

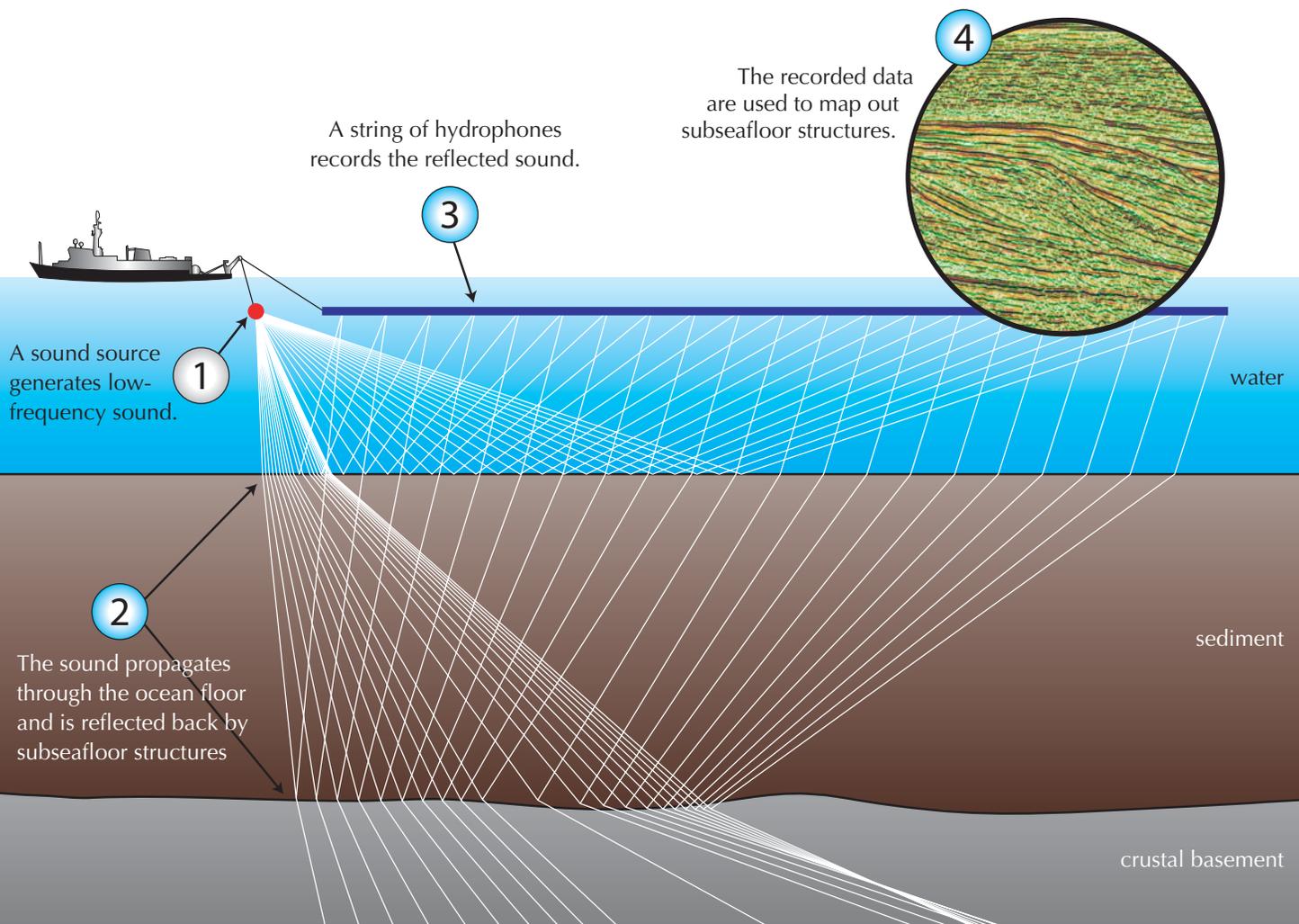
Imaging Earth History

Beneath the Ocean Floor

Three Decades of
Major Scientific Accomplishment

IN THE LAST SEVERAL DECADES, efforts to understand the natural forces that shape and change our planet have accelerated rapidly, particularly in the field of marine geophysics, where researchers use advanced technology to probe deep beneath the oceans and observe Earth's interior. Here we find records of sea-level rise that are key to understanding global climate change, clues about fault behavior that lead to great tsunami-generating earthquakes, and structures that might contain new hydrocarbon resources. We can now "see" magma chambers beneath seafloor volcanoes (where two-thirds of the planet's surface is created) and locate deep faults that provide insight into the processes that control the movement of the continents.

Progress in earth science often has been related to the development of new and more capable observational techniques. In marine geophysics, one of the most important advances in understanding the structure of the shallow Earth has been the development of the marine multichannel seismic (MCS) technique. The MCS technique uses low-frequency (10–50 Hz) sound generated by bubbles of compressed air released every 10–15 seconds into the surface ocean by a slowly moving (~4 knots) research vessel. This sound propagates through the ocean





The R/V *Maurice Ewing* has collected two-dimensional seismic images for the marine earth science community since 1990. Most of the scientific highlights presented in this document are based on data collected by the R/V *Ewing*.

floor, sometimes as much as 20–30 km below it, and is reflected back by geological discontinuities. A long (2000–6000 m) string of hydrophones that is towed behind a research vessel records the reflected sound (echoes). Sophisticated computer algorithms process the many channels of data (hence “multichannel”) and display them so that the echoes map out subsurface structures. Depth to the structures is calculated by measuring the amount of time it takes for the sound to make its round trip from the sea surface to the structures and back—two-way travel time (TWT)—which can be converted to depth below the seafloor.

This document chronicles a selection of significant scientific achievements enabled by data collected using the MCS technique. It also provides the context and background for the recent acquisition of one of the U.S. academic community’s newest and most powerful geophysical observational tools—the research vessel *Marcus G. Langseth*—that for the first time will make three-dimensional seismic imaging routinely available for basic scientific research.

HISTORY

The method of seismic reflection imaging has progressed constantly for nearly sixty years, since analog systems were developed and put in the field by John and Maurice Ewing, aided by other scientists and engineers from what was then the Lamont Geological Observatory of Columbia University. The images created by those primitive systems represented a revolution in marine geophysics, producing for the first time, continuous, two-dimensional profiles of sediment thickness in the ocean basins. Early results confirmed that sedimentary thickness increases with crustal age away from mid-ocean ridges—important data supporting the plate tectonic paradigm.

By the late 1960s, techniques developed to tow long strings of hydrophones (“streamers”) that recorded many separate channels of data improved the ability to “see” inside the Earth. Interest in the hydrocarbon exploration industry fueled many of these developments, and

in the early 1970s, several U.S. academic institutions operated MCS systems for academic research. In 1988, to provide researchers with improved capabilities, Lamont-Doherty Earth Observatory of Columbia University, together with the National Science Foundation, acquired the industry ship *M/V Bernier* and converted it for academic research. Beginning in 1990, this vessel, renamed the *R/V Maurice Ewing*, became the *de facto* national facility for MCS operations for all members of the U.S. academic community. Nearly all of the scientific breakthroughs chronicled in this document were made using data collected by the *R/V Maurice Ewing*.

THE FUTURE

By early 2002, the *R/V Maurice Ewing* had been operating for 12 years. The ship's capacity to collect two-dimensional data no longer satisfied the research needs of the scientific community. To take the next leap in scientific understanding, the community needed to be able to build three-dimensional images of Earth's crust and underlying mantle. For years, the hydrocarbon

SPECIFICATIONS

Built1991 (*Western Legend*)
 Conversion2006 (*Marcus G. Langseth*)
 Length (LOA)71.5 m/ 235 ft
 Beam (moulded)17.0 m/ 56 ft
 Draft (max)5.9 m/19.5 ft
 Gross Tonnage2925
 Crew~20
 Scientific Personnel~35
 Speed Cruising/Full.....11/13 kts
 Range13,500 nm

SCIENCE CAPABILITIES

Laboratory Space..... Total of 425 m²/4572 ft² in 6 labs
 Multibeam Seafloor Imager..... 1° x 1° Simrad 120
 Dynamic Positioning Controller.... Simrad
 Internet Access High Seas Net
 Seismic Acquisition 4-streamer Syntrek 960
 Seismic Streamers..... 4 x 6000 m Thales Sentry, solid-state,
 max across beam spread 600 m

MARINE MAMMAL MONITORING CAPABILITIES

Observation tower control center
 2 x Fujinon "Big Eye" reticular binoculars
 SeaMap passive acoustic monitoring system
 Cameras to monitor bow wave
 Ship-wide communications and data logging

The newly converted research vessel, *Marcus G. Langseth*.



The *R/V*
Marcus G. Langseth

industry had been routinely acquiring three-dimensional data using vessels capable of towing multiple hydrophone streamers. The marine scientific community was seeking comparable data collection for academic research. After careful consideration, it became clear that the community's needs could not be met by a modified R/V *Ewing* and that a new vessel would be needed.

In December 2002, Lamont-Doherty Earth Observatory took the first steps leading to eventual purchase, through a grant from the National Science Foundation, of a used commercial seismic vessel, the *Western Legend*. After being modified for academic research, she was renamed the *Marcus G. Langseth* in honor of the Lamont scientist who was a pioneer in geophysical heat-flow studies. The ship can tow multiple hydrophone streamers (where each 6-km-long streamer is separated laterally from the other by 50–200 m) and can conduct multi-purpose research operations. She can also deploy and recover a full range of over-the-side oceanographic equipment to satisfy the needs of physical, biological, geological, and chemical oceanographers, in addition to collecting the seismic data required to build three-dimensional Earth images.

Of growing interest in recent years is the study of the potential impacts of the sounds that are used to study the Earth on the behavior, habits, and distributions of marine mammals. Rigorous procedures to help ensure that none of these impacts is damaging have been in place on academic seismic research ships for several years. These procedures include, but are not limited to: expert review of the ocean region and time of year to ensure that surveys are not coincident with, for example, critical breeding seasons; use of expert National Marine Fisheries Service (NMFS)-approved marine mammal observers who are authorized to shut down the seismic systems if an animal is observed to enter within a pre-established safety zone; and use of passive acoustic monitoring systems to detect vocalizations from submerged individuals. All academic seismic programs are conducted under the terms stipulated in the NMFS permits issued in accordance with the requirements of the Marine Mammal Protection Act of 1972.

Efforts to minimize impacts on marine mammals have been hampered by inadequate knowledge of their physiology, behavior, and even their most basic distributions and habits. There is a critical need for increased fundamental research in this area (Advisory Committee on Acoustic Impacts on Marine Mammals, 2006). The R/V *Marcus G. Langseth* will have avail-

Safeguarding Marine Mammals



able substantial laboratory space and specialized observation platforms for marine mammal research. Partnerships are being established with leading marine mammal researchers around the United States who will be invited to use the R/V *Langseth* as she steams around the world's oceans conducting research missions.

HAZARDS

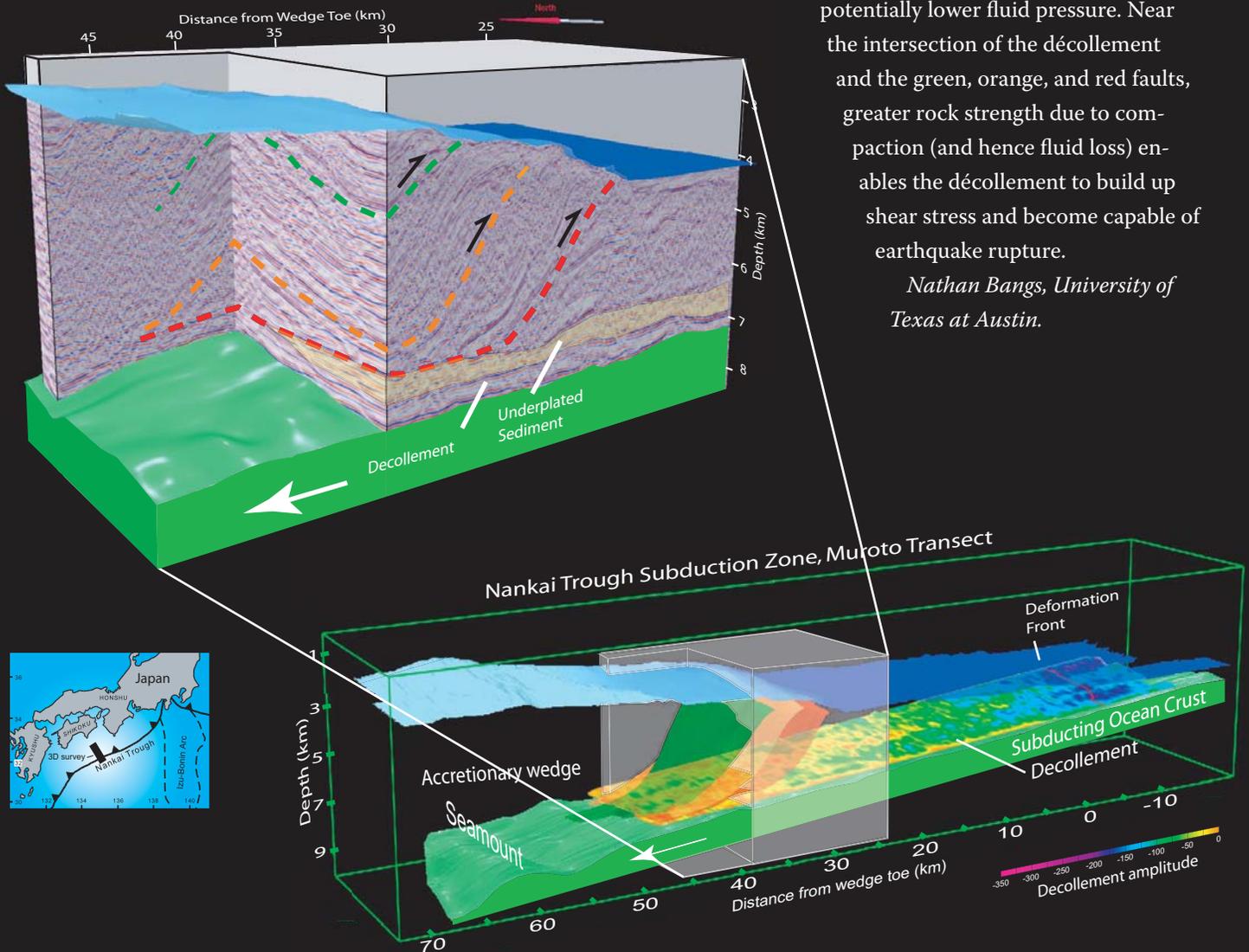
Earthquake Genesis Along the Nankai Trough

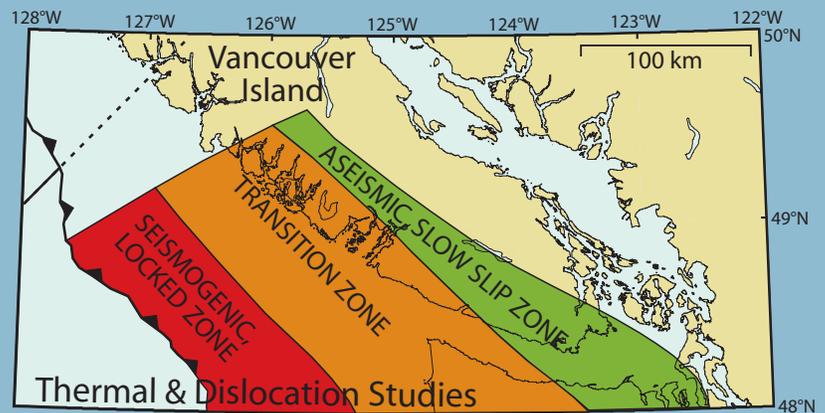
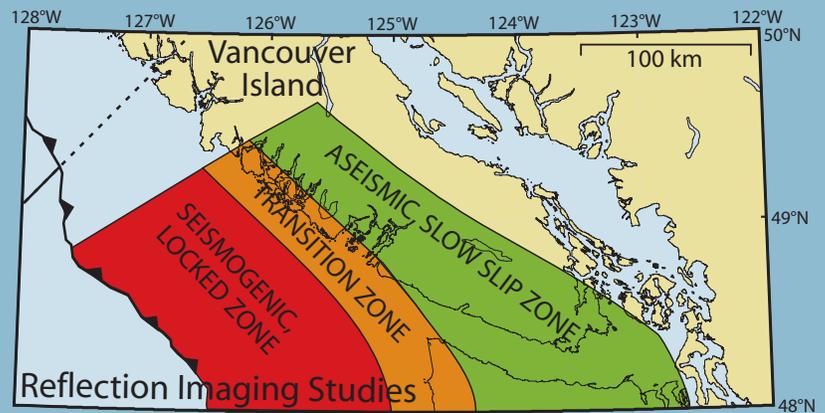
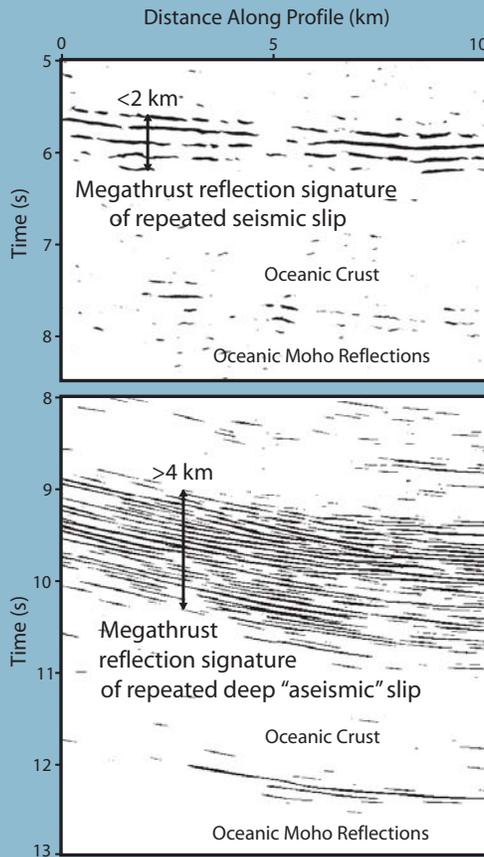
The world's largest earthquakes are generated tens of kilometers below the seafloor as tectonic plates scrape by one another in subduction zones. The massive earthquake along the Sumatra subduction zone, which caused the devastating December 2004 tsunami, is a dramatic example of a subduction-zone rupture. The Nankai subduction zone along the Japan margin can potentially generate an equally powerful earthquake and tsunami. Knowledge of the deep structure and active geological processes along the Japan margin is critical for understanding the genesis of large earthquakes in subduction-zone settings.

The three-dimensional seismic reflection technique was used to image the bumps and irregularities in the Nankai subduction zone where the upper and lower tectonic plates come into contact—the décollement fault. The survey also examined the pressure created by fluids captured within the sediments' pores, which effectively lubricate faults and control their mechanical behavior.

The cool colors (blues) of the décollement (see figure, bottom) are attributed to a fluid-rich fault with high fluid pressures that prevent accumulation of shear stress and thus prevent major seismogenic rupture. With depth into the subduction zone (to the left), the seismic data indicate fluid loss and potentially lower fluid pressure. Near the intersection of the décollement and the green, orange, and red faults, greater rock strength due to compaction (and hence fluid loss) enables the décollement to build up shear stress and become capable of earthquake rupture.

Nathan Bangs, University of Texas at Austin.





Mapping Great Earthquake Rupture Areas

Deep seismic reflection imaging has the potential to become a tool for accurately determining the rupture areas of future great earthquakes. In parts of any subduction zone, the two converging tectonic plates slide freely along their boundary (the *décollement*) or grind against each other, becoming partially or fully “locked.” Plate locking causes stress build-up that is eventually released during an earthquake. Repeated seismic slip—movement that causes a detectable earthquake—over the same stretch of *décollement* causes development of unique structures on that surface that are easily recognized “reflection signatures” on seismic reflection profiles. The same is true for slow “aseismic” slip.

Analysis of multichannel seismic data collected along the northern Cascadia subduction zone near Vancouver Island and Washington State supports this hypothesis. The reflection signature in the zone of repeated seismic

slip in this area appears to be much thinner than that in the slow “aseismic” slip zone (figure, left). Interpretation of seismic images recorded in that region (figure, right) suggests that the locked zone is larger than previously estimated using sophisticated computer modeling—and 30-km closer to land. The populous Pacific Northwest region perhaps faces a greater threat from large earthquakes than previously predicted.

Subduction zones extend over vast tracks of land and sea. Despite significant past efforts to cover them with multichannel seismic profiling, the coverage is sparse and the widths and limits of seismogenic zones are presently not well constrained. There is an urgent need to refine our knowledge of large earthquake seismic hazards worldwide, and certainly for the Cascadia and Alaska margins.

*Mladen R. Nedimovic, Columbia University and
Nathan Bangs, University of Texas at Austin.*

CRUSTAL GENESIS

Flooded with Magma at Volcanic Rifted Margins

Although temperatures exceed 1300°C in Earth's mantle, high pressure keeps the rocks that are deeply buried there mostly solid. When continents break apart to form new ocean basins, these mantle rocks are brought close to the surface where the release of pressure causes them to partially melt. When enough melting occurs, molten rock erupts at Earth's surface as dark-colored lavas called basalts. One puzzle of plate tectonics is that the amount of lava erupted during this process varies greatly—from almost none (see “The Mantle Exposed”) to enormous quantities in very short time periods (called flood basalts). Large volcanic events can result in several-kilometer-thick lava piles such as those along Greenland's coast.

Rifted-margin-related volcanic events are among the largest eruptions on Earth, yet onshore we see remnants of only a small fraction of them. As continents break apart and new ocean basins form, most of these flood basalts

sink below sea level and are buried offshore. Seismic imaging provides key evidence that flood basalts are there. Characteristic tilted (“seaward-dipping”) reflections observed in these data are interpreted to be layered basaltic lava flows that were erupted during the early stages of continental breakup. Interpretation of seismic images suggests that when it formed 56 million years ago, the volcanic province between Greenland and northern Europe covered a land area of nearly one million square kilometers, somewhere between the size of Texas and Alaska.

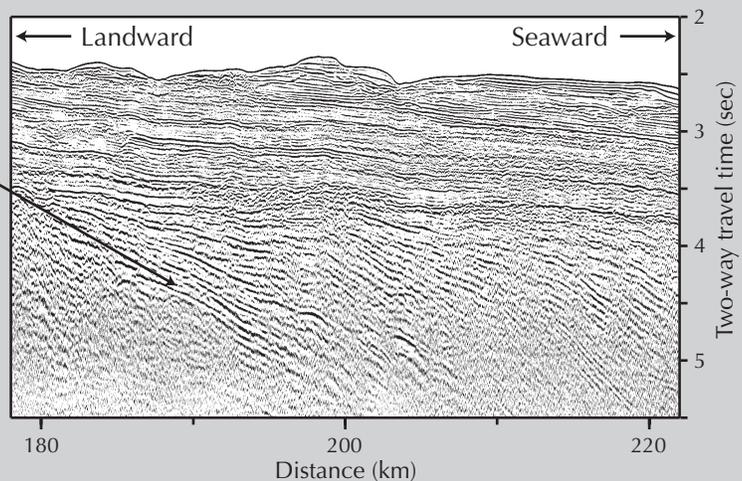
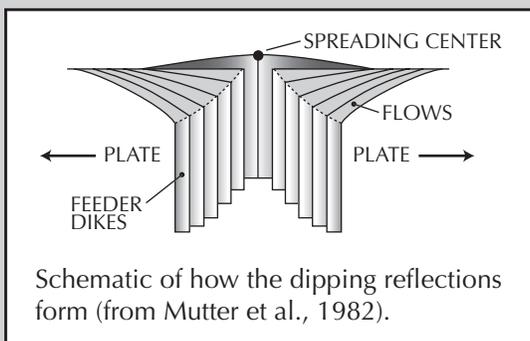
Current research aims to understand the nature and origin of these large eruptive anomalies. The kind of mantle that feeds the global mid-ocean ridge system (where oceanic crust is generated) clearly does not feed continental margins at the earliest stages of ocean-basin formation. Some scientists favor the hypothesis that rifted-margin magmatism results from some form of chemical anomaly or dynamic instability in the mantle, but most believe that an anomalously warm mantle is responsible for these large volcanic events.

John R. Hopper, Texas A&M University



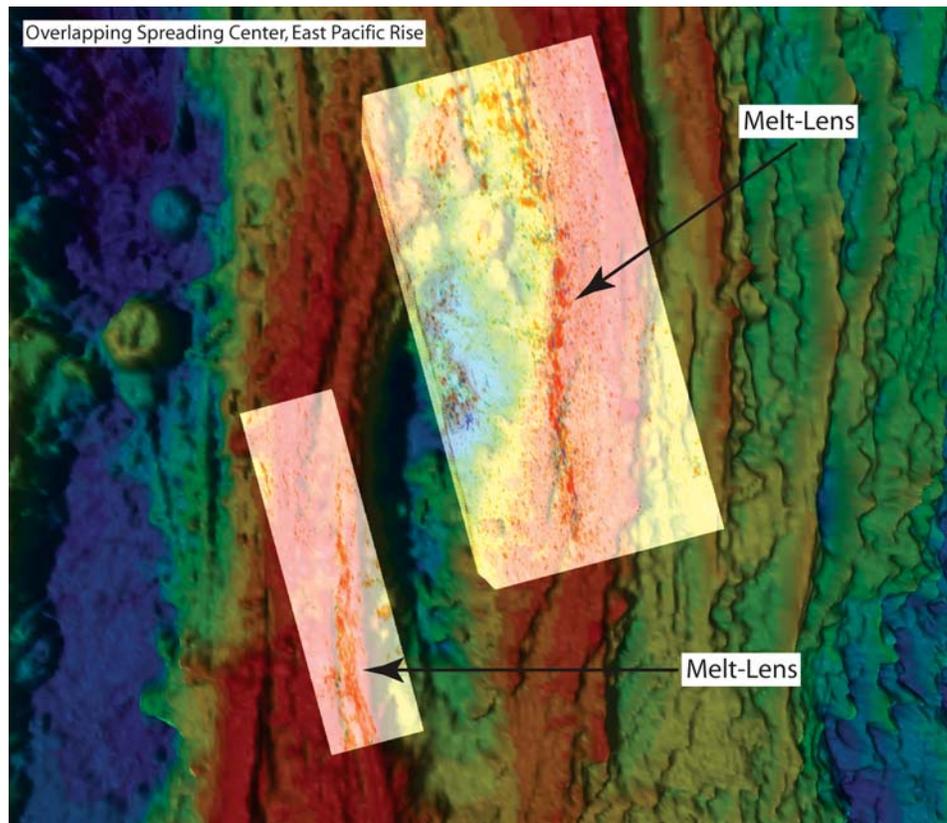
Layered basalts in Greenland exposed on shore...

...are expressed as seaward-dipping reflections in offshore seismic images.



In the seismic section above, the seafloor is at approximately 1900 m water depth; the seismic energy penetrates to 5–6 km below the seafloor.

A top-down view of an overlapping spreading center along the East Pacific Rise. The darker colors represent seafloor topography (blues deeper seafloor and reds higher areas). The colors in the bright boxes represent reflectivity at approximately 2 km below the seafloor, revealing the location of the magma chamber.



A 3-D View of Magma-Chamber Structure

Nearly 70 percent of Earth's crust is formed along the global mid-ocean ridge system, yet little is known regarding the three-dimensional (3-D) nature of this fundamental seafloor feature. For several decades, marine geologists and geophysicists have attempted to understand ocean-crust generation by probing the crust's surface using swath bathymetric surveying, rock and fluid sampling, and visual mapping. Although these seafloor data link melt delivery to active biological, chemical, and geological processes observed at the seafloor, their relationship to subsurface geology remained a mystery.

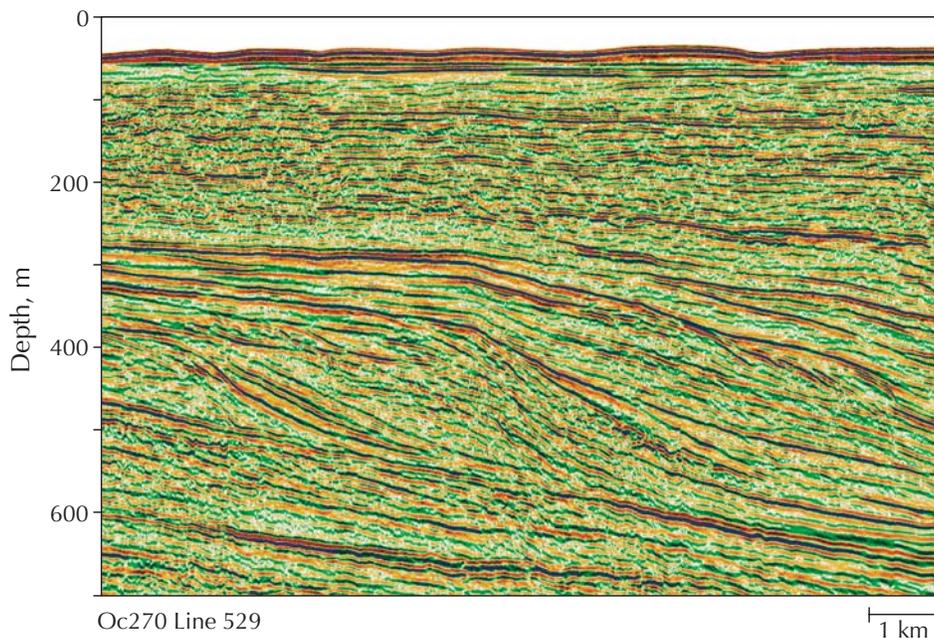
Early two-dimensional MCS data collected along the East Pacific Rise provided the first glimpse of subsurface geology at an active mid-ocean ridge. These data showed a melt lens ("magma chamber") beneath the surface only a few kilometers wide and just tens of meters thick—very small considering the great magma output at the East Pacific Rise. Unexpectedly, this narrow magma chamber was found to be continuous along axis for many tens of kilometers. Also imaged was a larger zone beneath the mag-

ma chamber that consisted of partially melted rock that was likely responsible for continuously replenishing the magma chamber.

Three-dimensional reflection seismology has enabled scientists to now map subsurface features of oceanic crust at resolutions approaching surface-mapping techniques. An early use of this 3-D technique at the East Pacific Rise was to test the hypothesis that irregular features mapped at the surface—discontinuities in the ridge axis, bends and turns of the axis, and the highest topography—reflected the location of axial magma chambers. A surprising result was that some of the largest magma lenses were found beneath topographic lows. These and other findings are leading to new theories of oceanic crust formation at mid-ocean ridge axes.

Future 3-D imaging at mid-ocean ridges will likely focus on the relationship between magma-chamber structure and the distribution of hydrothermal venting.

Graham Kent, Scripps Institution of Oceanography



MCS profile in 35-m water depth ~60 km offshore New Jersey showing sediment sequences that have generally built seaward (towards the right) during times of falling sea level, and upwards during times of rising sea level. Vertical exaggeration ~12:1.

Deciphering the Sea-Level Signal

The idea that seismic reflection data from sedimentary basins might contain a record of past sea-level changes was controversial at the time Peter Vail proposed it in the mid-1970s. But over time, it revolutionized the way in which geologists analyze the stratigraphic record and petroleum companies explore for oil and gas. The principle is simple enough. Sea-level rise generates space in which sediments can accumulate. Sea-level fall results in erosion of previously deposited sediments. Vail and his colleagues concluded that this seismic reflection pattern indicated repeated shifts in sites of sediment accumulation. They found similar reflection patterns and hence stratigraphic arrangements at widely separated locations. Samples from offshore wells indicated that the patterns were broadly of the same age, and therefore that some global mechanism—sea-level change—must be involved.

While the central idea has withstood the test of time, the details have evolved considerably. Precise dating of sediment core samples from boreholes enabled more accurate documentation of the timing of sea-level changes. Two-dimensional analysis of the stratigraphic data clarified the amount of sea-level rise and fall. High-resolution seismic imaging facilitated precise understanding of how the

locus of sedimentation responded to sea-level change.

A surprising result from borehole data analysis is that the wave climate on a continental shelf is at least as important as sea-level change in controlling sediment distribution. Comparison with the deep-sea oxygen isotopic records, which provide information on sediments' age, allowed sea level to be calibrated back into the Paleogene (23 to 65 million years ago), and amplitudes of sea-level change to be determined at much higher age resolution than is possible at continental margins. Seismic data from the deeper-water parts of continental margins have established the importance of submarine landslides and contour-hugging currents in developing stratigraphic discontinuities. And evidence from tectonically active basins now indicates that at some times and in some places, the stratigraphic patterns that Vail first noticed may relate primarily to deformation of the underlying oceanic crust. However, while data interpretation has become a little more complicated than initially envisioned, much of what has been learned may be traced back to Vail's novel idea, and to the advances it inspired in seismic acquisition and processing.

Nicholas Christie-Blick, Columbia University, and Gregory S. Mountain, Rutgers University

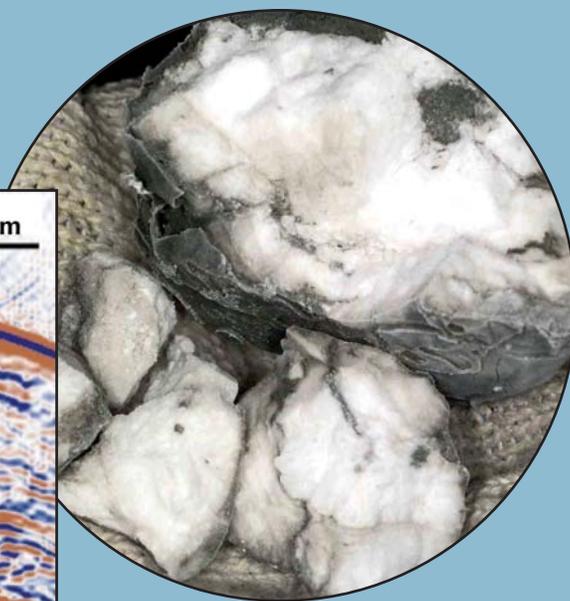
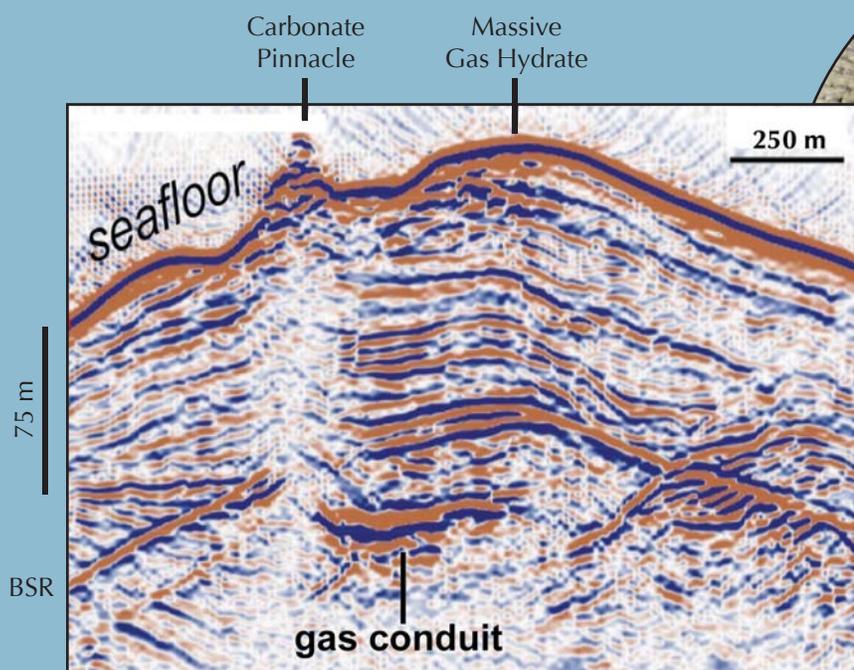
EARTH'S ENVIRONMENT

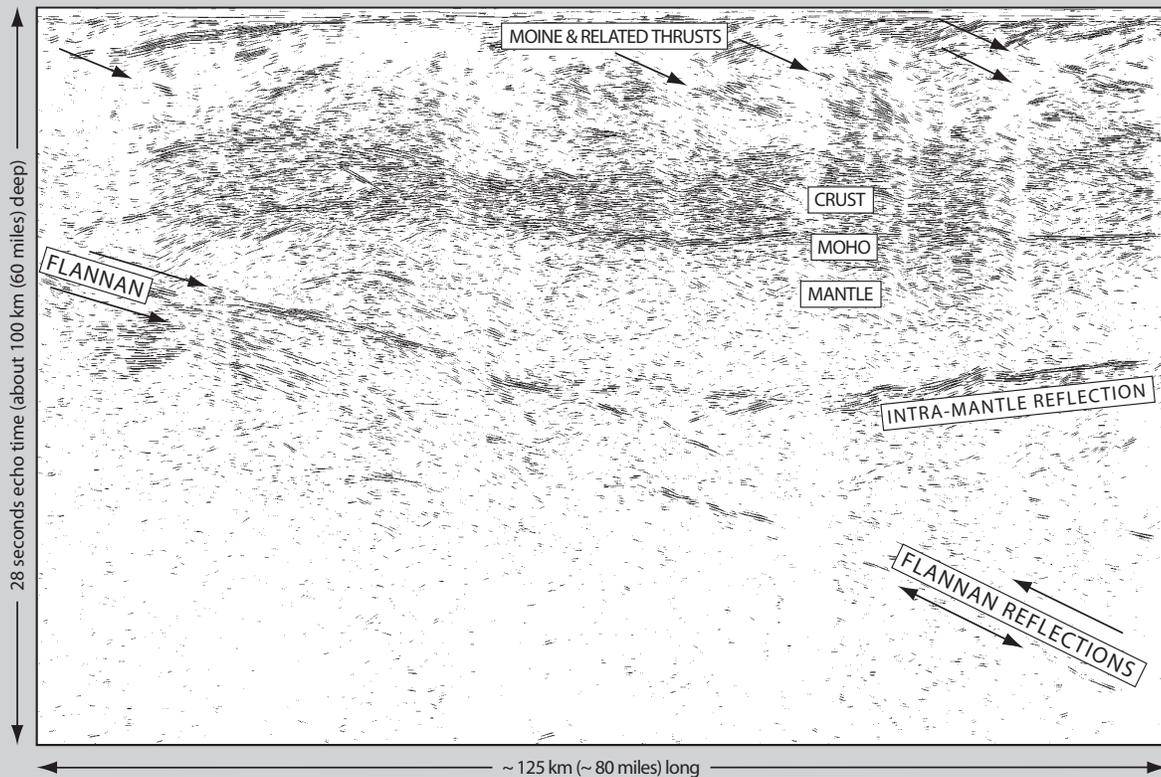
Tracking the Ice that Burns

Gas hydrates are ice-like compounds that form at the low-temperature and high-pressure conditions common in shallow marine sediments at water depths greater than 300–500 m when concentrations of methane and other hydrocarbon gases exceed saturation. Although estimates of the total mass of methane carbon that resides in this reservoir vary widely, marine geologists generally agree that gas hydrates must be considered when evaluating the global near-surface carbon budget. In fact, gas hydrates may act as a “carbon capacitor”; they trap and store methane and thus remove it temporarily from carbon cycle, only to be released suddenly as the environmental conditions that control gas-hydrate stability change. Such abrupt and massive releases of methane from gas hydrates have occurred several times in the geologic past. To include this effect in climate models, a better understanding of how much gas hydrate is present and how it is distributed in seafloor sediments is needed.

Multichannel seismic data have played a critical role in recognizing how widespread gas hydrate is in nature. The base of the gas-hydrate stability zone is often marked by a characteristic seismic “bottom simulating reflection” (BSR). The BSR is readily identified because its contours mimic seafloor topography and it is found at a depth below the seafloor where gas hydrate is no longer stable. BSRs have been found on the margins of continents worldwide. The value of MCS surveys to gas-hydrate studies, however, extends well beyond signaling the presence of gas hydrates. High-resolution seismic data, especially three-dimensional data, are essential for understanding the plumbing system that feeds gas hydrate deposits, for identifying local gas-hydrate concentrations, and for planning follow-up expeditions to sample gas hydrates using remotely operated vehicles and deep-drilling technologies.

Anne M. Trehu, Oregon State University.





Relics of Closure of an Ancient Ocean Basin

In 1981, British scientists formed BIRPS (British Institutions' Reflection Profiling Syndicate) to follow the lead of the U.S. COCORP program, which was pioneering large-scale, deep multichannel seismic profiling of the continents. There was one difference: under the influence of the U.K. hydrocarbon industry, focused offshore in the North Sea, the profiles were to be recorded at sea, as the coastline is largely an accident of modern sea level, and continental crust continues far offshore.

The first profile in 1981 imaged the deep structure of the Moine Thrust, a structure in the Scottish Highlands where geologists first recognized thrust faults 100 years earlier. The Moine Thrust was subsequently identified as one of the principal structures involved in the closing of oceans that sutured together fragments of the North American and European continents over 400 million years ago. Although the Moine Thrust was imaged down to about 15-km depth in mid-crust, the real surprise came from twice as deep, below the Mohorovicic Discontinuity (the Moho—the boundary between the crust and the mantle).

Clearly visible faults continued to at least 80-km depth. These seismic images provided the first evidence that the mantle took up a significant amount of the compression along a newly discovered deep fault (“Flannan reflection”).

In the twenty years following its discovery, the Flannan reflection has been intensively mapped in three dimensions by a grid of profiles covering 10,000 km², tracked along its length for several hundred kilometers, and had its physical properties carefully studied. Data demonstrate that the Flannan reflection likely represents relics of oceanic crust that remained within the lithosphere after subduction halted, rather than sinking deep into the mantle and melting. Other such structures are now widely recognized worldwide, and most are similarly interpreted to be relics of ancient subduction zones. The existence of subduction-related structures of this age seems clear proof of the antiquity of plate tectonics.

Simon Klemperer, Stanford University; Richard Hobbs, Durham University; and David Snyder, Geological Survey of Canada.

LITHOSPHERIC DEFORMATION

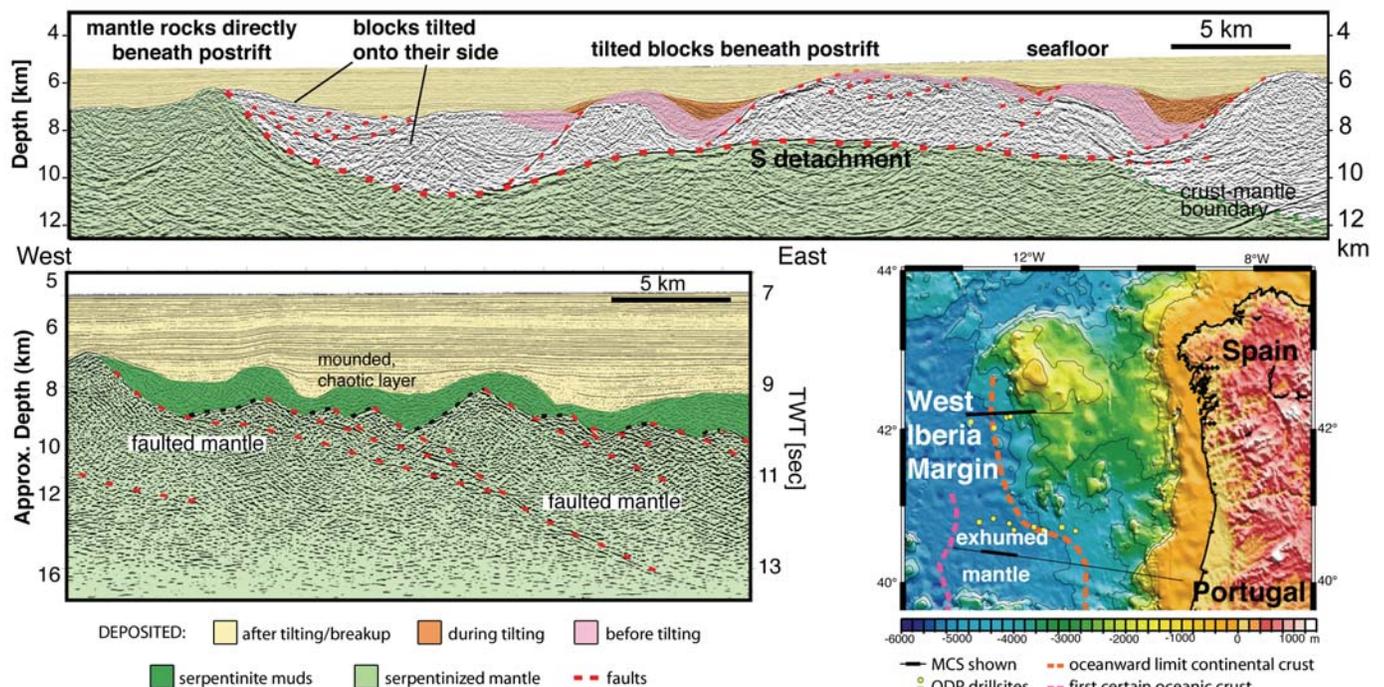
Mantle Exposed

In the geologic past, continents have at times pulled apart to create ocean basins. The extended, broken edges of the continents, known as rifted margins, occur along both sides of the Atlantic Ocean. Along these margins, MCS reflection profiling has been used to discover hydrocarbon reserves. The same technique has been used to image geological structures that resulted from continental rifting.

Where tectonic plates pull apart, hot mantle usually rises to fill the gap to produce new basaltic oceanic crust 6-km thick (see “Volcanic Rifted Margins”). At some rifted margins, such as that west of Spain and Portugal, however, new oceanic crust is not produced. Instead, when the continents pulled apart at this location, the crust broke into many blocks and tilted without new lavas filling in gaps, thus exposing mantle rocks that would ordinarily be found many kilometers deeper inside the Earth. This discovery is enabling scientists to study the boundary between the crust and mantle.

Even where the mantle is still covered by blocks of broken crust, seawater can pass through cracks and into the mantle and alter it into a rock called serpentinite (also known as soapstone). Serpentinites are extremely weak and slippery and allow broken crustal blocks to slide further oceanward along a detachment—a gently tilted fault zone that allows blocks to move easily. (Detachment faults are rather like a tilted, highly polished shelf). Multichannel seismic reflection data suggest that these detachments had unusually high fluid pressures during block movement, facilitating slip along the fault. Elsewhere, it appears that the serpentinites become so hydrated that they are less dense than the overlying crust and flow upward between the blocks, creating mounds of serpentine muds and broken bits of rock on the seafloor.

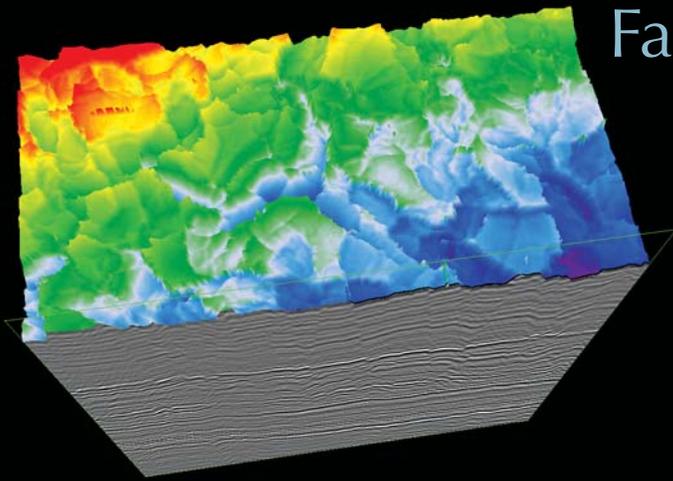
Tim Reston, University of Birmingham.



Time-Lapse Imaging of Magma Movement

The world-encircling mid-ocean ridge is a continually evolving volcanic system driven by magma upwelling from deep in Earth's interior. This magma ponds in reservoirs, forming new oceanic crust through intrusion and eruption. Using four-dimensional multichannel seismic imaging (repeat surveys over months or years), scientists can track movements of magma deep beneath the seafloor to answer questions such as: What triggers volcanic eruptions? What governs where an eruption will occur? How are magma chambers replenished from the deeper mantle? Four-dimensional multichannel seismic studies are also enabling scientists to examine how changes in the interior of seafloor volcanoes relate to the dynamic biological and physical environment observed there. *Suzanne Carbotte, Columbia University.*

Polygonal Fault Systems



A fundamental problem in geology is understanding how seafloor sediments, which initially contain a substantial amount of water, compact to form hard rock. Scientists have always looked at this problem in one dimension where gravity plays a key role in the compaction process. Scientists have identified polygonal fault systems in three-dimensional (3-D) MCS data from the central North Sea Basin that appear to result from compaction of clay-rich sediments. The multidirectional nature of these buried fault systems is evidence that some sediments compact three dimensionally and that some agent other than gravity is responsible. Since first identified, many more polygonal fault systems have been observed globally along passive continental margins in 3-D seismic data. These data are providing unique insights into fault motion, fluid flow, and mineral transformations in the diverse lithologies that make up sedimentary systems. *Joe Cartwright, Cardiff University.*

Seismic Oceanography

In an innovative application of the marine reflection seismology technique, scientists have mapped the ocean's temperature/salinity (density) fine structure with sensitivity down to temperature contrasts of $\sim 0.05^\circ\text{C}$. Similar to the way in which reflection seismology images the boundary between rocks of different densities, "seismic oceanography" images the boundary between ocean water layers of different densities. Seismic reflection profiling is a promising new tool for studying ocean structure and dynamics, which is important for understanding climate change. *W. Steven Holbrook, University of Wyoming.*

Additional Reading

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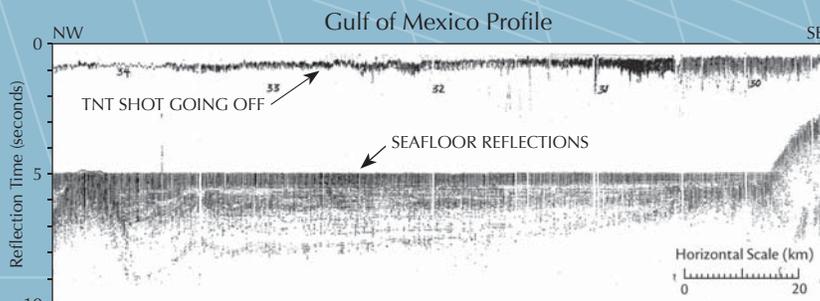
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A WALK THROUGH HISTORY

1960s

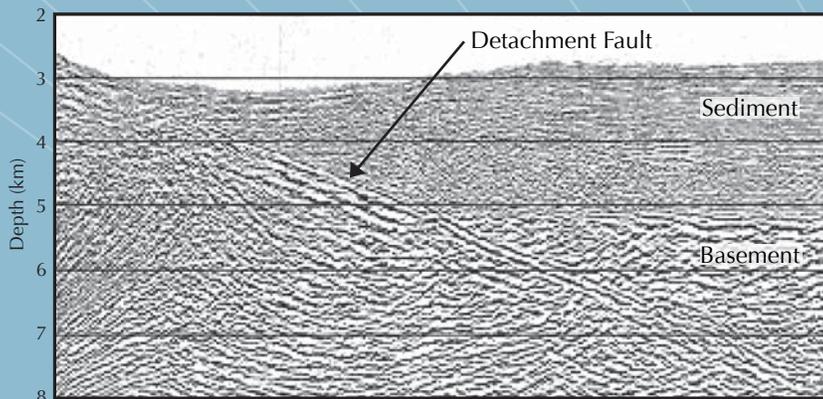
The first ever “serious” marine seismic profiles were made in the 1960s from Lamont Geological Observatory’s R/V *Vema*. The sound source was a handful of explosive TNT (a “shot”). For every shot, a single trace was recorded; the distance between traces depended on ship speed, trace record length, and how quickly the shots could be repeated. Thirty seconds was about the minimum time required, and at typical ship speeds for the day, this translated into 150 meters between seismic traces. Two months after this profile was taken, Lamont scientist John Hennion was killed in a TNT accident during profiling aboard the R/V *Vema*.



R/V *Vema* Cruise 17-04, January 18-19, 1961
Source: Ewing, J.L., and G.B. Tirey. 1961. Seismic Profiler.
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1970s to 1980s

In the 1970s, multichannel seismic equipment, featuring digital recording, began to be used by academic researchers. With a multichannel hydrophone array, a series of traces could be recorded simultaneously, each located at a different distance from the source. This arrangement resulted in quite a few benefits: spacing between traces decreased; along-track spatial resolution improved; the number of traces increased so they could be grouped and summed, increasing the ratio of signal to noise; and the data could be analyzed to determine the velocity of sound within the Earth. Seismic image of a large fault in the Woodlark Basin (near Papua New Guinea) courtesy of Brian Taylor, University of Hawaii and Philippe Huchon, CNRS.



1990s to Present

The marine earth science community has been able to collect three-dimensional data using a single seismic source and receiving array, although it has been a tedious, time-consuming, and expensive process. The R/V *Ewing* has to “mow the lawn,” collecting multiple two-dimensional profiles in a grid. The R/V *Marcus G. Langseth*’s capability to tow multiple, widely spread out source and receiver arrays will enable scientists to efficiently collect the three-dimensional data needed to enhance understanding of Earth’s deep interior. This three-dimensional perspective view of the Barbados Ridge was collected aboard the R/V *Ewing* in 1992. Data from Bangs et al., 1999.

