MARINE SEISMIC IMAGING:

ILLUMINATING EARTH'S STRUCTURE, CLIMATE, OCEANS AND HAZARDS

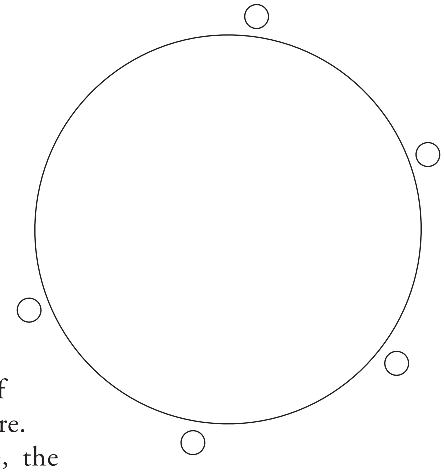
STRENGTHENING A CRITICAL NATIONAL FACILITY

IMAGING THE EARTH IN THREE DIMENSIONS

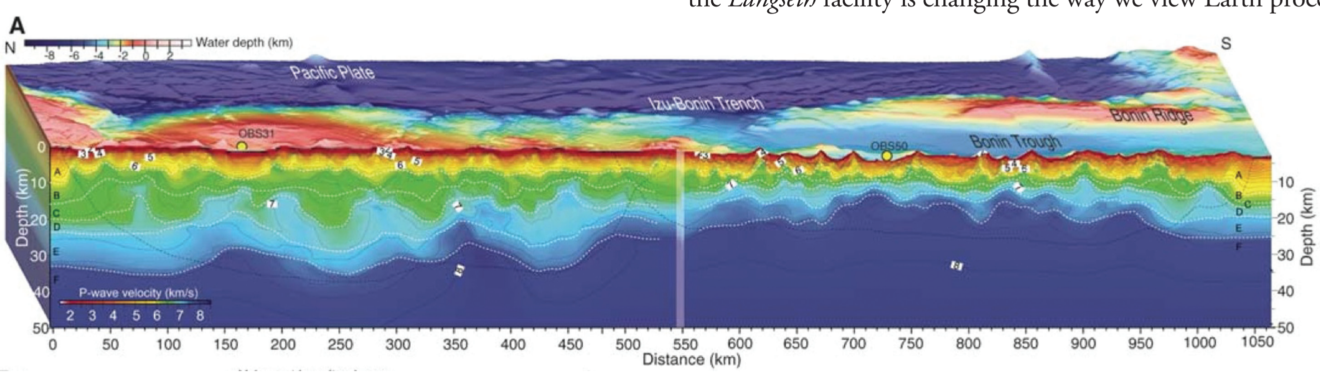
For decades, geoscientists settled for viewing the Earth in two dimensions. For geologists, the two dimensions were "north" and "east" – the horizontal coordinates of the Earth's surface that can be walked and mapped. For seismologists, the two dimensions were "across" and "down" – the coordinates of the vertical cross-sections produced by typical geophysical surveys. But the Earth exists in three dimensions, not two – so most active-source seismic investigations into Earth processes have been limited to incomplete glimpses of true Earth structures.

With the R/V *Langseth* facility, the academic community has its first fully capable 3D seismic vessel. 3D seismic reflection imaging provides a view of the Earth's interior that is unmatched in clarity, quality, and detail by any other method. As a result, a wide array of key Earth processes can now be studied in all three dimensions (and, indeed, four dimensions via time-lapse imaging). With 3D images, scientists can don their "3D glasses" and see the Earth's interior as it really is.

Imaging in 3D furnishes a view commensurate with Earth's internal complexity. Magma bodies can be tracked from their source to their emplacement; gas chimneys can be outlined in full detail; fault planes can be followed as they interact in complex structural systems. In addition, 3D images allow the visualization of Earth properties on horizontal planes or inclined surfaces. The figure at the top of page 2, for example, shows (in red) "patches" of fluid-charged sediments that likely lubricate the megasplay thrust fault off Japan, which has implications for the size of earthquakes and the likelihood of tsunamis generated here. Without a 3D image, the controls on such overpressured zones would be impossible to decipher.



In addition to the new 3D capabilities, the *Langseth* facility offers an advancement to 2D imaging, both for reflection imaging and for sourcing wide-angle surveys using ocean-bottom seismometers and onshore instruments. Owing to an exceptional source array and longer cables, the *Langseth* can collect 2D data that penetrates deeper and with greater clarity than ever before. Such surveys will remain a staple of marine seismology, both for studying large-scale features that extend beyond the reach of a 3D survey, and for reconnaissance surveying of large regions in order to properly site more detailed 3D work. By bringing new imaging capabilities to geoscientists and students, the *Langseth* facility will create a future of exciting discoveries in a broad range of scientific themes, some of which are highlighted in this document. Read on, and see how the *Langseth* facility is changing the way we view Earth processes.

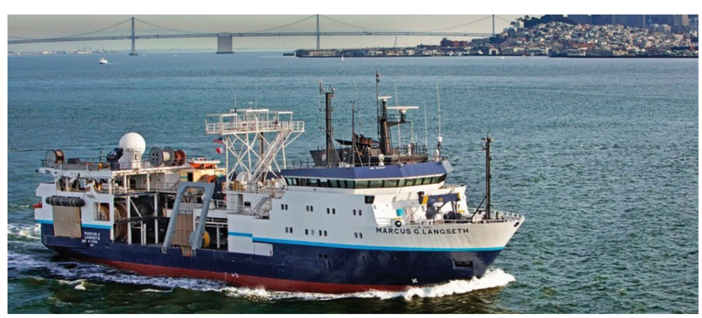


S. Kodaira et al., 2007, *Geology*

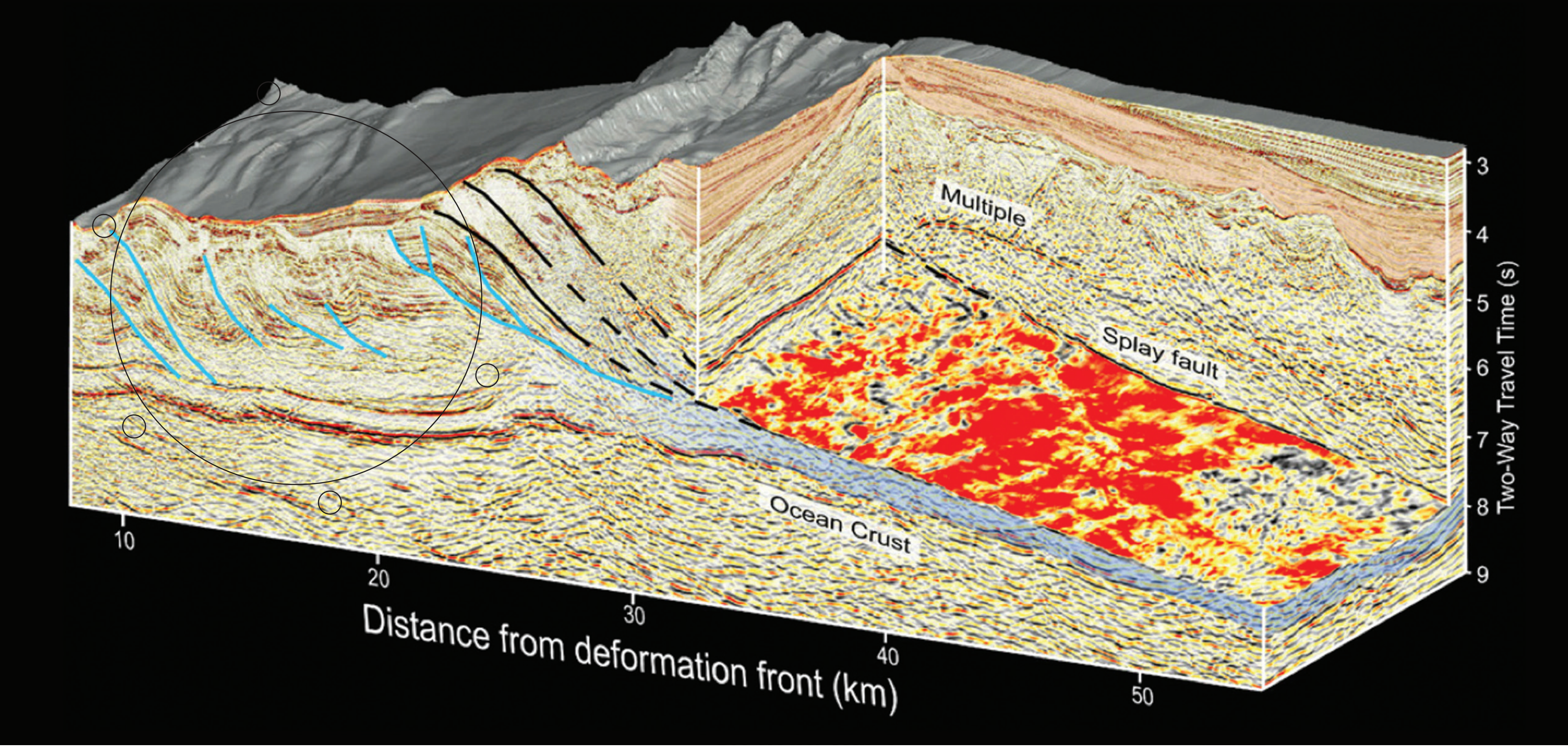
THE R/V *LANGSETH* FACILITY

The R/V *Marcus G. Langseth* joined the U.S. academic fleet in 2008 and serves as an oceanographic research vessel, with special focus on marine seismic profiling. The *Langseth* is owned by NSF and operated by Columbia University's Lamont-Doherty Earth Observatory under a cooperative agreement.

The *Langseth* is distinct among ships in the academic fleet in that it is a designated National Facility. This status highlights the *Langseth's* key role in serving a broad community by providing a unique capability to image beneath the oceans. Unlike other ships in the fleet, the *Langseth* is overseen by an oversight panel, the *Marcus Langseth* Science Oversight Committee (MLSOC), which consists of scientists from the community and serves as a liaison between the science community, the facility operator, and the NSF.



Lamont-Doherty Earth Observatory



N. Bangs et al., 2009, *EPSL*

FACILITY CAPABILITIES

The *Langseth* facility provides a unique combination of capabilities for imaging the ocean, the seafloor, and the solid Earth beneath the sea — as well as general oceanographic instrumentation. Future plans include installing a long-coring capability on the vessel. Current shipboard equipment includes:

- 3D seismic capability, including four 6-km-long hydrophone streamers and dual airgun source arrays
- Long-offset capability, with possibility of towing up to an 8-km-long streamer in 2D mode
- Tuned, linear source array, consisting of up to 36 airguns with a total capacity of 6600 cu. in.
- Kongsberg EM122 multibeam sonar system for seafloor mapping
- RDI 75 kHZ acoustic doppler current profiler (ADCP) to measure ocean currents
- Seabird thermosalinograph to measure seawater temperature and salinity
- Sippican expendable bathythermograph launcher
- Bell BGM-3 gravimeter and Geometrics 882 magnetometer to measure gravity and magnetic fields

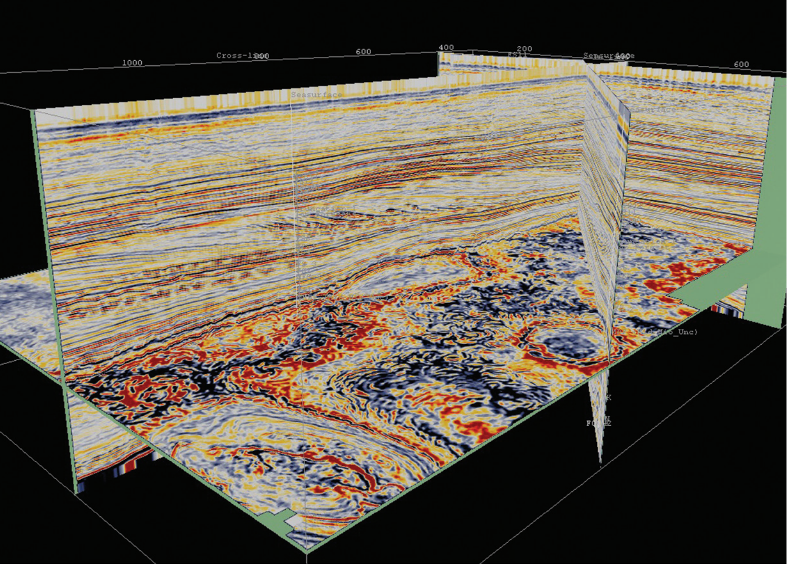
SAFEGUARDING MARINE WILDLIFE

D. Shillington

A fundamental priority of the *Langseth* facility is to conduct scientific research while safeguarding marine wildlife. The facility follows strict protocols while operating at sea, to ensure full compliance with all federal regulations under the Marine Mammal Protection Act and the Endangered Species Act. To aid in this mission, the *Langseth* has a unique marine wildlife observation tower amidships, equipped with two Fujinon Big Eye binoculars, as well as a passive acoustic monitoring system, which are used by trained specialists during all seismic operations.

INSIDE

Compiled and edited by: W. Steven Holbrook. Questions, please contact: steveh@uwyo.edu. Designed by: Brandon Gellis.



PUTTING IT IN CONTEXT
THE CENTRAL ROLE OF MARINE SEISMIC IMAGING

WHY DO WE NEED A NATIONAL MARINE SEISMIC FACILITY?

Numerous key geological processes occur in the solid Earth beneath the oceans:

- Many of the world's most threatening geological hazards occur beneath the oceans.
- Ocean sediments contain the most continuous record of Earth's geological and climate history available.
- 80% of the world's population lives at or near the coast, and they influence, and are affected by, marine geological processes.
- Most of the world's petroleum resources are hosted in marine sediments.

In order to peer beneath the blue ocean, which covers 70% of the planet's surface, research vessels equipped with specialized seismic gear are required. The R/V *Langseth* is the best such seismic vessel serving the world's research community. Without it, Earth scientists would be "blind" to many of the processes that govern Earth's climate, tectonics, environment, and hazards.

RELATION TO CRITICAL SCIENCE AND INFRASTRUCTURE PROGRAMS

The capability provided by the *Langseth* facility — imaging the Earth beneath the oceans and continental margins — is fundamental to modern Earth science. The scientific themes outlined throughout this report testify to the critical importance of maintaining a thriving national marine seismic facility.

In addition to supporting investigator-driven science on these scientific themes, the seismic imaging tool undergirds many U.S. and international science initiatives, including:

- IODP, the Integrated Ocean Drilling Program
- GeoPRISMS (the MARGINS successor program)
- R2K (the RIDGE 2000 initiative)
- Continental Dynamics
- The Ocean Bottom Seismometer Instrument Pool
- IRIS/PASSCAL, including EarthScope

Each of these programs relies to some degree on the ability to image the solid Earth beneath the sea. For example, ocean drilling cannot proceed without knowledge of the targets at depth; continental margin processes cannot be understood without images of subseafloor structure. The unique geophysical capabilities of the *Langseth* make it an asset to a wide range of Earth science programs.

UNDERSTANDING MARINE GEOHAZARDS

GREAT SUBDUCTION EARTHQUAKES AND TSUNAMI

Recent great earthquakes, such as the 2004 Sumatra earthquake and Indian Ocean tsunami, the 2010 Chile earthquake, and the 2011 Tohoku earthquake and tsunami are poignant reminders of the serious hazards from subduction zone earthquakes and associated tsunami. Marine seismic imaging is a critical tool to understand the settings and mechanisms that generate those earthquakes.

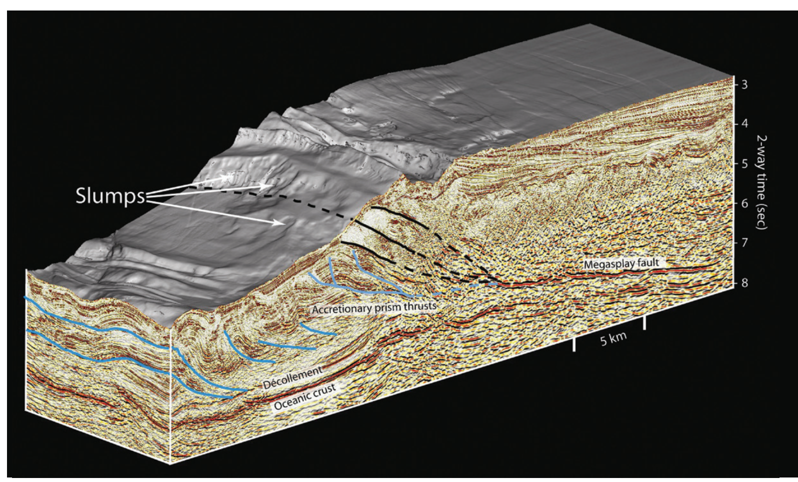
Subduction zones release 90% of the global energy from earthquakes and produce the largest, most destructive events. The Tohoku subduction zone earthquake is particularly prominent as an illustration of our limited understanding of stress accumulation and release along plate-boundary faults. Until the Tohoku earthquake, the Japan Trench was thought to produce frequent relatively small events that relieved stress, and thus it was thought to be incapable of accumulating stress large enough to generate a great earthquake. The 2011 Tohoku great earthquake illustrates our poor understanding of key subduction zone characteristics around the globe and, consequently, the significant gaps in our knowledge of stress accumulation and the earthquake process.

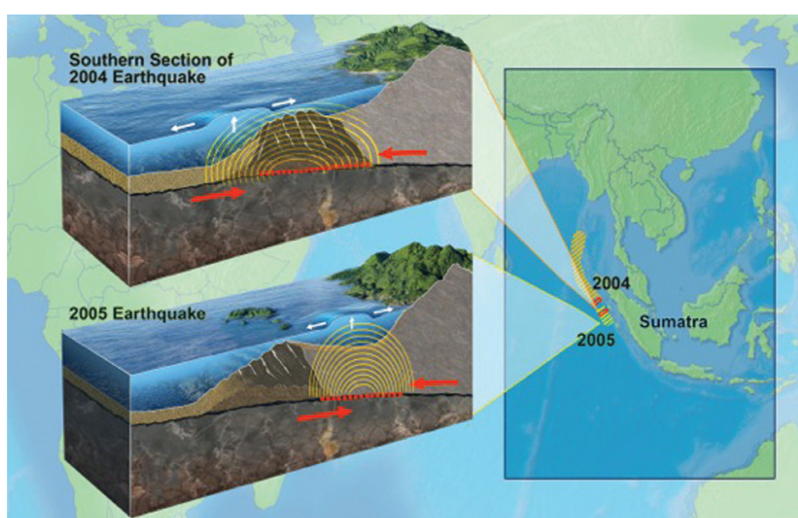
In recent years seismologists have made good progress in reaching these deep, offshore and inaccessible earthquake faults using seismic imaging techniques. Seismic imaging, particularly 3D imaging, which can unravel the distortions of complex deformational structures and bring small details into focus, enables us to map plate-boundary faults down into the seismogenic zone, expose the structure of the colliding plates, and unravel the tectonic history of these settings. Seismic images, particularly when combined with ground truth from cores and borehole observations, provide a powerful tool to map faults and fault characteristics, to constrain rock physical properties and map their lateral variability, and to detect fluids and their migration pathways. These data, along with seismic monitoring, are critical for unraveling subduction zone processes so that we can understand the mechanics of earthquake processes and assess their potential for deadly, destructive earthquakes and tsunami.

The *Langseth* facility represents a major advance in the ability of the academic community to study the mechanisms that generate devastating subduction earthquakes.

Page 3: top to bottom: opendtect.org; wikipedia.org; iodp.tamu.edu.

Page 4: top to bottom: en.wikipedia.org; AP Photo/Radio Tele Ginen; G. Moore et al., 2007; *Science;* National Science Foundation.



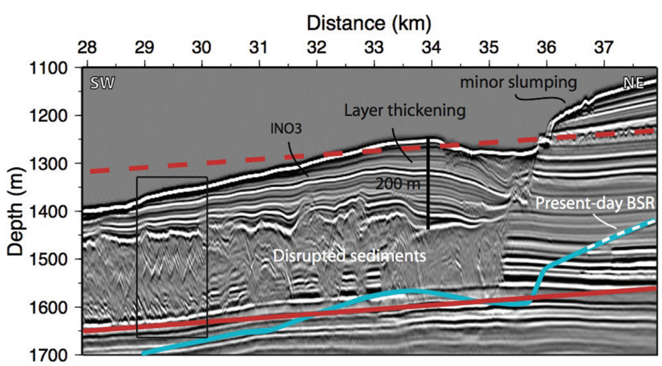


LOOKING AHEAD: GEOHAZARDS

Marine seismic imaging is likely to play an increasing role in assessing and mitigating offshore geohazards. The tragic 2011 Tohoku earthquake off Japan and the consequent tsunami were potent reminders of the importance of understanding offshore seismic hazards. A planned survey by the R/V *Langseth* of the Cascadia subduction zone (pictured) will elucidate the plate boundary structure in a key segment of the subduction zone that is equidistant from Seattle and Portland. This survey will be the first fully open-access, open-participation survey conducted by the *Langseth* and will give students and early-career scientists from around the country a chance to help determine the physical properties of potential rupture zones off the Pacific Northwest.

SUBMARINE LANDSLIDES

Avalanches of seafloor sediment play a major role in sediment transport on continental margins, cause dangerous tsunami, and threaten infrastructure. Seismic imaging can unravel the history of seafloor slides and thus quantify risks.



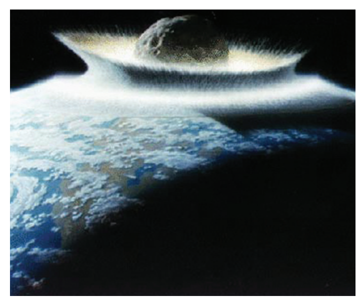
Brown et al., 2006, *Marine Geology*

The seafloor on continental slopes bears the scars of numerous "avalanches" of rock and sediment. These submarine landslides are triggered by earthquakes or volcanic activity and can involve the movement of huge masses of sediment. 8000 years ago, for example, the Storegga Slide (see figure) affected an area of seafloor the size of Portugal, moved five times more sediment than the Amazon River delivers to the ocean annually, and caused a 10-m-high tsunami that inundated the coasts of Norway, Iceland, and Greenland. Smaller, more frequent slides can endanger seafloor infrastructure.

A crucial unknown is the recurrence rate of landslides on different parts of the world's continental margins. While the most recent landslides can be interpreted from seafloor bathymetry, past landslides are buried beneath later sediments. 2D and 3D seismic imaging can uncover the history of landslide events and thus help quantify the risk to populations and infrastructure posed by these event.

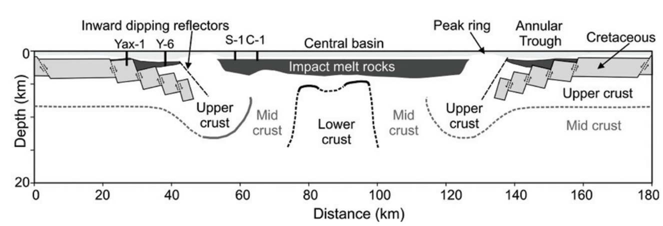
IMPACTS FROM OUTER SPACE

Impacts of extraterrestrial bodies have caused major extinctions and altered climate throughout geologic history. Seismic mapping of impact craters can help elucidate the size and trajectory of the impactor.



NASA/Don Davis

Impacts of objects in Earth-crossing orbits pose an existential threat to life on Earth. While impacts with large objects are rare, they occur throughout geological history, often with devastating consequences: several of the largest mass extinctions in Earth history have been linked to impacts, including the well-known "dinosaur killer" at the Cretaceous-Tertiary boundary. Impact craters less than 200 million years old are well-preserved



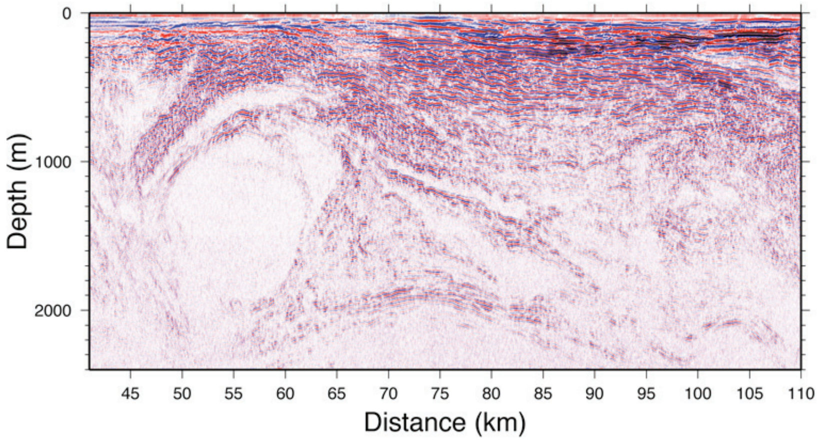
Vermeesch and Morgan, 2008, *JGR*

in the marine environment and provide unique opportunities to study the dynamics – and consequences – of large impacts on Earth.

EXPLORING EARTH'S ENVIRONMENT

PROBING OCEAN MIXING

Marine seismic imaging offers an entirely new view of the internal structure of the world's oceans.



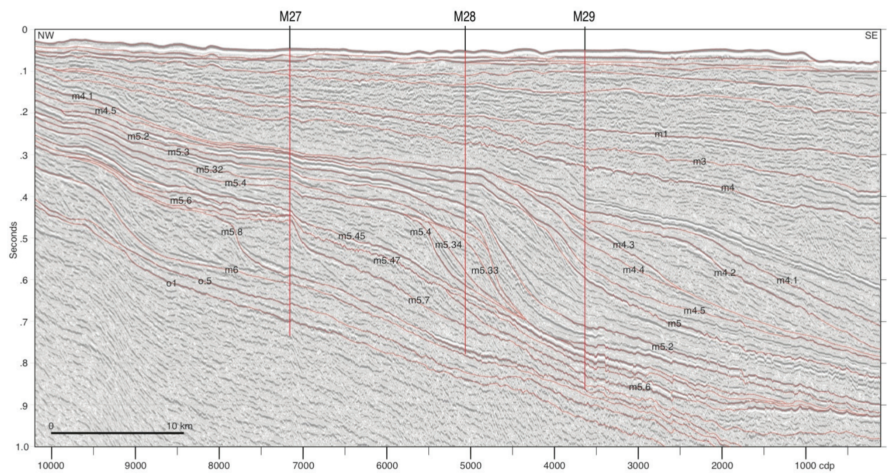
Holbrook et al., 2003, *Science*

The oceans are often called the "flywheel of climate" due to their profound role in Earth's climate system. The global ocean stores much of the hydrosphere's heat, transports fresh water and heat to polar regions, and sequesters carbon dioxide from the atmosphere. A critical factor in these processes is ocean mixing, the turbulent blending of contrasting water masses. Although mixing intensity is a key parameter in climate models, its distribution in the oceans is poorly understood, due to the difficulty of measuring it *in situ* over broad regions.

Now marine seismology has added a surprising new tool to the oceanographer's toolkit. While seismic reflection profiling has been used for decades to image the solid Earth beneath the ocean, recent work has focused the seismic "lens" upward, into the ocean itself. By turning their attention to previously ignored "whispers" in reflection profiles, seismologists can now create spectacular images of oceanic processes, including fronts, eddies, internal waves, and turbulence. This "old dog with a new trick" now offers a high-resolution tool for imaging ocean structure and mixing, including newly developed techniques to estimate and map key quantities, such as internal wave energy and turbulent dissipation rates.

SEA LEVEL AND SHORELINES

Sea level changes in Earth's past help scientists understand the changes happening today. Marine seismic imaging provides the stratigraphic evidence for global sea level changes and the context to understand samples from isolated drill cores.

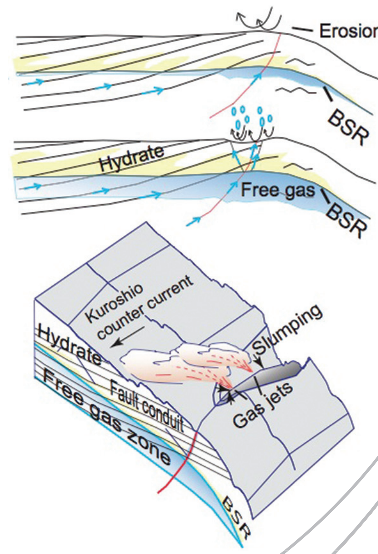


Mountain et al., *IODP Exp. 313*

In order to predict future changes in sea level and shoreline location, it is vital to constrain the range of past variability. For example, the geological record shows that climate and sea level do not always respond linearly to forcing and that abrupt events can disrupt gradual trends. Computer models used to predict future change must be capable of reproducing the conditions we know to have existed in the past. A key technique for estimating past sea-level change uses scientific ocean drilling of continental margins. Such drilling targets the geological environment directly affected by sea-level change as the shoreline migrates back and forth across the continental shelf. Coring the resulting record of sediments and unconformities (sequence stratigraphy) provides information on ages, depositional environment and paleowater depths during sea-level cycles from coastal plain to outer shelf settings. Since boreholes provide information at only a few locations, integration of seismic imaging is vital to place drilling results within a two- and three-dimensional context in order to evaluate the influence on sequence architecture of along-strike changes in sediment input and structural controls, as well as to provide geomorphological information about sedimentary processes and paleoenvironments.

LOOKING AHEAD: IMAGING THE ENVIRONMENT

The world's oceans are on the leading edge of climate change: changes in sea level and in ocean temperature have profound effects on the marine environment. Several of these processes can lead to feedbacks (positive or negative) that need to be studied to gain a complete understanding of the impacts of climate change. Bottom-water warming, for instance, has been linked to the dissociation of methane hydrate at and beneath the seafloor in high-latitude regions – but we know little about how widespread this process is, nor about the time scales involved. Seafloor erosion and landslides can also lead to massive releases of methane (see figure), a potent greenhouse gas. All of these processes can be elucidated with 3D and 4D ("time-lapse" 3D) seismic imaging.



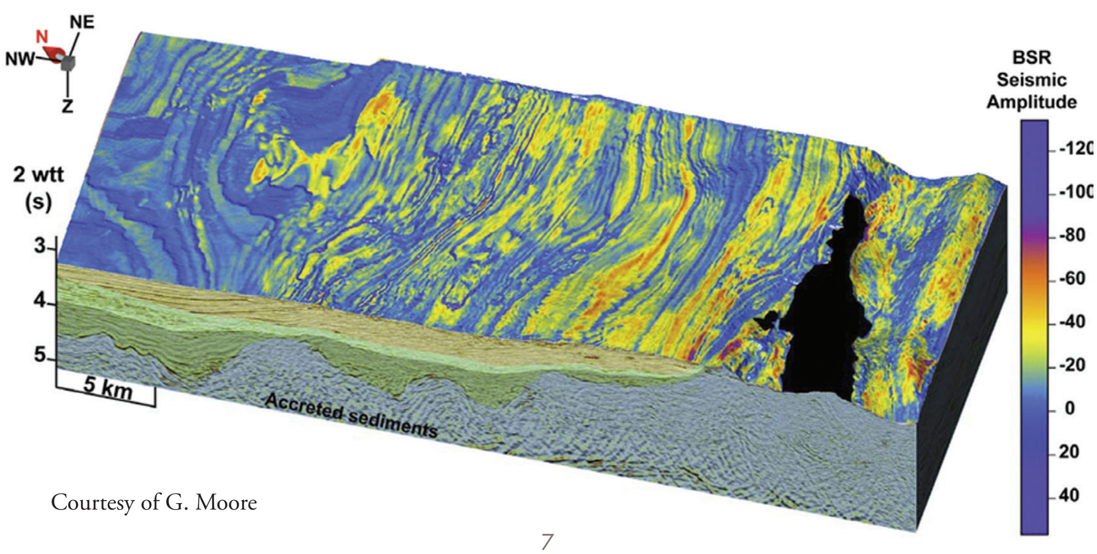
Bangs et al., 2010, *Geology*

MAPPING THE ICE THAT BURNS

Methane hydrate is an ice-like, solid form of methane plus water that is widespread on Earth's continental margins and has implications for seafloor stability, energy resources, and Earth's climate history. Marine seismic imaging is the best means of remotely detecting and mapping this elusive but important substance.

Methane (natural gas) formed by microbial respiration or deep thermal processes is common in the pore spaces of continental margin sediments. In many locations, that methane exists not as gas bubbles, but rather as an ice-like solid called methane hydrate – a substance that is unstable at room temperature and pressure but forms readily at the high pressures and low temperatures common in deep-sea sediments. Gas hydrate contains so much methane that holding a match to the hydrate causes it to ignite, creating "burning ice."

Seismic, geochemical, and drilling surveys over the past decade have shown that methane hydrate exists on every continental margin on Earth and constitutes an enormous reservoir of potentially mobile carbon. Yet the role of methane hydrates in the global carbon cycle is very poorly understood. Because gas hydrate can destabilize due to changing ocean temperature and pressure (i.e., sea level), changing environmental conditions could release large quantities of methane – a potent greenhouse gas – into the oceans and atmosphere. Such destabilization can affect seafloor stability, cause submarine landslides, and contribute to climate change. 3D seismic imaging is capable of mapping hydrate concentrations in stunning detail (see figure) and thus promises fundamental progress in understanding the geological, biological, physical and hydrological controls on the formation and accumulation of methane in marine sediments.



Courtesy of G. Moore

CONSTRAINING EARTH FLUXES AND CYCLES

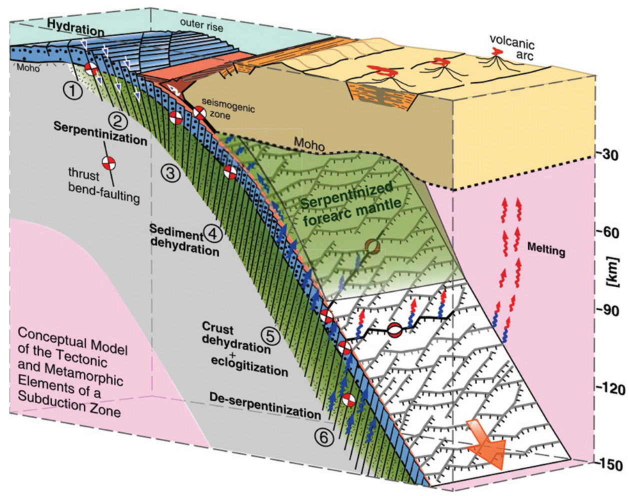
D. Shillington

THE SUBDUCTION SPONGE: SEAWATER IN EARTH'S MANTLE

Seismic imaging has shown that faults at subduction trenches provide pathways for seawater to infiltrate the downgoing oceanic lithosphere, causing hydration reactions that can regulate the chemistry of arc volcanoes, the strength of subducting plate boundaries, and global fluid budgets.

One of the most far-reaching discoveries of the past decade is the observation that vast amounts of seawater penetrate into the oceanic crust and upper mantle at subduction zone trenches. The seawater seeps down faults created when the downgoing tectonic plate bends and cracks on its way into the trench. These faults have been imaged on marine seismic data and appear to penetrate up to 20 km into the downgoing plate. Low seismic velocities in the upper mantle have been measured in ocean-bottom seismometer surveys and indicate that, in places, up to 30% of the mantle has been converted into water-bearing serpentinite, so that water comprises 3-4% of the total rock volume. Such large quantities of water can have profound consequences for chemical, tectonic and hydrologic processes on the plate boundary and in the overlying melting zone and arc volcanoes.

While this phenomenon has been well studied at a few locations, at present we know little about the global significance of the "subduction sponge." Trench faulting has been observed on the seafloor at many trenches, but we lack a systematic understanding of the depth of penetration and spatial distribution of serpentinization at trenches, to say nothing of the transport pathways and consequences of released water deeper in subduction zones. Marine seismic imaging will play a major role in addressing these outstanding questions.



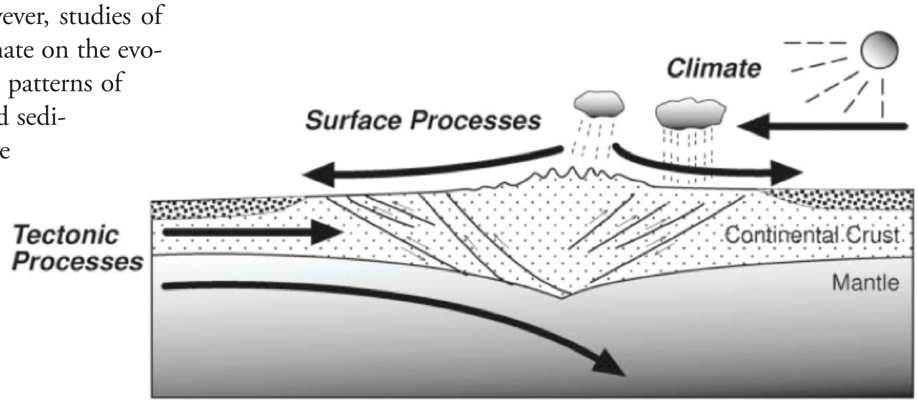
Ranero et al., 2005, *G-Cubed*

TECTONIC-CLIMATE FEEDBACKS

Tectonics and climate are more tightly linked than previously thought. The record of that interplay can be imaged offshore.

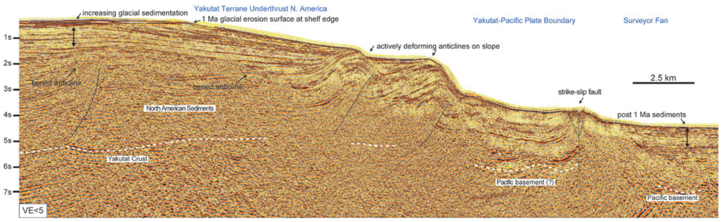
A paradigm shift has occurred in the last two decades in understanding the interplay between tectonic and climatic processes in the evolution of the Earth's surface. Examples of tectonic plate movement affecting climate are well known — for example, the opening of the Southern Ocean ~35 million years ago, when South American separated from Antarctica. However, studies of mountain belts have now shown the effect of climate on the evolution of tectonic deformation, rock exhumation, patterns of erosion, and transport and re-deposition of eroded sediments. In other words, climate appears to influence mass and volatile flux within and out of regions of tectonic deformation such as mountain belts; increases in erosion from, for example, intensified glacial-interglacial cycles or cyclonic storms can fundamentally influence tectonic evolution.

The records of past climate-tectonic feedbacks are stored in the eroded products of mountain ranges, in sedimentary basins offshore. Marine seismic imaging, together with drilling, is required to measure the volume, extent, and history of this erosion. Some key targets for tectonic-climate research include examining the relationship of the Asian monsoon system and the rise of the Himalaya, the interaction of the Cordilleran ice sheet and the northern Cordillera mountain ranges, and connections between Patagonian dust production and Antarctic climate cycles.



Modified from S. Willett, 1999, *JGR*

LOOKING AHEAD: CLIMATE CONNECTIONS



Modified from Worthington et al., 2010, *Tectonics*

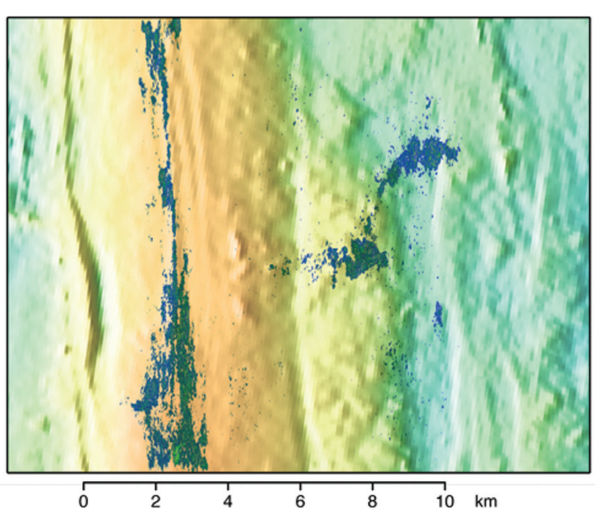
The interplay of tectonics and climate is complex, yet the use of long streamers in 2D has allowed for imaging structures and stratigraphy in the subsurface that allow unraveling these interrelated processes. Future directions involve deep imaging in 2D and progressing into 3D along continental margins and in deep-sea fans that record climatic events and their effects on tectonics (or vice-versa). The example shown here is from the Gulf of Alaska, where a cooling Plio-Pleistocene world first results in greater sedimentation and shutting down of faults on the shelf followed by Mid-Pleistocene glacial advances to the shelf edge, causing erosion and re-deposition of sediments in an adjacent deep sea fan.

MAPPING MAGMA FROM THE MANTLE TO THE SURFACE

CREATION OF THE OCEAN'S FLOOR

Oceanic crust forms the majority of Earth's solid surface; its creation at mid-ocean ridges and destruction at subduction zones are fundamental engines of plate tectonics. Marine seismic imaging is a crucial tool for studying the structure and evolution of oceanic crust and mantle.

The mid-ocean ridge system encircling the planet is not only responsible for creating two-thirds of the planet's surface, but provides critical heat to drive vigorous hydrothermal circulation of fluids that exit the seafloor at vent sites known as "black smokers". These hot, nutrient-laden fluids reach temperatures approaching 400°C, and support complex "life in extreme environment" biological communities — composed of exotic tube worms and other species that have adapted to a lightless environment. Early life on Earth may have evolved from within this environment, and the mineral deposits that precipitate at vent sites are analogs for important economic sulfide mineral deposits on land. With seismic imaging we have been able to probe beneath these vent sites to image an axial magma lens or sill some 1-3 km below that is the primary heat source driving the hydrothermal system (see figure). This sill is typically a few kilometers wide and tens of meters thick, but can have along-strike continuity of 10s or perhaps 100s of kilometers. Sophisticated seismic processing can discriminate between "melt-rich" portions of this elongate magma system and the overlying fluid pathways in the rock matrix. Early indications show a strong relationship between melt-rich pockets within the magma sill and the hydrothermal communities above. Successful mapping in 3D along the East Pacific Rise over the past decade provides an exciting opportunity to now study how these dynamic systems evolve through time (the "fourth dimension"). With application of advanced "4D" seismic imaging technology, numerous questions can be addressed, such as: What triggers a volcanic eruption and can eruption location be predicted from structure within the magma lens? On what time scales and how is melt fed from the deeper mantle to the crust? How do vent communities respond to temporal changes in the magma source below? With the modern imaging capabilities provided by the *Langseth* we can now move beyond a structurally-based view of the mid-ocean ridge to a true understanding of the active dynamic processes underlying one of the dominant features on planet Earth.

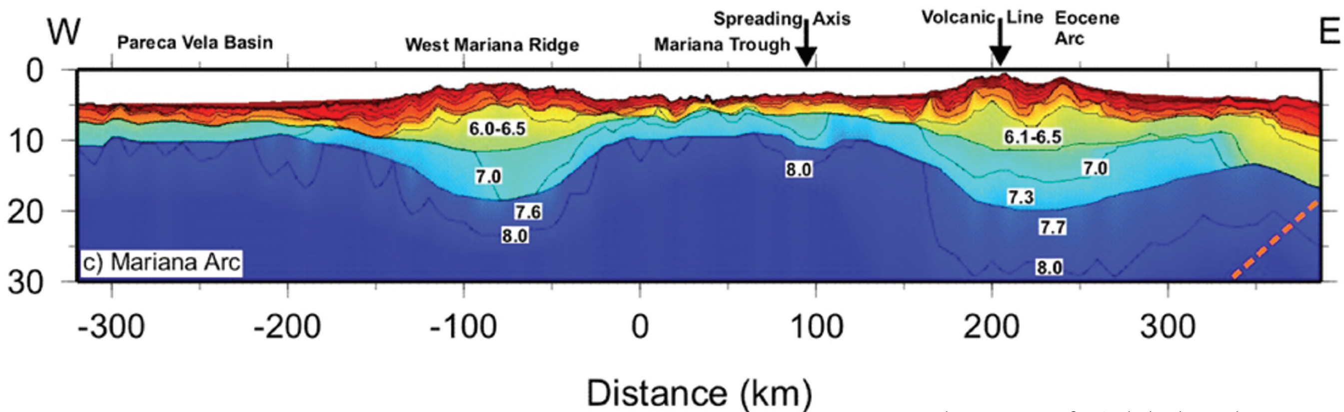


3D image of axial and off-axis magma chambers, courtesy of J. Canales.

BUILDING CONTINENTAL CRUST

Much of Earth's continental crust is believed to have been formed in volcanic arcs – the magmatic chains created by melting in subduction zones. Active-source seismic data are providing new insights into the magmatic processes that occur in these crustal nurseries.

A long-standing mystery of Earth science is the so-called "andesite paradox:" continental crust is thought to originate largely from partial melting of the Earth's mantle beneath island arc volcanoes, yet it has a bulk composition that is considerably more granitic than most mantle melts. Several hypotheses have been advanced to reconcile this paradox – for example, arc crust might be "decapitated" when it collides with a continental margin, with the denser, more mafic root falling off into the mantle. Alternatively, magmatic processes in some arcs may produce more granitic products than elsewhere. Testing these ideas requires accurate, spatially dense surveys of the thickness and physical properties of island arcs, which can only be accomplished with marine seismic data. Recent seismic results (see figure) show systematic variations in crustal composition within arcs, pointing the way to definitive hypothesis tests in the near future.



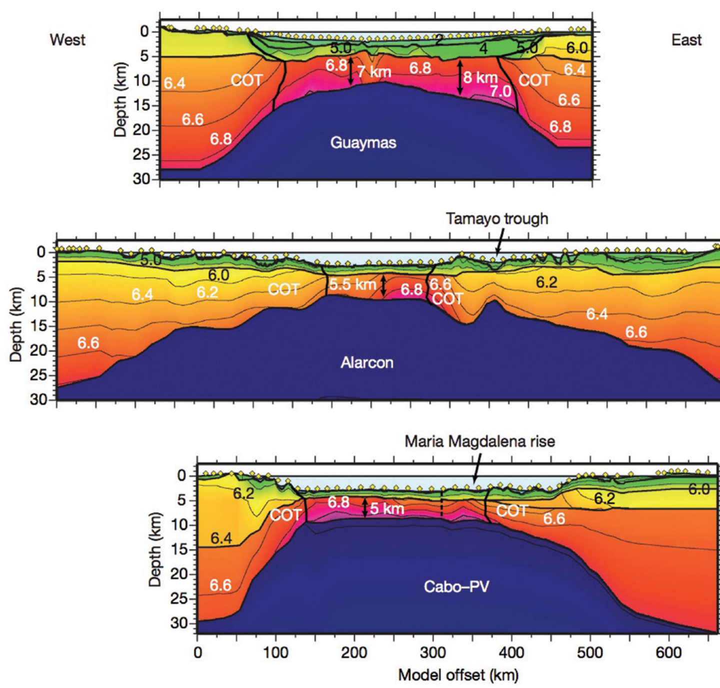
A. Calvert, 2011; after Takahashi et al., 2007, *Geology*

MAGMATISM DURING RIFTING

Continental breakup often creates voluminous magmatism that builds some of the largest igneous provinces on Earth. Marine seismic profiling is the only way to map the volcanic products of continental breakup, which are largely buried under thick continental margin sediments.

Ocean basins are formed when continents pull apart and ultimately rupture. In many places, this rifting produces prodigious volcanism that rims the continental margin with thick packets of seaward-dipping volcanic flows and underlying intrusive rocks. These "volcanic rifted margins" appear to extend along entire ocean margins, constituting some of the largest igneous provinces known, with profound implications for crustal genesis, mantle convection, margin sedimentation, and Earth's climate.

Most models explain these volcanic outbursts by invoking hot mantle beneath the rift zones, perhaps from mantle plumes. Recent 2D seismic data, however, reveal profound variability in the amount of magma generated within individual rift systems, calling into question simple notions about the controls on magmatism during breakup. Little is known about how these magmatic systems vary at the local basin scale, let alone at the margin scale. The *Langseth* facility will enable denser 2D and 3D reflection images and crustal seismic velocity models that can characterize the volume, distribution, genesis and implications of rift-margin volcanism.



Lizarralde et al., 2007, *Nature*

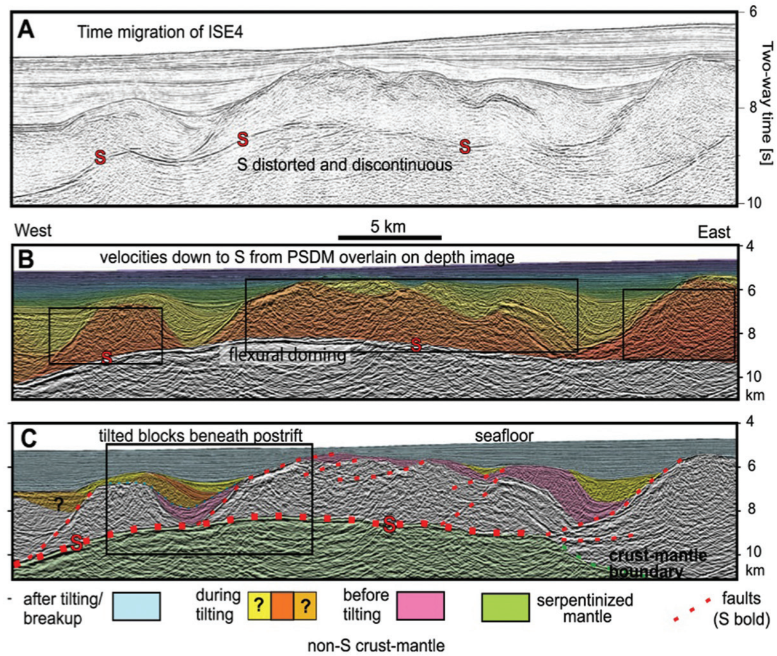
MEASURING LITHOSPHERIC DEFORMATION

BUSTING UP A CONTINENT

Forming a new ocean basin means breaking apart a continent — a fundamental but poorly understood plate tectonic process that created the continental margins that ring most of the continental U.S. and host much of the world's fossil fuel resources. Marine seismic imaging is the primary means by which scientists map the structural and stratigraphic clues of breakup processes.

Continental breakup is tantamount to ripping apart a 150-km-thick layer of rock – an arduous process that can produce large earthquakes and massive volcanism. Although geologists have known for half a century that continents stretch and ultimately break apart, debates still rage over the processes and geologic structures that enable this core part of the plate tectonic cycle. Rifts are inherently 3D at a range of scale lengths, from the sediments deposited in newly formed basins, to the fault systems that dissect and thin the crust, to the magmatic bodies that crystallize at depth below rifts. Our present knowledge of continental breakup is based almost exclusively on 2D data, which provide tantalizing hints of 3D structure, but cannot by any means constrain it.

Several long-lived controversies regarding rifting can finally be resolved with the 3D capabilities of the *Langseth*. In both terrestrial and marine settings, adding up the numbers and sizes of faults from 2D data offshore or geologic mapping onshore often cannot account for the total amount of thinning of the crust. Additionally, the role of low-angle faults, which are observed in rifts but whose mechanics are enigmatic, is poorly understood. Only 3D data can solve these riddles by imaging the true geometries of faults, their relationships to one another, and the relative timing and orientation at which they were active.



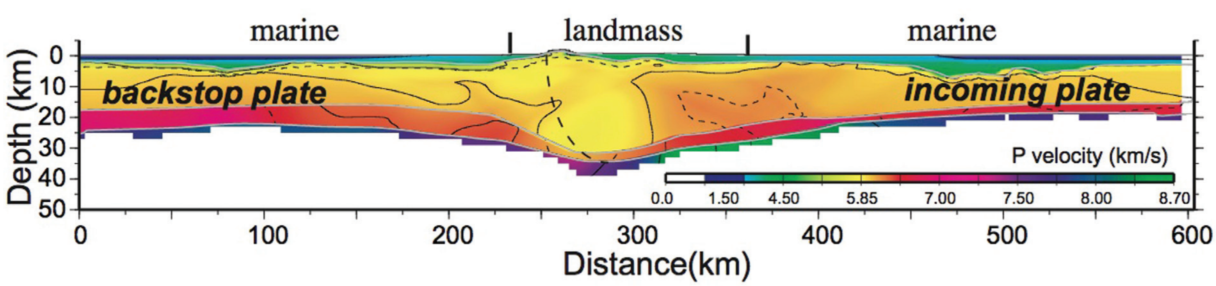
Reston et al., 2007, *G-Cubed*

THE BIG CRUNCH: CONTINENTAL COLLISION

The plate tectonic cycle sometimes brings continents into collision, thickening the crust and creating earthquake prone faults. Marine seismic imaging uses onshore-offshore surveys to illuminate processes at these plate boundaries situated at the land-marine transition.

Collision between continental plates produces intense crustal deformation and some of the most spectacular mountain ranges in the world. Rapid uplift and exhumation of these mountains are driven by large-scale plate convergence or by lithospheric thickening and removal processes. Within these orogens, types of faulting range from steep plate boundary faults to low-angle or "blind" thrusts that are seismically hazardous. Additional styles of continental deformation occur where submerged plateaus, ocean ridges, or island arcs collide with continents at subduction plate boundaries.

When situated near the land-marine transition, the interiors of these collisional zones can be revealed using airgun-based seismic onshore-offshore profiling. At localities where the landmass is a narrow island or peninsula, double sided onshore-offshore profiling provides complete high-resolution imaging of the crust and upper mantle from coast-to-coast and well into the marine environment.



Okaya et al., 2003, *The Leading Edge*

BRINGING IT INTO
THE CLASSROOM

For Earth science students, seismic images provide a rare window into the Earth's interior structure and processes. Because no other method comes close to the level of structural and stratigraphic detail afforded by seismic imaging, marine seismic data provide a unique educational platform from which students can explore the Earth. 3D data are especially eye opening for students and can be surprisingly accessible, even to undergraduates. Modern seismic interpretation software is intuitive, easy to use, and often free to academic users. Moreover, the field mapping skills that geology students learn are directly applicable to the interpretation of 3D seismic data: "horizon slices" in 3D data volumes closely resemble geological maps. When students use 3D data to explore Earth processes, they are not merely trained – they are inspired.

A successful national marine seismic facility will include tightly integrated educational activities that capitalize on those unique advantages. *Langseth* educational activities will include:

- Rapid public release of 3D data sets in user-ready formats
- Online resources for data access and interpretation
- Partnerships with community college and undergraduate-focused faculty
- Formal collaborations with seismic software companies to facilitate data access

Jessica Maxwell, University of Alabama

- Training courses for students in seismic data analysis and interpretation
- Development and sharing of classroom activities that integrate *Langseth* data
- Presentation of unique educational approaches at national scientific meetings
- Wide use of social media technologies to reach and connect a diverse user base
- Partnerships with existing programs (GeoPRISMS, IODP) to leverage other NSF resources

BRINGING THE CLASSROOM TO THE SEA

The educational opportunities afforded by marine seismic imaging extend beyond the typical classroom. As an active seagoing facility, the *Langseth* offers students the chance to participate in the excitement of at-sea data acquisition. The *Langseth* labs provide an excellent at-sea training ground for students to learn all aspects of marine geophysical data acquisition, and the vessel's berthing capacity is sufficient to allow students to participate on most legs. A formal, funded program of "*Langseth* Student Fellows" would be a cost-effective way to broaden access to the *Langseth*, especially for students at landlocked institutions. Targeting seagoing opportunities for undergraduates as well as graduate students will provide an influx of young scientists into marine seismology, thus ensuring healthy growth of the field well into the future. "Classroom-At-Sea" activities should be integrated into scheduled *Langseth* cruises whenever practical, and can even make use of transits between areas of operation.

D. Shillington

BLOGGING AND SOCIAL MEDIA

Social media and student blogs are key ways to extend educational experiences and establish peer-to-peer connections. Tools such as Facebook and Twitter will be key parts of the outreach and education activities of a national marine seismic facility.

MAKING IT HAPPEN: IMPLEMENTING A STRENGTHENED PROGRAM IN MARINE SEISMIC IMAGING

CHARTING THE FUTURE: A COMMUNITY WORKSHOP

In March 2010, over 70 marine seismologists met in Incline Village, Nevada, to seek consensus on a path toward greater community participation in R/V *Langseth* cruises and broader use of data products, and to find new mechanisms for stabilizing funding within our community. A key element of this workshop was the participation of a large number of young scientists — nearly 20 graduate students, post-docs and early career researchers — who helped provide constructive criticism of the status quo, and a unique perspective on the path forward.

Broad consensus now exists on ways to improve the relevance, operation, impact, and access to the R/V *Langseth* facility. This large segment of the marine seismology community strongly endorsed the notion of both PI-driven and community-based experiments, with the latter representing a strong break from business as usual. This new type of project would include immediate data access to all interested parties, rapid commercial processing of 3D reflection data, and wider use of the initial and final data products in classrooms. The major recommendations adopted at the Lake Tahoe workshop are listed below.

THE ELEMENTS OF SUCCESS

- Funding. A new program at NSF to stabilize funding for work using the R/V *Langseth* facility.
- Advanced Planning Cycle. Plan areas of operation several years in advance, so that proposal calls can be issued on a regional basis.
- Proposal Process. Hold a separate panel for judging R/V *Langseth* proposals against each other. Establish a pre-proposal process to provide input and advice to prospective users of the facility and to facilitate advanced planning.
- Training the Next Generation. Endorse "training cruises" in which science berths are open to scientists wishing to gain at-sea experience on R/V *Langseth*. Reserve 1-2 berths on each cruise for early-career scientists via an open application process.
- Open-access, community programs. Establish a hybrid model that maintains standard, PI-driven cruises for smaller projects, but that incorporates and encourages new modes of cooperative projects that create open-access, rapidly released data sets available to the entire community.
- Rapid data processing. Encourage rapid commercial processing for all 3D (and some 2D) cruises.
- Improving the Educational Footprint: Develop mechanisms to broaden the reach of *Langseth* facility data in college and K-12 classrooms, including an expanded website, a Distinguished Ambassador program, expansion of teacher-at-sea programs, use of social networking media, and training of undergraduate and graduate students in open-access 3D processing and interpretation software.

BIGGER TENT, BETTER SCIENCE: A VISION FOR THE MARINE SEISMIC COMMUNITY

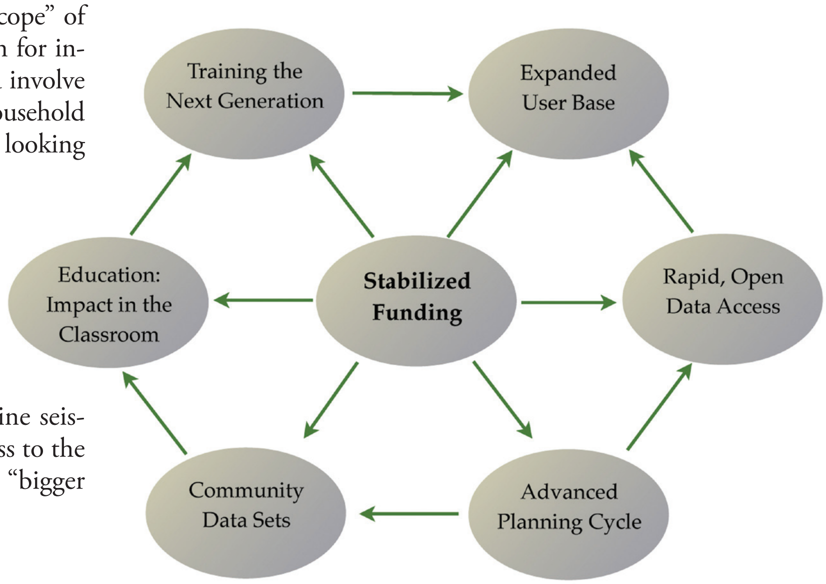
Half a century ago, access to large seagoing research platforms was the nearly exclusive domain of the major oceanographic institutions. This is no longer true: UNOLS vessels, including the *Langseth*, are now openly available to scientists anywhere who have been funded to conduct seagoing research. In practice, however, opportunities to conduct research using the *Langseth* (and its data) are limited, due both to finite funding and a status quo of relatively "closed" research expeditions.

For the *Langseth* facility to thrive in a climate of increasing budgetary pressure, it must be open to all interested practitioners in more than a *de jure* sense – it must become a *de facto* part of the research and education portfolios of a much broader range of scientists and educators. The *Langseth* must become the "Hubble telescope" of Earth science: a stably funded, widely accessible platform for integrated educational and research activities that serve and involve a diverse community. The *Langseth* should become a household name, famous among the lay public as the downward looking "telescope" that is unlocking the Earth's secrets.

Fortunately, we are entering an auspicious moment in history that makes this possible: technology provides a level of connectedness that enables the sharing of data, ideas, and images in ways that were unimaginable a decade ago. New, user-friendly software lowers the barriers of entry to marine seismology, especially at the undergraduate level. The plan outlined by the marine seismic community at its 2010 workshop will broaden access to the national marine seismic facility and its data – creating a "bigger tent" that will lead to better, higher-impact science.

The figure on this page shows one way to visualize this new future. The elements of success listed on the previous page work together in mutually reinforcing ways. Central to this plan is stabilized funding for the *Langseth* facility, which enables an expanded user base, enhanced workforce training, rapid and open data access (including community-endorsed data sets in areas of high scientific priorities), and a more significant educational footprint.

The marine seismology community is poised for game-changing transformations, both in scientific discoveries and in geoscience education and outreach. A strengthened *Langseth* facility will be a primary catalyst for those breakthroughs.



FURTHER READING

Bangs, N. L., et al. (2010), Massive methane release triggered by seafloor erosion offshore southwestern Japan, Geology, 38(11), 1019-1022.

Calvert, A. J. (2011), The Seismic Structure of Island Arc Crust, in Arc-Continent Collision, edited by D. Brown and P. D. Ryan, Springer-Verlag, Berlin.

Holbrook, W. S., et al. (2003), Thermohaline fine structure in an oceanographic front from seismic reflection profiling, Science, 301, 821-824.

Kodaira, S., et al. (2007), New seismological constraints on growth of continental crust in the Izu-Bonin intra-oceanic arc, Geology, 35(11), 1031-1034.

Lizarralde, D., et al. (2007), Variation in styles of rifting in the Gulf of California, Nature, 448, 466–469, doi: 410.1038/nature06035.

Moore, G. F., et al. (2007), Three-dimensional splay fault geometry and implications for tsunami generation, Science, 318, 1128-1131.

Okaya, D., et al. (2003), Imaging a plate boundary using double-sided onshore-offshore seismic profiling, The Leading Edge, 22(3), 256–260.

Ranero, C. R., et al. (2005), Relationship between bend-faulting at trenches and intermediate-depth seismicity, Geochemistry Geophysics Geosystems, 6.

Reston, T. J., et al. (2007), Movement along a low-angle normal fault: The S reflector west of Spain, Geochemistry Geophysics Geosystems, 8.

CONTRIBUTORS

W. Steven Holbrook, University of Wyoming
Graham M. Kent, University of Nevada
Donna J. Shillington, LDEO, Columbia University
Sean Gulick, UTIG, University of Texas
Gregory Moore, University of Hawaii
Juan Pablo Canales, Woods Hole Oceanographic Institution
David Okaya, University of Southern California
Suzanne Carbotte, LDEO, Columbia University
Nathan Bangs UTIG, University of Texas
Andrew Goodliffe, University of Alabama
Craig Fulthorpe, University of Texas
Greg Mountain, Rutgers University
Ken Miller, Rutgers University

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