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LOCATIONS OF MID-OCEANIC EARTHQUAKES
CONSTRAINED BY SEAFLOOR BATHYMETRY

Jianfeng Pan, Michael Antolik, and Adam M. Dziewonski
Department of Earth and Planetary Sciences
Harvard University, Cambridge, MA 02138
(617) 496-8364
jpan@seismology.harvard.edu

Earthquakes associated with the creation of new ocean floor are difficult to locate precisely because they normally occur far away from seismic stations. We use the CMT focal mechanism solution of an earthquake to relate the event to either a transform fault (strike-slip) or a ridge (normal fault). Therefore, epicenters of these events can be constrained by the topography of the ocean floor. If we rotate the Earth to a coordinate system defined by the pole of rotation between two plates, a transform fault should be a parallel and ridge a meridian (except for oblique ridges). We are able to reduce the number of free parameters in the horizontal plane from two to one. Using the Harvard CMT catalog and arrival times from ISC Bulletins, we have relocated about 1,500 globally distributed events ("it Master Events") for years from 1976 to 1998. Our results show that ISC locations can be as much as 100 km away from the appropriate topographic features. For events of smaller magnitude, which either are with unknown focal mechanism or predate the CMT catalog, we use a simultaneous JHD (Joint Hypercenter Determination) procedure to relocate them around those already relocated master events. Tests on master events along the Romanche Fracture Zone (RFZ) show new locations for each cluster delineate the RFZ more closely. We superimpose the inversion for all master events in the Mid-Atlantic ocean from North 30 degrees to South 30 degrees and introduce a smooth weighting scheme for overlapping master events. Results show clearly reduced residuals and that all the events become more clustered along the linear bathymetry features.
Source parameters for the 1994 Japan Sea, 2000 Bonin, 1991 Argentina and 1995 Mariana deep earthquakes are inferred from broadband data of the Global Seismograph Network. The spatial relationship between these events and the active portion of the slabs is investigated by locating these earthquakes and their aftershocks relative to the background seismicity. The 1994 Japan Sea event ruptured downward with a velocity of 3 km/s along the shallow dipping nodal plane of the centroid mechanism. The earthquake consisting of two episodes of moment release ruptured the entire width of the seismically active slab. For the 2000 Bonin event, rupture propagated bilaterally toward NNW and SSE along the steeply dipping nodal plane of the average focal mechanism. During the 1991 Argentina event rupture propagated subhorizontally over a distance of about 55 km with a velocity of 3.5 km/s. The 1995 Mariana event produced one of the strongest deep earthquake aftershock sequences known. The main shock ruptured downward across the entire width of the active slab along a plane dipping southwestward. Most of the 17 well-located aftershocks occurred along or very near the rupture plane.

We have now assembled a dataset of nine large deep earthquakes (Mw ranging from 7.1 to 8.3) from 6 different subduction zones that have been studied with the same methodology. This comparison suggests that deep earthquake source properties are dependent on the temperature of the slab. Events in cold slabs generally show high aftershock activity, high rupture velocity and high seismic efficiency. In contrast, earthquakes in warm slabs have low aftershock productivity, and show generally low rupture velocity and low seismic efficiency. However, the 1991 Argentina event has source properties that are rather characteristic for earthquakes in cold slabs, and that differ from those of other large South American events. We suggest that two types of deep earthquakes occur in South America, and we interpret these results in the context of the shear instability model for the mechanism of deep earthquakes. In this model, shear failure occurs through a thermal runaway mechanism within a shear zone at great depth, and low seismic efficiency might indicate significant energy dissipation due to heating and possible melt production. The 1991 Argentina event, located in a pocket of deep seismicity within the slab core, may represent a shear instability with little melting as would be the case for large deep earthquakes in cold subduction zones, whereas the other known South American large deep events such as 1963 Peru, 1970 Colombia and 1994 Bolivia, are located in relatively aseismic regions and may involve significant melting within warmer regions of the slab.
Preliminary results of a high-resolution seismic reflection experiment across the Salar de Uyuni on the Altiplano of Bolivia will be presented. The data were acquired using IRIS PASSCAL multichannel equipment during two field excursions in July and August 2000. A jackhammer was used as the source, providing surprisingly high-frequency data (over 500 Hz) down to depths of at least 300 m.

The Salar de Uyuni is the largest salt flat in the world and is a conspicuous remnant of the late Pleistocene Lake Minchin/Tauca. The seismic profiles were designed to cross the site of a 220 m deep corehole drilled by Baker and others (Nature, 8 Feb 2001) to investigate the paleoclimate history of this part of tropical South America. The two main objectives of the seismic experiment are (1) to produce a seismic stratigraphic record for Pleistocene deposits within the southern basin of the Altiplano by imaging the interbedded layers of salar salts and lacustrine muds down to depths of 300-500 m and (2) to document the extent to which the Quaternary lake stratigraphy is affected by neotectonic deformation in the form of either isostatic rebound or active faulting. Data quality is quite good despite the 2-10 m thick surficial salt layer and some very windy conditions. Velocity in the surficial salt layers is from 3000 to 4000 m/s. These high-velocity salt layers generate peculiar looking shot records, with high-velocity direct waves, groundroll and possible guided waves, but reflections are easily identified throughout the section.
METHODS OF DETECTING ULVZ’S AT THE CMB

Sidao Ni, Shengnian Luo and Don Helmberger
Seismological Laboratory Caltech 252-21, Pasadena, CA 91125

The first evidence for ultra low velocity zones was derived from SKS+SKPdS/SPdS waveform anomalies near 110 degrees. Some of the most extreme observations have been modeled by 2D structural ridges (roughly 30km high, 300 km across) with 30% reduction in shear velocities. Such structures can explain other waveform complexities: (1) the existence of ScS as a separate phase from S beyond 100 degrees, (2) broadband precursors of PKP observed between 130 to 144 degrees. (3) multi-pathing of PKPab and SKS. Moreover, such abrupt variations in velocity structures can explain some very rapid changes in differential travel time of the PKP branches. A few anomalous structures have been sampled by a combination of these methods, greatly increasing the likelihood of their existence, though there remains some questions about their true uniqueness in terms of being above and/or below the CMB. Various examples of these observations and 2D synthetics will be presented in this poster.
The M 7.1 Hector Mine earthquake ripped through the Californian Mojave Desert on October 16, 1999. The earthquake, which occurred on a fault with an estimated repeat time of thousands of years, happened only seven years after and 30 km away from the 1992 M 7.3 Landers earthquake. This closeness has led to intense speculation that Landers triggered, i.e. was responsible for the timing of, the Hector Mine quake. A common way to check if one earthquake has triggered another is to calculate whether the first earthquake increased static stress at the hypocenter of the second. Yet static Coulomb stress change analysis have demonstrated that there is significant uncertainty as to whether Landers increased static stresses at Hector Mine.

In our work we explore the possibility that Landers was not a direct trigger of Hector Mine, but rather that it initiated a set of smaller earthquakes, a chain of dominoes, which eventually hit the Hector Mine hypocenter. The circumstantial evidence for such a scenario is strong. A (11*20km) cluster of Landers aftershocks was active in the Hector Mine epicentral region from shortly after the Landers mainshock until Hector Mine, and the activity level in this cluster was clearly influenced more strongly by local events than by Landers. The M5.4 Pisgah earthquake, for example, which occurred in the cluster seven days after Landers, caused a 29-time fold increase in the post-Landers daily earthquake rate. In 1996, M4.3 and M4.1 earthquakes caused significantly larger seismicity rate increases than Landers had within 2km of the Hector Mine hypocenter. A number of other small earthquakes, including the Hector Mine foreshocks, are likely to have also played important parts.

To quantify the likely role of these smaller, but closer, earthquakes, we statistically model the occurrence of direct aftershocks and aftershocks-of-aftershocks of Landers. We find that seven years after the Landers mainshock, over 80% of the ongoing seismicity are aftershocks of aftershocks of Landers, rather than direct aftershocks of Landers itself. This provides a baseline estimate for the probability that Hector Mine was triggered indirectly. We show further that as a general rule, the sum total of earthquakes in each magnitude level are equally responsible for triggering future seismicity. (That is, all of the M 2-2.9 combined trigger just as many aftershocks as all of the M5-5.9 combined). Therefore, in general, the stress triggering effects of smaller earthquakes cannot be ignored.
The Broadband Experiment Across the Alaska Range (BEAAR) is in its third and final data acquisition phase. PASSCAL instruments are deployed along two nearly perpendicular lines. The main line runs north-south across the Alaska Range along the Parks Highway between Fairbanks and Anchorage, and a cross line of stations runs east-west along the Denali Highway and through Denali National Park. Data acquisition began in the summer of 1999 with seven stations on the main line at approximately 50 km spacing. In the second phase, summer 2000, an additional twenty nine stations (total of 36 stations) were deployed for three months with a denser station spacing of approximately 10 km. The final phase includes eighteen stations which have been running through the 2000-2001 winter, and will continue until August 2001. Data collected from this experiment will be used to investigate the structure and tectonic setting of the Alaska Range.

Teleseismic receiver function analysis can provide constraints on crustal thickness and velocity structure beneath the BEAAR network. Receiver functions from events recorded at each station can be stacked to reduce noise and enhance phase information. Arrivals generated by conversions at the North American plate Mohorovicic discontinuity can be correlated across the network showing a thickening of the crust beneath the mountains. The crust thickens from about 30 km at the northernmost station to nearly 50 km under the Alaska Range, and remains relatively thick to the south. Phases converted in the subducting slab, most likely the subducted oceanic Moho, can also be correlated across the southern portion of the network. The mantle wedge gradually pinches out to the south, and at the southernmost station the Alaska continental crust is directly underlain by subducted Pacific plate to produce an extremely thick (50-60 km) crustal section.
The formation and evolution of continental orogenic zones such as the Rocky Mountains is one of the most fundamental yet poorly understood problems in geoscience. During the past 40 years numerous geophysical studies have been conducted in the Rocky Mountains (See Keller et al., 1998, and Karlstrom and Humphreys, 1998 for detailed reviews about the major findings of those studies). Study of the mantle transition from the orogenic zones to the nearby cratons can provide critical information about the processes that led to the formation of this orogenic event. Here we present preliminary results about the mantle transition from the Rocky Mountains to the Great Plains using broadband seismic data obtained from an 8-station portable seismic experiment across Kansas (KSArray) conducted for the period of July, 2000 to February, 2001.

Preliminary results using data recorded by KSArray and data from the 1992 Rocky Mountain Front Experiment (Sheehan et al., 1995) suggest that the mantle transition between the Rocky Mountains and the Great Plains is located near 98 degrees W, which is approximately 600 km east of the Rocky Mountain front, and 350 km east of the boundary that was previously suggested (Chen and Lerner-Lam, 1993). This preliminary conclusion is supported by the following observations:

(1). P-wave travel time residuals show a westward increase of about 1.2 s over the distance range from 98 degrees W to 104 degrees W;

(2). 98 degrees W is an apparent boundary between the "eastern U.S. type" shear wave splitting pattern, which is characterized by mostly NE-SW fast polarization directions, and "Rocky Mountain type" pattern, which is a mixing of null and rapid-varying fast polarization directions and splitting delay times; and

(3). Crustal thickness determined from stacking of receiver functions shows a westward increase from about 38 km at 98 degrees W, to about 52 km at about 105 degrees W.

Implications of these observations on the formation of the Rocky Mountains will be discussed.
We use mantle and inner-core sensitive normal modes to invert for laterally varying mantle and transversely isotropic inner core seismic velocity structure. To obtain an inner-core model that is compatible with long-period mode and short-period body-wave data, we incorporate mantle-corrected absolute and differential travel-time data in our inversions. Using diverse data, we investigate the dependence of inner-core models upon mantle parameterization and possible radial structure within the inner core.

The density model is better constrained with the addition of inner-core modes having substantial sensitivity to density structure within the mantle. The results for the inner core are insensitive to whether the mantle is inverted only for shear-velocity structure or for shear- and compressional-velocity structure as well as density. Our results show that an inner-core model with constant anisotropy of approximately 1.5% is capable of fitting all types of data.
The combination of interferometric synthetic aperture radar (INSAR) measurements with seismic data is a powerful tool to analyze regional earthquakes. INSAR is capable of measuring both the location (within meters) and the amplitude (within mm line-of-sight) of regional earthquakes with high accuracy. However, the focal mechanism and depth is poorly constrained using only INSAR data. Seismic data (both phase and waveform) provides much better constraints on the focal mechanism and depth. By using broadband reflectivity modeling to fix the depth and the approximate focal mechanism the surface displacement can be modeled well. The combined techniques not only provide better data on the individual earthquake but also provide a set of accurate locations to assess location accuracy for the seismic data and error estimates of the focal mechanism. Differences between the seismic moment and the geodetic moment may also provide clues on the physics of small earthquakes. The method is demonstrated on a set of moderate size earthquakes in Southern California. The results of a (so far unsuccessful) search for precursory slip are also shown.
We study the lateral variations in P-wave attenuation in the upper mantle by analyzing the spectra from more than 18,000 P and 14,000 PP arrivals from selected seismograms from the IRIS FARM database between 1988 and 1999. We select seismograms from shallow earthquakes (≤50 km depth) at epicentral distances of 40°–80° for P waves and 80°–160° for PP waves. Each spectrum is the product of receiver, source, and propagation response functions as well as local source- and receiver-side effects. We correct each spectrum for the known instrument response, a source model with an ω^{-2.15} falloff at high frequencies, and a one-dimensional Q_a model [Warren and Shearer, 2000]. Since there are multiple receivers for each source and multiple sources for each receiver, we can approximate the source- and receiver-side terms by stacking the appropriate P log spectra. The resulting source-specific response functions include any remaining source spectrum and the effect of near-source attenuation in the upper mantle; the receiver stacks include the site response and near-receiver Q structure. We correct the PP log spectra for the appropriate source- and receiver-side stacks found from the P waves. Since attenuation in the lower mantle is small, the residual log spectrum approximates attenuation in the upper mantle near the PP bounce point, and can be used to estimate δt* at frequencies between 0.16 and 0.86 Hz. We see variations of ±0.4 s in our δt* measurements. Using previous results, we constrain the anomalies to the top 220 km of the mantle and translate the δt* measurements to variations in 1000/Q. The patterns of more and less attenuating regions that we see in the Q^{-1} maps generally correlate with previously published Q models and surface tectonics. Continents are usually less attenuating than the global average, whereas oceanic regions tend to be more attenuating. Australia progresses from more to less attenuating as you move from west to east, in agreement with its tectonic history. There are interesting exceptions to the tectonic pattern, such as an attenuating region beneath southern Africa.
We have summarized earlier and obtained some new data on short-period coda characteristics in Central Asia region. We have been processing recordings of local earthquakes and quarry blasts at distances up to 300 km. Stationary and temporary seismic stations were installed in the regions of Pamirs, Tien Shan, Turan plate and Kazakh platform.

We have established, that strong variations of coda envelopes for frequencies of ~1-3 Hz are observed for close paths at epicentral distances of 10-20 km for lapse time intervals up to ~ 50ts (ts – time of S wave arrival). When frequency increases, variations of coda envelopes become essentially smaller.

In many cases at frequencies of ~1 Hz particle motions in coda are oriented predominantly in the horizontal plane. Analysis of the wave fields using a small-aperture array shows, that after S-wave arrival the slowness of wave groups in coda increases, reaching the values of ~ 10 s/km. At the same time, a direction to the epicenter on the average is preserved.

It is easy to be convinced, that these data for frequencies of ~ 1 Hz do not agree with the model of coda formation as a result of isotropic scattering. The totality of experimental data strongly supports a conclusion, that in Central Asia region at such frequencies S-coda is being formed mainly by shear waves, reflected from multiple close to horizontal boundaries in the crust and upper mantle. On the basis of this model we have developed a simple method of shear wave attenuation field mapping in the lithosphere and asthenosphere using coda of local events.
POTENTIAL ADVANTAGES OF A STRONG MOTION VELOCITY METER AS OPPOSED TO A STRONG MOTION ACCELEROMETER

J.F. Clinton, T. H. Heaton
Department of Civil Engineering, Caltech

Current state-of-the-art strong motion seismometry employs force-balance accelerometers recording over a dynamic range of 7 orders of magnitude, using 24-bit dataloggers. This study examines whether it would be better to deploy a velocity-recording strong motion instrument; this would be comparable to a low-gain version of existing broadband seismometers. Using a large suite of earth signals, we compare a hypothetical long-period velocity seismometer (clipping level set to 5m/s) with the existing Kinemetrics FBA-23 accelerometer. We show that a velocity instrument would have several orders of magnitude more sensitivity in the period band from 1 to several hundred seconds. This would allow the recording of long-period basin response from earthquakes as small as M3.5. In addition, such stations would record teleseismic ground motions from earthquakes as small as M6. This could potentially lead to dense spatial recording of small amplitude motions that are not recorded by traditional strong motion networks. Furthermore, recovery of ground displacement is likely to be more stable from the low-gain broadband seismometer, which would have a more compliant mechanical suspension.

In addition, we looked at FBA-23 data gathered by IRIS GSN. They record FBA output in a 100sps triggered mode in order to recover near-source strong shaking, as well as at 1sps continuously to recover on-scale long period motions from giant earthquakes that may overdrive current broadband seismometers, even at teleseismic distances. We found the FBA capable of successfully recording surprisingly long periods of motion - for example, for the 1998 M8.1 Balleny Island event at SNZO (New Zealand), a distance of almost 3000km, the FBA record correlated well with the KS3600 record (which was within 20% of clipping a 1cm/s STS-2) out to a period of 75s.
STUDY ON MANTLE DISCONTINUITIES BENEATH THE NORTH-WEST PACIFIC USING CONVERTED WAVES

Shao xian Zang, Yuanze Zhou
Department of Geophysics, Peking University, Beijing, 100871, China.
Email: sxzang@pku.edu.cn, yzzhou@263.net

We investigate the mantle discontinuities beneath the north-west pacific area where subducting slabs reached deep part of the mantle and try to find some clues for the interaction between subducting slabs and discontinuities. The converted waves of P-SV and SV-P were used to study the discontinuities.

Three component broadband waveform data of 126 earthquakes recorded by HIA station and MDJ station in the north-east part of China where Japan Sea subducting slab reached. The data were obtained from IRIS. Both rectilinearity-polarization filtering analysis and the modified N-th root slant stack method were applied to analysis the data. It was found that not only the globally existing 410km and 660km discontinuities beneath the northeast of China are observed obviously, but also it is possible that there are discontinuities existing near the depths of 140km, 220km, 350km, 520km, 570km, 740km and 1080km. It is shown that Japan sea subducting slab does not penetrate into the lower mantle, but it is deflected and stays above the 660km discontinuity, for the discontinuities beneath MDJ between the depths of 660km and 840km are much more complicated than those beneath HIA. The 660km discontinuity beneath HIA is at the global average depth. The complexity of the 660km discontinuity beneath MDJ shows that the subducting slab materials are piled above the discontinuity, and the existence of this discontinuity beneath HIA shows that the effect of the subducting slab on the discontinuity is very weak.

To study the discontinuities beneath Izu-Bonin area, vertical short period waveform data for earthquakes with Mb > 5.5 from 1992 to 2000 recorded by the Southern California Seismic Network and the Northern California Seismic Network were collected from The Southern California Earthquake Data Center and The Northern California Earthquake Data Center respectively. SV-P phases near sources picked out by processing these waveform data with the Nth root slant stack method show that there are obvious discontinuities near 660km beneath Izu-Bonin area and that the conversion points are distributed between the depths of 660-700km. There are evidences for possible velocity discontinuities near the depths of 770km, 830~850km, 950km and 1050km~1100km, because there are other relatively strong SV-P converted phases following the converted phases from the 660km discontinuity. The existences of these discontinuities show obvious regional characteristics.
ACTIVE SUBDUCTION OR DELAMINATION?:
DEEP SEISMIC EXPLORATION OF LITHOSPHERIC STRUCTURE IN THE VRANCEA SEISMOGENIC REGION, ROMANIA

Camelia C. Diaconescu(1,2), James H. Knapp(1), G. Randy Keller(3), Randell Stephenson(4), Victor Mocanu(5), Victor Raileanu(2), Andrei Bala(2), Mihail Diaconescu(2), Cornel Dinu(5), Liviu Matenco(5), Claus Prodehl(6), Franz Hauser(6), and Friedemann Wenzel(6)

(1)Department of Geological Sciences, University of South Carolina, Columbia, SC 29208 USA; (2)National Institute for Earth Physics, Bucharest-Magurele, PO Box MG-2, Romania; (3)Department of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968, USA; (4)Faculty of Earth Sciences, Vrije University, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands; (5)Faculty of Geology and Geophysics, University of Bucharest, 6 Traian Vuia St., 70139 Bucharest, Romania; (6)Geophysical Institute, University of Karlsruhe, Hertzstrasse 16, 76187 Karlsruhe, Germany

Situated within the 110° bend region of the southeastern Carpathians, the Vrancea zone constitutes one of the most active seismic zones in Europe, with high recurrence rates (~10 years) of strong (Mb>7.0), deep (70-200 km), volumetrically confined (30x70x200 km) mantle earthquakes. Two primary competing theories to explain this unusual distribution of mantle seismicity involve either (1) active subduction of a remnant oceanic slab, or (2) delamination of a thickened lithospheric root within the bend region. Constraints from existing geological and geophysical data for differentiating these mechanisms are equivocal. Furthermore, models for the geodynamic setting of the Vrancea zone and tectonic evolution of the Carpathian bend continue to be limited by a lack of high-resolution data on the lower crustal and upper mantle structure of this region. With such data, the Vrancea zone may prove to be a unique setting in which to establish evidence either for active lithospheric delamination, or a very unusual geometry of slab subduction.

We propose to carry out acquisition and analysis of an ~200 km-long deep seismic reflection profile as part of a multinational collaboration to study the lithospheric structure and geodynamic setting of the Vrancea seismogenic zone of Romania. Specifically, this work will serve to (1) map the geometry of the main structural detachment(s), and their westward continuation into the hinterland (and lower crust and upper mantle?), (2) constrain the amount of shortening across the orogen through construction of lithosphere-scale balanced cross-sections, (3) relate crustal thickening from the Transylvanian hinterland (30 km) to the Carpathian foreland (40 km) to specific crustal-scale geologic structures and processes, (4) provide reliable constraints on the existence, position, and polarity of a postulated subduction zone directly beneath the Carpathian arc bend, (5) image the architecture of Tertiary/Quaternary basins developed within the southeastern Carpathian bend region, adjacent to the Vrancea zone, (6) elucidate the relationship between active shallow (crustal) structures and deep (mantle) structure and seismicity, and ultimately, (7) evaluate competing active subduction / delamination geodynamic models for the origin of mantle seismicity in the Vrancea zone based on these results.

This project will illuminate the crustal and lithospheric mantle structure of the southeastern Carpathians and their adjacent foreland and hinterland basins, and will complement data from a combined wide-angle reflection/refraction and a Comprehensive Test Ban Treaty (CTBT) calibration experiment planned for the fall of 2001.
New seismic reflection and refraction images of the upper 1 km illuminate geologic structure at the site of the proposed SAFOD deep drill hole across the San Andreas Fault. A prestack depth migrated reflection image contains reflections from the near-vertical plane of the fault. This is the first migrated image of fault-plane reflections from a major strike-slip fault, proving a valuable new technology. The image suggests that the fault is vertical in the upper 0.5 km, then begins to dip steeply to the west. The western dip may reconcile the ~1 km difference between the locations of earthquakes and the surface fault trace. A seismic velocity cross-section observes strong lateral variations. Relatively low velocity is observed for about 1 km west of the San Andreas Fault, corresponding with a previously observed zone of high electrical conductivity. The fault-plane reflections, an interpreted fault to the southwest, low seismic velocity, low density, and high electrical conductivity all suggest anomalous structure of the shallow SAF. These features are interpreted to be due to a complex 1 km wide shallow fault zone west of the surface trace. The deeper seismogenic fault plane is interpreted to lie to the west of the surface trace.
THE SPATIAL CORRELATION OF HOTSPOTS WITH THE LOWEST VELOCITIES VERSUS STRONGEST LATERAL GRADIENTS IN LOWERMOST MANTLE SHEAR STRUCTURE

Michael Thorne (1), Ed Garnero (1), and Steve Grand (2)
(1) Dept. of Geological Sciences, Arizona State University, Tempe AZ 85287
(2) Dept. of Geological Sciences, University of Texas, Austin TX 78712

Heterogeneity in lower mantle shear velocity displays strong lateral variation. Tomographic travel time inversion from different studies has revealed long wavelength (up to 3000 km) patterns in seismic velocities that exhibit a high degree of similarity, using different techniques and data sets. Past studies have displayed a correlation between the surface locations of hotspots and the long wavelength zones of low shear velocities. More recently stronger correlation has been noted between ultra-low velocity zones (ULVZ) and hotspot locations. Here we calculate lateral gradients in shear and compressional velocities for a number of recent and past independently derived mantle models, including those of the groups of Berkeley, Caltech, Harvard, MIT, Scripps, Academia, UTexas, and Utrecht. As the degree of heterogeneity in the seismic models limit the length over which meaningful gradients may be calculated, scale lengths between 500 and 1000 km were used. The correlation between the lateral gradients and the surface location of hotspots for these different models is compared. The strongest lateral gradients of the globe's surface area correlates significantly better with hot spots than the most extreme low velocities (again, defined by % of globe surface area). For the 10% strongest gradients and lowest velocities, all models display significantly higher hot spot count over gradients compared to velocities, the most extreme case being for the Caltech model: 23 hotspots above gradients, 11 above velocities. Similar comparisons for P-wave models are more varied, for velocities and gradients. The variance and statistical significance of the correlations made in the models will also be shown in addition to the variance between models.
IMAGING BROAD RANGES IN STRUCTURAL VARIATIONS BENEATH SOUTHERN AFRICA

Matthew J. Fouch(1), David E. James(2), Paul G. Silver(2), John C. VanDecar(2), Suzan van der Lee(3), Jean N. Lee(4), and the Kaapvaal Seismic Group(5)
(1) Department of Geological Sciences, Arizona State University, Tempe, AZ 85287; email: fouch@asu.edu; (2) Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015; (3) Institute of Geophysics, ETH, Honggerberg, Zurich CH-8093, Switzerland; (4) Department of Physics, Harvard University, Cambridge, MA 02138; (5) URL: http://www.ciw.edu/kaapvaal

Data from the Southern Africa Seismic Experiment provide a unique opportunity to image crust and mantle structure over a wide range of spatial scales beneath southern Africa. Results from the two seismic components of the experiment have documented structural variations over distances as small as 50 km from body wave analyses. This range is exemplified in two independent studies: 1) shear wave splitting analysis beneath the Kimberley array, a 32-station broadband array with 5 km spacing and an aperture of ~60 km x 30 km, which was located directly within the region of the diamondiferous kimberlite pipes near Kimberley, South Africa; and 2) tomographic inversion of body wave travel times from the Kaapvaal array, an 82-station broadband seismic array located in South Africa, Zimbabwe, and Botswana, with a footprint of ~1 million km².

Results from shear wave splitting analyses from the Kimberley array are particularly intriguing. Fast polarization directions across the array are well-constrained, and given the uncertainties in the analysis, have a consistent orientation of approximately N50E. Splitting delay times, however, reveal well-resolved, spatially coherent variations across the array, increasing from 0.25s in the southeast to 0.75s in the northwest. These variations are clearly observed from the array response to individual events. One particularly striking example shows clear, coherent radial energy for all stations across the array, while energy on the transverse component grades smoothly from strong to none over a distance of only 50 km. These results provide clear support that conventional views of Fresnel volumes may overestimate the average sampling region for seismic waves. Our preliminary results suggest that, even over small regions, there are structural variations in the crust and upper mantle that may be either Archean in age or due to more recent kimberlitic magmatism.

Results from body-wave tomography exhibit P-wave velocity variations of ~±1%, and S-wave variations velocities of ~±1.4% that generally mimic patterns of P-wave velocities. These tomographic images reveal well-resolved high velocity mantle keels that extend to depths up to 300 km in regions beneath the undisturbed Archean Kaapvaal and Zimbabwe cratons. Some of the strongest fast velocity anomalies in the keel exist near Kimberley. Beneath post-Archean terranes, however, we do not observe analogous keel structures. In the vicinity of the 2.05 Ga Bushveld magmatic event, seismic velocities are resolvably lower than for surrounding regions, suggesting that significant cratonic disruption occurred during the development of the Bushveld. Within cratonic regions, the maximum contrast in velocity perturbation is ~0.5%, consistent with compositional variations in mantle nodules. These results, combined with observations of younger Re/Os model ages of mantle nodules, suggest refertilization of the cratonic mantle during the Bushveld magmatic event.
Using waveforms and travel times from deep earthquakes, we construct 13 seismic profiles across the northern Philippine Sea and investigate the lateral variation of P- and S-wave speeds (Vp and Vs) in transition zone. For each profile, both the high-resolution, broadband data and the dense, short-period records are utilized to tightly constrain the distribution of wave speeds at depth.

Our results indicate that the distribution of anomalously fast Vs beneath the northern Philippine Sea is similar to that of Vp. Prominent anomalies of fast Vs in the transition zone is confined to a region west of the Izu-Bonin subduction zone, the Northern Philippine Sea Anomaly (NPHSA), where DVs across the 660-km discontinuity reduces to only around 3%. On contrast, the Vp and Vs beneath Japan Sea or west of the Mariana subduction zone is close to those of the IASP91 model with DVp and DVs of 6% - 6.5%. For the NPHSA, fast anomaly in both Vp and Vs suggests that cold, subducted lithosphere is stagnant immediately above the 660-km discontinuity.

Using the precise value of DVs (~6%) and the reflection coefficient reported by Kato and Kawakatsu [2001], we estimate the density contrast (Dr) across the 660-km discontinuity to be about 8% (cf. 9.3% for PREM model). This estimate circumvents the usual trade-off between DVs and Dr, yielding a value that is significantly greater than those reported by Kato and Kawakatsu [2001] and Shearer and Flanagan [1999] (~5%).
MODERN DIGITAL MULTI-FUNCTIONAL REAL-TIME SEISMIC NETWORK FOR SOUTHERN CALIFORNIA: CALTECH/USGS TRINET


We report on new technologies, approaches and new products in part developed and implemented by the Caltech/USGS TriNet. Caltech and USGS Pasadena Office are nearing completion of building of the Caltech/USGS Element of TriNet. TriNet already records and analyzes earthquake ground motions, and distributes that information quickly, to improve our understanding of earthquakes and their effects, to contribute to improving building codes and structural design, and to facilitate emergency response in cooperation with other agencies. Already 135 out of 150 planned broadband and strong motion stations have been deployed and connected with IP networking to the central site. The TriNet real-time systems and database have been operating online for more than a year, processing real-time data from more than 350 stations, or 1400 high sample rate data channels. These capabilities were tested in the 1999 Mw7.1 Hector Mine earthquake. Implementation of new post-processing and catalog generation approaches is currently underway.
Project INDEPTH is a consortium of institutions from China, the United States, and Europe dedicated to deciphering the lithospheric and upper mantle structure of Tibet and the Himalayas. As part of Phase III of INDEPTH, fifty-seven PASSCAL broadband and short period seismic stations were deployed in central Tibet from July 1998 through August 1999. The array consisted of a north-south profile that stretched from about 100 km north of the Indus-Tsangpo suture in the south northward across the Banggong suture. A six-station cross line was deployed parallel to the Banggong suture to compliment the north-south profile. The geometry of the array was designed to accommodate a broadband transect and a wide-angle refraction study. This linear, closely spaced geometry facilitates the use of active as well as passive source techniques in the processing and interpretation of the recorded data. Important tools in the analysis include PASSCAL software, SAC 2000, HypoInverse, and Landmark’s ProMAX seismic processing package, augmented with additional codes developed at Cornell University.

Key objectives of the local seismicity analysis include an assessment of the active tectonics of central Tibet, defining the depth of the seismogenic zone, refining velocity models for Tibet, and identification of PxP and SxS phases that represent reflections from crustal magma chambers. The results of each of these analyses have important implications towards the mechanism of uplift of the world's highest plateau.

Current efforts focus on local earthquake location. Preliminary results indicate high levels of microearthquake activity, 2-3 events per day, along with spatial and temporal patterns that may indicate swarm-like seismic activity in central Tibet. Earthquakes related to volcanic swarms would provide key evidence for magma accumulation in the Tibetan crust, an important factor in assessing models for the uplift of Tibet. The seismogenic zone for well-located, nearby events is between 5 and 20 km depth, consistent with depths determined from waveform modeling of medium-size earthquakes.
Seismic anisotropy allows us to study mantle deformation, and it can thus help to constrain mantle flow in the vicinity of hotspots. Hypotheses for the cause of seismic anisotropy in this environment include the "parabolic asthenospheric flow" model: radial flow from a mantle plume impinging on a moving lithosphere is dragged by the plate in the direction of absolute plate motion. In map view, this gives a parabolic pattern of flow, opening in the direction of plate motion.

We present new shear-wave splitting observations from land and ocean stations around the Hawaiian Islands that are explained by the parabolic flow model. The observations suggest asthenospheric anisotropy under the Hawaiian islands, which may be explained if dislocation-creep persists to deeper depths there than in other regions, perhaps due to the higher temperatures near hotspots.
Various forms of the diffraction stack integral can be used to depth migrate teleseismic receiver functions, and a number of straightforward expressions relate reflection seismology to receiver function seismology. The principles of Kirchhoff pre-stack depth migration developed for reflection seismology are applicable to imaging Earth structure with receiver functions with only modest modifications. The receiver function imaging condition is given as the sum of the compressional wave time from the source to the conversion point and the shear wave time from the conversion point to the surface. The travel times can be computed for a radially and laterally variable Earth model.

Examination of the unstacked, migrated receiver function gathers across a range of ray parameters provides estimates of velocity corrections to the migration velocity model needed to properly focus the image, provided that the ray parameter range is large enough. Similarly a broad ray parameter range is required to reproduce the details of an isolated scattering object. Synthetic studies of migrated receiver functions show that an array with a 70km instrument interval, the likely spacing of the rolling component of USArray, can image targets as shallow as 100km depth and likely as deep as the CMB in the low frequency (<0.06Hz) passband. Resolution of discrete objects is 45 km, and that of interface variations is 15 km. Arrays with instruments spaced at 10 km, a likely spacing of the flexible component USArray experiment, can image features in the high frequency passband (>0.5Hz) at least as shallow as 25 km. Resolution of objects is about 4 km, and that of interface depths is about 2 km. Array aperture effectively limits the target depth that can be clearly imaged.

We demonstrate Kirchhoff imaging with teleseisms from the MOMA broadband experiment. The MOMA array was a large aperture (1750km) linear array, but with a relatively coarse (90km) instrument spacing. Well recorded earthquakes in the proper distance range for receiver function analysis arrive in three different azimuth ranges (northern Pacific sources, Mediterranean sources, South American sources). Migration of events in each azimuth group produces somewhat different images in each of the three sampling regions: The 410 and 670 discontinuities are well imaged from all azimuths and show some variation in depth with azimuth, consistent with previous studies (Li et al, 2000). Other prominent events appear at ~300 km and at ~525-550km depths. These horizons show considerable azimuthal variation in continuity.
In October 1999, a consortium of government agencies and universities conducted the second phase of the Los Angeles Region Seismic Experiment (LARSE II). A north-south striking and 160 km long refraction line (Line 2) was recorded from Santa Monica Bay in the south to the southern Sierra Nevada in the north. Additionally five shorter lines (12 to 22 km long) were recorded: two in the Santa Monica area (lines 6-7) and three in the San Fernando Valley (lines 3-5). These lines had shotpoints at their ends and, in several cases, additional shotpoints in between. Lines 3-5 were designed to constrain the basin geometry and seismic velocities of the San Fernando Valley in an effort to identify areas of potentially high seismic hazard.

Line 3 (11.5 km long) strikes northwest-southeast along the Los Angeles River (through the Sepulveda flood control basin), in the southern and relatively shallow part of the sedimentary basin. Lines 4 and 5 cover the northern and deeper part of the basin; line 4 (22 km long) strikes east-west from Hansen flood control basin to a point north of Chatsworth reservoir, crossing the Verdugo fault, the Northridge anticline (and Northridge Hills blind thrust fault), and the Chatsworth reservoir fault. Line 5 (14 km long) extends northwestward from the east end of line 4 to join Line 2 in the Santa Susana Mts, crossing the gravity minimum of the San Fernando Valley (-90 mgal).

The tomographic inversion model for line 3 has good ray coverage to 1.3-km depth and shows slightly different structures in the northwest and southeast parts of the line. In the northwest, seismic velocities increase from 1.75 km/s at the surface to 3.75 km/s at 1.3-km depth. In the southeast, velocities increase from <1.75 km/s at the surface to 4.5 km/s at 1.3-km depth. In the west part of the Sepulveda flood control basin, there appears to be a discontinuity between velocity structure in the northwest and southeast parts of the line. The higher velocities at 1.3-km depth in the southeast may represent older (Cretaceous?) sedimentary rocks or crystalline basement rocks.

The velocity model for line 4 has good ray coverage down to 5-km depth. Differing velocity structures are seen in the west, middle, and east parts of the model. In the west, velocities increase from 2.75 km/s at the surface to 4.5 km/s at 1.5-km depth. In the middle, velocities increase from 1.75 km/s at the surface to 5 km/s at 5-km depth. In the east, the 3-km/s contour rises steeply to the surface from 1.5-km depth, defining a horst-like body 1 km in width. The boundary between the structures in the west and middle parts of the line may represent the Chatsworth reservoir fault. The horst-like body in the east appears to be bounded on its west side by the Verdugo fault.
LITHOSPHERIC STRUCTURE OF THE CANADIAN HIGH ARCTIC FROM ANALYSIS OF TELESEISMIC RECEIVER FUNCTIONS AND RAYLEIGH WAVES

Fiona A. Darbyshire
Geological Survey of Canada, 7 Observatory Crescent, Ottawa, Ontario K1A 0Y3, Canada. tel: +1-613-992-0240, fax: +1-613-992-8836, email: fiona@seismo.nrca.gov.ca

CHASME (Canadian High Arctic Seismic Monitoring Experiment) is a study of the Earth structure and seismicity of northernmost Canada and the Baffin Bay region. In summer 2000, seven three-component broadband seismic stations were deployed in small communities across the Canadian High Arctic and western Greenland. These temporary stations will remain in place until summer 2001.

We investigate the lithospheric structure across the Canadian Arctic region using teleseismic earthquakes recorded by the seven temporary CHASME stations together with four permanent broadband seismic stations in the region. A data set of P waves was used to create teleseismic receiver functions for each station, from which the shear wave velocity structure of the crust is modelled. Although the azimuthal variation in the receiver functions at the stations indicates some three-dimensional structure, we consider the one-dimensional approximations made by the receiver function analysis to be valid. Results from the inversion and forward modelling of the receiver functions show that the crust thins from south to north across the region, with the thickest crust (~45 km) at station FRB (southern Baffin Island) and the thinnest (~25-30 km) at ALE (northern tip of Ellesmere Island).

Measurements of Rayleigh wave phase velocity for paths between sets of two seismic stations were made using teleseismic data from the network. These are used to provide information about the deeper shear wave velocity structure across the High Arctic region. Results from this analysis are presented and compared to the ‘CANS’ Canadian Shield velocity model of Brune & Dorman (1963).
INNER CORE ATTENUATION AND SCATTERING

Xu Li and Vernon F. Cormier, Department of Geology and Geophysics, University of Connecticut, Storrs, CT 06269-2045

Broadband PKIKP waveforms are modeled by convolving attenuation operators with reference source time functions, determined by inverting P-waves in the distance range 30° to 90° for far-field point source representations. The attenuation operators are parameterized to predict pulse shapes from either the effects of intrinsic anelasticity or scattering. A mean QP(1 Hz) = 324 ±80 is determined for the depth range 200 to 1100 km. Frequency dependence, depth dependence, and anisotropy of attenuation can be resolved from the densest path sampling beneath North America, with attenuation (Q^-1) increasing with depth beneath the ICB, increasing with frequency in the band of short period body waves, highest for paths closest to the rotation axis. In a scattering interpretation, the observed frequency dependence is consistent with the effects of heterogeneities having a characteristic scale length of 1 to 4 km, zero density perturbation, and P and S velocity perturbations of 5 to 10%. These scale lengths and perturbations agree with those found in recent interpretations of the coda of PKiKP at narrow angles of incidence. The origin of the heterogeneities may be a solidification fabric either of inclusions of partial melt or of intrinsically anisotropic crystals, individually having intrinsic anisotropy higher than 10%.

Variation of Q^-1 at 1 HZ under the North America versus ray orientation and the radius at the turning points. Note: 1) strong evidence for depth-dependent attenuation; 2) some weak evidence for anisotropic attenuation.
The Advanced National Seismic System (ANSS) is a major national initiative that will serve the needs of the earthquake monitoring, engineering, and research communities as well as national, state, and local governments, emergency response organizations, and the general public. Under the ANSS plan, the current United States National Seismic Network (USNSN) will be expanded to at least 100 stations in order to provide uniform national coverage. A total of 1,000 digital seismographs will be deployed within regional earthquake networks to replace existing analog equipment. The remaining 6,000 seismic stations will be located in urban areas with significant seismic risk. About 3,000 of these instruments will be free field or reference sites and the other 3,000 instruments will be installed in buildings and other structures of interest. Most of the instruments deployed in the ANSS will transmit their data in real time to regional data collection centers. Installation of more than 7,000 new digital seismographs that can record motions up to 2g would represent an order of magnitude increase in the number of instruments in the United States capable of recording large, damaging earthquakes on scale.

The fundamental goals of the ANSS are:

- Establish and maintain an advanced infrastructure (modern seismographs, communications networks, data collection and processing centers, and well-trained personnel) for real-time seismic monitoring throughout the United States that operates with high performance standards, gathers critical technical data, and effectively provides timely and reliable information products and services to meet the Nation’s needs.

- Continuously monitor earthquakes and other seismic disturbances throughout the United States, including earthquakes that may cause tsunamis or precede volcanic eruptions, with special focus on regions of moderate to high hazard and risk.

- Thoroughly measure strong earthquake shaking at ground sites and in buildings and critical structures, especially near major active fault zones and urban areas at risk.

- Automatically broadcast timely and authoritative information on the occurrence of an earthquake, related information about earthquake source properties and distribution of ground shaking, and where feasible, broadcast early warnings and alerts for the onset of tsunamis and volcanic eruptions.

The USNSN transformation into the ANSS is underway. The Global Seismograph Network (GSN) and USNSN have begun to select possible locations of the 100+ broadband seismograph stations that will form the "backbone" of the ANSS. This 100+-station national component of the ANSS is critical to the success of both the complete ANSS program and the USArray component of the Earthscope initiative. As stated in both the USArray and ANSS documentation, approximately 80% of the stations of the national component of the ANSS will be USNSN-type stations and 20% will be GSN-type stations. New USNSN/ANSS stations are being planned and/or deployed through cooperative agreements with universities, States, and/or other organizations. Technical committees currently are finalizing guidelines for station siting and instrumentation as well as ANSS infrastructure, data archiving and dissemination, and data analysis and distribution.
CONSTRAINTS ON CORE STRUCTURE FROM PCP-PKIKP DIFFERENTIAL

Keith D. Koper, SASO
Dept. of Geosciences, University of Arizona, Tucson, AZ 85721

We are currently refining a data set of over 500 differential travel times between outer core reflections (PcP) and inner core reflections (PKiKP) occurring at distances less than 80 degrees. The use of differential travel times mitigates the effects of source mislocation and upper mantle heterogeneity. The data are primarily sensitive to deep Earth structure and especially the thickness of the liquid outer core. Although the geographical distribution of our data is nonuniform, we have dense observations at a diverse series of locations including Australia, Indonesia, Japan, Alaska, and Central America. An initial analysis shows that PREM fits the data well, with a mean differential residual near zero, while the newer reference model AK135 gives a mean differential residual of about -1.5 s.

In an effort to improve the accuracy of our dataset we are redetermining PKiKP-PcP travel time residuals (originally taken directly from the REB catalog) using a simple beamforming and cross-correlation method on the array station waveforms. Many of these times are similar to the original REB values, however significant differences do exist especially for shallow focus earthquakes. The amplitude of the PKiKP phase is surprisingly strong is some cases. For example, at the array station in Alice Springs, Australia we find a clear PKiKP arrival at a distance of 19.3 degrees from an earthquake with a magnitude of only 4.4 mb. We have also observed pPcP and pPKiKP arrivals that went unreported in the REB and may prove useful for augmenting our dataset.
THE TOP OF THE INNER CORE: THE SEISMIC VELOCITY AND ATTENUATION STRUCTURES AND THEIR IMPLICATIONS

Lianxing Wen
Department of Geosciences, State University of New York at Stony Brook, Stony Brook, NY 11794, USA
Fenglin Niu
Department of Terrestrial Magnetism, Carnegie Institution of Washington
5241 Broad Branch Rd. NW, Washington, DC 20015, USA

We collect PKP data recorded at a distance range between 130-142 degrees from the Global Seismic Network (GSN) and many regional seismic networks to study the seismic velocity and Q structures at the top of the inner core. The PKIKP and PKiKP observations show different characteristics between those sampling the "eastern" hemisphere (40E - 180E) of the inner core and those sampling the "western" hemisphere (180W - 0E). PKIKP phases 1) arrive about 0.4 second earlier than the theoretical arrivals based on PREM for those sampling the "eastern" hemisphere of the inner core, and about 0.3 second later for those sampling the "western" hemisphere; 2) bifurcate at smaller epicentral distances for those sampling the "eastern" hemisphere, compared to those sampling the "western" hemisphere; and, 3) have smaller amplitudes for those sampling the "eastern" hemisphere. The waveform and differential travel times have no dependence on both ray azimuth and ray angle to the polar direction. There also exists a strong lateral variation of the differential travel time for PKP phases sampling the top of the inner-core beneath the Caribbean sea.

Waveform modeling of these observations suggests two different types of models for the "two hemispheres" of the top of the inner core, with a model in the "eastern" hemisphere having a P velocity increase of 0.765 km/sec across the inner core boundary, a small radial velocity gradient of 0.000055 (km/sec)/km, and a Q structure decreasing from 50 to 200 rapidly from the inner-core boundary (or alternatively with strong seismic scattering with isotropic velocity variations of 9% to 5%), and, a model in the "western" hemisphere with a P velocity increase of 0.633 km/sec across the inner core boundary, a radial velocity gradient of 0.000533 (km/sec)/km and a Q value of 600. The difference of seismic structures between the "two hemispheres" may be explained by different geometric inclusions of melt and/or different alignments of iron crystals with anisotropic properties in both velocity and attenuation. We speculate that this large-scale pattern of seismic heterogeneities may be caused by a large-scale heat flow anomaly at the bottom of the outer core and/or convection within the top of the inner core.
SHEAR-WAVE VELOCITIES TO 100 METERS DEPTH FROM REFRACTION MICROTREMOR

Louie, J. N., Nevada Seismological Laboratory, Mackay School of Mines, The University of Nevada, Reno, NV 89557-0141, louie@seismo.unr.edu.

Standard techniques of estimating shallow shear velocities for assessment of earthquake site response are too costly for use at most construction sites. They require large sources to be effective in noisy urban settings, drilling of boreholes, or specialized independent recorders laid out in an extensive array. I propose that microtremor noise recordings made on 200-m-long lines of seismic refraction equipment can estimate shear velocity with 15% accuracy, often to 100 m depths. The combination of commonly available equipment, simple recording with no source, a wavefield transformation data processing technique, and an interactive Rayleigh-wave dispersion modeling tool exploits the most effective aspects of the microtremor, SASW, and MASW techniques. The slowness-frequency wavefield transformation is particularly effective in allowing accurate picking of Rayleigh-wave phase-velocity dispersion curves despite the presence of waves propagating across the linear array at high apparent velocities, higher-mode Rayleigh waves, body waves, air waves, and incoherent noise. I illustrate application of this technique at many urban and rural locations in Nevada, Southern California, and New Zealand. Thirty-meter average velocities estimated from P-wave hammer refraction agreed with surface-wave results to better than 10%, under the assumption that soils have Poisson's ratios of 0.25-0.30. This technique duplicated microtremor array results above 3 Hz, but could not estimate velocities deeper than 100 m. Surface-wave dispersion modeling cannot duplicate the detail in the velocity profile yielded by a suspension logger, but was able to match the average velocity of 10-20 m depth ranges and suggest structure below the 100 m logged depth of a hole in Southern California. This degree of accuracy can match that of procedures described by ASTM D5777 for active-source refraction surveys, but at lower cost.
Earthquake seismic images show three-dimensional spatial and temporal properties of a subduction fault interface. A seismograph array recorded an unambiguous forward-scattered P-P phase from the interface of the Hikurangi subduction zone in New Zealand. P-P scattering was most prominent within days of the Feb. 19, 1990 Weber I M6.2 earthquake in the lower plate below the 20-km-deep interface, and less prominent three months later. S-P phase conversion at the sediment-laden interface was absent although it had been widely prominent previously.

We suggest that dilatation of fluid-filled pores by the Weber I normal-faulting earthquake caused mineral precipitation by depressurization, sealing thin cracks to yield more spherical pores, and lowering Poisson’s ratio in the interface. The forward-scattering arose in a wedge of sediment, 3-5 km thick, bulldozed into the interface by a subducted fault offset. Activation of a duplex thrust by the temporary sealing and locking of the interface may have triggered a second earthquake, the May 13, 1990 Weber II M6.4 event, within the upper plate.
We use shear wave anisotropy together with the surface deformation field, constrained by GPS and Quaternary fault slip rate observations, to solve for the direction and magnitude of the mantle flow field beneath western North America. We assume that west of central Nevada, where S wave tomography studies show a slow upper mantle (150 km depth) relative to regions to the east, the mechanism for development of lattice preferred orientation of olivine in the mantle results from a shearing between the base of the lithosphere and upper mantle. The expected fast polarization directions of split shear waves will be parallel to the direction of progressive simple shear in the mantle. Assuming that this shear flow is depth-localized in an asthenosphere, the fast polarization direction gives the orientation of the difference vector, \( \delta \), between the plate velocity, \( V_p \), and the velocity of the base of the asthenosphere, \( V_B \). Our goal is to estimate \( V_B \) through estimates of \( \delta \). We consider several idealized cases. (i) Plate motion drives asthenospheric flow above a mantle that is fixed in a hotspot frame (simple asthenospheric flow). Since \( V_B = 0 \) (mantle fixed in hotspot frame) and \( \delta = V_p \), the fast polarization direction gives the orientation of \( V_p \). (ii) The mantle drives the plate. The mantle is moving in the same direction as the surface plate, only faster. The sense of shear is reversed compared to simple asthenospheric flow, as is the direction of \( \delta \). However, the fast polarization direction is still parallel to absolute plate motion. For anisotropy observations on a rigid plate, this ambiguity means that we cannot distinguish between the two cases. I.e., we can retrieve the orientation of but neither its magnitude nor sign. However, across plate boundary deformation zones, where there are lateral changes in relative horizontal motion, it is possible to fully determine. Thus we not only can distinguish between cases (i) and (ii), but can directly estimate the velocity of the mantle in a hotspot frame. Where there are significant changes in relative horizontal motion (e.g., plate boundary zones), for example, simple asthenospheric flow will yield completely different net shear directions across the zone compared to the case where the mantle flow leads the lithosphere. Within western North America the case of the mantle leading the lithosphere can be rejected at the 99.999% confidence level. The best fit solution for the angular velocity vector that defines \( \delta \) has a pole at (-74.0 N, 25 E), and magnitude of 0.6 deg./Myr. This is close to the hotspot pole position for North America [Gripp and Gordon, 1990], but is more than twice the magnitude of velocity. The difference between this best fit motion and the expected hotspot motion is significant at the 95% confidence level. With respect to a hotspot frame, the base of the asthenosphere beneath Western North America (\( V_B \)) is moving at 2 - 2.5 cm/yr eastward. This eastward directed flow beneath Western North America is different from the southward flow directions predicted using a mass balance approach [Chase, 1979; Hager and O’Connell, 1981] but is consistent with flow directions predicted by Lithgow-Bertelloni and Richards[1998] that result from sinking of the Farallon slab into the lower mantle.
SEEKING SUPPORT FOR EARTH SCIENCE, 
OR GETTING THE PUBLIC EXCITED ABOUT DIRT AND ROCKS

Peter Folger
Public Affairs Manager, AGU

Support for Earth science research, and scientific research in general, is broad but shallow among the public and policy makers. Deepening that support typically requires: 1) explaining what the research is all about in non-technical terms, 2) linking the fruits of the research to their everyday lives, 3) connecting the research to the "local" community (district, state, country), and 4) appealing to the sense of wonder and excitement about new discoveries.

A project such as Earthscope lends itself to a successful outreach campaign to the public and their representatives in Congress along the four approaches listed above. First, define which part of the "public" is the target audience, namely who will lend their support to the project in a meaningful way once they are convinced that this is science worth supporting. This audience includes the education community, the community interested in natural resources, state geological surveys, and other state-level agencies that use Earth science information. USArray cuts a broad swath across the U.S. and should touch many of these communities in each state. PBO and SAFOD allow the research advocates to emphasize links to the local (geographic) community.

The research field currently enjoying the richest support from the public and policy makers is biomedicine. That success is largely due to the public perception that funding biomedical research affects everyone everyday. The benefits of Earth science research, and Earthscope specifically, can also be personal. Appealing to the average citizen's sense of wonder about new discoveries and human exploration, however, should not be neglected and can be powerful. Astronomy and space exploration, for example, enjoy hefty public support despite lacking direct links to the practical aspects of daily life.

Public support bolsters Congressional support for Earth science research, when and if citizens take the time to urge their senators and representative to vote for research programs. Advocates urging support for Earth science research should focus on certain "communities" within Congress who are receptive and able to act. Within the committee structure in Congress appropriators wield the most power regarding annual funding for scientific research. Advocates will need to appeal to appropriators and their staffs along the same lines as described for the public at large. Successful senators and representatives pay close attention to their home states and districts, therefore connecting the research to their constituents is a priority. An outreach campaign will benefit when those constituents, ranging from school kids to university professors, appeal directly to the lawmakers on behalf of Earth science research.
The global digital broadband seismic data made available through the IRIS is an invaluable tool for mapping the three dimensional structure in the Earth's mantle.

Most tomographic studies use a combination of surface wave dispersion data and body wave travel time data to obtain resolution in the whole mantle. For our tomographic inversions, we use time-domain body and surface waveforms as data, which we model using non-linear asymptotic coupling theory (NACT), (Li and Romanowicz, 1996). Our technique utilizes isolated packets of energy on the seismogram which are picked either by hand or with automated algorithms. Unlike many full-waveform techniques, which can be dominated by the highest amplitude phases of a given record, we are able to individually weight wavepackets. This allows us to emphasize lower amplitude phases which may still have good signal to noise ratios such as S diffracted. With this approach, we are able to improve our sampling of the lowermost mantle. Our theoretical approach involves 2D broadband sensitivity kernels appropriate for the modeling of body waveforms.

In previous modeling efforts, we have focused on developing SH mantle models from data handpicked on the transverse component. Recent development of automated picking algorithms has enabled us to speed the picking process and expand our dataset to the more complicated coupled P-SV information on the longitudinal and vertical components. With this dataset, we have already obtained some preliminary SV models, which show evidence of significant anisotropy, similar to that observed in previous studies using surface waves (Montagner and Tanimoto, 1991; Ekstrom and Dziewonski, 1997). Work is underway to invert for three dimensional anisotropic structure throughout the mantle.

The analysis of the automatically picked wavepackets also enables us to look at the quality of the GSN stations. Comparing the long period records of specific stations with those predicted by synthetics allows us to document station noise levels and accuracy of reported response functions.
P WAVE AMPLITUDES IN THE 3D EARTH

Nolet, G, Caryl Michaelson, Ileana Tibuleac,
Dept of Geosciences, Princeton University, Princeton, NJ 08544 United States
Koulakov, I
UIGGM, Jemchujnaya Str. 10/14, Novosibirsk, 630090 Russian Federation

The information contained in the amplitudes of seismic phases has so far largely been neglected in the construction of global models for P velocity. While it is generally acknowledged that the effects of focusing/defocusing make amplitudes very sensitive to velocity heterogeneities along the raypath (the ray amplitudes focus with the second derivative of the velocity perpendicular to the path), amplitudes are considered too noisy or too complicated to interpret. As a result, global models differ appreciably in their prediction of P wave amplitude variations.

With the advent of well calibrated stations of the GSN it seems appropriate to reconsider the question of use of amplitudes in seismological studies of the mantle structure. We report on a pilot study in which we took several measures of the amplitude variations observable in broad-band teleseismic P wave displacement pulses s(t) from deep earthquakes: (1) the zero-to-peak, (2) peak-to-peak, (3) the integral int s(t) dt, and (4) the rms amplitude (s(t)^2 dt)^1/2 Of these, the latter two appear to to be the most stable. We compare these observed amplitudes with predicted amplitudes for several global 3D models, as well as for a spherically symmetric earth.
PASSCAL REAL-TIME ARRAY AT PARKFIELD, CA:
PREPARING FOR EARTHSCOPE

Cliff Thurber, UW-Madison
Steve Roecker, RPI

In July 2000, a team from RPI and UW-Madison deployed an array of 15 PASSCAL RefTek instruments with 3-component sensors around Parkfield, CA, initially in "stand-alone" mode. The primary motivation for the deployment is to improve the accuracy of the location of microearthquakes in the SAFOD drilling target zone. At the same time, we will be improving the knowledge of the 3D velocity structure in the vicinity of the drill site. In October 2000, with the help of the UCSD broad-band array group, 14 of the 15 sites were converted to real-time telemetry, but due to the lack of Internet connectivity in Parkfield, recording and archiving had to be done locally for a period of time. Then, in February 2001, a satellite connection was established, and data began to flow out in near-real-time. The array, known as PASO (Parkfield Area Seismic Observatory), now stands as a model for future USArray flexible array deployments.

The availability of near-real-time data flow has greatly facilitated rapid analysis. By January, we had accumulated enough non-real-time data to merit the determination of an initial 2D (fault-normal) model for the velocity structure, showing the expected strong P-wave velocity contrast across the fault (SW side fast) and evidence for a zone of high Vp/Vs adjacent to the fault. In March 2001, USGS collaborators identified the occurrence of one of the repeating earthquakes that is a possible target for the final stage of SAFOD drilling, when satellite boreholes will be drilled to puncture the active fault at selected points such as an earthquake rupture patch. Having the near-real-time data flow allowed us to add the target event to our tomographic inversion the day we were alerted to its occurrence, and we were able to provide an epicenter and depth estimate for the event virtually as soon as its arrivals were picked. We will show our results for the location of the target event and its uncertainty, plus the updated 2D velocity model.

This summer, the array will be expanded to a total of 60 stations. With the aid of a high-resolution DEM, we have generated a deployment plan that should allow all of our new sites to utilize real-time telemetry. We will show the process of our array design. Our plan is to use the densified array and a few calibration explosions to tighten our estimates for the epicenter and depth of the target earthquake zone prior to the first stage of drilling. Once the vertical section of the hole is done, we will set off shots at selected station sites and record the shots downhole to provide a "reciprocal source" for relative location analysis, which will be used to help guide the next phase of drilling.
Lower crustal and uppermost mantle earthquakes are rare in continent-continent collision zones so their occurrence provides unique information about the prevailing rheological conditions in convergently deforming lithosphere. A handful of small, intermediate-depth earthquakes were recorded in the continental collision region in central South Island, New Zealand over a period of 11 years. The events are up to 90 km deep and are clearly not associated with subduction-related seismicity. An investigation of the earthquakes in light of recently obtained crustal and uppermost mantle seismic velocity heterogeneity images shows that they all lie within or on the margins of significantly thickened crust or uppermost mantle high-velocity anomalies. The three-dimensional tomographic images were obtained by teleseismic P-wave travel-time inversion (Kohler and Eberhart-Phillips, 2001). They show a near-vertical, high-velocity (2 to 4%) structure in the uppermost mantle that underlies thickened crust along the NNE-SSW axis of the Southern Alps. The spatial patterns in the hypocenters illustrate that the occurrence of mantle earthquakes may be controlled by large shear strain gradients associated with the physical processes that are responsible for the seismic heterogeneity, as well as depressed geotherms below the region of convergence. The size of the brittle failure patches controls the size of the mantle earthquakes. The largest of the earthquakes has ML=4.0 corresponding to a rupture radius of between 200 and 400 m assuming a constant stress drop of 3 MPa and circular rupture. When a range of constant stress drops (0.5 to 50 MPa) is considered, the resulting range in rupture area (0.03 to 2 km²) provides bounds on the upper limit to the area over which brittle failure is taking place in the uppermost mantle below central South Island. If convergence has depressed the brittle-ductile transition zone by depressing geotherms, this suggests a scenario in which the relatively deep transition zone consists of patches of rock on the order of one square kilometer or less undergoing brittle failure surrounded by rocks deforming by plastic flow.
The Continental Dynamics of the Rocky Mountains (CDROM) investigation is a multidisciplinary study to understand the complex evolution of the Rocky Mountain lithosphere from its assembly during the Proterozoic, to the present. The active source seismic experiments of CDROM focus on investigating the northeast-striking lithospheric Proterozoic accretionary boundaries. These structures, established during 1.8-1.6 Ga accretion of island arcs to the Archean passive margin, appear to have persistently influenced the tectonic history of southwestern North America during subsequent episodes of deformation. One of the boundaries within the Mazatzal province is the Jemez lineament, a broad, ~100 km wide NE-SW trending zone. The Jemez lineament is an alignment of Tertiary volcanic centers that extends from the westernmost Great Plains, across the southern Rocky Mountains, Rio Grande Rift and the southern margin of the Colorado Plateau. In northern New Mexico, the lineament roughly passes between Sante Fe and Taos.

Two north-south deep reflection profiles were acquired to investigate the Jemez lineament and an additional east-west profile was acquired to study the Laramide uplifts in the Sangre de Cristo Mountains. The lines were acquired with Vibroseis sources (100m source interval) recorded by a 25km long, 1001 channel seismograph array. Additionally, ~120 Refteks Texan were deployed to extend the aperture of the array to 25-50km offsets on ~60 km of the reflection profile. The reflection lines show impressive reflectivity to depths of ~35km.

Precambrian and Phanerozoic sediments are imaged in the upper ~2km of the sections. The north-south profiles clearly show Proterozoic crustal structures at upper to lower crustal depths. North of the southern edge of the Jemez lineament, the lines clearly image a broad south dipping structure that is likely a Paleo-Proterozoic ramp associated with island arc suturing during continental assembly. The south dipping suture appears to reach upper mantle depths at the southern edge of the surface expression of the Jemez lineament. Bright reflections overprinting the ramp are interpreted as young mafic sills associated with the Jemez lineament. South of the southern boundary of the Jemez lineament the entire middle crust consists of a south vergent duplex/antiformal stack of thrust sheets.

On the E-W profile into the eastern half of the Sangre de Cristo mountains, a series of Laramide basement thrusts can be traced to surface outcrops. The Laramide thrusts sole into an upper-crustal detachment at ~12 km depth. A deeper blind thrust system in the middle crust at 22-24km beneath the Rockies ramps up to 14 km beneath the eastern front of the range and extends under the Great Plains. This detachment appears to change from being a 2 km thick ductile deformation zone to a narrow brittle fault as it shallows.
GLOBAL BULLETINS OF SEISMICITY: CURRENT PROBLEMS AND FUTURE SOLUTIONS

Richards, P.G., Lamont-Doherty Earth Observatory, Palisades, NY 10964, and Department of Earth and Environmental Sciences, Columbia University, richards@LDEO.columbia.edu, Khalturin, V.I. and Kim, W.-Y., Lamont-Doherty Earth Observatory, Palisades, NY 10964.

Bulletins of seismicity, whether they are produced on a local, regional, national, or global basis, are now undergoing profound changes. Improved methods of event location have the potential to give new insight on earthquake processes. Better accuracy, and/or better coverage to lower magnitude, has often been the key to new insight into earthquake processes and Earth structure; and has enabled new levels of confidence in the ability to monitor a region of interest. Of course, new insights and new monitoring capabilities are the very rationales upon which much work in seismology is funded.

At present, the global bulletins produced by the US Geological Survey, the International Seismological Centre, and the International Data Centre of the Comprehensive Test Ban Treaty Organization (the Reviewed Event Bulletin, or REB), all rely heavily upon standard one-dimensional Earth models for purposes of interpreting arrival times. The resulting locations can still be quite accurate provided there are enough reporting stations, with no large gap in azimuthal coverage. But for a sparse network, such as the International Monitoring System (IMS) upon which the REB is based, a new approach must be adopted.

The approach selected by the International Data Centre to improve event location using regional waves is described in this poster, with particular reference to an integrated series of projects being carried out by a consortium led by Lamont, all with the goal of improving the capability to locate seismic events based on data acquired by IMS stations in Eastern Asia. Our general approach is to acquire as many ground truth event locations as possible, from operators of regional and local networks, for seismic events large enough to be detected at IMS stations in Eastern Asia. In this way, it becomes possible to build up empirical station-based information on travel times for observable regional waves. For aseismic regions, modeling is required --- which in our case is greatly assisted by the several decades of Deep Seismic Sounding carried out by the Soviet Union.
We present results from the SIGHT experiment, a 1996 active-source study of the SOUTH Island, New Zealand, that was aimed to investigate crustal deformation at this continent-continent collision zone. We show a profile that gives a 600 km cross-section of South Island, New Zealand, where Pacific and Australian continental crust are juxta-posed at the Alpine Fault. Roughly 80 km of shortening has been taken up across the plate boundary at this location. We obtained a compressional seismic velocity model by a reflection tomography inversion of 65,000 travel times from ocean-bottom and land-recorded wide-angle data. The Australian plate does not thicken towards the plate boundary, indicating that little deformation has taken place here. In contrast, the Pacific plate appears to have accommodated shortening by thickening of the upper crust, as well as extrusion of Mesozoic schist and greywacke east of the plate boundary. The root of the Southern Alps lies ~15 km east of the crest of the Southern Alps and the eastern slope of the root is much shallower than its western slope. This asymmetry seems consistent with shallow underthrusting of the Pacific plate. However, the amount of thickening of the crust and the volume of Cenozoic sediments offshore are sufficient to explain the shortening accommodated by the Pacific crust and the subduction of a large volume of Pacific crust can therefore be excluded. Seismic velocities beneath the Southern Alps are < 6.0 km/s, or ~0.5 km/s less than elsewhere in the Pacific upper crust. This velocity anomaly can be explained by elevated temperatures due to the extrusion of rocks, the presence of fluids, or brittle deformation of rocks. A combination of these three factors may play a role, but in either case the 6.0 km/s contour in our velocity model marks a region of rock uplift that extends well east of the Southern Alps. This suggests that the Pacific upper crust may detach from the lower crust at the eastern boundary of the crustal root. An explanation for the asymmetry of the continent-continent collision can be sought in the rheology of the Pacific and Australian crust. The quartz-rich upper crust of the Pacific plate must have extended to at least 25 km depth at the start of compression, while the base of the Australian upper crust lies at 18 km. Consequently, the deepest Pacific upper crust may have formed a weak and ductile zone that caused all the deformation to occur east of the plate boundary.
We present a summary of results from two separate studies: the first study discusses the effects of melt depletion on mantle density, and the second study presents our shear wave splitting measurements in the Wyoming-Colorado region.

Significant advances in experimental mineral physics have been made since Jordan's [1979] seminal work on depletion, density, and velocity. In particular, density, thermal expansivity, and bulk and shear moduli measurements have been made for most of the solid-solution end member compositions of garnet peridotite minerals. In addition, substantial data now exist on the thermal and pressure dependence of the above parameters. We present density and velocity, as a function of depletion, for near solidus mantle at 100 km depth. We apply these results to the Yellowstone Swell, where we discuss the trade off between thermal and compositional effects.

Our second study presents shear wave splitting measurements made by the Deep Probe and Lodore PASSCAL arrays, which crossed the Cheyenne Belt, a boundary between Archean and Proterozoic crust. Despite the observations of mantle anisotropy below 200 km depth made using other means, shear wave splitting shows no large scale coherent anisotropy, although interesting small scale patterns exist. In addition, the accuracy and precision of two shear wave splitting algorithms is discussed, based on jack-knifing calculations.
The Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) is a new earth science project recently funded in Canada. The POLARIS network includes three arrays, each consisting of 30 three-component broadband seismographs. The arrays will be installed in Ontario, British Columbia and NW Territories, as will be complemented by magnetotelluric (MT) mobile field systems. Data from all stations (seismic and MT) will be transmitted by satellite in real time to multiple central stations. The aims of the POLARIS project are detailed investigations of seismic activity, seismic sources and three-dimensional imaging of the deep structure in the populated regions of southern Ontario and southwest British Columbia and of the Slave Province in Canada’s NWT, and investigating of geomagnetically induced currents that can cause major disruptions to electrical and pipeline infrastructure.

The seismic risk to southern Ontario is a significant social and economic issue due to its density of population and concentrations of critical facilities, such as nuclear power plants. The scientific objectives of Ontario Seismic array are improving the spatial resolution of seismicity, and characterization of earthquake source parameters and active tectonic processes in southern Ontario; improving existing models for earthquake ground motion and site response; three-dimensional imaging of lithospheric architecture in relation to the tectonic evolution of the Grenville orogen and Paleozoic rifting, etc. Some calculations of the expected capabilities of the planned array show that it will be able to record earthquakes with magnitude above 2 by at least 4 stations.

The installation of the Ontario Seismic Array of POLARIS network is currently underway and will continue for the next four years until the network is fully installed. Data from this array will be available live at the central station in the University of Western Ontario by the end of this year.
The Great Slave Lake Shear Zone (GSLSZ) is a major northeast-trending dextral strike-slip fault in the northwestern part of the Canadian Shield with associated offsets of up to 700 km. It is interpreted as a type example of a vertical crustal-scale intracontinental transform fault, and is associated with the eastward convergence, and collision, of the Archean Slave province into the largely reworked Churchill province. On aeromagnetic maps, the 1.9 Ga shear zone appears as a prominent 1300 km linear anomaly. Exposed rocks of the GSLSZ from the southeastern shores of the Great Slave Lake are comprised mainly of granulite to lower greenschist facies mylonite belts.

In May to October, 1999, thirteen broadband teleseismic stations were deployed across the GSLSZ. Receiver functions (RFs) were calculated for 41 teleseismic events recorded during this period. Various schemes were used to stack receiver functions, including stacking events based on combinations of back-azimuthal direction and epicentral distance. Stacked RF profiles indicate that the shear zone penetrates the crust and offsets the Moho by 0.5 seconds (~ 4 km). Furthermore, the shear zone does not appear to be vertical through the crust, but instead dips toward the southeast at an estimated angle of ~ 67 degrees.
Applying a niching genetic algorithm (NGA) to receiver function analysis provides robust crustal models for regions such as Patagonia, the Antarctic Peninsula, and the Transantarctic Mountains, where few a priori constraints are available. The classic linear inverse method is non-unique because the inverse problem is non-linear [Ammon et al., 1990]. The NGA solves for distinct local and global model optima using an evolutionary principle [Koper et al., 1999]. The NGA improves upon the standard genetic algorithm by allowing multiple populations to compete for local optima. This prevents convergence upon a single local optimum rather than the global minimum. Comparison between several locally optimal models provides some estimate of tradeoffs within a model. Another benefit of the NGA receiver function technique is the flexibility of the forward model. The forward model allows parameterization of layer thickness and Vp/Vs ratios, in addition to the traditional parameterization of Vs. Comparison with noisy synthetic data showed that sensitivity to layer thickness results in better resolution of shallow structures. Resolution tests show that crustal thickness estimates may be as accurate as 1 km.

Application of the proposed technique provided Moho depths of 27 km and 28 km beneath Patagonia and the Antarctic Peninsula, respectively. This study assumed the Moho to be the largest interface at depth with appropriate velocities. Previous crustal thickness estimates ranged from 25 to 40 km in both regions. The combination of individual one-dimensional models produced self-consistent, two-dimensional models of crustal and uppermost mantle structure for Patagonia. We observed a large sub-crustal seismic velocity gradient underlying Western Patagonia Sites. This sub-crustal gradient may explain the variance of previous crustal thickness estimates in the region. Some studies image the large interface at the top of the gradient, while others image the bottom of the gradient. The similarity between Antarctic Peninsula and Patagonia models may stem from similar tectonic histories.

Preliminary studies from the Transantarctic Mountain Seismic Experiment (TAMSEIS) revealed ~21 km and ~29 km Moho depths within and bordering the West Antarctic Rift System. Large surface sedimentary layers were observed within and bordering the Ross Sea. These results are similar to those found in other studies. This preliminary study shows that the proposed technique can distinguish between thick and thin crust without a priori constraints. Future work will create one-dimensional seismic velocity models across the Transantarctic Mountains. Combination of these models will provide two-dimensional, seismic velocity profiles through the largest non-compressional mountain range in the world.


CRUST AND UPPER MANTLE STRUCTURE OF THE COLORADO PLATEAU - RIO GRANDE RIFT TRANSITION ZONE USING TELESEISMIC RECEIVER FUNCTIONS FROM A BROADBAND PASSCAL ARRAY

David Wilson, Richard Aster, and John Schlue, New Mexico Institute of Mining and Technology, Department of Earth and Environmental Science and Geophysical Research Center, Socorro, NM United States

James Ni, New Mexico State University, Department of Physics, Las Cruces, NM

Steve Grand, University of Texas, Austin, Department of Geological Sciences, Austin, TX

Scott Baldridge, Los Alamos National Laboratory, EES-1, Los Alamos, NM

Steve Semken, Dine College, Division of Natural Sciences, Shiprock, NM

Project LA RISTA (Colorado PLAtateau, Rio Grande Rift Seismic TRAnsect) has completed one and a half years of deployment of a 57 station PASSCAL broadband seismic array across the central Rio Grande Rift. The NW-SE trending, 950 km long linear array extends approximately from Lake Powell, UT to Pecos, TX. We have calculated receiver functions from teleseismic arrivals at the array to gain new insights into the seismic structure of the crust and upper mantle and hence the tectonics beneath this part of the western U.S. A preliminary analysis of the receiver functions reveals a number of crustal features. First, we observe a 200-km-wide crustal low velocity zone beneath the southeastern Colorado Plateau (from the southern Chuska Mountains to Mt. Taylor), which may extend into the central Rio Grande Rift in the vicinity of the Socorro magma body. We are currently conducting forward modelling and inversion to determine the extent and properties of this low velocity zone. Second, there are significant differences in the depth and character of the Moho on either side of the Rio Grande Rift. While the P-to-S conversion from the Moho beneath the Four-Corners region of the Colorado Plateau is rather weak, it appears as a dominant phase at the stations within the Rio Grande Rift and the Great Plains. The Moho is shallowest at the center of the rift and deepens gradually away from it. Third, sharp conversions from a mid-crustal, southeastward-dipping horizon are observed in western Texas and southeastern New Mexico. This feature may represent the buried northwestern edge of the Grenville continental margin.
TWO-LAYER ANISOTROPY BENEATH A PRECAMBRIAN CONTINENTAL TRANSFORM FAULT IN THE NORTHWESTERN CANADIAN SHIELD

D. Eaton and J. Hope
Department of Earth Sciences, University of Western Ontario

I. Asudeh
Geological Survey of Canada

The Great Slave Lake shear zone is the deeply eroded remnant of a Paleo_proterozoic continental transform fault system that is preserved in the western Canadian Shield. It is inferred to have accommodated over 700 km of right-lateral strike-slip motion during the interval 1.97-1.86 Ga. Observations of teleseismic SKS arrivals recorded by a portable seismograph array have yielded well constrained apparent splitting parameters that vary systematically with backazimuth, generally consistent with waveform interference resulting from a simple two-layer scenario. Least-squares inversion of the data has produced a two-layer model containing a deep layer with a fast-axis direction of $104^\circ \pm 10^\circ$ and a shallow layer with a fast-axis direction of $43^\circ \pm 9^\circ$, very close to the magnetically defined strike of the shear zone. In this model, the intensity of the deep-layer anisotropy increases systematically to the southeast, whereas the shallow-layer anisotropy is most intense near the axis of the shear zone. Within the shear zone, the splitting parameters and their azimuthal variations change rapidly over distances of a few km, suggesting a more complex model that includes strong anisotropy and heterogeneity in the crust. The fast-axis direction of the deep layer makes a high angle with the absolute plate-motion direction ($225^\circ$), implying that the inferred mantle anisotropy is more likely to be caused by frozen anisotropy than contemporary asthenospheric flow. In our interpretation, the fast-axis direction of the shallow layer is parallel to flow direction within the shear zone. The fast-axis of the deep layer reflects the maximum compressive paleostress orientation associated with a subduction/accretion system in the Taltson domain on the southeast side of the shear zone.
MEASUREMENTS AND MODELS OF VERY LONG PERIOD SURFACE WAVE PROPAGATION

M. Nettles, G. Ekstrom, A.M. Dziewonski
Department of Earth and Planetary Sciences, Harvard University

Fundamental mode surface wave phase velocities, now routinely measured at periods of 40-150 s, provide strong constraints on the 3-D structure of the top 300-400 km of the mantle. These intermediate-period surface waves have greatly reduced sensitivity in the mantle transition zone, however, and Earth structure in the depth range 400-700 km remains less well determined than that above 400 km. Robust measurements of Love and Rayleigh wave phase velocities at longer periods are more difficult to obtain, but with their greater sensitivity at transition zone and lower mantle depths, such measurements would substantially improve our knowledge of deep structure. In particular, the analysis of wavetrains including minor arc as well as great-circle arrivals would provide constraints on odd-degree mantle structure which cannot normally be obtained from free oscillation spectra.

We measure phase velocities for Love and Rayleigh waves in the period range 150-600 s utilizing an approach described by Woodhouse and Dziewonski (1984) for the path-by-path determination of Earth structure parameters. A CMT solution is first determined by inversion of long period mantle wave data in the passband of interest. These source parameters are then fixed, and an iterative, least-squares inversion is performed for each path independently to determine the best-fitting Earth structure for that path. Transverse component seismograms are considered separately from vertical and longitudinal components to account for first-order effects of radial anisotropy. The Earth models derived predict the phase velocities of surface waves along each path. Pathwise phase velocity estimates determined to be of high quality based on fit to the data in narrow frequency windows are then inverted for global phase velocity maps.

Numerous high-quality fundamental mode splitting functions are available in the frequency range we study. The even-degree parts of our phase velocity maps agree well with the corresponding splitting functions, even when the maps are obtained from minor arc measurements only. This agreement suggests that the odd-degree structure we determine is reliable.

The one-dimensional structure coefficients determined for each path can also be used directly in an inversion for global 3-D Earth structure. We construct a 3-D Earth model in this fashion, and compare the results with those obtained from inversion of our pathwise dispersion curves.
EVALUATING THE GLOBAL SEISMIC NETWORK USING SIGNAL-TO-NOISE RATIOS

Christine Reif (1), Peter Shearer (1), Luciana Astiz (2)
(1) Scripps Institution of Oceanography, La Jolla, California
(2) CTBTO, Vienna, Austria

The value of a seismic station depends upon many different factors, including the quality and quantity of the data that it provides, the location of the site, and the research goals of individual scientists. While there can never be a single measure of station value that is appropriate for all the users of seismic data, when resources to maintain seismic stations are limited, some evaluation of station performance and usefulness for research is important in order to maximize the effectiveness of the network. One important factor in evaluating the quality of seismic stations is studies of their noise levels as a function of frequency (e.g., Astiz 1997). Here we take a slightly different approach and consider the fraction of global events that are actually recorded by individual stations and the average signal-to-noise that they achieve in these records. Our evaluation criteria thus depend upon the typical noise levels, the global distribution of teleseismic events, and the percent "uptime" of the stations. Our study is limited to data from the global seismic networks that are available through the IRIS "FARM" facility. We include events with Mb > 5.7 (shallow events) and Mb > 5.5 (deep events) from 1988 to 1999. The signal-to-noise is measured using a simple short-term-average to long-term-average (STA/LTA) filter. We examine P + PKP waves for vertical component data and S + SS waves for transverse component data, and apply filters to isolate both the short- and long-period responses. Our results show very large differences between stations, with the best stations recording as many as 10 times more events than the worst stations. Some variations are clearly due to local site conditions because nearby stations in regions of dense coverage can exhibit large differences. Other quality variations are geographically coherent. Superior results are seen for China and adjacent parts of the east Asian continent, whereas oceanic islands and southern Africa and southern South America have generally underperforming stations.
Sandia National Laboratories has tested and evaluated three digitizer sub-systems for IRIS applications. The Q680-IRIS/GSN Digitizing Waveform recorder (DWR) sub-system built by Quanterra, the Q736 DWR sub-system built by Quanterra and the SAN2012 DWR sub-system built by SAIC. The DWRs were configured to interface to a Streckeisen STS-1 seismometer.

The test results included in this report were for response to static and dynamic input signals, seismic application performance, and data time-tag accuracy.

Most test methodologies used were based on IEEE Standard 1057 for Digitizing Waveform Recorders; others were designed by Sandia specifically for seismic application evaluation and for supplementary criteria not addressed in the IEEE standard. When appropriate, test instrumentation calibration was traceable to the National Institute for Standards Technology (NIST).

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SEARCHING FOR EVIDENCE OF ULTRALOW-VELOCITY ZONES AT THE EARTH'S CORE-MANTLE BOUNDARY

Steven E. Persh, John E. Vidale, and Paul S. Earle

Recently a thin (5-50 km) layer at the base of the mantle has been identified as having sharply reduced P-wave velocities (10% lower than average at those depths). If such ultralow-velocity zones (ULVZs) are the result of partial melting of mantle material, the consequent S-wave velocity reduction is estimated to be ~30%. ULVZs have been mapped under the mid-Pacific and Africa, and correlations established between their presence and that of surface hotspots, implying a relationship with mantle upwellings originating near the core-mantle boundary (CMB). Much remains unknown about ULVZs, however, including the short-length-scale variability of their properties, the sharpness of their upper boundaries, and, most importantly for the attribution to partial melting, a direct observation of the S-wave velocity reduction.

Two phases that can measure these properties are the core-reflected phases PcP and ScP. We stack PcP and ScP arrivals from regional networks (the Northern and Southern California Seismic Networks, the Large Aperture Seismic Array, and the Japan array) to conduct careful searches for precursor arrivals associated with ULVZs, and from the global network to characterize globally-averaged CMB reflection properties.

We fail to observe precursor arrivals to PcP and ScP in the regional stacks, even in regions where diffracted phases indicate low P-wave velocities. These results can be explained if ULVZs transition gradually from the lower mantle or are extremely thin in the regions we sample. From the global stacks, we measure PcP/P amplitude ratios in agreement with standard Earth models, suggesting ULVZs are not a globally constant feature.

We will also present stacks of Pdiff waves recorded at LASA that bottom at the CMB in the mid-Pacific. These show anomalously weak arrivals from a region 200-300 km across. Stacks of P-waves bottoming near the CMB on either side of the anomalous region appear normal. This may indicate short-length-scale variation of an attenuating layer at the CMB.
The continued existence of untoppled precarious rocks near the San Andreas fault is incompatible with most ground motion prediction models. We present amplitude spectra of Hector Mine aftershocks and shallow shear wave velocities from microtremor analyses at ten locations near the Mojave section of the San Andreas fault. This section of the fault has ruptured numerous times in the last thousand years, most recently in 1857. Three of the ten sites are locations of precarious- or semi-precarious rocks. The site effects at precarious rock sites are consistent in magnitude and spectral shape with site effects from "generic rock sites" from other studies. Site effects alone are insufficient to explain the continued existence of precarious rocks. Velocity characterizations at two precarious rock sites show 30-meter average shear-wave velocities well into the generic rock site range. Unusually low near surface velocities at each site couple with high velocities below 7 meters to create the high 30-m average. This is in contrast to the shear-wave velocity profiles used in seismic hazard models, which show more smoothed velocities relative to the 30-m average. As a result, comparisons of \( \pi \) wavelength amplifications predict amplification at the precarious rock sites, above 4 Hz, relative to B-C boundary and generic rock sites.
MANTLE RESERVOIRS AND GEOCHEMICAL COMPONENTS: WHAT’S THE CONNECTION?

Erik Hauri
Department of Terrestrial Magnetism, Carnegie Institution of Washington
5241 Broad Branch Rd. NW, Washington, DC 20015 USA
Hauri@dtm.ciw.edu

Geochemical studies of magmas derived from the convecting mantle, particularly mid-ocean ridge basalts (MORB) and ocean island basalts (OIB) have delineated four chemically-distinct mantle “endmembers” (DMM, EM1, EM2, HIMU), which are defined by extremes of the Sr, Nd and Pb isotopic data (Zindler & Hart, 1986). Inclusion of He isotope data, and its correlations with the above isotopes, indicates the presence of a fifth component with elevated 3He/4He ratios (FOZO, c.f. Hauri et al., 1994). This taxonomy of a limited number of mantle components suggests the possibility of using seismology to locate a similarly limited number of observable deep-earth reservoirs from which they may be derived. The depleted MORB mantle (DMM) is perhaps the only reservoir which can be definitively located. Previous attempts at correlating the surface distribution of mantle components with seismic observables have met with limited success (Oschmann, 1991; Ray & Anderson, 1994).

In addition, as more examples of the “mantle endmembers” are found and better characterized geochemically, two truths are becoming self-evident; (1) multiple examples of the mantle endmembers (e.g. Pitcairn and Hawaii for EM1) are not geochemically identical, and (2) the mantle signatures intermediate to the extremes are not simple linear combinations of the endmembers. It now appears likely that the chemistry of each hotspot is the result of a unique history of geochemical processing and aging in the mantle.

These developments would appear to greatly complicate efforts to link specific geochemical components with such identified mantle reservoirs as the transition zone, mid-mantle boundary layers, the lower mantle, or D". However, one common denominator among nearly all hotspots is the presence of recycled slab materials, specifically ancient mafic crust (Hauri & Hart, 1993) which may or may not preserve an oxygen isotope signature of rock-water exchange near the Earth’s surface (Eiler et al., 1996). Seismological detection of subducted slabs in the deep mantle is improving, and numerical convection studies are ongoing to determine the possible ranges of conditions which permit the preservation of ancient slabs over 1-3 billion year time scales (Van Keken & Ballentine, 1999). The time is ripe for improving our understanding of the physical and chemical links between reservoirs in an actively convecting Earth, and their surface expression in derivative magmas.

The January 26, 2001 Bhuj, India (Republic Day) earthquake (M 7.7) caused widespread heavy damage and killed upwards of 18,000 people. Unlike the recent damaging earthquakes in Taiwan and Turkey, which were of comparable size, the Bhuj earthquake occurred in an intraplate setting, although in a fairly rapidly deforming region for a plate interior.

The focal mechanism is consistent with the N-S direction of maximum compressive stress previously documented within the Indian plate. Early reconnaissance reports indicate that intensities reached MM X over a large region and widespread liquefaction and sand blows occurred. As of this date, no discernible surface rupture has been found but aftershocks delineate a possible deep rupture plane bordering the south edge of the Kutch graben and dipping 40-50 degrees toward the south.

As local strong motion records are unavailable, we invert teleseismic body waves recorded by the Global Seismographic Network for the rupture history of the Bhuj event. The time history is simple with a duration of about 24 sec. Preliminary results indicate most of the slip occurred in a small 40 x 20 km area near the hypocenter and at deep depths (15-25 km).

The source dimensions indicate a very high stress drop for the earthquake. However, a second subevent is imaged on the presumed south-dipping fault plane, extending updip to shallow depths and containing as much as 6 m slip. This subevent occurs near an area of intense lateral spreading and ground deformation observed in the field (W. Lettis, EERI field report), indicating the possible presence of shallow slip although the fault rupture appears not to have reached the surface. It is possible that directivity focussed much of the strong motion toward the city of Bhuj, which sustained some of the heaviest damage. We compare the ground velocities predicted by our rupture model to the observed seismic intensities.
The deployment of an earthquake warning system was first discussed in the aftermath of the "great San Francisco earthquake" of 1868. The concept then, as now, is simple: Earthquakes occurring some distance from a metropolitan area could be detected near the epicenter and a warning signal transmitted ahead of the associated ground motion. Such a system has not yet been implemented in California as available technologies and analysis algorithms were not capable of detecting, transmitting, processing and issuing warnings within the short time between the event onset and damage occurring.

The deployment of the dense TriNet network across southern California provides the potential for truly real-time ground motion detection and warning. The algorithm currently under development uses two approaches to ground motion prediction. Firstly, for the worst case scenario of an event directly beneath a metropolitan area, we use the predominant period of the P-arrival. This parameter is relatively insensitive to epicentral distance allowing an estimate of magnitude from the arrival at a single station. Attenuation relationships then provide the predicted peak ground motions and approximate times. Depending on the depth of the event, much of this process is possible before the peak shear motion (responsible for most damage) reaches the surface. This system could provide ground motion warnings of zero to a few seconds in the region directly above an earthquake.

As time progresses and the system warnings update, the second approach using peak ground motion observations becomes possible. The best-fit attenuation relation is used to predict ground motion further from the epicenter. This technique may only be used after a number of stations have experienced their peak ground motion, but it provides more accurate predictions of ground motion than the predominant period method. We anticipate this approach will be of most use for the "great" earthquakes, which propagate along significant lengths of known and monitored faults. It could provide tens of seconds of warning.

Perspective map of the Los Angeles area showing recorded peak acceleration (vertical bars) between 9 and 10 sec after the Northridge earthquake. Grey bars are predominantly horizontal motion, white are the predominantly vertical P-arrivals. The sites above the fault plane start to experience their peak ground motion in this time window, 3 sec after a magnitude estimate can be made from the P-arrivals at the same stations.
In July and August 2000, we conducted 3-D reflection, 3-D tomography, and downhole seismic studies at Operable Unit 2 (OU2) at Hill Air Force Base in Ogden, Utah. OU2 is the subject of ongoing remediation efforts to remove dense nonaqueous phase liquids (DNAPLs) that contaminate a shallow (less than 20 m) aquifer.

The survey target is a paleochannel buried beneath Quaternary sands, gravels and clays that acts as a local trap for contaminants. The highly irregular, steep walled paleochannel was imaged by our pilot 2-D survey conducted in 1998, demonstrating the viability of seismic methods at this site.

The experiment area, which occupied an area of 95m by 36m, utilized ~610 RefTek Texan instruments and included six check shot surveys in 15m boreholes for velocity estimation. A 223-caliber rifle was used as the seismic source, producing frequencies from 40Hz to 300Hz. For the 3-D reflection survey, the instruments were deployed in swaths of six receiver lines 2.1m apart, with geophone intervals in the inline direction of 0.35m. The shot pattern was a rotated brick pattern with 0.35m shot intervals inline and crossline, producing a nominal 52 fold survey.

For the 3-D tomography experiment theTexans were deployed on a staggered 2.8m by 2.1m grid. Shots were taken adjacent to each receiver location, producing signals at offsets greater than 100m.

In addition to the 6 check shot surveys, 2 vertical seismic profiles were shot with offsets to 21m between two adjacent drillholes. Approximately 6000 shot records were taken during the combined experiment, generating as much as 9Gbytes of data per day. Data quality appears to be excellent, despite noise from remediation activities. The shot gathers show strong reflections with conflicting dips, characteristic of steeply dipping features.

The field effort involved approximately 20 people. IRIS/PASSCAL and UTEP provided a high level of field support.
SEISMIC ANISOTROPY IN THE VICINITY OF THE CRUST-MANTLE BOUNDARY: CONSTRAINTS FROM ROCK PHYSICS OBSERVATIONS

Nikolas I. Christensen, Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706

Approximately a century ago, the development of instrumental seismology began to produce, for the first time, facts related to definite levels inside the Earth. The discovery of a major seismic discontinuity at approximately 30 km depth by A. Mohorovicic and subsequent accurate determinations of its depth on a world-wide basis gave physical reality to earlier petrological concepts of an Earth's crust. Recent seismic refraction studies have shown that the depth to the Mohorovicic discontinuity is well correlated with tectonic province, with extended crust showing an average thickness of 31 km and orogens an average of 46 km. Shields and platforms and continental arcs average crustal thickness nearly equal the global average of 41 km. Lower crustal layering imaged by deep seismic reflection profiling appears to be common in many tectonic environments and has often been attributed to ductile stretching and/or igneous intrusions. Deformation immediately below the crust-mantle boundary appears to be a common feature of the uppermost continental mantle as evidenced from recent Pn anisotropy observations. Thus to understand the nature of the Mohorovicic discontinuity in a particular region we have to be concerned not only with the distribution of rock types, but also mineral fabrics and layering and their orientations relative to the crust-mantle boundary.

A combination of field observations and rock physical property studies has been used to investigate the seismic nature of the Mohorovicic discontinuity in three regions with contrasting deformation regimes: 1) the base of an Alaska ultramafic-mafic arc assemblage, 2) the European Cenozoic rift system, and 3) a continental scale strike-slip shear zone of the South Island, New Zealand.

The Talkeetna arc crustal section of south central Alaska is a well exposed crustal section through an accreted, subduction-related magmatic arc, from volcanic rocks, volcaniclastic rocks and sediments at the top to residual mantle peridotites at the base. Detailed studies of the lower section of the Talkeetna arc provide much insight on the geophysical properties of the Mohorovicic discontinuity in active arcs. The mantle rocks in the region are dunite and harzburgite overlain by a narrow zone of websterite and clinopyroxenite. These ultramafic rocks have well developed foliations which are approximately parallel to the Mohorovicic discontinuity. Olivine and pyroxene have strong preferred orientations which produce 8% Pn anisotropy in the upper mantle. Above these ultramafic rocks is a 5 km thick layered gabbro with weak anisotropy and a velocity of approximately 7.0 km/s.

A suite of lower crustal and upper mantle xenoliths from the Neogene Kozákov volcano, central Europe, originating from depths of 25 to 70 km provide an exceptionally continuous record of the depth variation in seismic and petrological properties of subcontinental lower crust and lithospheric mantle. The lower crustal rocks, which have originated from mafic underplating, have velocities of 6.8 to 6.9 km/s. Extraction
depths of the xenoliths and thermal history and rheological properties of the mantle have been evaluated from a tectonothermal model for basaltic underplating associated with Neogene rifting. Texturally, the sampled mantle consists of an equigranular upper layer (32-43 km), an intermediate protogranular layer (43-67 km), and a lower equigranular layer (below 67 km). Olivine petrofabrics show strong axes concentrations, which change with depth from orthorhombic symmetry in the equigranular upper layer to axial symmetry in the lowermost layer. Calculated compressional and shear wave anisotropies, which average 8% and 6% respectively, show significant depth trends that correlate with variations in depth of olivine fabric strengths and symmetries. Comparisons of the xenolith anisotropies with field observations of Pn anisotropy and SKS shear wave splitting in the region suggest that foliation is horizontal in the upper layer of the lithospheric mantle and vertical in the middle and lower layers. The depth variations in mantle properties and complexity in central Europe is the result of Devonian to Early Carboniferous convergence, continental accretions, and crustal thickening, followed by Late Carboniferous to Permian post-thickening extension and gravitational collapse, and final modification by Neogene rifting, thinning, and magmatic heating.

Recent investigations of crustal and upper mantle structure across the Alpine Fault Zone provide new evidence on the structure in the vicinity of the Mohorovicic discontinuity across continental-scale strike-slip shear zones. Teleseismic shear wave splitting measurements show strong anisotropy of the upper mantle with deformation associated with the Alpine fault extending over a zone of 200 to 400 km away from the fault. These observations are consistent with vertical upper mantle of 200 to 400 km away from the fault. These observations are consistent with vertical upper mantle foliations subparallel to the strike of the fault. Samples of lower crustal rocks, which have been exposed by vertical movement in the vicinity of the fault, are well foliated, highly anisotropic garnet amphibolites. Thus foliation across the crust-mantle boundary of New Zealand are likely to be at high angles of dip and lower crustal anisotropy is important to the region.
INTEGRATED SEISMOLOGICAL INVESTIGATIONS
OF THE EIFEL PLUME

Joachim R.R. Ritter(1), Goetz H.R. Bokelmann(2) and the
Eifel Plume Team(3)
(1) Institut for Geophysics, Herzberger Landstr. 180, D-37075
Goettingen, Germany – ritter@uni-geophys.gwdg.de
(2) Department of Geophysics, Stanford University, Mitchell Building,
Stanford CA 94305-2215, USA – goetz@pangea.stanford.edu
(3) www.uni-geophys.gwdg.de/~eifel

The Eifel region is a part of the Rhenish Massif in Central Europe. Following earlier Tertiary volcanism (about 43-23 Ma) two volcanic fields were active from 700,000 to 11,000 years B.P. There were 350 eruption centers with mainly basaltic volcanism. The Quaternary activity has been accompanied by up to 250 m uplift. Massive exhalation of magmatic mantle gases are still ongoing today. The source of this intra-plate volcanism has been attributed to a mantle diapir or small plume in the past, but high-resolution data were not available until recently.

Within an interdisciplinary program, focusing on the origin of the Eifel volcanism, a major seismological program was initiated to image the crust and upper mantle with passive methods such as teleseismic tomography, receiver functions, SKS-splitting and local seismicity. To get an appropriate data set a field project was conducted by 10 institutions from November 1997 to June 1998. Within a nearly 500 km by 500 km area, 156 mobile stations were deployed between 84 permanent seismic observatories. The first results are very promising: Teleseismic P-wave tomography found a 100 km wide low-velocity anomaly that extends from 70-80 km depth to at least 400 km depth. The velocity contrast is minus 1-2% and the structure looks like a small upper mantle plume. A similar structure is seen by the S-wave tomography with a velocity contrast of about minus 2-3%. Teleseismic attenuation tomography based on spectral ratios indicates increased damping in the same region down to at least 250 km depth. The damping mechanism seems to be a combination of anelastic and scattering attenuation, because we observe also significant seismic scattering in the lithosphere underneath the Eifel volcanic fields.

At the GeoForschungsZentrum at Potsdam and at Stanford receiver functions and SKS-splitting are investigated. There is a clear down-welling of the discontinuity at 410 km depth, but the 660 km discontinuity seems to be undeflected underneath the Eifel region. The SKS-splitting data show a prominent anomaly in the Eifel region: In contrast to the regional trend in Central Europe, the observations in and close to the Eifel volcanic fields are negative, indicating no SKS-splitting. This is interpreted to arise from recent deformational processes in the upper mantle that may be related to the Eifel plume. The local seismicity directly below the Eifel volcanic fields is quite low. Local events are clearly related to the (boundary) faults of the Lower Rhine Embayment which is an independent structure from the Eifel plume.
The mechanism of plate tectonics is one of the most important yet open questions in geosciences. While there is a consensus that the mechanism is internal to the Earth, it is not clear whether the tectonic plates are pulled/pushed from the side or whether mantle convection helps to drive the plates from below. Large-scale tectonic motions of the surface plates don't help to discriminate between the two mechanisms, but seismology can, through inferring the sense of shear deformation in the lithosphere/asthenosphere system.

The sense of shear is recorded in the directions in which seismic fast axes dip. We discuss recent seismological measurements of the dips of fast axes. Interestingly, seismological stations on the stable North American craton show P-wave fast axes that dip into the third quadrant (direction of North American plate motion), while stations off the craton have fast axes dips that are distributed onto the other three quadrants, while the horizontal projections of the fast P-axes are generally consistent with shear-wave splitting. If the plate were driven from the side we'd expect fast axis dips in the opposite direction (first quadrant).

The fast axes dips are consistent with a simple-shear deformation of the lithosphere under the North American craton, and they suggest that the driving component from below, by mantle convection, is the dominant one. This mechanism can explain several seemingly unrelated phenomena in North American tectonics, including why the westward motion of North America has slowed down dramatically throughout the past 100 million years.