

# Introduction: Five Years of Innovation, Discovery, and Transformation

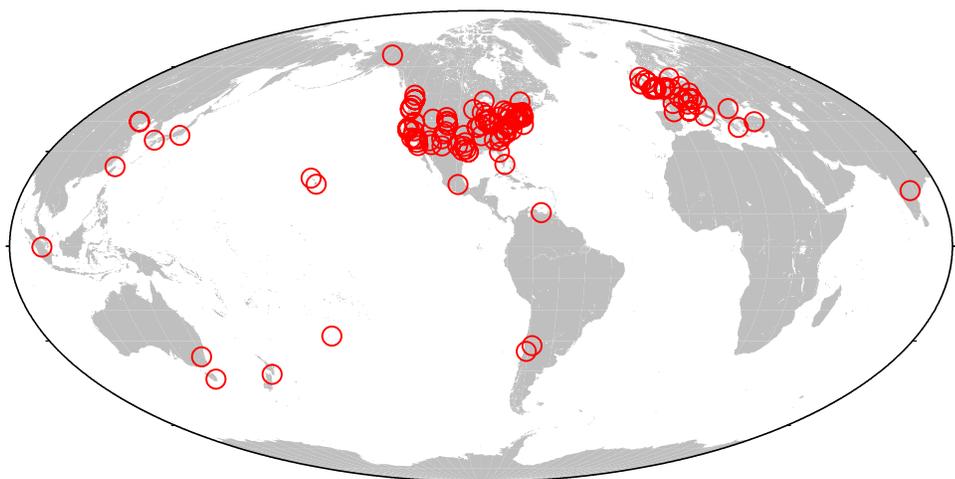
Edward J. Garnero (*Arizona State University*)

The combination of investment in efficient community facilities such as IRIS, a deeper embrace of open data practices exemplified by IRIS, and rapid and cross development in complementary fields embraced by IRIS, has resulted in explosive progress in the geosciences over the last five years. Material presented in this Accomplishments Section clearly demonstrates such progress in numerous aspects of the Earth sciences and in related disciplines of the oceanic, atmospheric, and polar sciences. Much of the research presented here is facilitated directly by the IRIS core programs; some is facilitated by USArray and other components of the EarthScope project, which is in part based on the principals and expertise of the IRIS core programs. Some research requires use of multiple facilities, including those operated by IRIS. The material in this volume exemplifies progress in the Geosciences that would have been slower, more difficult, or in some cases impossible without shared facilities to collect, manage, distribute, and process data.

Scientists at large and small institutions across the U.S. and around the world now regularly contribute to scientific progress in joint and complementary projects that are tractable in part because of ready access to key data and products provided by IRIS facilities. Thus, it is unsurprising that the project descriptions come from authors based at institutions all across the U.S., with nearly one-third of contributor institutions in other countries. This network of investigators contributes to understanding both in areas traditionally studied through seismology—earthquake source and fault processes and structure, and Earth structure from crust to core—and in emerging areas of research—such as climate science, environmental monitoring, natural resource mapping, national security, and planetary science. Especially in these new applications of seismology, collaborations are often multi-disciplinary and transformative, which presents both new opportunities for individual scientists and new challenges for facilities to meet their needs.

Nearly 250 community-submitted “one-pagers” have been collected and organized into eleven categories. The Earth is a continuum, with mineralogical and dynamical phenomena spanning large regions or depths; this, combined with the fact that many investigations cross traditional boundaries, results in an organizational challenge: the ordering of research projects is somewhat subjective and some projects might fit naturally into more than one category. For example, studies of the uppermost mantle—perhaps as revealed by seismic shear wave anisotropy—both describe lithospheric fabric and mineralogical structure and offer insight about deeper dynamical phenomena in the upper mantle associated with subduction. Classification challenges aside, the breadth of discoveries remains readily apparent. Following the topic of Education and Outreach, the one-pagers are grouped into four categories about seismic sources and faults, and then six categories linked to structure and dynamics generally in progressively deeper layers of the Earth:

- Education and Outreach
- Earthquake Source Studies
- Episodic Tremor and Slip, and Triggered Earthquakes



IRIS was founded as a consortium of 34 U.S. research institutions. Today, projects that utilize IRIS-managed facilities are led by investigators at hundreds of institutions world-wide. Red symbols indicate institution of researchers that contributed to this volume.

- Non-Earthquake Seismic Sources
- Fault Structure
- Crustal Structure
- Lithosphere and Asthenosphere Structure
- Upper Mantle Structure
- Lower Mantle Structure
- Whole Mantle Structure
- Outer and Inner Core Structure

The one-pagers are preceded by topical summaries that frame IRIS-enabled science in traditional and emerging areas of research. The summaries emphasize a number of areas that were central to Seismological Grand Challenges in Understanding Earth's Dynamics Systems, a community written document resulting from the Long-Range Science Plan for Seismology Workshop (September 18-19, 2008, Denver CO). The summaries were not intended to exhaustively survey the science of all of the contributed one-pagers; rather, they provide clear examples of exciting areas of research that are core to understanding how Earth works, from the outer veneer of Earth upon which we live, to the planet's center. The summaries also include scientific pursuit of understanding resources and hazards, including coupling of the solid Earth with the oceans and atmosphere. The following summaries are included:

- Why Do Faults Slip?
- How Do Plates Evolve?
- The Lithosphere-Asthenosphere Boundary
- The Global Stress Field: Constraints from Seismology and Geodesy
- How are Earth's Internal Boundaries Affected by Dynamics, Temperature, and Composition?
- Near-Surface Environments - Hazards and Resources
- Interdisciplinary Study of the Solid Earth, Oceans and Atmosphere

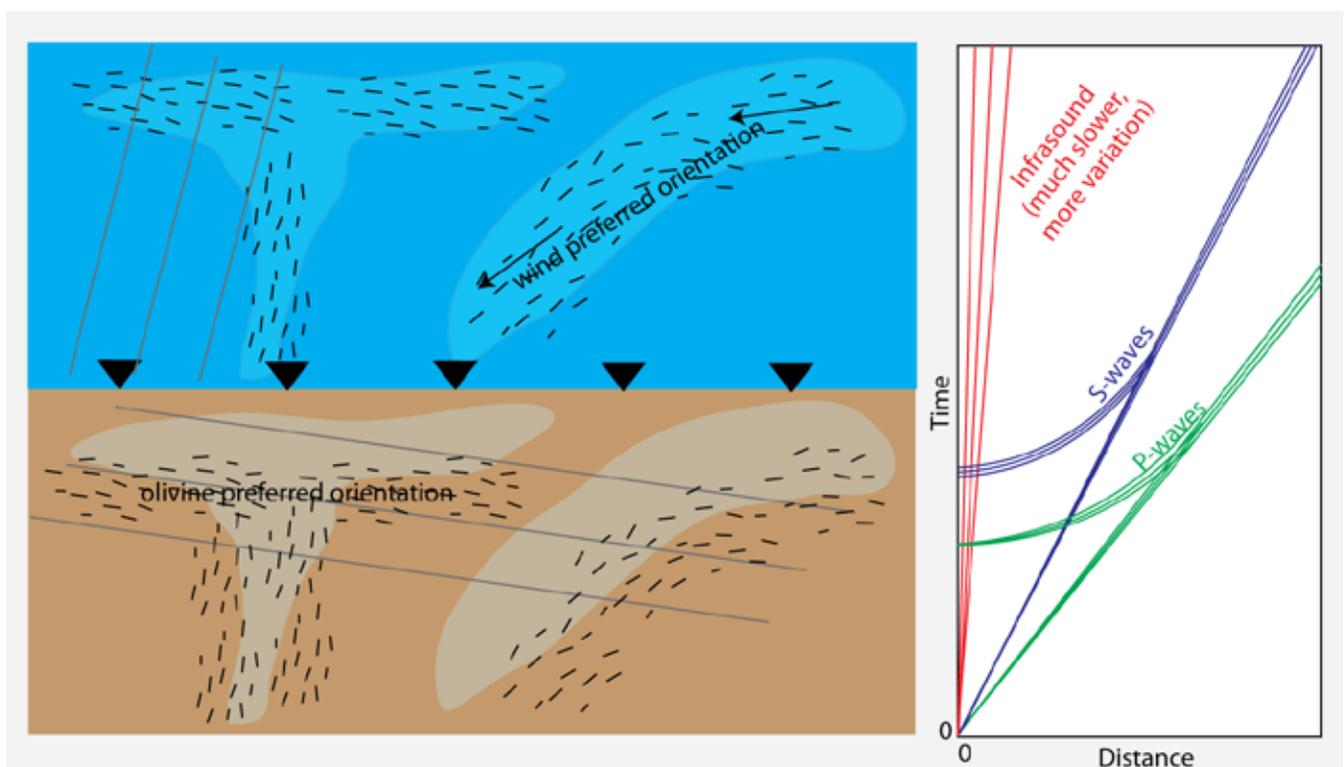
A number of fields not in the traditional scope of seismology have grown immensely over the last five years, including ambient noise tomography, documentation and characterization of episodic tremor and slip, the triggering of earthquakes, mapping of the lithosphere-asthenosphere boundary, mapping of the mantle's dynamical motions (e.g., slabs and plumes), especially as they relate to surface observables (e.g., plate tectonics), and coupling between Earth's outermost shells (hydrosphere, atmosphere, and solid Earth). While the successes are readily apparent, many of the discoveries introduce new unknowns and exciting future directions, some of which are framed in the topical summaries. Thus, the first 25 years of IRIS powerfully exemplify a community coming together to build and sustain services that both accelerate progress and stimulate unanticipated and serendipitous development and discovery by freely providing data and resources to the whole globe. The data quality and quantity have enabled a far clearer picture into earthquake processes and Earth circulation science (from plates to whole mantle and core convection), and at the same time raised important new questions. It is important to note that E&O has been defined by similar innovation and progress over the last 5 years. The E&O one-pagers demonstrate IRIS-facilitated science, tools, and products not only are entering the classroom, but also living room and libraries, and beyond.

The topical summaries and project descriptions frame the emergence of IRIS into a new era, one in which traditional boundaries are being crossed as scientists and educators from a wide swath of disciplines are coming together to answer scientific questions well beyond the traditional scope of seismology. The pages that follow demonstrate the remarkably broad (and broadening) scope of research enabled by the IRIS facilities. In an era where other disciplines have also progressed rapidly over the last decade—active tectonics, geomorphology, mineral physics, glaciology, and geodynamics, to name a few—these pages demonstrate how readily researchers from those disciplines can form productive collaborations with seismologists, in part from strong support by responsive services. As high quality data continue to be collected, archived, and widely disseminated, the scientific scope of seismologically related research will continue to grow; we anticipate new research directions will be motivated by the discoveries described here.

# Interdisciplinary Study of the Solid Earth, Oceans and Atmosphere

Michael Hedlin, Kris Walker and Catherine de Groot-Hedlin (*University of California, San Diego*)

In many respects the geophysical study of the Earth's atmosphere and oceans is akin to our study of the Earth's solid interior. Geophysical phenomena radiate energy in all three media providing signals that can be used to study the source characteristics as well as illuminate the structure of the media the signals probe. The three media are interconnected not only by similar intellectual challenges and opportunities but also by physics. Boundaries between the media are not rigid; signals that originate at a source in one medium often transmit into the adjacent medium. Alternatively, some sources (e.g. volcanoes, shallow earth or ice quakes, ocean swell) are located at a boundary between media and may inject energy into both media simultaneously. Considering this interconnectedness, and given that today we have unprecedented coverage of the three media with global and dense regional networks of sensors, there are unprecedented opportunities for groundbreaking interdisciplinary research [Arrowsmith *et al.*, 2010]. In this brief summary we outline a few key research areas and sketch out potential avenues for interdisciplinary research.



This cartoon shows typical wavefront geometries observed at the Earth's surface for atmospheric infrasound (left-top) and solid earth seismic P and S waves (left-bottom) for teleseismic and teleseismic events, respectively. This cartoon also illustrates atmospheric acoustic velocity anisotropy due to the wind (left-top) and mantle seismic velocity anisotropy due to the alignment of olivine crystals (left-bottom). Both seismic energy and acoustic energy can be detected by seismometers (triangles) at the solid earth/atmosphere interface because of seismic-acoustic coupling. The panel on the right shows the move-out of relatively slow infrasound waves and relatively fast P and S seismic waves in the solid earth. Although not illustrated here, similar coupling occurs at the atmosphere-ocean interface and at the seafloor.

## Constraining atmospheric structure

Much progress has been made drawing on data from ground-based sensors and meteorological satellites to model the structure of the atmosphere. One plainly evident and key difference between the structure of the atmosphere and the solid earth is that the atmosphere varies constantly at all time scales. A key difference in constraining this structure is that direct measurements of acoustic travel times are not incorporated into atmospheric models. Models of atmospheric wind speed are less certain above 35 km altitude as there are no direct routine global measurements at these altitudes. Winds above 35 km are inferred from temperature and pressure fields. Improving the accuracy of atmospheric models would not only benefit the atmospheric

acoustics community by permitting a better understanding of infrasound waveforms but many other communities in atmospheric science that rely on accurate models of the atmosphere.

Another related key issue in atmospheric acoustics is that the global network is very sparse. There are currently ~ 45 globally spaced infrasound arrays that sample infrasound signals that traverse structure of the atmosphere, which varies at all length scales, as well as time scales. This structure is grossly under-sampled by these infrasound stations, impeding great progress in our understanding of certain aspects of infrasound propagation. For example, the sparse global network impedes progress in testing and refining atmospheric velocity models using acoustic travel times.

The fact that infrasound signals readily couple to the Earth's surface and generate seismic waves is proving to be very helpful in infrasound science. The USArray seismic network records several hundred large atmospheric acoustic sources each year at a density that is considerably greater than what is offered by the infrasound network. Although the infrasound community has known that acoustic energy from any source may take one of several paths to the ground, and have inferred the existence of acoustic wave travel time branches, it has not been possible to view and study these branches in any detail using infrasound data. The USArray is shedding light on acoustic branches that are akin to seismic branches that exist in the solid Earth, paving the way for progress in probing the structure of the atmosphere and testing, and eventually improving, our models of atmospheric structure [Hedlin *et al.*, 2010].

## Interdisciplinary study of “dual” geophysical phenomena

Much of the activity in the solid Earth, atmosphere and oceans occurs near a boundary between these media. Although we have long known that various sources that are located at a boundary between media and inject energy into both, we have historically more often studied such sources using one type of sensor.

*Volcanoes:* A common example is volcanoes, which can be intense acoustic sources, but have long been monitored and studied seismically. Although much progress has been made on the physics of volcano processes using seismic data, our understanding of the seismo-acoustic volcano source is likely to remain incomplete without also considering the information carried up into the atmosphere by acoustic energy that these sources emit.

*Shallow earthquakes:* Thrusting earthquakes readily couple to infrasound above the hypocenter due to piston-like vertical ground motion, and at greater distances due to surface waves. It is now well documented that rugged topography set in motion by a distant earthquake also radiates acoustically into the atmosphere [e.g. Le Pichon, 2002]. Infrasound arrays are shedding light on these extended earthquake sources by providing the data needed to accurately track the progression of the seismic wavefield across entire mountain chains.

*Ice quakes:* Ice quakes are readily detected seismically however locating them with these instruments is complicated by inherently complex, and inaccurate, ice velocity models. These events are also readily detected, and accurately located, by infrasound arrays. Understanding processes that lead to ice-edge loss has major implications in a changing climate, as coastal currents are impacted by fresh-water discharge.

## Joint studies and inversions using microbaroms and microseisms

“Microbaroms” are acoustic oscillations with a period of 3 to 10 s and are typically recorded with amplitudes in the tenths of Pascals. The seismic counterpart, “microseisms,” have periods of 3 to 20 s. It has been known for a long time that the occurrence of microbaroms and microseisms are correlated to ocean wave activity, either in the deep ocean or along the coastlines. These two signals are often studied individually, with relatively small infrasound arrays or seismic networks. Recent studies seek to use variations of microseism generation over the long-term (decades) to study changes in ocean wave energy that may be related to climate variations. Hypotheses to explain microseisms have existed for a long time, but rigorous testing of these have proven to be difficult due to limited data availability. Hypotheses for microbarom source generation have more recently been advanced. When the USArray transportable array will be upgraded with infrasound sensors, as described below, this network will be

extremely well suited for not only studying the source physics associated with microseisms and microbaroms in unprecedented spatial and temporal detail, but also imaging the structure of the solid Earth and atmosphere probed by this “song of the sea.”

## The seismo-acoustic USArray

Although seismic and acoustic sensors have been deployed together (e.g. seismo-acoustic arrays deployed by Southern Methodist University in Texas, Nevada and South Korea, some stations in the Global Seismographic Network) it is not common to combine the two. The 400 station USArray transportable array is currently being enhanced with the addition of infrasound microphones and long-period (DC to tens of seconds) air pressure sensors at each element. The recording of acoustic energy will accelerate the study of acoustic branches by yielding direct recordings of atmospheric acoustic signals, rather than acoustic-to-seismic coupled signals. Simultaneous and continuous observations of atmospheric and seismic noise should facilitate adaptive seismometry – a process analogous to adaptive optics in which the effects of atmospheric loading at the Earth’s surface are accounted for on seismic channels to reduce noise at long periods.

The unprecedented semi-continental seismo-acoustic network should also benefit atmospheric science. The surface air pressure is one of the key observables in atmospheric dynamics. The structure and evolution of the surface pressure field characterizes and to some extent drives atmospheric processes on planetary scales (climate, general circulation, atmospheric tides), synoptic scales (“weather”), mesoscales (gravity waves, jet streams, inertial oscillations) and microscales (convection, turbulence, Kelvin-Helmholtz instabilities, nocturnal drainage flows). Therefore, monitoring, predicting and understanding climate, weather and air quality are impossible without accurate and precise observations of the surface pressure over a wide range of time and length scales.

## Looking to the future: interdisciplinary research

The solid earth, oceans and atmosphere are interconnected and it seems clear that interdisciplinary studies can provide new insights into the workings of a wide range of geophysical phenomena. It should be possible to use the well-developed seismic recording, archiving, and data distribution approach of IRIS to effectively study not only the earth’s solid interior structure and geophysical phenomena, but to provide a deeper understanding of atmospheric structure and atmospheric and oceanic activity. Perhaps as this interconnectedness between fields becomes clearer it will become more common to collect multiple types of data (e.g. add infrasound sensors to a seismic deployment, and vice versa) and increase the scientific return from our investment in infrastructure.

## References

- Arrowsmith, S.J., Johnson, J.B., Drob, D. and Hedlin, M.A.H., 2010, The seismo-acoustic wavefield: A new paradigm in studying geophysical phenomena, *Rev. Geophys.* (in press).
- Hedlin, M.A.H., Drob, D., Walker, K. and de Groot-Hedlin, C., 2010, A study of acoustic propagation from a large bolide in the atmosphere with a dense seismic network, *J. Geophys. Res.– Solid Earth* (in press).
- Le Pichon, A., J. Guilbert, A. Vega, M. Garces, and N. Brachet (2002b), Ground-coupled air waves and diffracted infrasound from the Arequipa earthquake of June 23, 2001, *Geophys. Res. Lett.*, 29(18), 1886, doi:10.1029/2002GL015052.

# Near-Surface Environments – Hazards and Resources

M. Beatrice Magnani (CERI, University of Memphis)

As worldwide population grows, so do societal demands on our planet. In the last few decades, human activity has expanded to areas never previously colonized, sometimes at the cost of extensive environmental degradation and resource depletion. Communities have developed in areas prone to geohazards and have become vulnerable to seismic, volcanic and landslides threats. Even renewable resources, such as groundwater, have become increasingly scarce and fragile. Within the scientific community there is wide recognition of the challenges scientists and policymakers face in effectively forecasting natural events, preparing communities to survive hazards, and sustainably managing available resources.

In this context, near surface geophysics, intended as the study of the shallow layers of the Earth from the surface to a depth of ~3 km, plays a critical role. Crucial information for hazard assessment is locked within the upper crust and most human activities rely on vital resources that are within the first 5 km of our solid planet. The mechanical properties of the shallow materials are critical both for engineering purposes and for seismic hazard assessment and mitigation policies, as they control ground motion and amplification effects during large earthquakes. Imaging of deformation (faulting and folding) of shallow layers is important in predicting future ground rupture and associated hazards. The youngest sediments deposited at/near the surface have recorded with great detail past climate changes and therefore can provide us with a key to decipher the present climate variability.

From a historical point of view, virtually every shallow investigation technique can be traced back to petroleum exploration, and even earlier, as electrical methods applied to mining date as far back as the 1860s. The growth and success in the last 75 years has been guided by advances in instruments and computer-processing techniques. Thanks to technological progress, today's near surface equipment is financially affordable, easily deployable and user-friendly. This versatility has made near surface investigation approachable to a large number of investigators, so that the community of scientists/users has grown both in number and diversity and, over the last three decades, sections and focus groups have emerged within every major professional organization. Today, near surface geophysics applications are as numerous and multidisciplinary as societal needs, and span from groundwater and mining exploration to engineering, from archeology to seismic hazard, from remediation planning at contaminated sites to glacial and paleo-climatology studies.

## Examples

The adaptability of the near surface high-resolution method makes it one of the best tools to deploy in the field for rapid response missions in case of catastrophic natural events such as large magnitude earthquakes, landslides and volcanic eruptions. Immediately after the January 12, 2010 Haiti M7.9 earthquake, an NSF-funded rapid response expedition was able to image the underwater effect of the earthquake by mapping the shifted sediments on the seafloor and by imaging the Enriquillo-Plantain Garden Fault beneath the seafloor using CHIRP, multibeam and sidescan sonar (Fig. 1). Rapid response and high resolution imaging tools in these situations are critical for assessing the risk of large earthquakes in the same area in the weeks and months after a large earthquake.

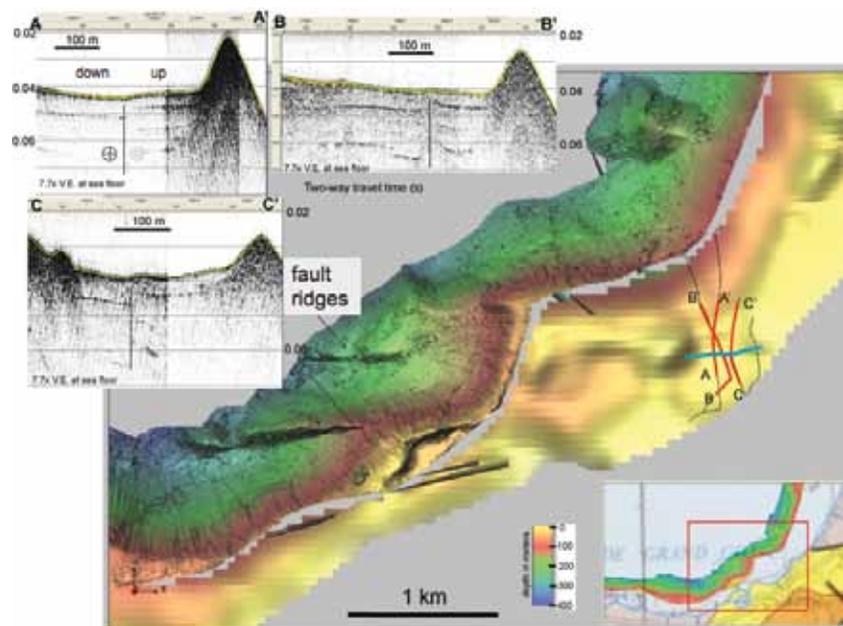


Figure 1: High resolution seismic and bathymetry data collected using a Kundson pole mounted 3.5 KHz CHIRP and by a Reson SeaBat 8101 gridded at 8 m merged with the seafloor picked on the “mini-chirp” gridded at 50 m over the area of the January 12, 2010 M7.9 Haiti earthquake. Two strands of the Enriquillo-Plantain Garden Fault are visible as seafloor scarps on the slope and in the shallow subsurface (Hornbach et al., submitted to Nature Geosciences).

The application of near surface geophysics (especially seismology) has been particularly successful in seismic hazard assessment and neotectonic studies. Locations, magnitudes and dates of earthquakes are critical information for probabilistic seismic hazard assessments, which in turn dictate modern hazard zoning, emergency response and risk mitigation strategies. Near surface seismic imaging often bridges the gap existing between deeper, more conventional basin-scale data and the surface (Fig. 2), allowing the integration of information derived from other disciplines (e.g. geology, paleoseismology).

Last, but not less important, near surface geophysical methods are an excellent tool to use for education. Thanks to the availability of equipment, teachers and researchers routinely include field courses in the existing curriculum where students learn hands-on to plan, deploy, acquire, process and interpret geophysical data. Field courses provide dynamic and challenging environment where students learn the fundamentals of this discipline and its practical application from beginning (planning) to end (interpretation).

## The way forward

In spite of its accessibility, imaging the shallow subsurface poses a formidable challenge, because of the heterogeneity of the near surface Earth structure. The most reliable solutions of near surface problems are achieved by using a combination of shallow exploration methods (e.g. seismic, electrical, electromagnetic, gravity and radar). Integration of different datasets (through joint inversion, for example) is producing promising results in extracting mechanical properties of materials (e.g. permeability, porosity) and their variation through time. This is vital information for monitoring water (or contaminant) transport through aquifers and to plan a sustainable management of this precious resource.

Virtually every field can benefit from an expansion from 2D to 3D methods. Due to the daunting heterogeneity of the shallow Earth, the third dimension is critical in several applications of near surface geophysics. For example, site amplification and non-linear response of shallow materials associated with strong shaking can only be effectively evaluated by mapping the subsurface seismic properties in 3D over large areas.

Without doubt the strength of near surface geophysics lies in the high resolution it provides, which is second only to drilling, trenching and other direct investigation methods. Improving resolution and bandwidth can and should be pursued, as well as achieving faster and more reliable data processing methods capable of abating the noise that plagues near surface data. This progress will naturally unfold as the user base continues to expand and new practical applications of this method emerge.

## References

- Hornbach, M.J., Braudy, N., Briggs, R.W., Cormier, M.-H., Davis, M.B., Diebold, J.B., Dieudonne, N., Douilly, R., Frohlich, C., Gulick, S.P.S., Johnson, H., Mann, P., McHugh, C., Mishkin, K., Prentice, C.S., Seeber, L., Sorlien, C., Steckler, M.S., Smythe, S.J., Taylor, F.W., Templeton, J., Uplift and sliding and tsunamigenesis along a strike-slip fault, *Nature Geosciences*, in review, 2010.
- Leon, L.A., Christofferson, S.A., Dolan, J.F., Shaw, J.H. And Pratt, T., Earthquake-by-earthquake fold growth above the Puente Hills blind thrust fault, Los Angeles, California: Implications for fold kinematics and seismic hazard, *J. Geophys. Res.*, Vol. 112, B03S03, doi:10.1029/2006JB004461, 2007.

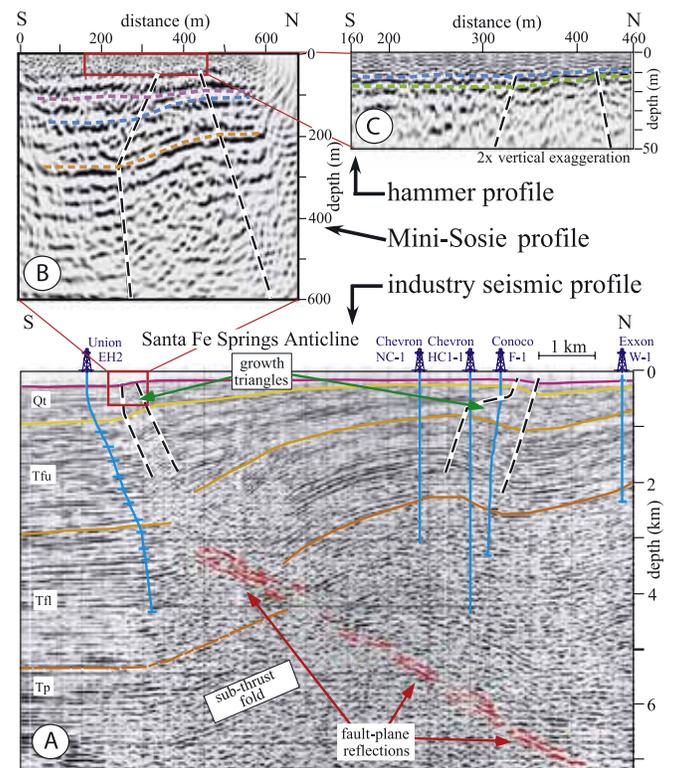


Figure 2: Multiscale seismic reflection images of the forelimb fold structure of the Puente Hill Thrust (PHT) near the Los Angeles (CA) metropolitan area, showing upward narrowing zone of active folding (growth triangle) delimited by sharply defined axial surfaces. A) Industry profile; B) MiniSosie profile; C) Hammer profile. These overlapping profiles provide a complete image of forelimb folding above the segment of the Puente Hills thrust fault that ruptured during the 1987 M6.0 Whittier Narrows earthquake. (After Leon et al., 2007).

# Why Do Faults Slip?

Emily Brodsky (University of California, Santa Cruz)

One of the most fundamental goals of seismology is to define the forces and processes initiating and propagating earthquake fault rupture. Generating such a mechanistic understanding requires probing the variety of slip events on faults with the full seismological arsenal.

Determining the physics of fault slip first requires the identification of the earthquake locations, the kinematics of the slip, and the relationship of both to long-term tectonic processes. IRIS's GSN combined with temporary deployments and the extensive shared data from other networks available at the DMC has enabled new connections between slip and plate motions to be made, from the Pacific rim to Southern Africa. Identifying the rupture kinematics correctly is a prerequisite to using geological constraints to identify the physical conditions necessary for rapid slip. For instance, *Bilek et al. (2009)* show that there are systematic along-strike variations in rupture velocity in the Aleutians, suggesting distinct geological features that affect rupture propagation can be identified. Having a global database of rupture properties for all moderate to large earthquakes is now within reach. New methodologies that capitalize on the expanded continuous waveform archive promise vastly more precise locations in the near future [*Barmin et al., 2010*].

Earthquake locations can also generate surprises. As USArray marches across the country, new populations of intraplate earthquakes are being discovered throughout the continent [*e.g., Lockridge et al., this volume*]. The high quality seismograms being recorded by both the TA and FA deployments allow seismologists to measure the stress changes, rupture properties and kinematics of these intraplate events to determine whether or not they are systematically different in any way from interplate earthquakes. Such comparisons can elucidate the role of fault maturity in determining rupture properties.

One of the most exciting new avenues for probing fault rupture has arisen out of the discovery of episodic tremor and slip. This novel set of seismological phenomena provides information about the array of fault failure processes. No longer is it thought that faults are limited to either stick-slip (seismic slip) or long-term creep. The observations in Cascadia, California, Japan, Chile, Mexico, Costa Rica and New Zealand, all demonstrate that the spectrum of fault slip is much richer than anticipated. Like earthquakes, the episodic creep events occur over a range of sizes; but unlike earthquakes, the largest creep events tend to be fairly regular and predictable. These regular changes in the stress state of major subduction zones could make large earthquakes more likely during these predictable periods. At least one observation finds that a creep event triggered a large (M7) earthquake [*Prichard et al., this volume*].

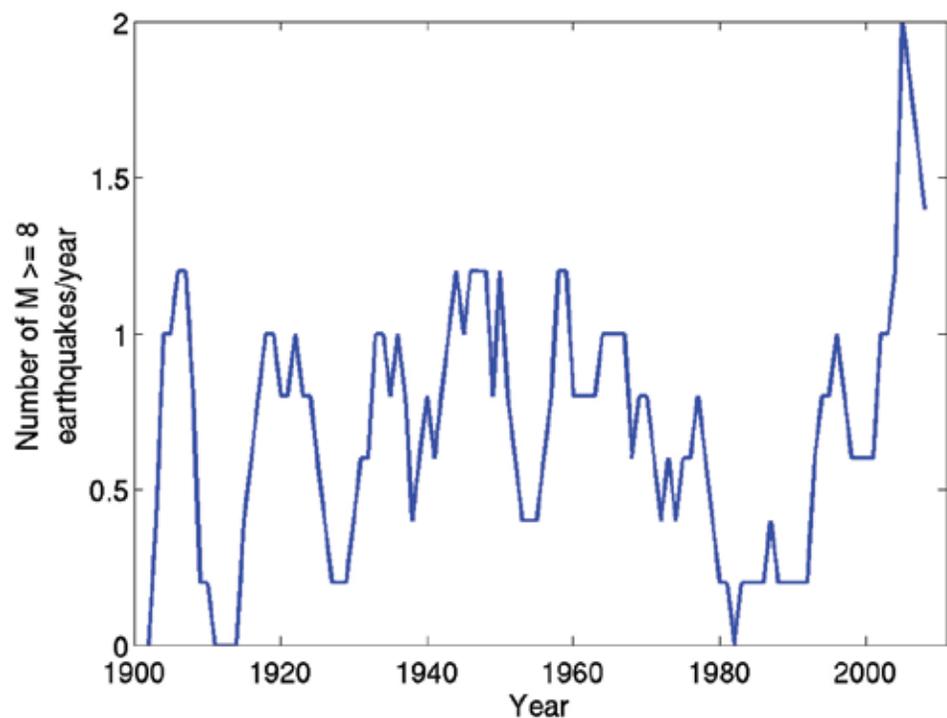


Fig. 1. Number of shallow (depth  $\leq 60$  km) earthquakes per year with  $M \geq 8.0$  for the composite PAGER Catalog10, with  $M$  being the preferred magnitude as reported by the catalog. Data are smoothed with a five-year running average. The average rate prior to 2004 is  $0.63 \pm 0.34$  earthquakes/year. The rate peaks at 2 earthquakes/yr after the 2004 Sumatra-Andaman event, which is over 60% higher than any prior peak rate, and more than 3 times the average rate over the previous century. The average rate over the 5.5 years following the 2004 Sumatra-Andaman earthquake is 1.64 earthquakes/yr, which is 2.5 times the long-term average.

Measurements thus far indicate that episodic tremor and slip occurs in distinct zones from seismic rupture or steady creep. These observations lend strong evidence to the hypothesis that rupture characteristics are controlled by the frictional properties of the fault at well-bounded pressure and temperature conditions. This evidence is particularly interesting in light of the recent work on the velocity dependence of rock friction. A series of laboratory experiments and theoretical studies in the last decade have shown that high-speed fault friction is expected to be dramatically lower (coefficient of friction  $\mu=0.1-0.2$ ) than the static failure values normally used in Byerlee's Law ( $\mu=0.6-0.85$ ) [e.g. *Brodsky and Kanamori*, 2001; *Andrews*, 2002; *Di Toro et al.*, 2004; *Rice* 2006; *Yuan and Prakash*, 2008; *Tanikawa and Shimamoto*, 2009]. These inferences are currently supported by the relative low heat flow measured over faults after earthquakes [*Kano et al.*, 2006] and geological evidence for unusual products formed in seismogenic zones [e.g., *Boullier et al.*, 2009]. Therefore, the fault traction during the relative slow slip of the creep events should be governed by a distinct set of processes from those governing slip during earthquakes. Comparing the seismologically derived source histories of creep events and earthquakes provides an opportunity to test these predictions.

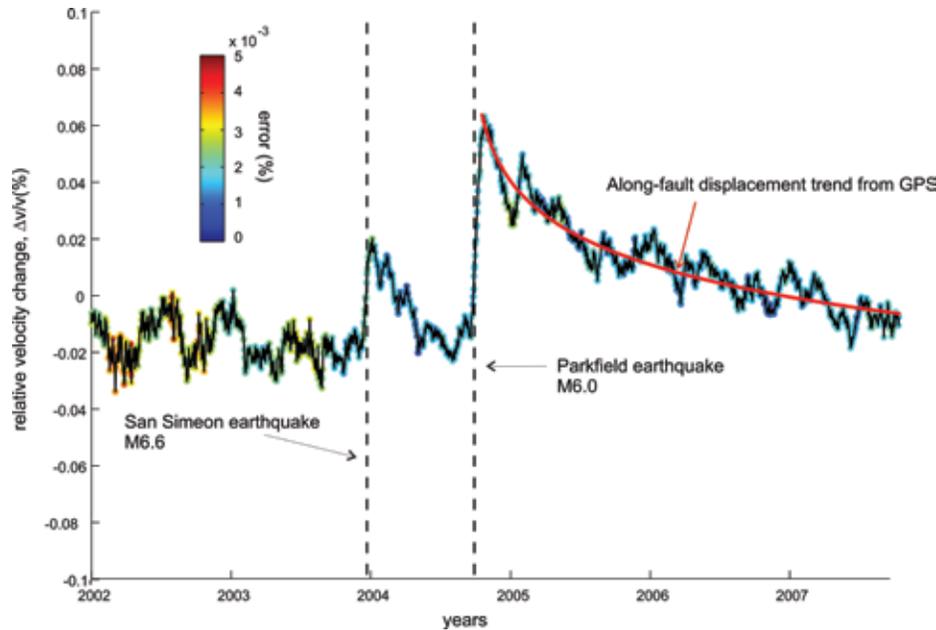


Figure 2: Temporal evolution of the velocity in the region of Parkfield for the period 2002-2008 (see *Brenguier et al.* 2008 for details).

Any further understanding of the control fault properties have on rupture requires an understanding of the role of heterogeneity in determining nucleation sites and controlling the extent and vigor of rupture. Interestingly, some of the clearest insight into this problem in recent years has come from seismological observation on non-tectonic slip processes. A suite of observations on landslides, icebergs and glaciers with PASSCAL portable instruments show that the non-tectonic systems can have repeating, regular earthquakes and distinctive regions (asperities) of initiation. Such regular behavior is occasionally also seen on tectonic fault systems,

such as the repeating multiplets at Parkfield [*Nadeau and Johnson*, 1998]. The comparison suggests that some of these novel non-tectonic systems behave surprisingly like a simple slider-block. The applicability of a simple fault model to several novel classes of failure provides new physical models for those phenomena while also illuminating the important role of interaction in tectonic systems. For simple isolated regions with some degree of creep, a slider block framework works well. The analogy may run even deeper. For instance, non-tectonic asperities can have radiated energy just like tectonic ones [*Moyer et al.*, this volume; *Dreger et al.*, this volume]. The juxtaposition of these behaviors suggests that some of the complexity of tectonic systems may be a result of the strongly coupled nature of fault systems.

The interactions among fault strands is a hallmark of most tectonic systems. The mutual triggering also provides opportunities to directly measure the stresses required for earthquake or tremor initiation. This strategy is yielding insight into the role of afterslip in generating nearfield earthquakes [*Peng and Zhao*, this volume]. At a larger scale, *Brodsky et al.* [this volume] suggest that the measured triggering thresholds combined with the strong global shaking of the M9.2 Sumatra earthquakes can explain the recent spurt of magnitude 8 earthquakes. These triggering studies are beginning to directly address earthquake prediction by probing the conditions necessary for earthquake initiation and providing a methodology to track whether the failure stress changes in time. New technologies, like distributed MEMS sensors, promise to provide more information about earthquake interactions during the hard-to-capture critical moments of an early aftershock sequences [*Lawrence and Cochran*, this volume].

Another probe of fault evolution is provided by measuring the seismic velocity (and by inference the stress) changes during an earthquake cycle. This method has only recently become feasible on a large scale as a direct result of the now continuous recording at high resolution of stations archived at the IRIS DMC. *Xu et al.* [this volume] used an ambient noise strategy to capture strength changes in the Southwest Pacific after the 2004 Sumatra earthquake and *Brenguier et al.* (2008) showed spectacular tracking of the fault zone velocity evolution and aftershock rates following the 2004 M6 Parkfield. As this measurement was made near the SAFOD drill site, the study illustrates the potential of combining modern geodetic, seismic, rheologic and geologic information to ultimately determine why faults slip.

## References

- Andrews, D.J., 2002. A fault constitutive relation accounting for thermal pressurization of pore fluid. *J. Geophys. Res.*, 107(B12), 2363, doi:10.1029/2002JB001942.
- Barmin, M.P., A.L. Levshin, Y. Yang, and M.H. Ritzwoller, 2010. Epicentral Location Based on Rayleigh Wave Empirical Green's Functions from Ambient Seismic Noise. Submitted to *Geophys. J. Int.*
- Bilek, S.L., H.R. DeShon, and E.R. Engdahl, 2009, Along-Strike Variations in Shallow Earthquake Distribution and Source Parameters Along the Kurile-Kamchatka Arc, EOS Trans AGU, 90(52), Fall Meet. Suppl., Abstract T23B-1908.
- Boullier, A.M., Yeh, E.-C., Boutareaud, S., Song, S.-R., and Tsai, C.-H. 2009. Microscale anatomy of the 1999 Chi-Chi earthquake fault zone. *Geochem. Geophys. Geosyst.*, 10, Q03016, doi:10.1029/2008GC002252.
- Brenguier F., M. Campillo, C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, E. Larose, 2008, Postseismic Relaxation Along the San Andreas Fault at Parkfield from Continuous Seismological Observations, *Science*, 321, 1478 – 1481.
- Brodsky, E.E., and H. Kanamori, 2001. Elastohydrodynamic lubrication of faults. *Journal of Geophysical Research*, 106(B8), 16357–16374.
- Kano, Y., J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K.-F. Ma, 2006, Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, 33, L14306, doi:10.1029/2006GL026733.
- Nadeau, R. M., and L. R. Johnson, Seismological studies at Parkfield VI: Moment release rates and estimates of source parameters for small repeating earthquakes, *Bull. Seismol. Soc. Am.*, 88, 790–814, 1998.
- Rice, J.R., 2006. Heating and Weakening of fault during earthquake slip. *J. Geophys. Res.*, 111, B05311, doi: 10.1029/2005JB0040006.
- Tanikawa, W., and T. Shimamoto, 2009, Frictional and transport properties of the Chelungpu fault from shallow borehole data and their correlation with seismic behavior during the 1999 Chi-Chi earthquake, *J. Geophys. Res.* 114, B01402, doi:10.1029/2008JB005750.
- Yuan, F. and V. Prakash, 2008. Slip weakening in rocks and analog materials at co-seismic slip rates, *J. Mech. and Phys. Solids*, 56, 542-560.

# The Global Stress Field: Constraints from Seismology and Geodesy

William E. Holt (Stony Brook University)

Seismology has played a fundamental role in advancing our understanding of the dynamics of the Earth's lithosphere. Quantitative dynamic models of the lithosphere rely on accurate structural constraints of the crust and mantle. Other constraints are provided by earthquake source mechanisms, seismic anisotropy measurements, and attenuation studies. IRIS has provided a major infrastructure that has facilitated more than two decades of progress in understanding Earth structure and earthquake source mechanisms. These structural and kinematic constraints form the observational basis upon which dynamic models can be built that address the driving forces of plate tectonics and the role of lateral and vertical variations in rheology.

For example, the global model of *Ghosh et al.* [2008, 2009] relies heavily on constraints from seismic observations. They address the dynamic problem by solving the vertically integrated force balance equations for a self-consistent solution of the depth-integrated deviatoric stress field within the Earth's lithosphere. The driving forces that feed into this model are observationally constrained values. The first driving force is associated with differences in gravitational potential energy (GPE) of the lithosphere. GPE is the depth integrated vertical stress, and thus depends on topography (including dynamic topography) and density values of layers from surface to base of lithosphere. Therefore, constraints for GPE values are constrained, in part, by surface wave and receiver function analyses [e.g., *Xu et al.*, 2007; *Yang et al.*, 2009]. A second major driving force is associated with coupling of lithosphere with mantle flow, which yields both radial and horizontal tractions at the base of the lithosphere. This coupling gives rise to lithospheric stresses. *Ghosh et al.* [2008] determined these tractions using an instantaneous global 3-D convection model that had both lateral and radial mantle viscosity structure; mantle seismic tomography models helped to define the mantle density variations. Because tomographic models often reveal the complexity in geometry and depth extent of foundered (subducted) lithosphere [e.g., *Pesicek et al.*, 2010], calculations used in *Ghosh et al.* [2008] include a model 3-D flow field that mimics subduction on a global scale.

The global dynamic model described here was then tuned

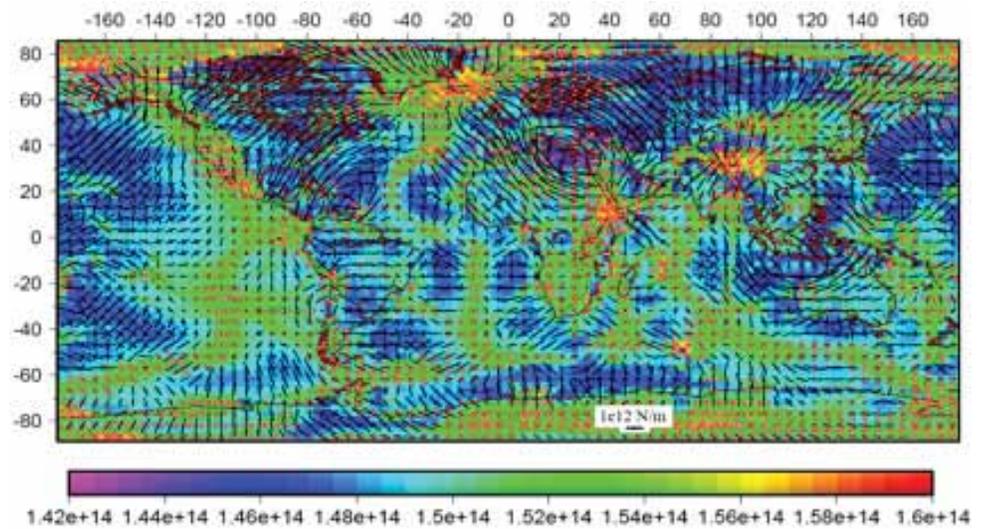


Figure 1. Depth integrated deviatoric stress field solution [Ghosh et al., 2009] (lines), plotted on top of gravitational potential energy (GPE, colored map). The GPE values are defined by seismically constrained crustal thickness values as well as ocean plate cooling models. Red arrows are deviatoric extension directions; bold arrows are deviatoric compression directions.

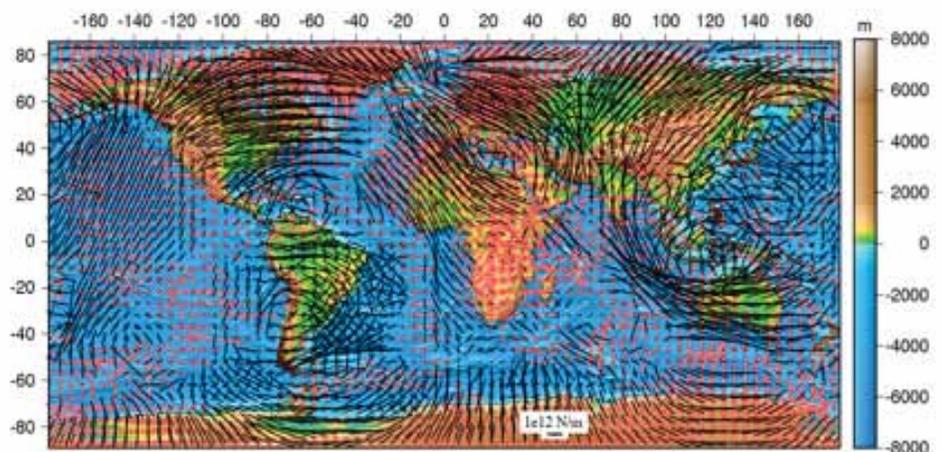


Figure 2. Best fit total deviatoric stress field that is associated with global GPE differences (Figure 1) and applied tractions from a mantle circulation model that includes effects of subduction and upwelling regions [Ghosh et al., 2008]. Red arrows are deviatoric extension directions; bold arrows are deviatoric compression directions.

to provide a best match with the Global Strain Rate Model [Kreemer *et al.*, 2003], which is defined by over 5000 GPS observations, with additional constraints from the Global Centroid Moment Tensor Catalog [Ekström *et al.*, 2005; Hjorleifsdottir and Ekström, 2010]. Modeling reveals that a best fit to plates and deforming plate boundary zones is achieved if driving forces are partitioned equally between stresses arising from GPE differences and stresses associated with coupling between lithosphere and mantle convection. Other factors required are (A) a strong viscosity contrast (2-3 order magnitude) between lithosphere and asthenosphere (asthenosphere viscosity is of order  $1 \times 10^{19}$  Pa-s), (B) mantle flow that leads plate motion beneath major orogens such as the Andes and Central Asia, and (C) a long wavelength counterflow beneath western North America. Depth integrated stress magnitudes within the lithosphere are  $1-4 \times 10^{12}$  N/m. This level of stress energy in the plate tectonic system implies that weakening mechanisms (weak faults, presence of water in upper mantle, etc.) are important for enabling strain accommodation within the plate boundary zones on Earth. Many of these findings, such as the mantle flow field that yields a best match to stress indicators, can be further tested in a variety of tectonic regions with additional seismic observations.

Although the dynamic model of Ghosh *et al.* [2008, 2009] includes the influence of 3-D subduction related flow, it nevertheless lacks the effects of stress guide connectivity between deep slabs and surface plates, and it also lacks the effects of slab bending at the trenches. Therefore, further refinements in our understanding of the driving forces responsible for earthquakes, plate motions, and tectonic processes of mountain building and basin formation in general, will require high resolution, full 3-D dynamic models of the entire planet from core to surface. Constraints for such high-resolution models will come, in part, by continuing to take advantage of advances in seismology [e.g., Spasojevic *et al.*, 2009]. These future advances will be made possible through improved future station coverage of continents and oceans, and the strong PI-driven science that IRIS enables.

## References

- Ekstrom, G, Dziewonski, AM, Maternovskaya, NN, Nettles, M (2005), Global seismicity of 2003: centroid-moment-tensor solutions for 1087 earthquakes, *Phys. Earth Planet. Inter.*, 148.
- Ghosh, A., W. E. Holt, L. Wen, A. J. Haines, and L. M. Flesch (2008), Joint modeling of lithosphere and mantle dynamics elucidating lithosphere-mantle coupling, *Geophys. Res. Lett.*, 35, L16309, doi:10.1029/2008GL034365.
- Ghosh, A., W. E. Holt, and L. M. Flesch (2009), Contribution of Gravitational Potential Energy Differences to the Global Stress Field, *Geophys. Jour. Int.*, doi: 10.1111/j.1365-246X.2009.04326.x
- Hjorleifsdottir, V., Ekstrom, G (2010), Effects of three-dimensional Earth structure on CMT earthquake parameters, *Phys. Earth Planet. Inter.*, 179.
- Kreemer, C., W.E. Holt, and A. J. Haines (2003), An integrated global model of present-day plate motions and plate boundary zones, *Geophys. J. Int.*, 154(1), 8-34.
- Pesicek, JD, Thurber, CH, Widiyantoro, S Zhang, H DeShon, HR Engdahl, ER (2010), Sharpening the tomographic image of the subducting slab below Sumatra, the Andaman Islands and Burma, *Geophys. J. Int.*, 182.
- Spasojevic, Sonja, Liu, Lijun, Gurnis, M. (2009), Adjoint models of mantle convection with seismic, plate motion, and stratigraphic constraints: North America since the Late Cretaceous, *Geochem. Geophys. Geosyst.*, 10.
- Xu, LL, Rondenay, S., van der Hilst, RD (2007), Structure of the crust beneath the southeastern Tibetan Plateau from teleseismic receiver functions, *Phys. Earth Planet. Inter.*, 165.
- Yang, YJ, Ritzwoller, MH, Levshin, AL, Shapiro, NM (2009), Ambient noise rayleigh wave tomography across Europe, *Geophys. J. Int.*, 168.

# How Do Plates Evolve?

Gene Humphreys (*University of Oregon*)

Understanding the nature, creation, and evolution of plates has progressed rapidly in the ~40 years since the plate tectonics scientific revolution recognized their existence and dominant role in Earth behavior and evolution. This remarkable progress is a result of advanced observations in many disciplines, often focused with concepts provided by consensus models, but also by accidental discoveries. The following represents a consensus framework of this complex subject; further integration, model development, and fundamental observations will surely lead to refinements of these views.

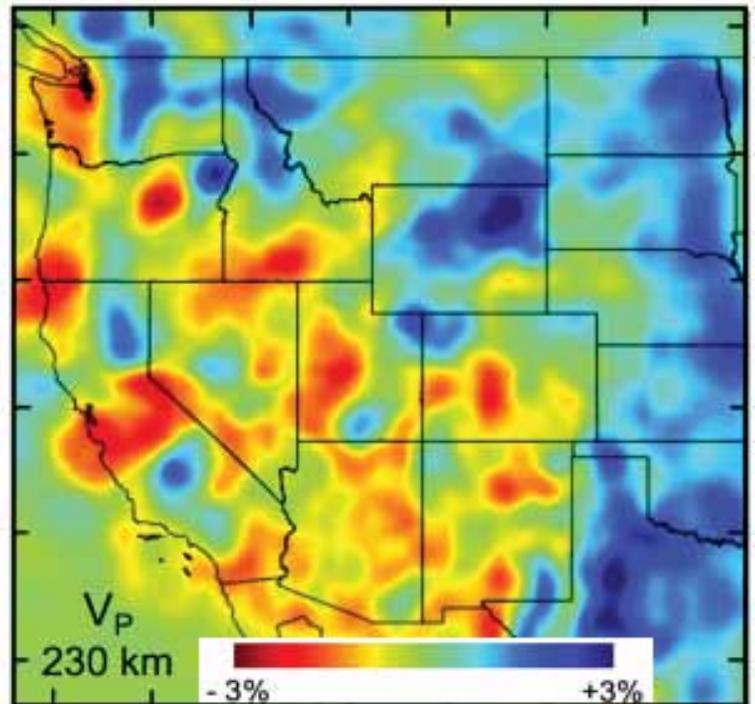
## Oceanic Lithosphere.

The relatively short life, rigid behavior and regular cycling of ocean lithosphere from ridge to subduction zone results in plates that appear simple compared to continents; this simplistic view arises in part from oceanic plates being under water and hence difficult to observe and study in detail. It is well understood that oceanic lithosphere is created at mid-ocean spreading centers, cools as it moves away, and sinks into the Earth at subduction zones. Important processes include decompression melting

beneath the spreading center; seismic imaging finds magma chambers are small or absent, suggesting they are transient and magma residence time is short. Off-axis magmatism and asymmetric spreading reflect interactions between the lithosphere and underlying asthenosphere that, at scales larger than the mid-ocean ridge, are not completely passive. Anomalously low seismic velocities beneath spreading centers at depths of 100 km or more may indicate small amounts of vapor-induced partial melting, dehydrating the asthenosphere at these depths. Much higher degrees of partial melting occur above ~70 km, depleting the asthenosphere of basaltic components, thereby increasing both buoyancy and solidus temperature. As the ocean lithosphere moves away from the spreading center and cools, it incorporates this compositionally stratified structure. Further cooling thermally accretes asthenosphere into the growing thermal boundary layer. Cooling, dehydration, depletion and relatively mafic compositions are responsible for making an ocean lithosphere that resists deformation. Ocean floor flattening (relative to predictions of thermal cooling) is taken as evidence for significant rates of convective loss of lower lithosphere, and as the plates age, the occurrence of off-axis magmatic events (e.g., hotspot construction of plateaus and aseismic ridges) locally builds thick crust, further depleting the upper mantle, and creates compositional and density heterogeneity within the plate. Seawater circulation through the upper ocean lithosphere, occurring primarily near the spreading center and where the plate flexes near a subduction zone, creates hydrous minerals in the upper plate, and it is this fairly complicated lithosphere that subducts.

## Continental Lithosphere.

Compared to oceanic lithosphere, continents are more complex and less understood. It is clear that compositional differentiation through magmatism creates relatively felsic rocks that are more buoyant, radiogenic, hydrous, and easier to melt than their parent rocks, and sufficient accumulation of such rocks creates a mass that resists subduction. The magmatic complement to the felsic rocks, typically depleted mantle, is also strong and compositionally buoyant compared to parent rocks, thus collecting beneath the relatively felsic accumulation. Subduction at the margins of proto-continents leads to further differentiation,



P-wave velocity structure near the base of the western U.S., from Schmandt and Humphreys (2010). Velocity variations this great reflect temperature variations. Such structure indicates that vertical flow velocities create temperature variations at rates greater than are healed by conduction, i.e., the region is experiencing vigorous small-scale convection. High-resolution imaging at this scale has only been possible since the deployment of EarthScope's USArray.

tectonic disruption and mass accumulation (through arc magmatism and accretion), resulting in the creation of complex and relatively stable continents. Magmatic segregation was more complete early in Earth's history, and the resulting depleted mantle lithosphere formed especially stable cratons. Knowledge of this process is informed by xenolith, seismic, and isostatic studies. But to more thoroughly understand continental evolution, knowledge of mass balance, the rates and processes by which mass moves, and how these have changed through time is necessary. Processes of growth tend to be preserved, whereas processes of consumption are inferred indirectly.

A theme in the last decade is a growing awareness of the diversity and significance of processes that remove and cycle continental crust back into the Earth's interior. Beyond mass budgets, processes of segregation and the creation of internal structure are basic to continental evolution. Nearly all of these facets are not well understood on very long time scales (or even in the recent past or present). But this is changing rapidly, and important new insights are coming from mantle studies, such as seismic identification of: a lithosphere-asthenosphere boundary, continental lithosphere that apparently convectively falls or drips downwards (possibly by delamination processes), and larger scale mantle circulation as revealed by tomography (in some cases from crust to core). Western U.S. studies have been central to many of these findings, with EarthScope providing many of the key data.

As a community we are trying to understand how present day observed and imaged structures and processes relate to long-term plate evolution. The concept of a simple thermal boundary layer continental lithosphere is being fundamentally revised into one with an important compositional (depleted) origin and a lithosphere-asthenosphere boundary layer, requiring revision of thermal boundary layer and cooling models. A number of exciting findings are emerging, which relate to plate history in varying degrees, and may manifest in seismic structures. For example, there appears to be relatively rapid lithospheric removal beneath volcanic arcs, currently most prominently beneath the Andes but also beneath western U.S. [e.g., *DeCelles et al.*, 2009]; if correct, how is this mantle lithosphere rebuilt? Much of the presumed downwelling beneath the western U.S. involves depleted Precambrian mantle, apparently eclogite loaded and destabilized by magmatic infiltration. Furthermore, xenolith studies suggest that basal North American lithosphere was removed during the Laramide orogeny, most compellingly in and around Wyoming [e.g., *Carlson et al.*, 1999]. Mantle tomography images a high-velocity feature extending to ~250 km beneath most of Wyoming, a depth from which the post-Laramide xenoliths argue for a lithosphere not of North America origin, suggesting a lithospheric growth process of unknown character. Another example involves the accretion of ocean lithosphere (and its presumed "continentalization") and magmatic growth away from subduction zones, most recently related to the Yellowstone hot-spot and, in the recent past, by regional heating and widespread volcanism in what now is the Basin and Range, related to the removal of the Laramide-age flat slab.

The western U.S. continues to provide an opportunity to study important continental evolution processes. With EarthScope and IRIS data, a truly unique and unprecedented opportunity exists to image and examine active plate processes like never before. In looking forward, we wish to better understand continental evolution in a global context, especially through geologic time, informed by findings in the western U.S. As more data become available, new processes, some complicated and complex, will continue to be discovered and replace simpler old paradigms. By all appearances, much of the character of continents appears active and far from equilibrium.

## References

- Carlson, R.W., A.J. Irving, and B.C. Hearn Jr., in Gurney, J.J., J.L. Gurney, M.D. Pascoe, and S.H. Richardson, eds., *Proceedings of the 7th International Kimberlite Conference*, Vol. 1: Cape Town, Red Roof Design, p. 90-98, 1999.
- DeCelles, P.G., M.N. Ducea, P. Kapp and G. Zandt, Cyclicity in cordilleran orogenic systems, *Nature Geoscience*, v. 2, doi:10.1038/ngeo469, 2009.
- Schmandt, B., and E. Humphreys, Complex subduction and small-scale convection revealed by body-wave tomography of the western United States upper mantle, *Earth Planet. Sci. Lett.*, doi:10.1016/j.epsl.2010.06.047, 2010.

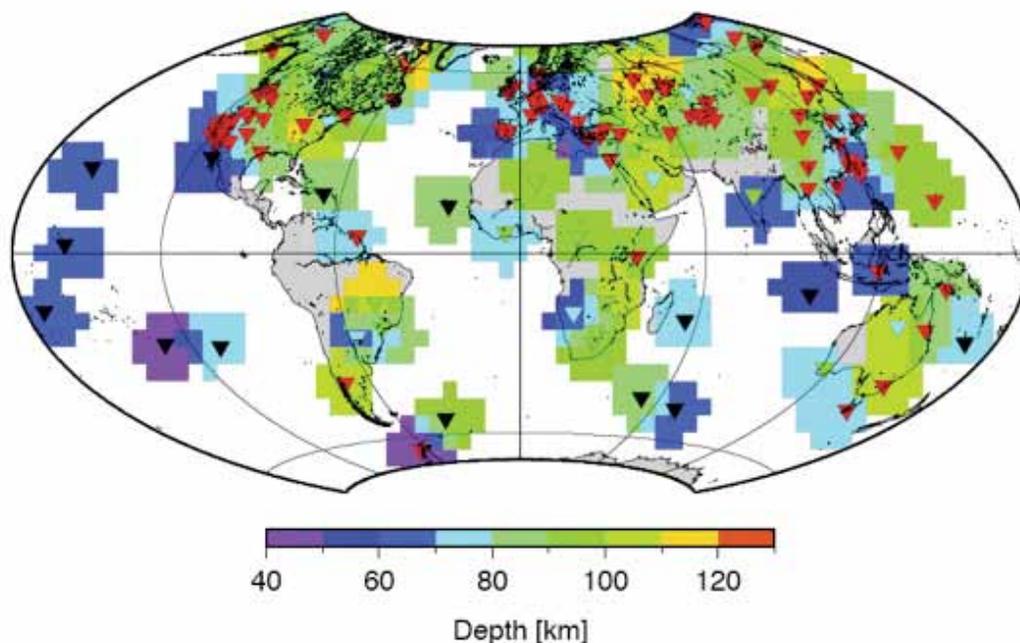
# The Lithosphere-Asthenosphere Boundary

James Gaherty (*Lamont-Doherty Earth Observatory*)

The lithosphere-asthenosphere boundary (LAB) represents one of the most dynamically important boundaries in the Earth. Essentially all surface deformation— earthquakes, volcanic activity, slow tectonic deformation – results from forces associated with mantle convection in the asthenosphere; the transmittal of these forces (and related melting products) through the nearly rigid lithosphere depends on the nature of the LAB. In particular, the viscosity contrast across the LAB is a key but largely unknown element of plate tectonics. This contrast almost certainly has a thermal component related to the cooling of the lithosphere, but investigators have long speculated that layering of composition and/or melt content may strongly modulate or control the rheological transition across the LAB.

Over the last decade, the nature of the LAB has crystallized into a “grand challenge” within the seismological community, fuelled by advances in laboratory observations of deformation mechanisms and the elastic properties of mantle rocks combined with improved seismological imaging techniques for shallow mantle structure. The new laboratory data provide the means to accurately account for the effect of temperature, volatiles, and grain size on seismic wavespeed, and these studies suggest that the seismic velocity transition observed across the LAB in both continental and ocean regions is too sharp, and too large, to be purely thermal [e.g., *Faul and Jackson, 2006*]. The question of whether this discrepancy implies a wet and/or partially molten asthenosphere, a change in grain size, or something else entirely, remains unanswered.

The IRIS community is rallying to address this question. The past five years have seen a surge of activity utilizing IRIS data to provide better seismological constraints on the LAB, as documented in the accompanying research accomplishments. A number of groups are utilizing P-to-S and S-to-P conversions to explore the discontinuity structure of the shallow mantle. Historically these analyses have exploited single-station P-to-S conversions that are relatively insensitive to structure within the upper 200 km of the mantle due to noise associated with crustal reverberations. Advanced P-to-S imaging techniques, and adaption of the analysis to S-to-P conversions, are providing relatively robust images of discontinuities within this depth interval (Figure 1). Regional surface-wave analyses, in particular using large-aperture (e.g., PASSCAL) arrays, are yielding high-resolution estimates of absolute velocity and attenuation across the lithosphere-asthenosphere transition that can be directly compared to the laboratory-based predictions. Finally, estimates of variations in the layering of seismic anisotropy provide an alternative means to map the LAB.



Global map of the depth to the lithosphere-asthenosphere boundary imaged using Ps receiver functions (Rychert and Shearer, 2009). Color indicates depth. Triangles show the 169 stations used in this study. Station color corresponds to tectonic regionalization: Oceanic – black, Phanerozoicorogenic zones and magmatic belts – red, Phanerozoic platforms – cyan, Precambrian shields and platforms – green. Average LAB depth varies from  $95 \pm 4$  km beneath Precambrian shields and platforms to  $81 \pm 2$  km beneath tectonically altered regions and  $70 \pm 4$  km at oceanic island stations.

A number of intriguing results are emerging from these analyses. They confirm that the seismically observed LAB does not correspond to the base of a thermally controlled lithosphere – the seismic boundary is much too sharp, and generally too shallow, to be dictated by temperature. On a global scale, the depth to the seismic LAB generally correlates with expected tectonic variations in lithospheric thickness: shallowest beneath oceans and regions of young tectonism, deeper beneath older cratonic interiors (Figure 1). However, in detail, the depth to the LAB from converted body-wave phases is not always consistent with lithospheric thickness inferred from surface waves; in particular, it is much too shallow in cratonic regions, where surface-wave velocities imply high-wavespeed lithosphere extending to 200 km or deeper. One interpretation of this discrepancy is that the LAB observed in the body-wave studies does not represent the base of the lithosphere at all; alternatives include layering in mantle fabric associated with continental assembly, as suggested by some of the new anisotropy results (Figure 2), and/or compositional layering within the continental lithosphere. Continued advances in imaging of the lithosphere-asthenosphere system will help to resolve these issues, which will be directly facilitated through continuation of the IRIS facilities that provide important data to the seismological community.

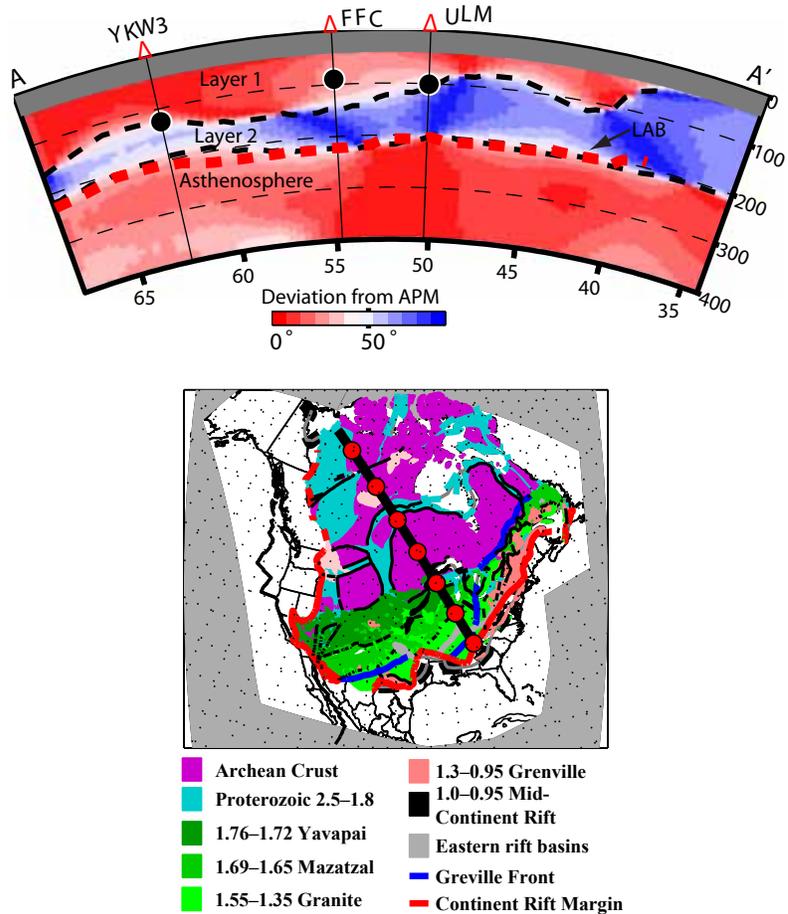


Figure 2. Upper mantle layering defined by changes in the direction of fast axis of azimuthal anisotropy. Change in anisotropy would produce Ps conversions, and is within the depth range of the Ps observations from global studies. Upper panel displays fast axis direction relative to the NA absolute plate motion direction, as a function of depth along a depth cross-section shown in the lower panel. Figure from H. Yuan and B. Romanowicz [this volume].

## References

- Faul, U. H., and I. Jackson, The seismological signature of temperature and grain size variations in the upper mantle, *Earth. Planet. Sci. Lett.*, 234, 119-134, 2005.
- Rychert, C. A., and P. M. Shearer, A global view of the lithosphere-asthenosphere boundary, *Science*, 324, doi: 10.1126/science.1169754, 2009.

# How are Earth's Internal Boundaries Affected by Dynamics, Temperature, and Composition?

Maureen D. Long (Yale University)

The nature of dynamic processes that operate in Earth's interior - and the thermal and chemical structures that result from these processes - remain fundamental questions for solid earth geophysics. The tools of observational seismology, facilitated by the increasing availability of broadband seismic data from around the world, yield the tightest constraints available on deep Earth structure, and in combination with geodynamical models and mineral physics experiments yield powerful insights into processes operating in the Earth. Dynamic processes affect the Earth's internal boundaries, including the asthenospheric upper boundary layer of the mantle convective system, the seismic discontinuities associated with the mantle transition zone, and the core-mantle boundary (CMB) region, including both the CMB itself and the D'' layer. Understanding the detailed structure in the vicinity of these internal boundaries can help us to distinguish the (often competing) effects of dynamic processes and variations in temperature and composition on seismological observations. Key observables include velocity and attenuation structure (both isotropic and anisotropic) and the location and character of seismic discontinuities. For example, observations of seismic anisotropy, which is particularly important in the boundary layers of the mantle's convective system, can yield direct constraints on mantle flow patterns and on the processes that control these patterns (Figure 1). Rapid progress has been made over the past several years in the seismological characterization of the Earth's internal boundaries, much of it enabled by IRIS facilities, and in using these observations to arrive at insights into deep Earth dynamics.

The Earth's upper mantle encompasses the upper boundary layer of the mantle convective system and includes both the rigid lithospheric mantle (including plates) and the weak asthenosphere, which manifests itself in low seismic velocities and which concentrates deformation that results in anisotropy (Figure 1). The nature of the lithosphere-asthenosphere boundary has been probed in detail using receiver function analysis and other methods, which has in turn yielded insight into the thermal and rheological nature of the asthenosphere. Information about the three-dimensional seismic structure of the upper mantle is available from global tomographic models, which have improved rapidly over the past several years due to increasingly dense seismic networks and theoretical improvements such as the use of full waveform tomography. On a regional scale, data from the EarthScope initiative and other projects have yielded spectacular images of seismic velocities beneath the western United States, which are still being interrogated for insight into upper mantle dynamics, as well as the evolution of plates and plate boundaries. Upper mantle velocity and attenuation structure contain information about temperature and composition (and therefore about the dynamic processes that cause lateral variations in these properties), but separating

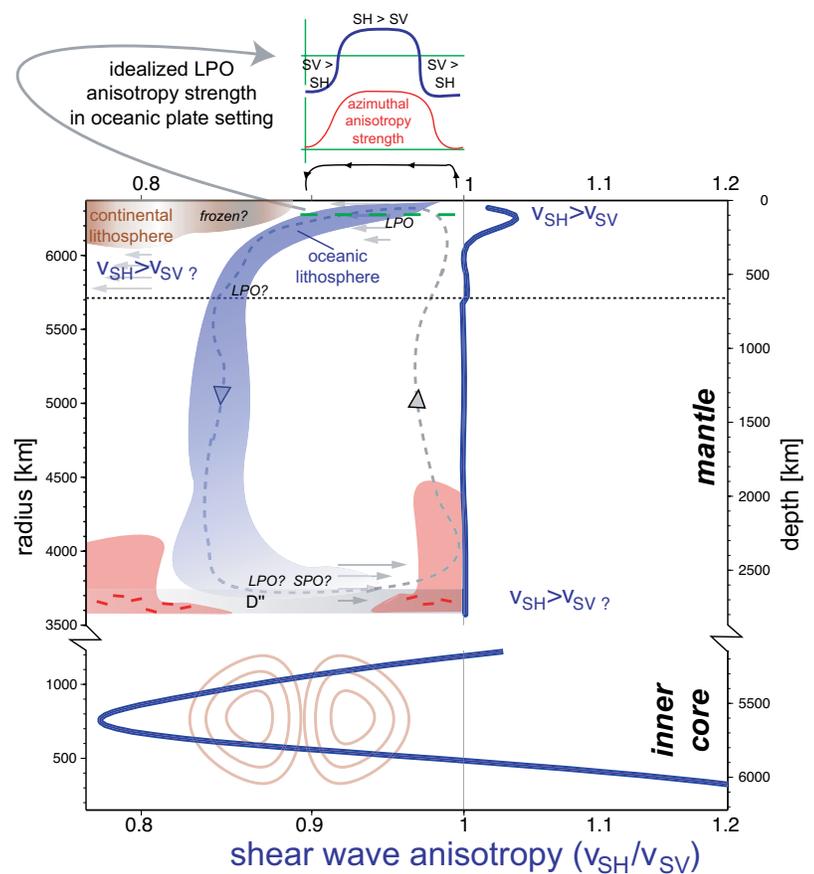


Figure 1. Simplified illustration of the first-order anisotropic structure of the Earth, from Long and Becker (2010). The heavy blue lines in the center show average radial anisotropy in the mantle and core, with a possible mantle flow trajectory for a downwelling slab (blue) displacing a thermochemical pile (red) at the CMB shown as a dashed line. Anisotropic structure is most pronounced in the upper and lower boundary layers of the mantle, as well as the inner core. In the upper mantle, flow is primarily horizontal, except beneath upwellings and downwellings, which are associated with primarily vertical flow. At the base of the mantle, possible horizontal flow due to slab material impinging upon the CMB is shown, which may lead to anisotropy.

thermal and compositional effects remains a significant challenge. Observations of upper mantle seismic anisotropy, including shear wave splitting measurements and surface wave observations, yield relatively direct constraints on the pattern of mantle flow in the upper mantle boundary layer, which can in turn be related to the larger-scale mantle convective system. First-order comparisons of seismic anisotropy observations beneath ocean basins to the predictions made by global convection models have been successful, but the patterns of anisotropy observed in more complex tectonic settings such as subduction zones remain to be completely understood.

The mantle transition zone, which encompasses the region between 410 and 660 km depth, plays host to a variety of phase transitions in mantle minerals, including the transitions from olivine to wadsleyite and from ringwoodite to perovskite and ferropericlase. Each of these phase transitions is associated with a sharp change in seismic velocities that manifests itself as a discontinuity; the precise depth and character of each transition is affected by temperature, composition, and volatile content. Therefore, knowledge about the depth, sharpness, and velocity gradient of transition zone discontinuities yields insight into physical conditions in the transition zone and into the dynamic processes that produce these conditions. While the first-order, one-dimensional structure of the transition zone has been known for decades, the recent explosion in the availability of broadband seismic data has enabled detailed transition zone discontinuity imaging on both a global scale and in the context of more regional problems. A regional example is shown in Figure 2, where the transition zone structure beneath South America is interpreted in terms of mantle dynamics and chemistry. In addition to the study of discontinuities, insight into the thermochemical structure and dynamics of the transition zone can be gleaned from global tomographic models, which have recently been interpreted in terms of lateral variations in temperature and water content which can be related to the locations of mantle upwellings and subducting slabs.

In one-dimensional seismic velocity models, the lower mantle (from the base of the transition zone to the top of the D" layer) is relatively simple, but recent work has demonstrated that there are, in fact, several features evident from the seismic wavefield that are associated with sharp "boundaries" in the lower mantle. For example, large-scale low shear velocity features have been identified in the lower mantle beneath the Pacific and Africa; sometimes referred to as "superplumes" (while their exact dynamical context is not presently constrained), these low shear velocity regions have been shown to have sharp lateral boundaries that are thought to reflect chemical, as well as thermal, variations. Seismic discontinuities at mid- to lower-mantle depths have also been identified, particularly beneath the western Pacific subduction zones, although these discontinuities do not appear to be global features. Their cause remains enigmatic, but their intermittent appearance likely reflects variations in thermal and/or chemical structure in the mid-mantle. The boundary at the base of the transition zone between the upper and lower parts of the mantle may itself constitute an important control on whole mantle dynamics; observations of inferred stagnant slabs at the base

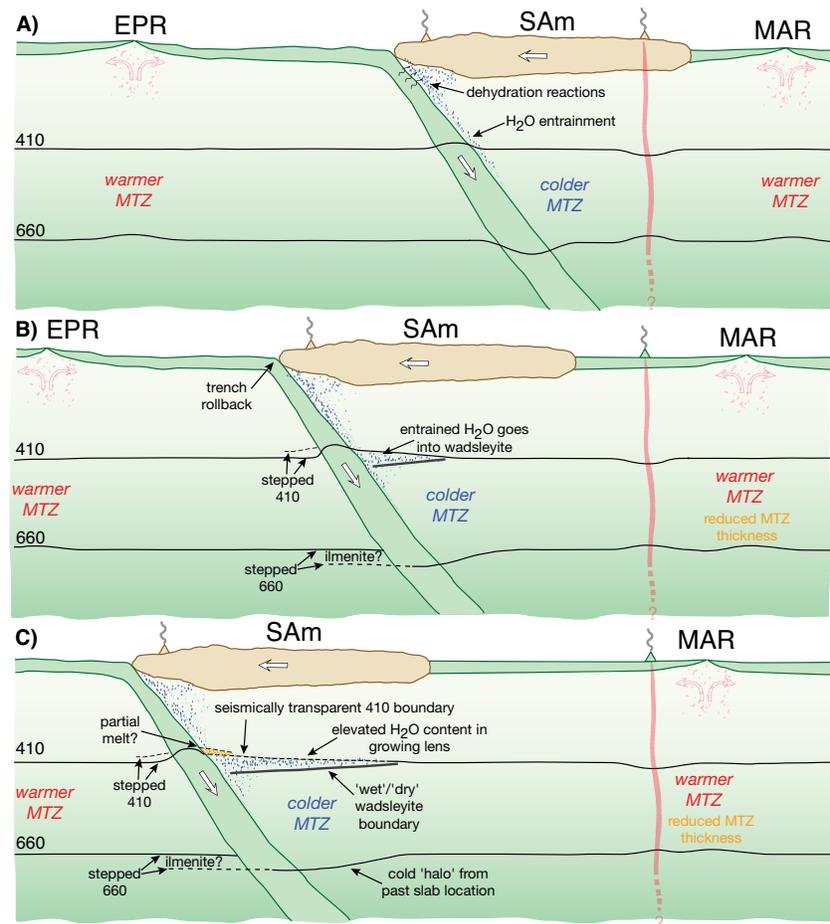


Figure 2. Illustration of possible effects of subduction and slab rollback on transition zone structure beneath South America, from Schmerr and Garnero (2007). In (a), water is brought into the transition zone by entrainment of hydrated upper mantle materials and/or transported within the slab. The cold downgoing slab initially results in an elevated 410-km discontinuity and a depressed 660-km discontinuity. As the continent moves westward due to trench rollback (b), buoyant hydrated wadsleyite collects at the top of the transition zone and elevates the 410-km discontinuity. The final geometry of the hydrated lens and the relatively colder and warmer regions of the transition zone are shown in (c).

of the transition zone and a difference in the spectrum of lateral heterogeneity between the upper and lower mantle in global tomographic models have been interpreted as evidence that mantle convection may be partially layered.

The D" region at the base of the mantle, located just above the CMB, represents one of the most exciting frontiers for exploiting seismological observations to gain insight into deep Earth dynamics. The existence of a seismic discontinuity at the top of the D" layer has been known for several decades, but its cause remained enigmatic until the discovery of the post-perovskite phase transition provided a natural hypothesis for its origin. Parallel developments in experimental and theoretical mineral physics and observational seismology, enabled particularly by dense broadband array data, has led to rapid strides in our understanding of the D" discontinuity and its dynamical implications. Detailed imaging of lowermost mantle structure has led to a suggestion of an intermittently observed double discontinuity indicative of regional "lenses" of post-perovskite above the CMB. In turn, these observations have been used to estimate CMB temperatures and heat flux values, yielding insight into first-order questions about the evolution of the Earth's interior. The D" layer is also associated with an increase in lateral heterogeneity in seismic velocity structure in tomographic models, which has recently been interpreted in terms of variations in both thermal and chemical structure, as well as the presence of ultra-low velocity zones (ULVZs) which are hypothesized to be due to the presence of partial melt and which have been characterized in increasing detail in recent years. Finally, the delineation and interpretation of seismic anisotropy at the base of the mantle has the potential to allow for the characterization of lowermost mantle flow patterns, with important implications for our understanding of mantle dynamics. In contrast to the bulk of the lower mantle, which is generally isotropic, D" exhibits anisotropy in many regions, with a variety of anisotropic geometries proposed. Much work remains to be done to characterize D" anisotropy in enough detail to understand the causative mechanism and to relate it reliably to mantle flow patterns, but this represents a promising avenue for understanding the dynamics of the lowermost mantle.

The deepest of the Earth's internal boundaries are associated with the core, and the vertical gradient in density between the silicate mantle and the liquid outer core is the most dramatic in the Earth's interior. The structure of the CMB itself, the lowermost outer core, the inner core boundary, and the solid inner core have been probed with increasing detail in recent years; as with much of the ongoing research on Earth's interior boundaries, this work has been enabled by both the long-running stations of the IRIS GSN and by dense broadband arrays that are often associated with the PASSCAL program. Spatial and temporal variations in the structure of both the inner core boundary and the inner core as a whole have been suggested, with implications for possible inner core super-rotation, the nature of outer core convection, the growth history of the inner core, and the driving forces of the geodynamo. Seismic anisotropy has been observed in the solid inner core using both normal mode and body wave observations, and it appears that the inner core encompasses several distinct anisotropic domains, although consensus on the nature and causes of inner core anisotropy has not yet been reached.

Progress in the characterization of thermochemical structure and dynamic processes associated with the Earth's internal boundaries over the past several years has been exciting and rapid. The continuing expansion of the availability of global broadband seismic data and the increasing use of analysis techniques that exploit more fully the information contained in the full seismic wavefield provide exciting avenues for future progress. Seismological observations, in combination with insights from complementary fields such as geodynamics and mineral physics, remain the most powerful tools available for probing the structure and dynamics of the Earth's interior, and discoveries such as those described here continue to be made possible by the IRIS facilities that allow for the collection and dissemination of data from both long-running global networks and from dense temporary experiments. The continued expansion of data availability from IRIS facilities will continue to enable advances in the study of the Earth's interior dynamics.

## References

- Long, M. D., Becker, T. W., 2010. Mantle dynamics and seismic anisotropy. *Earth Planet. Sci. Lett.*, in press.
- Schmerr, N., and E. Garnero, 2007. Topography on Earth's upper mantle discontinuities from dynamically induced thermal and chemical heterogeneity, *Science*, 318, 623-626.

