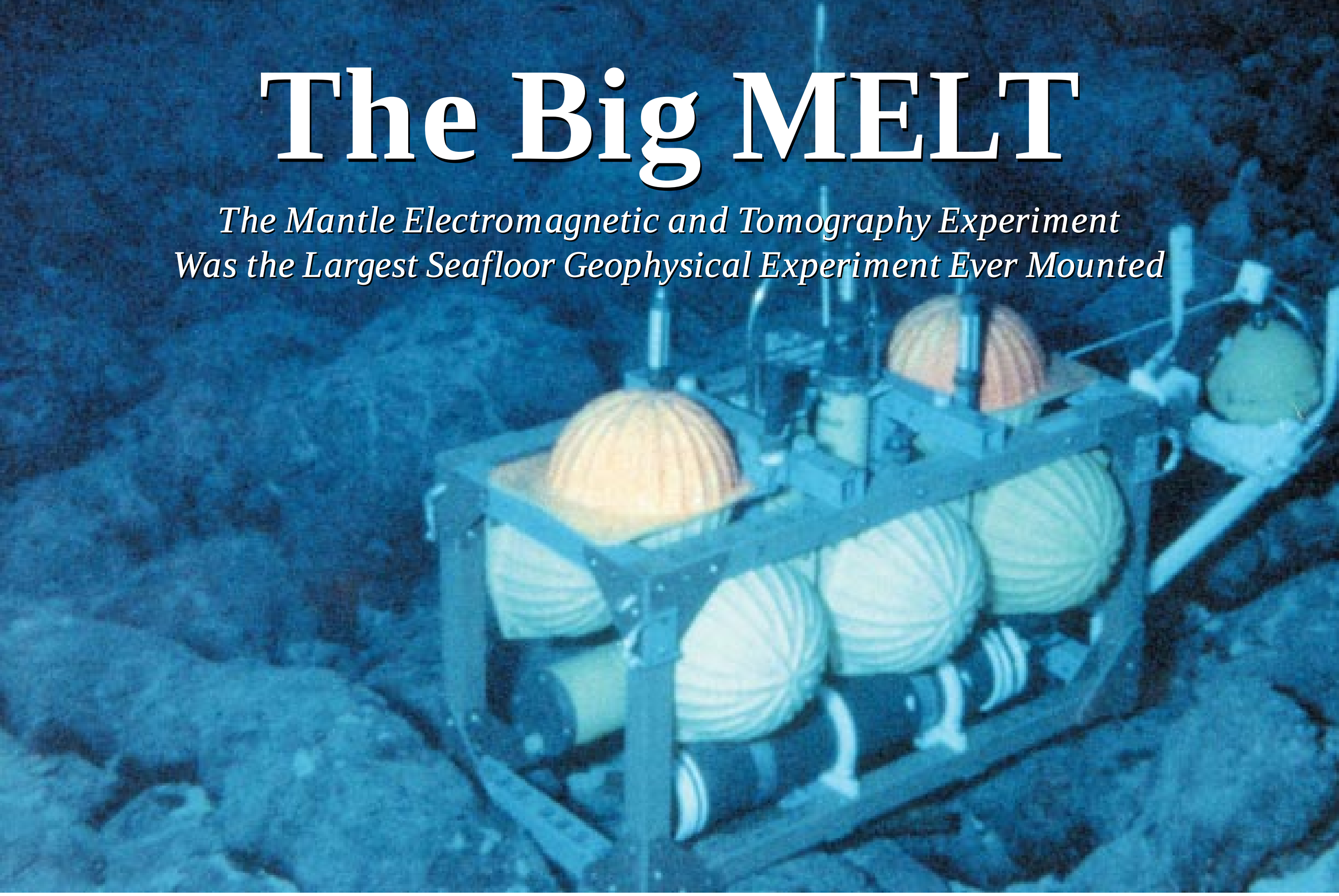
The Big MELT

The Mantle Electromagnetic and Tomography Experiment Was the Largest Seafloor Geophysical Experiment Ever Mounted



An ocean bottom seismometer on the Pacific Ocean floor measures the velocity of seismic waves traveling through the mantle and oceanic crust. These data allowed scientists to probe deep within the portion of the earth that generates new ocean floor.

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More than 95 percent of the earth's volcanic magma is generated beneath the seafloor at mid-ocean ridges. As the oceanic plates move apart at spreading ridges, hot mantle rock rises from deep in the earth's interior to replace material dragged away by the plates. This ascent releases pressure that had kept the hot mantle rocks solid. The mantle rock begins to melt and form basaltic magma, which then percolates up toward the surface through cracks and pores in the remaining solid, yet deforming, rock. At the ridge, the magma pools and solidifies to form a 6-to-7-kilometer-thick layer of new basaltic crust. This crustal layer underlies the seafloor throughout the ocean basins.

Most of what we know about this process of magma or melt production beneath ridges is inferred from the volume of melt indicated by the thickness of the crust and from the composition of basalts recovered at the seafloor by dredging, drilling, and submersible sampling. Much uncertainty remains about where and how the melt forms and is extracted from the mantle, because we have not had any means to directly probe into the melt production region tens to hundreds of kilometers beneath the earth's surface.

Geophysical measurements, however, can provide means to probe deep into the mantle to detect the presence of melt or hot rock. For example, studying seismic waves that travel through the mantle can tell us something about the structure of the earth along their paths, because these waves travel slower in hot rocks and slower still if there are melt-filled cracks or pores. In addition, the forces of flow and deformation within the mantle often cause crystals of olivine or pyroxene, the most common minerals in the mantle, to align in particular directions. This phenomenon, in turn, speeds up or slows down the propagation of seismic waves through the crystals, depending on the direction and vibration of the waves. We can also extract information by analyzing the propagation of electromagnetic waves through the mantle, because basaltic melt is a better electrical conductor than solid rock. If the melt pockets are connected together to form a conducting network, the wave propagation is strongly affected.

In previous studies, scientists examined velocities of seismic waves traveling from their earthquake sources through ridges and to land-based receivers. They mapped regions of slow wave propagation near ridges, but found the data lacked the


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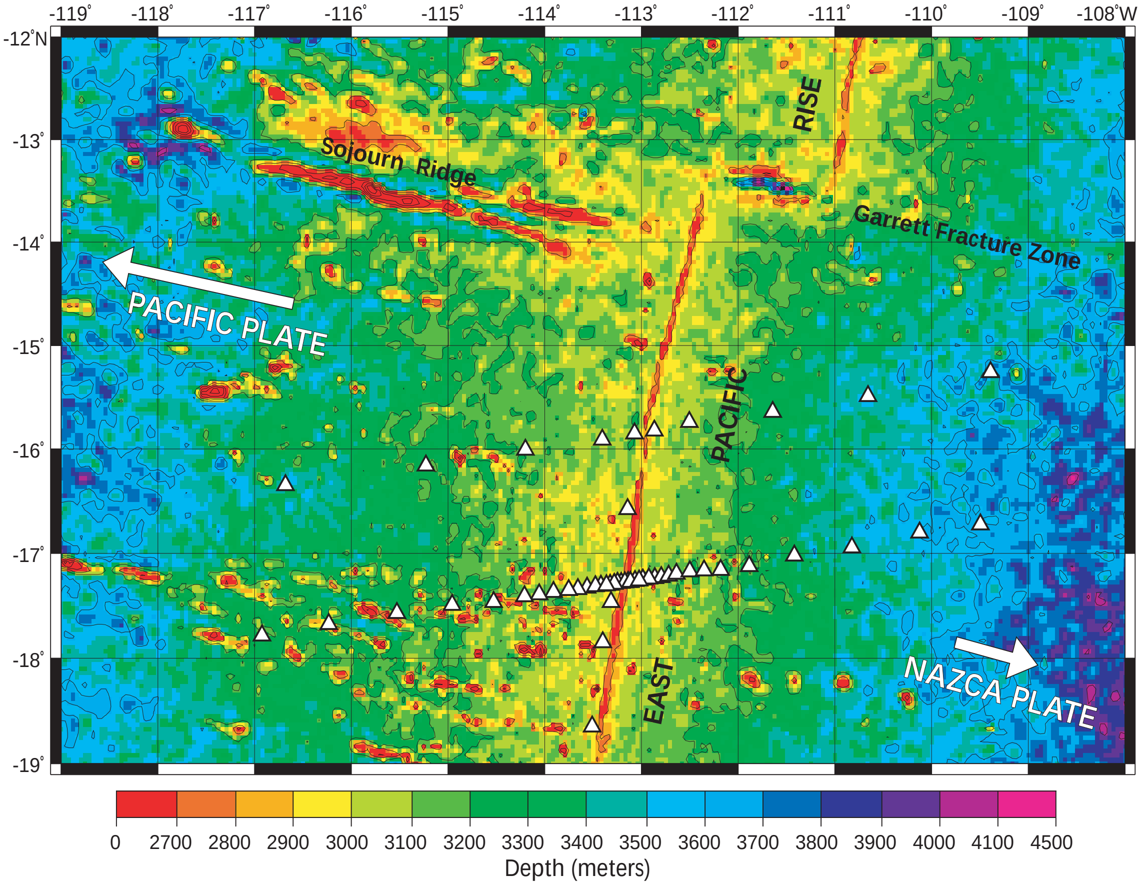
A WHOI ocean bottom seismometer (OBS) is deployed from R/V *Melville* (Scripps Institution of Oceanography) at the start of the MELT Experiment in November 1995. Seismometers within the yellow spheres record ground motion generated by seismic waves traveling through the mantle and the oceanic crust. In May 1996, an anchor on the OBS was released and the instrument floated to the surface, where it was recovered.

resolution to pinpoint the width or depth to which the region of melt production extends. That left room for two competing theories of how magma is generated beneath mid-ocean ridges: Some theoretical models predict that most of the upwelling and melting takes place in a narrow zone, perhaps less than 10 kilometers wide, directly beneath the ridge axis. In other models, melting extends over a broad region and the migrating melt is somehow forced back to the ridge axis to form new crust.

The Mantle ELectromagnetic and Tomography (MELT) Experiment was designed to distinguish between these competing theoretical models by investigating in detail the structure beneath a spreading center. In the largest deployment of geophysical instrumentation ever attempted on the seafloor, a total of nearly 100 ocean bottom seismometers (OBSs), electrometers, and magnetometers were placed in arrays across the East Pacific Rise (see map below). More than 50 scientists from 12 research institutions participated. The OBSs were supplied by groups from Woods Hole Oceanographic Institution and Scripps Institution of Oceanography (SIO), and electrometers and magnetometers by scientists from WHOI, Australia, France, and Japan. Beginning in November 1995, the seismometers recorded seismic waves generated by earthquakes around the world that propagated through the mantle beneath the ridge. In May 1996, the OBSs' anchors were released and the instruments were recovered along with their valuable recordings. The same cruise that retrieved the OBSs also deployed the electrometers and magnetometers to begin a one-year period of recording electromagnetic waves generated by ionospheric



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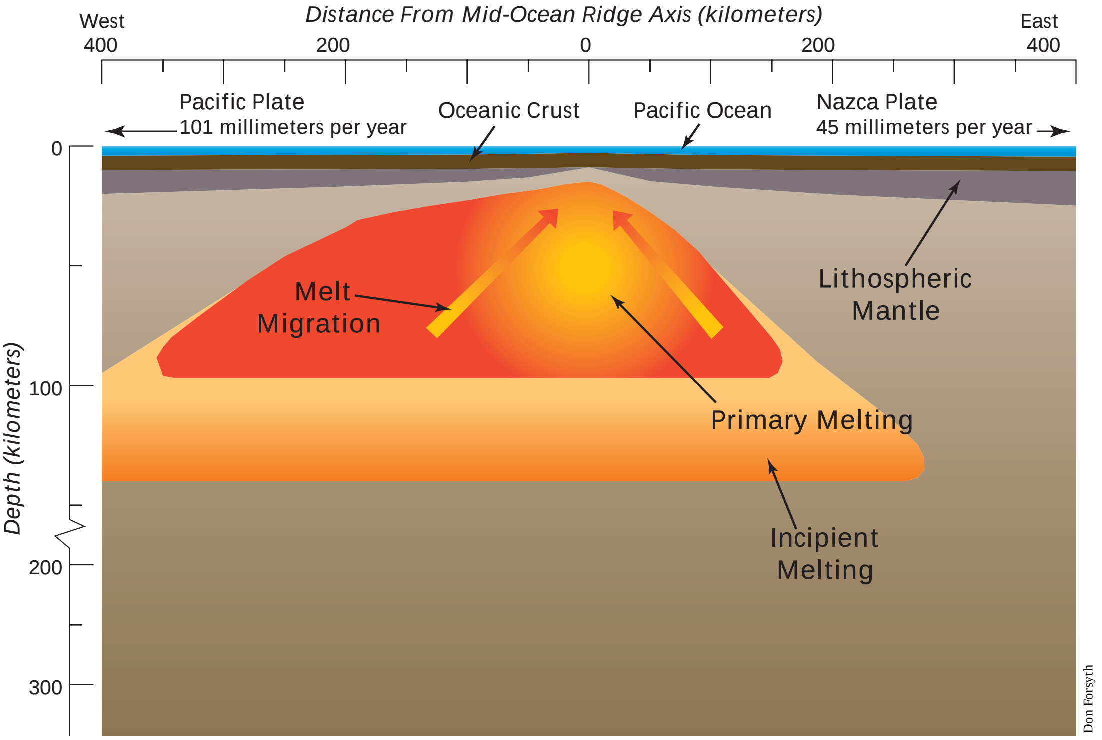
More than 50 ocean bottom seismometers (white triangles) were deployed across and along the East Pacific Rise off the west coast of Mexico during the MELT Experiment to probe the deep structure beneath the mid-ocean ridge. Arrows show the motions of the Pacific and Nazca plates, which are spreading in opposite directions from the ridge crest, shown by shallower depths (red).

currents that penetrate deep into the mantle (see article, page 32).

The East Pacific Rise at 17°S was chosen for the experiment because it is in the middle of one of the longest, straightest sections of the mid-ocean ridge system and is spreading at close to the fastest rate, about 14.5 centimeters per year. In addition, the subduction zones of the Pacific Rim provided an excellent surrounding source of seismic waves, since earthquakes frequently occur in these zones, where the seafloor created at the East Pacific Rise eventually sinks back into the mantle. We were lucky that our six-month recording period was seismically active; there were several earthquakes of magnitude 7 or larger, as well as some good, smaller events on other parts of the East Pacific Rise. One of the best sources was an earthquake 150 kilometers deep in the Tonga subduction zone. We also happened to record the last three underground tests of nuclear devices in French Polynesia, but the signals from these explosions were too small to be useful for our purposes. During the deployment cruise, a group led by Robert Detrick and Pablo Canales from WHOI and John Orcutt and Sara Bazin from SIO employed an array of airguns towed behind the ship as artificial sound sources to acquire data on the structure of the oceanic crust (see article on page 30). Differences in crustal thickness are caused by variations in the supply of magma to the spreading center and thus provide additional information about the process of melt production in the mantle.

Seismic results from the MELT Experiment appear to have settled the long-standing debate about the form of the upwelling beneath the ridge. We found low seismic velocities through a zone several hundred kilometers wide, indicating the presence of melt at depths of 20 to more than 70 kilometers. This wide zone suggests that the separating plates provide the primary force that drives upward flow of the mantle beneath the East Pacific Rise. It contradicts the theory that melting occurs primarily in a narrow zone directly beneath the ridge and that upwelling of the solid mantle is driven and focused by buoyancy forces.

The seafloor begins to subside as it cools and moves farther from the ridge, but at the East Pacific Rise, it subsides more slowly on the western flank than on the eastern. This suggests that the mantle is hotter to the west. Nevertheless, we were surprised by the apparent asymmetry of the mantle structure, as evidenced by the seismic data. The low-velocity region extends as much as 250 kilometers west of the axis, but only about 100 kilometers to the east, and the lowest velocities may even be located west of the axis. Since there are also many more seamounts on the western, or Pacific Plate, side of the axis, the asymmetry may be related to melting and upwelling involved in the off-axis volcanism that builds seamounts. However, this volcanism is much less voluminous than that caused by the seafloor spreading process, producing only 1 or 2 percent of the oceanic crust in this area.



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Initial results from the MELT Experiment are shown in this schematic cross-section of the upper mantle beneath the East Pacific Rise. The melting region below the mid-ocean ridge extends over a broad area several hundred kilometers wide. The region is asymmetrical, with a wider zone west of the ridge than east of it. The melting region also extends far deeper than many scientists have previously theorized: to depths of 150 to 200 kilometers beneath the ridge, although the greatest concentration of melt occurs above 100 kilometers.

Another intriguing asymmetry was found by Cecily Wolfe (WHOI) and Sean Solomon (Carnegie Institution). One type of seismic wave, the shear wave, splits into two components that travel at different speeds in the upper mantle; shear waves go faster when vibrating in a direction parallel to the alignment of the crystals in the mantle—that is, when the waves' vibrations are aligned with, rather than against, the crystalline grain. Wolfe and Solomon found that shear-wave splitting is twice as large beneath the Pacific Plate as beneath the Nazca Plate on the eastern flank, indicating that crystals may be better-aligned beneath the Pacific Plate. This difference may be caused by the different rates of plate motion; relative to the deep mantle, the Pacific Plate is moving twice as fast to the west as the Nazca Plate is moving to the east.

We have determined that the melting region, the region of anomalously low-velocity seismic waves,