pacific Rise. Instruments located at black triangles returned no data; those at open circles recorded pressure only. The seismometers were used to find the distribution of partially melted mantle near this ridge. Electrometers and magnetometers later deployed in the same area provided a measure of the electrical conductivity. Ocean depth, shown in color (redder colors denote shallower depths), shows an anisotropy across this ridge. (Adapted from ref. 1.)



PARTIALLY MELTED MANTLE as a function of ocean depth and of distance from the axis of the midocean ridge. The primary melt zone (light red) is wide, extending hundreds of kilometers from the axis and going down 100 km deep. It is also asymmetric, with more melt to the west (left of ridge). Some amount of melting (orange) may extend to 150 km, and the region has an embedded heterogeneity (red) with additional melting. Small ellipses denote the preferred polarization of olivine crystals in the mantle. (Adapted from ref. 1.)

made measurements of geophysical features of the region.

The experiment was sited along the East Pacific Rise because it is one of the longest and straightest sections of any midocean ridge and because it is one of the areas where plate spreading is most rapid. In November 1995, the seismic team put down 51 seismometers in two lines spanning the East Pacific Rise and separated by just over one degree of latitude. (The seismometers were provided by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution.) As shown in the figure on the previous page, both arrays were about 800 km long. They were oriented to be in line with as many expected sites of large earthquakes as possible. The arrays were pulled up in May 1996, when the magnetotelluric team put down two strings of electromagnetic sensors in the same area, keeping them there until June 1997. After two years of analysis, the seismic team has published an initial interpretation of its data,¹ but, having had only one year to analyze its data, the electromagnetic team cited only preliminary results at the AGU meeting.

Donald Forsyth of Brown University coordinated the seismic team, which included researchers from Scripps, Woods Hole, the University of Oregon, the University of Colorado at Boulder, the Carnegie Institution of Washington and the University of Washington. Alan Chave and Rob Evans, both of Woods Hole, led the group that gathered electromagnetic data, which they call mag-

netotelluric—that is, related to Earth's magnetism. This group included geophysicists from Flinders University of South Australia, the University of Tokyo, the University of Western Brittany in France, Chiba University in Japan, Scripps and the University of Washington.

Seismic data

According to Forsyth, the main source of information on the percentage of melt in the mantle was the seismic team's study of the travel time delays of both compression (P) and shear (S) waves from distant earthquakes. The data, analyzed by Douglas Toomey (University of Washington) and his team,² suggested melt

concentrations of 1–2% over a region several hundred kilometers wide. The delay times were greatest on or near the axis, but did not fall off very rapidly as one moved westward. The delay times decreased much more rapidly to the east.

Roughly the same asymmetric pattern was seen in studies by Forsyth and his colleagues³ of the phase velocities of Rayleigh, or surface, waves, although in that data set, the lowest velocities were centered off axis, to the west.

Regional earthquakes to the north along the East Pacific Rise were analyzed by Spahr Webb of Scripps and Forsyth.⁴ These data constrained the depth of the region of lowest velocities—that is, of highest melt concentration—to 100 km below the ocean floor, with lower concentrations of melt extending down to perhaps 150 km. Inversion of the body and surface wave data from teleseismic events is consistent with this conclusion.

From measurements⁵ of the S waves, Cecily Wolfe (Woods Hole) and Sean Solomon (Carnegie Institution) found that these waves split into two components in the upper mantle, one traveling faster than the other—an indication that the upper mantle is anisotropic. In particular, the S waves appeared to travel more rapidly when polarized in a direction parallel to that of the spreading plate motion. One possible explanation is that crystals of olivine, the most abundant mineral in the upper mantle, have become aligned as a result of plate motion or related dynamics. As depicted in the figure to

the left, far from the spreading center, the crystals line up so that the axes of fastest S-wave travel (major axes of the small ellipses in the figure) are parallel to the plate motion. A mystery still remains: Why is splitting of the S waves still seen at the ridge? One would expect the olivine crystals to be oriented vertically there, and hence to have no effect on the velocity of S waves polarized in different directions.

Another puzzle posed by the data is the magnitude of the time delay between the slow and fast S-wave signals; to the west of the rise, it is larger than can be accounted for by a reasonable fraction of aligned olivine crystals in the uppermost 100 km of the mantle. The researchers speculate that additional anisotropy is introduced at a greater depth by a return flow of anomalously warm mantle. Such a flow could come from the Pacific Superswell, an exceptionally shallow region some thousand kilometers to the west.

From the ratio of S-wave and P-wave travel-time delays, Toomey and his team were able to assess whether the melt is likely to be present primarily in spherical inclusions or in thin films (which would have a greater relative effect on the S waves). The data² are consistent with laboratory experiments that indicate a range of shapes, including both flat sheets and more rounded tubules.

Some geophysicists have suggested that whole-mantle convection may play an active role in the upwelling beneath a midocean ridge.⁶ To explore that possibility, a group headed by Yang Shen (Woods Hole) and Anne F. Sheehan (Colorado) examined⁷ whether there was any perturbation, such as elevated temperatures just below the ridge, in the seismic discontinuities at depths of 410 and 660 km, as one could expect if whole mantle convection were involved in the upwelling. These discontinuities are caused by phase changes in the mineral components of the upper mantle, so that any temperature change might affect the thickness of this region. By looking at the conversion of S waves to P waves that occur at these boundaries, the researchers inferred that the thickness was normal. The absence of any anomalous structure deeper than about 250 km suggests that the upwelling is not buoyantly driven from deep within the mantle, but probably is passively initiated by the separation of the plates.

Electromagnetic measurements

In the second phase of the MELT experiment, instruments on the ocean floor detected the time and spatial variations of electric and magnetic fields

Strong Evidence For Flavor Oscillation In Atmospheric Neutrinos

As we go to press, the applause has barely subsided for a 5 June talk by Takaaki Kajita at the Neutrino '98 conference in Takayama in the Japanese Alps, not far from the 50-kiloton Super Kamiokande underground water-Cherenkov neutrino detector. Speaking for the Japanese-American Super Kamiokande collaboration, Kajita reported by far the most convincing evidence to date of oscillation between different neutrino flavors. The evidence comes from the high-statistics observation of neutrinos created by cosmic-ray showers in the atmosphere. It appears that muon neutrinos on their way to the detector are exhibiting oscillatory metamorphosis into something *other than* electron neutrinos. Neutrino oscillation cannot happen if all flavors are massless. Details in the next issue. **BERTRAM SCHWARZSCHILD**

induced by solar winds or other sources of electrical currents in the ionosphere. The ratio of the electric to magnetic fields gives the complex impedance, from which one can extract the conductivity. The frequency bands are taken as a measure of the depth, with higher frequencies providing information about shallower structures. However, the data analysis is quite complicated. According to Evans, magnetotelluric results are a bit nonintuitive because one region of high conductivity will affect the value of fields throughout the region. So far, he and his colleagues have done what he calls "forward modeling," seeing if the data are consistent with certain patterns of conductivity. But they have not exhaustively explored the possibilities.

According to the MELT team's preliminary results, the background mantle structure agrees well with that

measured in a 1995 magnetotelluric study along a line from California to Hawaii.⁸ For a broad region in the upper 100 km beneath the East Pacific Rise, the researchers see conductivities that are higher than expected for a dry mantle. However, the conductivity is not high enough to support any more than about 1% of interconnected melt in that region. More melt may be present, but unless the pockets of melt are connected to one another, they will not have a substantial impact on the electrical conductivity. The conductive region may be broader to the west than to the east of the ridge crest. It is also possible that there is a narrow (only 10 km wide) region containing 4% of interconnected melt directly beneath the ridge, but this scenario is not required by the MELT team's data.

The magnetotelluric data reveal a striking anomaly: a region of high con-

ductivity at a depth of about 170 km, which the research team needs to explore more closely. Doing so will involve examining the role of water in the mantle. Water can raise the conductivity, of course, and maybe that alone is the cause of the high conductivity at 170 km. But when melt occurs (perhaps higher up in the mantle), the water can enter the mantle's melt phase, causing the remaining mantle to be drier.

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Microcalorimeters May Provide a Solution to the Big Problem of Small Contaminants

As microelectronic devices continue to shrink, submicrometer-sized contaminants pose a serious threat to semiconductor yields and performance—and thereby to the profits of the nearly \$200 billion a year industry. Chemical analysis of these tiny particles can suggest remedies for avoiding contamination by helping to pinpoint its sources. One of the most successful microchemical analysis tools combines electron microscopy with spectroscopic analysis of x rays excited in the target impurity by the microscope's electron beam. Unfortunately, the choice of x-ray detector has traditionally involved a trade-off between energy resolution and speed. So the semiconductor industry—where time equals a lot of money—has often had to supplement spectrometry with educated guesswork. Now, John Martinis, Kent Irwin, Gene Hilton and David Wollman, working at the National Institute of Standards and Technology facility in Boulder, Colorado, have developed an

In a drive to help the US semiconductor industry, researchers are developing x-ray spectrometers that will be able not just to identify any element in microscopic contaminants, but also to yield information about the element's chemical state.

x-ray detector^{1,2} that they hope will remove some of that guesswork.

In general, x-ray spectroscopy can be performed by two types of devices—wavelength-dispersive and energy-dispersive spectrometers. Wavelength-dispersive spectrometers use crystals to Bragg scatter x rays, which are then counted by a gas proportional counter. The short dead times of these counters make possible counting rates as high as 50 000 per second, and the narrow wavelength range scattered at the Bragg angle ensures excellent energy resolution. However, scanning over the entire x-ray spectrum (50 eV to 20 keV) in this mode involves changing

the scattering crystal orientation and switching between crystals—a very time consuming process.

In contrast, energy-dispersive spectrometers use a detector that measures the energy of each incident x ray, simultaneously covering the entire energy range of interest. In spite of the fact that their energy resolution is significantly worse, energy-dispersive spectrometers perform their function so much more quickly and cheaply than their wavelength-dispersive counterparts that they dominate the semiconductor industry.

For over a decade, researchers^{1,3,4} have been developing improved x-ray spectrometers based on microcalorimeters, which use sensitive thermometers to determine individual x-ray energies by measuring the temperature change they produce in an x-ray absorber. With the ability to cover the entire x-ray spectrum simultaneously and theoretical energy resolutions rivaling those of wavelength-dispersive spec-