The newest addition to the Scripps research fleet, the R/V Roger Revelle.
Introduction

The Scripps Institution of Oceanography is a multi-disciplinary department within the University of California, San Diego. The Department offers graduate degrees in a number of fields related to the Earth and marine sciences. Several research divisions within the Department participate in research in geophysics and share in graduate education through the Geophysics Curricular Group. Scripps divisions whose activities include research in geophysics are the Institute of Geophysics and Planetary Physics (IGPP), the Geosciences Research Division (GRD), and the Marine Physical Laboratory (MPL). Scientists engaged in geophysical research include:

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What follows is an overview of a number of research activities in geophysics that are currently underway at Scripps.
Marine Seismology

The inception of the theory of Plate Tectonics some 30 years ago shifted the focus of Earth scientists toward regions of the globe that feature active plate boundaries, in particular mid-ocean ridges, subduction zones, and transform faults. The basic framework of Plate Tectonics was soon realized by deciphering the relationship between magnetic lineations and seafloor spreading, but early on there was little detailed knowledge of plate boundary processes. Scientists across all disciplines at Scripps played critical roles in producing the ideas and observations that led to the formulation and subsequent refinement of this theory. Marine seismology at Scripps contributed greatly to the early studies of active plate boundaries and mid-ocean ridges in particular, and continues to be in the forefront of innovation and discovery with a wide range of on-going and upcoming research programs.

An early seismic investigation (1975) into the processes of seafloor spreading using ocean bottom seismographs (OBS) by John Orcutt and LeRoy Dorman provided the first evidence of the existence of an axial magma chamber beneath the fast spreading East Pacific Rise at 9° N. Since this ground breaking experiment, marine seismologists at Scripps have continued to pursue knowledge of the fundamental processes operating at mid-ocean ridges, especially, the existence, size and shape of ridge crest magma bodies. The presence of an axial magma chamber, at least intermittently, is an integral element of most geological and petrological models of the formation of the oceanic crust, although the formulation and evolution of magma chamber models have changed dramatically over the last 20 years.

Two major seismic experiments conducted by Scripps scientists along the northern East Pacific Rise during the 1980s have confirmed the existence of an axial magma chamber along this portion of the ridge system as well as fundamentally altering ideas about its size and along-axis continuity. In 1982, John Orcutt and Jim McClain at UC Davis conducted the first seafloor refraction/tomography experiment (MAGMA); the resultant rise axis structure provided the first good estimates of the size, shape, and velocity of the East Pacific Rise magma chamber. Studies of ophiolites (presumed to be sections of oceanic crust thrust up on continents) and thermal modeling had suggested a crustal magma chamber many 10s of kilometers wide; results from the MAGMA expedition revealed a magma body of diminished width of no more than 5 kilometers, an estimate that continued to shrink as more data became available.

In 1985, John Orcutt and Alistair Harding took part in a three institution, two-ship multichannel seismic (MCS) experiment along the East Pacific Rise between 9 and 13 degrees N. MCS reflection profiles were complemented by synthetic-aperture expanding spread profiles (ESPs) and wide-aperture profiles (WAPs), producing a rich dataset which would dramatically change our view of mid-ocean ridge dynamics in the years to come. Scripps scientists,
along with Bob Detrick (URI), John Mutter (LDEO), and Peter Buhl (LDEO) produced stunning images of a composite magma chamber consisting of a melt lens of reduced width, embedded in a halo of reduced velocities some 5-10 km in width. Graham Kent, Alistair Harding, and John Orcutt showed that the dimensions of this melt lens were typically a kilometer wide or less, and only tens of meters in thickness; a dramatic departure from ophiolite based models constructed a decade earlier. Although the cross-axis dimensions of the melt sill were quite small, it was found to be continuous for tens of kilometers along-axis. Alistair Harding along with colleagues at Scripps produced the first reflection-based images of seismic layer 2A showing a consistent thickening of the extrusives layer away from the ridge crest.

During the last 4-5 years the ocean bottom seismometers (OBS) used by SIO have undergone a major redesign, and a new inexpensive ocean bottom hydrophone (OBH) has been produced by John Orcutt and Steven Constable. In general, the new OBS/Hs now make use of more powerful but less power hungry microprocessors, SCSI disk drives capable of recording 9 GBytes or more of data, and an improved power supply. As a result of these changes, large arrays of OBS/Hs can be deployed more rapidly and are capable of experiments of longer duration. A large fleet of these instruments, 80-100, will soon be built at SIO to form the core of an NSF funded national facility for ocean bottom seismology. As deployment times increase and clock uncertainties improve, it should be possible to make long term deployments of OBSs on the ocean floor to fill in gaps in the coverage of world wide seismic networks and support global seismic studies of the Earth’s structure. Frank Vernon and John Orcutt in conjunction with investigators at the Woods Hole Oceanographic Institution have designed and built both a broadband seafloor seismometer and a broadband borehole seismometer. These instruments were successfully tested in a pilot experiment using a specially drilled hole near Oahu, Hawaii. A second pilot experiment is slated for an Atlantic borehole in the near future. If these experiments are deemed successful, and it proves possible to make broadband measurements reliably in the oceanic environment, SIO will play a substantial role in deploying an Ocean Seismic Network (OSN) to complement the Global Seismic Network (GSN) of which the IDA Network is such an important part.
The new SIO OBHs as well as OBSs built at Scripps with ONR funding by LeRoy Dorman, Spahr Webb and John Hildebrand, have enabled investigators at Scripps to deploy ever larger arrays of instrument at ridge crests and to study processes over a broad range of scales and spreading rates. For example, this decade has proved fruitful for investigations of ridge crest microseismicity along the Juan de Fuca spreading center. Hildebrand, Dorman and Webb have deployed their OBSs at a number of locations along this spreading center to understand the processes of crustal emplacement and deformation, most notably along the CoAxial segment shortly after an eruption was detected by the navy SOSUS hydrophone arrays that are now used to monitor activity remotely. This unique dataset placed additional constraints on the processes of along-axis melt migration, diking and emplacement at ridges. At the larger scale, the width and nature of mantle upwelling beneath ocean ridges has been directly investigated for the first time using ocean bottom seismographs in deployments across the fast spreading East Pacific Rise (MELT Experiment) and the Lau Spreading Center.

The nature and size of marine seismic datasets have been changing rapidly, providing the impetus for the development and application of new analysis methods. Older seismic experiments tended to use explosive sources

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ARAD experiment layout: Box depicts 3-D multichannel experiment. Open stars are IGPP L-Cheapo locations and closed stars are Cambridge University OBS/H. N–S and E–W lines were shot for tomography only.
and to consist of a sparsely spaced set of records. A standard set of one-dimensional travel time inversion methods and forward modeling methods were developed to analyze these datasets. The earlier work by John Orcutt and Alistair Harding made detailed comparisons between the seismic structures and the stratigraphy of the ocean crust as revealed by ocean drilling and the mapping of ophiolites. More recent experiments have tended to use repeatable airgun sources, to employ a larger receiving array either of OBSs or a multichannel streamer, and to benefit from better navigation and knowledge of seafloor topography. As a result, it is now possible to analyze data explicitly for two- and three-dimensional structure using, for example, seismic tomography, and to make greater use of waveform and amplitude information to resolve finer scale structure. To expedite the processing of such large datasets (which can exceed 0.25 TeraByte in size), IGPP/SIO has employed a Mass-storage system which is currently capable of holding 8 TB of data on-line. Complementing our on-line data storage capabilities are numerous high performance HP, SGI, and Sun workstations ensuring timely completion of research, and also enabling use of methods which only a decade ago were reserved for supercomputers. Scripps is uniquely equipped to exploit new analytical methods and experimental tools during the next ten years to understand the world’s ridge crests and to pioneer similar approaches in the study of even more complex structures including continental margins and trenches.

Two experiments which collected data in 1997/1998 typify the direction of marine seismology in the years to come: ARAD (Anatomy of a Ridge Axis Discontinuity) and SWELL (Seismic Wave Exploration of the Lower Lithosphere).

The ARAD experiment conducted in the Fall of ’97 by Graham Kent, Alistair Harding and co-investigators from the University of Cambridge typifies this trend towards larger, more comprehensive datasets. This experiment was designed to investigate the 3-D internal structure of the overlapping spreading center (OSC) sited at 9°03’N on the northern East Pacific Rise. This experiment was the first on a ridge crest to include a 3-D reflection survey. A total of 201 lines were shot covering a 20 x 20 km box with a line spacing of 100 m, yielding a total of 13+ million seismic traces. The 3-D reflection volume is complemented by a 3-D OBS/H tomography dataset collected by 30 instruments that simultaneously recorded all shots from the reflection experiment plus additional lines specifically designed for tomographic imaging. In one sense, marine seismology has gone full-circle at Scripps with the ARAD experiment returning to the original site of the ’75 OBS experiment, but this time, after 20 years of advances in technology and technique, instead of simply detecting the presence of a magma chamber we can now look at the inner structure in unprecedented 3-D detail.

In the SWELL pilot experiment Gabi Laske, Jason Phipps Morgan and John Orcutt deployed eight OBHs for roughly one year to the south-west of the Hawaiian Island chain to record intermediate-period surface waves. Such data allow researchers to study details of the seismic structure of the lithosphere/asthenosphere system beneath the oceans. The SWELL pilot study provided the first clear seismic evidence for a geographically confined deep-rooted mechanism that is responsible for the Hawaiian Swell uplift. The SWELL experiment is now part of the more comprehensive Hawaiian PLUME (Plume Lithosphere Undersea Mantle Experiment). This experiment, which is in collaboration with other institutions, also uses other seismic techniques to detect the location of the plume conduit, image its structure and extent to depth and image the fingerprint of mantle flow using the concept of seismic anisotropy. The first stage of the two-stage deployment has just been recovered and data analysis will begin in the near future. The second stage is ongoing and will be completed during 2007.

An ocean bottom Differential Pressure Gauge (DPG) in recovery configuration at the sea surface.
Global Seismology

Recent years have seen a rapid expansion in the quantity and quality of digital seismic data from global seismic networks. This has encouraged the use of new analysis techniques and led to significant progress in the ability of seismology to resolve details of Earth’s deep structure. Scripps is well-positioned to take advantage of these developments, building on its traditional strengths in seismic instrumentation and networks, normal mode seismology, inverse theory, and the analysis of large data sets. SIO researchers are at the forefront of efforts to create a new generation of Earth models that are beginning to provide detailed images of the three-dimensional structure of the mantle. These models promise to help resolve a number of long-standing questions in geophysics, including the deep structure of plumes and mid-oceanic ridges, the origins of continents, the nature of mantle convection, and the source of anomalies near the core-mantle boundary.

Top: concept figure of the Hawaiian Plume and the extent of the Hawaiian Swell along the island chain. Bottom: Two-stage PLUME deployment plan. The first deployment (blue symbols) occurred from January 2005 for one year. The second array (red symbols) will be deployed in April 2006 and will operate for one year. The Figure also shows the location of the 1997/98 SWELL pilot experiment and other instrument locations.
Scripps is one of a very small number of institutions that have the tools and expertise to conduct global seismic modeling using a wide variety of different approaches. This permits the construction of integrated models that combine results from normal modes, surface waves, and a number of different body wave phases. Guy Masters, Gabi Laske and several graduate students have compiled an extensive data base of long period travel times, surface wave phase velocities and polarizations, and normal mode splitting parameters. Models constructed from these data show that the mantle is heterogeneous at all depths, with the strongest lateral velocity variations concentrated in the upper and lowermost layers. Current modeling efforts include joint P and S inversions, the study of seismic anisotropy, and the incorporation of discontinuity topography information in upper mantle velocity models.

Inclusion of surface waves in the modeling process provides better depth resolution in the upper mantle than can be obtained from travel time data alone. In older models, the negative velocity anomalies under mid-ocean ridges appeared to extend as far down as the positive anomalies of old continental cratonic roots. In contrast, most recent high-resolution images of the upper mantle suggest much shallower depths for the ridge anomalies. This is a key result for distinguishing between ridge models in which the moving plates are driven by the pull of subducting slabs (in which case the ridges are essentially a passive feature) versus models driven by the push created by the emerging magma at the ridges. Another important topic is the question of slab penetration into the lower mantle and the extent of mass transfer between the upper and lower mantle. Current three-dimensional seismic velocity models tend to favor whole-mantle convection, but a definitive result will require improved resolution in the mid-mantle where the weak amplitude of the velocity anomalies causes problems in the inversions.

Guy Masters, Gabi Laske and Freeman Gilbert have recently developed a new matrix auto-regressive technique for analyzing the splitting of the Earth’s free oscillations. This has been used to learn about both the large-scale elastic and anelastic structure of the Earth’s mantle and core. In fact, an analysis of modes that are sensitive to structure in the inner core has provided new evidence that the superrotation of the inner core is insignificant and that the inner core is most likely gravitationally locked to the mantle.

Two slices through mantle shear velocity model SB4L18 of Guy Masters and coworkers. Variations are shown in percent with respect to the spherical average at each depth. In the upper mantle, positive anomalies are seen under old continental cratons and the old Pacific Ocean, while low velocity anomalies are mainly confined to beneath mid-ocean ridges. Variations in the mid-mantle are relatively small, whereas perturbations at the base of the mantle are quite large. Positive anomalies are thought to represent a remnant of ancient subduction zones while two negative anomalies beneath Africa and the western Pacific Ocean may represent two superplumes.
Scripps is also involved in the development of innovative new approaches for handling large data sets that involve automatic processing and stacking techniques. One such technique is based on waveform (or waveform envelope) cross-correlation with the application of cluster analysis to identify clusters of similar waveforms. We illustrate the technique by applying it to the estimation of relative group arrival times if 50 second Rayleigh waves recorded on the various global seismic networks and PASSCAL deployments through the end of 2004. The analysis resulted in a dataset of over 250,000 relative group arrival times.

To evaluate the internal consistency of our relative group arrival time measurements, we have performed a simple inversion based on ray theory assuming great circle propagation. We discretize the Earth’s surface into equal area cells of dimension 1 or 2 degrees at the equator (the 2 degree cells are sufficient to capture most of the signal in the data). Sampling of the Earth is quite non-uniform though most cells have more than 500 hits and all cells have more than 100 hits. Some cells in the western US have over 10,000 hits suggesting that more sophisticated inversions could use a finer parameterization in this region.

The data are inverted using a conjugate gradient technique with a light smoothing constraint on the first lateral derivative of structure. Convergence is fast, reflecting the well-conditioned nature of the inversion. The resulting map is shown in the figure to the right and a variance reduction of nearly 90% is achieved.

Clearly, the biggest signal in continental regions is due to variations in crustal thickness. Most extreme group velocity variations occur under Tibet (30%) and under the Andes. This is not surprising since the sensitivity of 50 second Rayleigh waves peaks at 70-100 km so we are actually seeing a crust-mantle signal. Other continental signals seems to be associated with hot spots (East Africa). The signal in oceanic regions is also interesting with extremely slow regions associated with back-arc basins (e.g. the Lau basin) and some hot spots (e.g. Galapagos) but not others (Iceland, Hawaii). Some parts of the East Pacific Rise are clearly very slow and there is a perceptible slow anomaly associated with the Australian-Antarctic discordance.

Our knowledge of crustal structure in many parts of the world is currently very limited, particularly in South
Group velocity perturbation maps for 50 sec Rayleigh waves (in percent). Note the extreme negative perturbations under Tibet and South America associated with continental crustal thickness variations. There are also many interesting signals in the oceans where the crust is relatively uniform.

Checkerboard test to show recovery of structure of 1000 km scale length.

America, Africa, Antarctica, and Indonesia. The figure above shows the ability of the data to globally resolve structure by using a checkerboard test. Features of 1000 km scale length and greater are resolved everywhere and we also get good resolution for most of Indonesia and South America. We anticipate that the final inversions of our datasets will result in vastly improved models of crustal thickness in these regions.

Other stacking methods can enhance the visibility of weak seismic phases that are not apparent on individual seismograms and produce images of the global seismic wavefield at different frequency bands. A major result of this work has been the identification of a family of minor seismic arrivals that result from reflections and phase conversions off velocity discontinuities in the upper mantle; these can be used to resolve details of transition zone structure that are difficult to obtain from the main seismic phases. In particular, by examining underside reflected precursors to the phase SS at long periods, Peter Shearer was able to resolve details of the 520-km discontinuity and velocity gradients within the transition zone. Using higher frequency data, Michael Hedlin, Peter Shearer and Paul Earle analyzed precursors to the core phase PKP and found evidence for small-scale heterogeneity throughout the mantle, rather than heterogeneity concentrated at the core-mantle boundary as modeled in previous studies.
Examples of the splitting function for the inner-core sensitive mode $13S_2$. A splitting function basically maps at the surface how a particular mode sees the Earth’s interior. The left panel is a splitting function derived from data from recent events (circa 1995), while the right panel uses earlier events (circa 1980). The effects of rotation, ellipticity and the Earth’s mantle have been removed so that the anomalies shown are due to structure in the inner core. For this particular mode, the splitting functions best match for a westward rotation of the inner core of 0.3 deg/year. However, the average inner core rotation rate from the analysis of many such modes is essentially zero.

The infrastructure supporting research in global seismology at SIO is substantial. Researchers have access to a modern network of high-speed workstations and several large sets of online seismograms, containing records from 1976 to the present day. Jon Berger, Pete Davis, and coworkers at SIO operate the IRIS/IDA network of broadband, three-component seismometers, one of the main providers of global seismic data internationally. The IRIS program (Incorporated Research Institutions for Seismology) is entering its second decade of funding. The IDA network now consists of 40 stations with several more planned. The three newest IDA stations (Diego Garcia, Chagos Archipelago; Pallekele, Sri Lanka; and Santiago Island, Cape Verde) illustrate the current emphasis upon deploying instruments on oceanic islands and other remote sites that, while logistically difficult to develop and operate, are very important for filling in gaps in the existing global coverage. Scripps has pioneered near-real time access to the stations, and 36 of our stations currently have telemetry capability to permit routine monitoring of data quality. One of the new stations (Mbarara, Uganda) is the first IDA station to transmit all data recorded on site back to La Jolla via satellite. As global telecommunications infrastructure continues to develop, an ever greater fraction of IDA data will be transmitted directly to SIO and made available to researchers via the Internet.

**IRIS/IDA Global Seismographic Network**

*Jon Berger, Pete Davis* and coworkers operate the IDA/IRIS network of broadband 3-component seismometers, one of the main providers of global seismic data.
Local Seismology

Locating Earthquakes and Faults in Southern California

The locations of small earthquakes in southern California provide one of the best ways to map the subsurface geometry of active faults. However, the accuracy of the earthquake locations in the Southern California Seismic Network (SCSN) catalog is often quite poor. During the last several years, IGPP researchers have worked to improve the quality of southern California earthquake locations in order to better delineate fault structures. We have relocated the SCSN catalog of over 300,000 events (1975 to 1996) by applying a variety of new methods, achieving greatly reduced scatter, particularly in depth, compared to the catalog locations. We have also analyzed aftershock sequences following several large earthquakes, including the 1986 Oceanside earthquake, the 1987 Whittier Narrows earthquake, the 1988 and 1990 Upland earthquakes, the 1992 Landers earthquake, and the 1994 Northridge earthquake.

The Whittier Narrows earthquake is of particular importance owing to its proximity to metropolitan Los Angeles. To improve the accuracy of depth estimates of Whittier Narrows aftershocks, we accounted for three-dimensional seismic velocity variations in two different ways: (1) We relocated the events using timing corrections for seismic stations derived from a well distributed set of 4800 events across southern California, and (2) For four stations close to the Whittier Narrows earthquake (FLA, GVR, AC1 and TCC) we obtained detailed velocity information from borehole velocity logs provide by John Shaw at Harvard. We relocated the events using the custom profiles at these stations and a reference one-dimensional model at all other stations. Both methods indicated that the Whittier Narrows events are shallower than the locations obtained without these corrections, which were biased downward by the slow near-surface velocities at stations close to the sequence. The position and orientation of the mainshock and aftershock sequence align with a fault observed in reflection seismic data 10 to 15 km south of the mainshock (Figure 1). Thus it appears likely that the M=6.0 Whittier Narrows earthquake ruptured only part of a more extensive blind-thrust fault, which we term the Puente Hills thrust, that is capable of larger and more damaging earthquakes. Due to its location beneath much of metropolitan Los Angeles, this fault is potentially very destructive.

Figure 2. Geologic cross section of the Santa Fe Springs anticline and fault segment with the relocated mainshock and aftershocks of the 1987 Whittier Narrows earthquake. Note the coincidence of the relocated aftershocks with the projected fault plane. Figure from Shaw and Shearer (1999).
**Broadband Seismic Arrays.** Understanding scaling laws is of fundamental importance for insight regarding earthquake mechanisms as well as for predicting strong ground motion. The second objective is to investigate basic issues of earthquakes’ interaction with each other and their relationship to the strain field changes, with the ultimate goal of understanding how small earthquakes and strain changes prepare the region for a larger earthquake.

The Broadband Array Project, under the direction of **Frank Vernon**, is focussed on acquiring and analyzing broadband high dynamic range seismic data from local, regional, and teleseismic sources. Basic research topics of interest include understanding the spatial variability and the propagation characteristics of the observed seismic wavefield from local, regional, and teleseismic events, understanding the properties of earthquake nucleation and rupture, and developing spectral and array analysis techniques which enhance the understanding of Earth structure from broad-band seismic data.

Specific research in earthquake seismology is directed towards two primary objectives. The first of these is to explore earthquake-source and ground-motion scaling laws over a broad magnitude range, and determine if earthquake-source/ground-motion scaling laws applicable for small magnitudes (for which data are abundant) could be used to extrapolate to large magnitudes (for which data were sparse to non-existent). Understanding scaling laws is of fundamental importance for insight regarding earthquake mechanisms as well as for predicting strong ground motion. The second objective is to investigate basic issues of earthquakes’ interaction with each other and their relationship to the strain field changes, with the ultimate goal of understanding how small earthquakes and strain changes prepare the region for a larger earthquake. These broadband studies have created opportunities to investigate many different aspects of seismology, including detailed source imaging, studies of the high-frequency excitation of small earthquakes, coda excitation and scattering.
mechanisms, shear-wave polarization and splitting, and waveform coherence across small and large aperture seismic arrays. In order to develop the datasets required for these research topics, it was necessary to develop an extensive instrumentation and field program. These projects include installing and operating the ANZA digital telemetry array in southern California, the Kyrgyz Broadband Network in central Asia, and small aperture arrays in southern California and Turkmenistan. Other field experiments include installing a digital strong motion network in northern Baja California, and various temporary deployments of portable digital recorders in California, Idaho, Mexico, and Saudi Arabia. These experiments have required developing several techniques of data telemetry which have included using the INTERNET, spread-spectrum, VHF, microwave, satellite, and courier and postal delivery.

In the next few years the group plans to have an active field program continuing to study the structure of the Tien Shan mountains in central Asia and the structure of the Arabian Shield as well as continuing analysis of data collected in southern California. Plans to continue developing the hardware and software techniques required to record and process large datasets for regional broadband networks and small aperture arrays will complement these research projects.

Geodesy

Geodesy, the determination of the size, shape, and gravity field of the Earth, is the oldest branch of geophysics, traceable over more than two millennia from the first estimates of the size of the Earth. In the last 30 years the subject has been revitalized by spectacular technical improvements, which enable geophysicists not just to measure the Earth, but to keep track of its motions: global plate motions, crustal deformation across plate boundaries, and time variations related to earthquakes and other transients. Scripps scientists are active in these areas, improving the instruments, developing new methods of data analysis, and applying these to advance our understanding of many geophysical phenomena.

The first of the new methods to make an impact was the Global Positioning System (GPS) system of satellites, developed by Department of Defense in the early 1980’s, and which have turned out to provide geophysicists with a sensitive tool to measure distances of many kilometers with millimeter precision. Scripps geodesists have pioneered methods of GPS data collection, analysis and interpretation. The Scripps Orbit and Permanent Array Center (SOPAC), led by Yehuda Bock, collects data from permanent GPS stations around the world and analyzes them for a number of purposes. Some of the focus areas have included deformation across the plate boundary in Indonesia (the site of the recent Sumatra-Andaman earthquake) and in southern California. A recent development is the use of GPS data sampled at a high rate to measure seismic waves, an approach that offers certain advantages over conventional seismometers; in support of this, SOPAC is partnering with local agencies in California and other Scripps investigators to create a network of high-rate GPS stations providing data in real time, with many potential applications.

As if one satellite system were not enough, another powerful source of new information has come from Interferometric Synthetic Aperture Radar (InSAR) satellites, which can provide detailed maps of surface deformations, whether from volcanos, plate motion, earthquakes, or flowing ice. Scripps scientists Dave Sandwell and Yuri Fialko are active in this area. Fialko’s InSAR measurements of the deformation from the Hector Mine earthquake of 1999 showed enhanced deformation within fault zones around the earthquake, thought to be due to a lower elastic modulus within these zones: a hypothesis to be tested with seismic and geodetic measurements over the next few years. InSAR studies of the 2003 earthquake in Bam (Iran) revealed significant deformation on a “blind” strike-slip fault (one with no surface trace), a result with significant implications for seismic hazard estimation. As the Earth keeps deforming and InSAR data accumulate, additional new results can certainly be anticipated, both for large and for subtle surface motions.

There is a third class of crustal deformation measurement, one that does not depend on satellite data, and in which Scripps scientists lead the world. This is the use of fixed instruments (strainmeters and tiltmeters) to measure deformation signals with a sensitivity that cannot be approached by space-geodetic methods over a very wide range of frequencies. The flagship of this program is the Cecil and Ida Green Piñon Flat Observatory, northeast of San Diego, operated by Frank Wyatt and Duncan Agnew. This is both a test-bed for geodetic instrumentation, and as the location for state-of-the-art measurements with laser strainmeters, long-base tiltmeters, and many other instruments. These data have shown the importance of careful anchoring of all geodetic measurements, and the high quality obtainable over long baselines. The instruments have been replicated by Wyatt and Agnew at a site near the Salton Sea (and the southern San Andreas Fault), in the Los Angeles Basin, and in the proposed nuclear waste repository at Yucca Mountain, Nevada.

A new NSF initiative, the Plate Boundary Observatory (PBO) is adding significantly to the data available from these methods along the boundary between the North American and Pacific plates. The PBO is constructing nearly 900 new continuous GPS stations, 100 borehole strainmeters, and 5 laser strainmeters (the last being built by Wyatt and Agnew). This will result in a large amount
Co-seismic displacement field due to the 1999 Hector Mine earthquake, Southern California, inferred from the analysis of radar interferograms acquired by the European Space Agency satellites ERS-1/2. Colors denote the horizontal displacement amplitude, in meters, and arrows show a sub-sampled displacement field obtained from the IFSAR data. Black triangles denote GPS stations, and “starred” arrows show horizontal displacement vectors inferred from the GPS data analysis. Black wavy line denotes the geologically mapped surface rupture.
of new data, with many interpretive opportunities, especially in data integration. A nontectonic example is shown in the figure below, which draws on data from the first large continuous network in the US, the SCIGN network in southern California, which Bock, Wyatt, and Agnew were involved in the construction of. The left panel shows the displacements of the stations, as found from the SOPAC analysis, for the first 4 months of 2005. There is a very large signal present in the north of Los Angeles, with all the stations around the San Gabriel Valley moving outwards. The right panel shows the time history of this motion, which coincides with heavy rainfalls. The mechanism connecting these hydrological effects with ground displacements is an active area of investigation.

In addition to measuring crustal deformation, satellite geodesy has revolutionized marine geophysics. What we know about the topography and tectonics of the ocean basins come largely from combining dense satellite altimeter measurements of the gravity field with sparse bathymetry and gravity data from ships. Satellite data provided not just a spectacular confirmation of plate tectonics but also revealed smaller-scale structures including ranges of seamounts, propagating rifts, ridge jumps, and global-scale variations in seafloor roughness. Scripps scientists have pioneered the methods for extracting gravity field and seafloor topography information from satellite data. Current research includes reprocessing the radar returns from the Geosat and ERS-1 radar altimeters to refine the seafloor topography models further. Scripps scientists are also helping to plan the next generation of radar altimeters, which will allow improvements in three areas of ocean science: 1) the fine-scale tectonic structure of the deep ocean floor (e.g., microplates, propagating rifts, 

*Landers earthquake coseismic displacements in southern California estimated by interferometric SAR (color portion) and continuous GPS. Solid arrows indicate total surface horizontal displacements estimated at 4 Permanent GPS Geodetic Array (PGGA) stations using 10 weeks of data centered on the Landers earthquake. Blank arrows show modeled displacements. The contours (in mm) show the magnitude of the horizontal displacement field predicted by a dislocation model that assumes 7 linear segments describing the rupture geometry of the Landers and Big Bear earthquakes. The heavy line denotes the surface trace of the Landers rupture, the dashed line is the Big Bear earthquake's subsurface trace.*
meteorite impacts); 2) the roughness spectrum of the seafloor, which affects models of tidal dissipation, vertical mixing, and mesoscale ocean circulation; and 3) improved gravity fields for research, exploration and navigation.

Scripps research also include the Earth’s cryosphere, in particular the Antarctic ice sheet, whose mass may be changing because of climate change. Given the vast size of the ice sheet, and the long times over which it can change, satellite data are again crucial for monitoring. Helen Amanda Fricker has used radar altimetry to map the topography of the Antarctic ice shelves and also to detect their vertical motions caused by the ocean tide. Since January 2003 Fricker and Bernard Minster have used data from the Geoscience Laser Altimeter System (GLAS) instrument on NASA’s ICESat satellite. To calibrate GLAS, Fricker led an expedition to the salar de Uyuni in Bolivia, the flattest surface on Earth, using GPS to precisely map the surface (another integration of geodetic measurements). Fricker has used ICESat data to map where ice shelves transition between grounded and floating ice, and also the rifts at the front of the ice shelves that eventually lead to iceberg calving; while such calving accounts for 70% of the total mass loss from Antarctica, little is known about the processes involved. Fricker has also led a fieldwork-based study of the propagation and evolution of active rifts, using GPS and seismic methods for four consecutive years to monitor rift activity on the Amery Ice Shelf; the rift propagation occurs in discrete events separated by around 2 weeks. Integration with satellite imagery shows that on longer time-scales rifts propagate faster in the summer than in winter.

The left panel shows the displacements of the stations, as found from the SOPAC analysis, for the first 4 months of 2005. There is a very large signal present in the north of Los Angeles, with all the stations around the San Gabriel Valley moving outwards. The right panel shows the time history of this motion, which coincides with heavy rainfalls.

Two views of rifts in a Antarctic ice shelves: left, from above (second helicopter for scale); right, as measured by the GLAS system on NASA’s ICESat.
**Seafloor Geodesy**

Geodesy plays an important role in gaining understanding of the tectonics that shape Earth’s crust. On land, geodesy is a mature, advanced science. Submarine geodesy, on the other hand, limited by the opacity of seawater to electromagnetic radiation, is relatively new and is in need of alternate techniques to detect seafloor deformation reliably.

For tectonic events, deformation is the basic descriptive tool for determining crustal motion and crustal modification by faulting and fissuring. For volcanic events, deformation is a window into subsurface motions of magma and intrusive emplacement of new crustal material. Magma emplacement and movement can be aseismic, thus long-term studies of seafloor deformation are essential for our understanding of the spatial and temporal patterns of oceanic volcanism. Methods to detect both horizontal and vertical components of crustal deformation are being studied at SIO.

**Horizontal Deformation:** At the smallest scale of observation, Mark Zumberge and coworkers are constructing a Fiber Optic Seafloor Strainmeter (FOSS). An optical fiber on a 250 to 1000 m baseline is stretched between large weights (benchmarks) placed on the seafloor. As the seafloor deforms, the length of the optical fiber also changes. These changes in the distances between the benchmarks are measured optically with a precision of about 1 mm. The FOSS is self-recording at a few samples per hour for one year deployments. Data are uploaded periodically acoustically to a nearby ship.

The position of a ship is determined simultaneously (1) with respect to the continents using GPS signals, and (2) with respect to the seafloor using acoustic signals. If the ship is roughly centered in an array of sea floor acoustic transponders, variations in sound speed along the vertical coordinate are mostly inconsequential. This method yields the tectonic motion of the mid-ocean crust with a precision of a few cm per year.
Also at a 1-km scale, Dave Chadwell and Fred Spiess measure horizontal deformation with a direct-path acoustic approach that resolves the two-way travel time between precision acoustic transponder units mounted atop 3-m-high towers. Travel times are converted to range with knowledge of the sound speed along the ray path. Sound speed is measured with sound velocimeters – devices that measure the change in travel time over a fixed range or by an empirical relationship to the observed seawater temperature, pressure, and salinity. Horizontal distances are measured with sub-centimeter resolution. Instruments deployed to span the axial rift on the Juan de Fuca ridge should no extensional motion over a 5 year span.

At 10-km scales, a towed survey vehicle is used to interrogate the transponders, allowing them to be placed at seafloor sites up to 5 km apart and in regions that do not have direct acoustic paths. This technique has position repeatability of 2 cm rms. Currently an approach is being developed where the towed vehicle is replaced by some number of more permanent bottom more interrogation systems to permit measurements to made continuously during the time no ship is in the vicinity.

At the 100-km scale, the seafloor sites can be located relative to shore stations, by also surveying the transponders from a surface ship which records GPS satellite signals along with similar tracking onshore. It effectively extends to the seafloor precision GPS positioning for crustal motion studies and has a sub-centimeter repeatability. This approach has been used to measure the convergence rate of the Juan de Fuca and North American plates offshore Vancouver Island to be in general agreement with the geologically predicted convergence rate. At a site 25 km east of the Juan de Fuca Ridge, full spreading of the JDF and Pacific plates has been observed along with a visco-elastic response of the plate to a strike slip event along the Blanco Transform. Offshore Peru, GPS-A measurements have measured landward displacement of the continental slope, consistent with shallow up-dip locking along the thrust interface.

**Vertical Deformation:** Vertical deformation measurements provide a quantitative characterization of the displacement due to faulting events, volcanism, or fluid withdrawal. A series of vertical deformation measurements is being conducted by Mark Zumberge and Glenn Sasagawa using seafloor benchmarks and measurements of gravity and pressure. Gravity is an effective vertical reference because gravity changes with distance from the center of the planet. The vertical gravity gradient underwater is approximately $2 \mu\text{Gal/cm}$, therefore, a gravity meter must be capable of several $\mu\text{Gal}$ measurement accuracy for several cm depth accuracy.

Zumberge and Sasagawa, built a new sea floor gravimeter that can be deployed by a remotely operated vehicle (ROV). This work was done in collaboration with...
the Norwegian oil company Statoil, who desire to monitor sea floor deformation in the North Sea. The North Sea Troll natural gas field is a site of intensive exploration and production. At full capacity, this field produces $10^8$ m$^3$ per day, a significant fraction of Europe’s natural gas requirements. Reservoir management studies attempt to answer questions regarding the size of the field, rates of extraction, and the quantities and location of recoverable reserves. As gas is extracted, the sea floor subsides by several cm per year. This subsidence, along with the mass withdrawal, can be monitored with a combination of pressure and gravity measurements.

The ROVDOG (Remotely Operated Vehicle Deep Ocean Gravimeter) system is built around a relative gravity sensor capable of $5 \mu$Gal measurements in a few minutes of observation. The sensor is held in a motorized gimbaled frame for leveling. A small microcontroller executes the various sensor functions and allows a shipboard operator to control the system. The sensor, gimbaled frame, and support electronics are contained within a pressure case with a depth rating of 700 m. Three precise quartz pressure gauges monitor the pressure, and thus determine the depth of the measurement.

In normal operation, the sensor is held in the manipulator arm of an ROV. The ROV is launched over the measurement site and dives to a seafloor benchmark; these concrete monuments serve as easily recoverable seafloor sites for accurately re-located, repeat measurements. The ROV pilot locates the benchmark with obstacle avoidance sonar and video cameras. After the ROVDOG is gently placed on the benchmark, the sensor operator sends commands to begin the observation and views the results in real time. After the measurement is completed (typically 20-40 minutes), the pilot recovers the ROVDOG package and a surface or underwater transit to the next site is begun. Using this approach offshore the south flank of Kilauea on the Hawaiian Island, Chadwell and coworkers have observed $\sim$5 centimeters/yr uplift of the mid-slope basin over a 4 year span, consistent with slip on the deeper decollement beneath the Island.
Seafloor Electromagnetic Sounding

Electrical conductivity is one of the few physical properties of Earth that may be sensed remotely and is the only property besides elastic velocities that may be sensed using a man-made source of energy. Electrical methods are therefore a vital tool in our exploration of Earth’s interior. Since electrical conductivity is primarily dependent on mineralogy, fluid content and temperature, electrical studies of the oceanic crust and mantle are highly relevant to our understanding of lithospheric evolution and mantle dynamics. Marine electromagnetic (EM) methods have also recently become economically important as the offshore petroleum exploration industry has adopted them in the quest to meet rising energy demands.

Scripps pioneered experimental marine electromagnetism during the 1970’s and today remains a world leader in this field. Steve Constable and the students and postdocs of the SIO Marine EM Laboratory continue to advance the method with new field experiments, instrumentation and interpretational tools. Two basic techniques are used for marine EM exploration. In the controlled-source electromagnetic (CSEM) method, a deep-towed transmitter broadcasts EM energy into the seafloor, which is measured as a function of range and frequency by seafloor EM receivers. The more conductive seawater rapidly attenuates the energy diffusing through the seawater within a short range and most of the measured energy is from diffusion through the seafloor rocks. Resistive rock, such as oil or gas (but also basalts and evaporites), increase the magnitude of the detected electric fields. For the magnetotelluric (MT) method, natural plane-wave variations in Earth’s magnetic field induce low frequency electric currents in the seafloor. The transfer function between seafloor electric and magnetic fields is used to compute seafloor resistivity to several hundred kilometers depth. The two methods are very complementary: CSEM can map structure to a few tens of kilometers depth while MT can constrain features as deep as a few hundred kilometers.

The SIO Marine EM Laboratory has designed and maintains an inventory of 50 state-of-the-art broadband EM receivers and 2 deep-towed EM transmitters. This capability was achieved through industrial sponsorships and provides a unique opportunity for the collection of new and exciting data sets for both industry sponsored research as well as investigation of the physical properties of the solid Earth. A recent experiment at the mid-ocean ridge on the East Pacific Rise near 9° 30’N resulted in the largest academic marine EM data set collected to date: 69 MT sites and 80 km of CSEM tows. These data are yielding new insights into the mantle melt supply and crustal magmatic and hydrothermal systems. An innovative experiment at Hydrate Ridge, offshore Oregon, has provided a proof of concept for marine EM mapping and characterization of seafloor methane hydrates. Marine MT data collected over a petroleum prospect in the northern Gulf of Mexico are being used to resolve ambiguities in the seismic interpretation.

More information can be found at:  
http://marineemlab.ucsd.edu

Two methods are used for marine EM exploration. For the controlled-source electromagnetic (CSEM) method, a deep-towed electromagnetic (EM) transmitter broadcasts energy into the seafloor, which is then measured as a function of range and frequency by seafloor EM receivers. For the magnetotelluric (MT) method, natural variations in Earth’s magnetic field induce low frequency electric currents in the seafloor. The transfer function between seafloor electric and magnetic fields is used to compute seafloor resistivity to several hundred kilometers depth.
Students and technicians deploy an ocean bottom EM/MT receiver during a research cruise at the East Pacific Rise near 9° 30' N. Electric fields are measured using electrodes located at the end of the yellow arms. Magnetic fields are measured using highly sensitive induction coil magnetometers.

Marine MT mapping of resistive salt structures in the northern Gulf of Mexico. MT inversion profiles (colored image) are overlain on seismic reflection images.
Geomagnetism

Earth’s magnetic field varies on time scales ranging from nanoseconds to many millions of years. This temporal variation may be separated into parts that are internal or external in origin. Variations on short time scales are usually attributed to external sources, because the conductive mantle screens out high frequency variations arising in the core. The external field variations induce currents in Earth’s mantle which can be related to the electrical conductivity profile (and thus more generally to structure and composition) within the earth. Long term internal field variations are of interest because they give clues to the workings of the geodynamo in Earth’s liquid outer core, as well as providing useful tools for magnetostratigraphic, paleoclimate and tectonic problems. Observations of the field come from magnetic observatory and satellite data, which provide good global coverage over short time scales, from deployment of temporary instrument arrays, and from paleomagnetic measurements and marine magnetic surveys for longer time scales.

Geomagnetists at SIO have made important contributions to the understanding of the field in numerous areas. George Backus provided many powerful theoretical insights: these include proof that a viable self-sustaining geodynamo could exist in the core; demonstrating that even an infinitely dense collection of scalar magnetic intensity data (as collected by early satellite missions) cannot uniquely determine the field; and determining conditions on the geomagnetic secular variation that are necessary for the dominance of convective over diffusive processes in the liquid outer core. Working with a class of models that parameterize those convective processes, Glenn Ierley has explored the dynamical constraints on the large scale magnetic field that emerge in the limit of vanishingly small viscous dissipation.

The development of inverse theory at SIO (with pioneering work carried out by George Backus, Freeman Gilbert and Robert Parker) and its subsequent evolution have had far reaching effects on the whole subject of geomagnetism (and indeed all of geophysics). It is now widely recognized, for example, that downward continuation of surface or satellite measurements of the geomagnetic field to the core surface is an intrinsically unstable problem and that additional so-called regularization constraints must be incorporated in the inversion process in order to obtain plausible models. The intrinsic non- uniqueness of the solution to the problem (caused by having only a finite number of inaccurate data) means that inferences about the physical state of the core are best made by various forms of hypothesis testing, to see if competing hypotheses are compatible with the available data. Development of computational and theoretical tools for the solution of such problems has continued at SIO, and these have been applied to some of the large satellite, survey and observatory geomagnetic data sets made available by NASA. Cathy Constable and Bob Parker have shown that it is possible to construct geomagnetic field models for this century that exhibit no effects of diffusion in the core. Nevertheless, the effects of diffusion must be important, although dependent on the spatial and temporal scales under consideration. Current geomagnetic research into the core field is focused in two areas. The first involves extending geomagnetic field models back in time, and studying the physical processes that contribute to geomagnetic secular variation on centennial to millennial time scales. One interesting result from this work is that in the context of field behavior over the past few thousand years the current decay of the geomagnetic dipole (which has led to speculations of a geomagnetic field reversal within the next few centuries) is not atypical. There have been several similar episodes of decreasing dipole moment, all followed by periods of increase. The second research area (Cathy Constable and Catherine Johnson, see also the paleomagnetism section)
involves even longer (million year) time scales and is a concerted effort to understand long-term biases in magnetic field structure that might be related to thermal or chemical variations at the boundary between Earth’s core and mantle.

Geomagnetic studies using modern field observations are currently flourishing, because after an almost twenty year hiatus there are now several magnetic satellites in operation and a steady stream of new data to analyze. Oersted, a Danish vector magnetic satellite was launched in early 1999, followed by the German CHAMP and Argentine/US SAC-C in 2000, and ESA’s SWARM mission, a cluster of 3 satellites, is expected to go up in 2009. At SIO we are using data from recent missions to study the electrical conductivity structure of Earth’s mantle. This is important for several reasons. It has already been noted that mantle conductivity determines the frequency of core-field variations that can propagate to Earth’s surface. As a transport property, conductivity is related to rheology, and also provides clues about the chemical and thermal state of our planet’s interior. Steven Constable has studied mantle conductivity both by applying inverse techniques developed at IGPP/SIO to global geomagnetic data sets, and, through laboratory measurements of mantle materials, constructing mathematical models to explain the results, and relating them to field studies of Earth conductivity. Cathy Constable, Steven Constable, and Bob Parker are investigating how magnetic satellite observations can be used to study variations in mantle conductivity. Since the magnetic signature of the geodynamo and the crust are sources of noise in conductivity studies, this work draws heavily on expertise in core and crustal geomagnetic field modeling. One exciting prospect is the possibility of collaborating with mineral physicist Sofia Akber to interpret the results of these analyses and determine the implications for lower mantle mineralogy.

Faculty member Bob Parker works in theoretical geophysics, with applications in geomagnetism, gravity and electromagnetic sounding. A theme of his work is the extraction of unambiguous, mathematically firm results from actual geophysical data sets. In the hands of many investigators data inversion usually results in a solution of unknown reliability, often heavily dependent on tacit assumptions and hidden biases. It is generally agreed that every model based on observation is uncertain, but quantification of the uncertainty is traditionally either primitive, or entirely absent. Parker believes that to be confident of a result one must often ask a question of restricted scope.

Here is an illustration, based on the remarkable, and at the time quite unexpected, pattern of magnetic anomalies on Mars first observed by Mars Global Surveyor in 1997. The discovery raised a number of difficult questions, which are still not satisfactorily resolved, such as why the fields are concentrated into a relatively small area of the planet. Also unexplained is the huge size of these fields, which are presumably caused by magnetized materials near the surface. But just how strong must the rock magnetization really be? Standard modeling of magnetic anomalies on Earth makes use of properties that are totally unknown in the Martian environment. Parker asked the following mathematical question: What is the smallest possible magnetization intensity that will match the observed magnetic field? This number represents a firm bound on any model: all models and the true magnetization on Mars must at least meet this bound somewhere within Mars. Parker presented the solution of this optimization problem in a paper, Ideal Bodies for Mars Magnetics, [Journal of Geophysical Research–Planets, 108, E1, doi:10.1029/2001JE001760, 2003]. Because the depth extent of the source layer is unknown, one must couple the bound with a layer thickness: for example, if the layer is no thicker than 50 km (an enormous number by terrestrial standards) the intensity must exceed 4.76 A/m. The bounds obtained were three times smaller than those reported in the first models found by conventional means, but they still represent values ten times larger than are found anywhere in such a volume on earth.

Projects in Geomagnetitism: http://mahi.ucsd.edu/cathy/projects.html
Paleomagnetism

At SIO there is a strong paleomagnetic group involved in field and experimental studies. Paleomagnetic research at Scripps covers a broad range of paleomagnetism, including geological applications, experimental work on basic rock magnetism and studies in paleo-geomagnetism. The laboratory itself is suited for just about any paleomagnetic endeavor, and current research by Lisa Tauxe and Jeff Gee reflects the diversity of the field in general, with studies in magnetostratigraphy, on the origin of magnetization in igneous and sedimentary rocks, the interpretation of rock magnetic data in terms of their paleomagnetic significance, the long-term behavior of Earth's magnetic field, particularly variations in intensity, details of mid-ocean ridge generation using the anisotropy of magnetic susceptibility, and the statistical analysis of paleomagnetic data.

An example of geological application of paleomagnetic techniques is in the study of the ocean crustal generation process. In a long term project, Tauxe and Gee, along with Hubert Staudigel, collected paleomagnetic samples from dike margins in the Troodos Ophiolite of Cyprus. This has provided excellent data on the anisotropy of magnetic susceptibility (AMS) from over 100 dikes, with interpretable flow direction indicators. These show conclusively, that dike intrusive directions span from quasi-horizontal to vertically up, with systematic differences related to the chemistry of the lavas. The ability to separate source volcanos on the basis of flow direction has led to the construction of an extremely detailed picture of one portion of the ancient spreading center.

Jeff Gee has recently concentrated on applications of paleomagnetic and magnetic anomaly data to understanding crustal accretionary processes at mid-ocean ridges. These studies include investigating the role of geochemistry and alteration in controlling magnetization variations, examining the uplift and alteration history of lower crustal gabbros and serpentinized peridotites exposed at the Mid-Atlantic Ridge, and a variety of projects in the Troodos ophiolite (e.g., magma flow in dikes, timing of epidosite alteration). Jeff Gee, Steve Cande and Bob Parker have

Paleomagnetic sampling has been carried out on basaltic glasses from extrusive units in the Troodos ophiolite. These samples are used to determine the strength of the geomagnetic field during the Cretaceous Normal Superchron, when the magnetic field had a consistently normal polarity for almost 40 Myr. Compared with the average the field is unusually strong during the CNS.
demonstrated using a variety of techniques that lineated marine magnetic anomalies may preserve a record of geomagnetic intensity variations as well as providing the template for the polarity timescale.

One of the early motivations for paleomagnetic research was to study past geomagnetic fields; the extreme variability discovered in paleomagnetic data had—and still has—profound implications for models of magnetic field generation. Contributions by Scripps scientists have been made on a variety of aspects of paleo-geomagnetism (such as studies of the behavior of the geomagnetic field during transition from one polarity state to another), and one of the most important has been in the study of variations in the intensity of the geomagnetic field. The ability to determine ancient field intensities using basaltic glass has been particularly exciting. Deep-sea sediments also provide constraints on relative paleointensity variations, and when combined with absolute data they can provide a quasi-continuous record of field strength. Work of this kind shows a correlation between average magnetic field strength and polarity interval length.

As a backdrop to geologically motivated studies, investigations of the origin of magnetic properties of a variety of igneous and sedimentary rocks, both continental and marine, are underway. Of particular interest are the controls on chemical, viscous, thermal and depositional remanence and the interpretation of hysteresis loops. Ongoing projects are concerned with magnetic remanence acquisition in sediments and how this affects the reliability of relative paleointensity variations.

Considerable effort has been expended on putting together paleomagnetic datasets for analysis of the global field. For the time period 0-5 Ma, work by Cathy Constable and Catherine Johnson has shown that there are significant non-zonal contributions to the time-averaged geomagnetic field, these are long term departures of the average field from that of a geocentric axial dipole. They are thought to reflect the influence of thermal or compositional variability at the surface of the core; they appear to correlate with seismic anomalies in the Pacific Hemisphere in both regional studies and global tomographic models (like that shown in the global seismology section). At Scripps Lisa Tauxe, Cathy Constable, and Catherine Johnson in collaboration with volcanologist, Hubert Staudigel, have been involved in a multi-institutional sampling and data gathering effort to obtain a pole-to-pole transect of high quality data for the last 5 Myr. On shorter time scales

![Graph showing correlation between field strength and polarity interval length](image)

**Paleointensity data** from basaltic glasses and marine sediments show a correlation between average field strength and length of stable geomagnetic polarity intervals. Dependence of polarity interval length on average virtual axial dipole moment VADM (upper). Open circles are from the time interval 22-35 Ma, triangles from 0-4 Ma, solid circle from the Cretaceous Normal Superchron, and star for the current Brunhes interval. Lower figure indicates the field variability (measured by its standard deviation) as a function of VADM.
detailed time-varying models of the global magnetic field for the past 7000 years have been developed and show that distinctive features seen in the present and historical field can persist over thousand year time scales but do undergo significant changes. These models which reflect secular variation on thousands of year timescales can also be used in comparisons with geodynamo simulations to assess whether they accurately predict the observed statistical properties of the geomagnetic field.

In the course of paleomagnetic research, problems for which the usual statistical procedures are inadequate or inappropriate are frequently encountered: these require alternative approaches. Techniques developed at Scripps based on the bootstrap and the jackknife statistical resampling methods work well and have proved to be easy to use, and powerful as well as popular. Scripps is also the site of a recent database initiative for rock and paleomagnetic data, and has been instrumental in developing the MagIC (Magnetic Information Consortium) database as a public archive for all paleo and rock magnetic data.

Paleomagnetic Laboratory:  http://sorcerer.ucsd.edu/

Geodynamics

A variety of geophysical methods are used to study geodynamics and tectonophysics at SIO: numerical modeling of mantle flow and lithospheric deformation; combined interpretation/inversion of shipboard gravity and topography data; analysis of satellite data and construction of global maps of seafloor and planetary morphology; and the use of teleseismic data to determine regional upper mantle structure and seismic anisotropy, which may result from flow-induced mineral alignment.

Large-scale flow in the mantle is one topic investigated by Jason Phipps Morgan. Global seismic models were used to estimate the density structure of the mantle and the low density regions provided the buoyancy force to drive a numerical model of flow. Calculations of material flux at the depths of olivine phase changes, constrained by Peter Shearer’s maps of lateral depth variation of the corresponding seismic discontinuities, suggest that the whole mantle is involved in large scale convection rather than separate upper and lower layers. Several parameters in the modeling (e.g. scaling between seismic velocity and density or viscosity variation) are not well known and further investigation into how these parameter values affect the results continues to be a focus of Phipps Morgan’s and co-workers’ research.

Regional mantle flow associated with oceanic spreading centers and hotspots is also a topic of current research at SIO. Both Jason Phipps Morgan and Donna Blackman have developed computer programs to simulate flow of the mantle beneath mid-ocean ridges. Basaltic melt forms as upwelling peridotite decompreses and, if this low density melt is retained between grains, localized buoyancy forces can strongly enhance vertical flow rates in a narrow zone beneath the spreading axis. 2-D finite element calculations predict that rather complex flow can result and interesting patterns of strain may develop. Mantle minerals can develop a preferred orientation when subjected to such strain fields and we are currently trying to assess how to use the signature that seismic waves develop as they pass through such an anisotropic region to map upper mantle flow patterns. Teleseismic data that can aid this work is just now becoming available from recent, and planned, seafloor experiments so we look forward to new progress in the next few years.

The long-term efforts of Dave Sandwell and co-workers in obtaining the release of satellite gravity data collected during GEOS-3, SEASAT, GEOSAT and ERS-1 missions have recently culminated in the production of a remarkable global marine gravity map. The satellite altimeters measured variations in the height of the seafloor which, at wavelengths less than 200 km, largely reflect the topography of the seafloor. Therefore, the new global map, and topographic models derived from the gravity, illustrate previously uncharted tectonic features throughout the worlds oceans: fracture zone trends; seamounts and volcanic ridges; and rough seafloor created in the wake of propagating rifts. Several SIO researchers and their students are currently working with these data to identify areas of tectonic interest and to design sea-going experiments which can test hypotheses of plate boundary evolution and hot spot activity.

Sandwell’s group has recently become a leader in processing synthetic aperture radar (SAR) acquired by satellites circling Earth and Venus. The SAR provides high resolution images of tectonic and geologic features of Venusian crust and these data have been used to study differences in the thermal structure and fracture behavior of Venus vs Earth crust. Minute changes in surface morphology, due to build up and release of stress associated with faulting in southern California, are being studied with a differencing technique, called SAR interferometry. Early work on this topic shows intriguing results which may indicate that changes in strain can be monitored on a time scale of several months. Further evaluation of possible signal contamination by atmospheric effects is underway on this potentially very exciting topic.

In addition to the SAR studies on deformation of the continental lithosphere described above, Donna Blackman is using numerical analysis to study lithospheric deformation in the oceans along ridge-transform plate boundaries. One interesting case is the development of high topography near ridge-transform intersections. complexes on continents may
Walter Smith and David Sandwell have created this color shaded relief image of sea floor depths estimated by combining shipboard bathymetric soundings with marine gravity anomalies derived from satellite altimetry. In the coming year, follow-up seafloor experiments will be conducted for detailed geologic mapping and sampling to provide the information needed to quantitatively test the oceanic core complex hypothesis.

**Complex Systems**

Brad Werner and coworkers of the Complex Systems Laboratory (CSL) in IGPP are working to advance the principles of nonlinear dynamics and complex systems and to apply them to modeling the natural and human-modified environment. The interactions between processes acting to shape the surfaces of the Earth and the planets and the forms comprising their surfaces generally are nonlinear, i.e., strongly coupled, and open, meaning material and energy flow in and out of the system in a manner neither controlled nor a priori quantifiable. Similarly, human systems (economic, political, social, cultural, organizational, ideological) share these properties. Systems with these characteristics often exhibit the property that
they evolve to a small subset of the available set of states, an attractor; a small number of variables interact through a set of interactions, known as emergent behavior, that are independent of the equations describing the time-evolution of the faster-scale constituents. The implication is that the long-time-scale dynamics of these systems can be modeled using a relatively small number of degrees of freedom and simplified descriptions of their interactions.

The CSL is investigating and developing modeling tools for the nonlinear dynamics of three categories of systems: landscape systems, human systems, and coupled human-landscape systems.

Landscape patterns are spectacular examples of how complicated systems composed of zillions of degrees of freedom self-organize into simpler patterns that can be described by only a handful of variables and simpler dynamics. Building on past modeling efforts for fields of sand dunes and shoreline features, the CSL’s current focus is on Arctic environments, with ongoing efforts in modeling sorted patterned ground — circles, polygons, mazes and stripes of stones and soil —, fractures in permafrost that develop into ice-wedge networks, self-organization in glacier and ice sheet flow, drumlin formation, and thaw lake terrain. Thaw lakes form in lowland permafrost, where organic-rich dark summertime waters preferentially absorb solar radiation over surrounding terrain, causing ice-rich permafrost to melt and consolidate. This process gives rise to lakes that expand and deepen, thereby melting permafrost and rendering frozen organics susceptible to decomposition. The CSL’s models of thaw lake terrain indicate that for deep lakes, such as in the northern Seward Peninsula of Alaska, enhanced melting of permafrost via thaw lake expansion and consequent greenhouse gas release will significantly lag climate warming.

Discussions of human systems, ranging from the philosophizing of Deleuze to scientific studies of consciousness, commonly fail to account for the severe constraints that nonlinear dynamics places on their possible states and outcomes. The CSL is attempting to clarify these discussions with the aim of facilitating the development of numerical models. Currently, we are working towards generating models for human consciousness and a model for the evolution of emergent scientific knowledge, given the pursuit of self-interest by researchers, reviewers, editors, funding agents, government and corporate users of science, the media and the general public.

Increasing population, economic development and technological advances have led to interactions between human agency and landscapes, oceanographic and atmospheric systems that are increasing in diversity and strength. From a dynamics perspective, these nonlinear couplings are expected to give rise to long-time-scale emergent behaviors for which there is no precedent in Earth history. The CSL is attempting to further the understanding of such emergent behaviors by modeling four systems: interactions between barrier island coastlines, tourism and hazard mitigation measures; economic development and levee building in New Orleans; the dynamics of the urban-wildland boundary in mountain catchments subject to wildfires, flooding, debris flows and landslides; and the interaction between global climate change, economic development, resource and land use, greenhouse gas emissions, and government policies.
Monitoring the Comprehensive Test Ban Treaty

One important branch of Earth Science uses signals not to describe the Earth but the source of the energy itself. While this is commonly done to better understand the physics of fault rupture, with the ultimate goal being an improved assessment of seismic risk, another source of intense interest is the man-made explosion. The Comprehensive nuclear Test-Ban Treaty (CTBT) has lowered to zero the testing yield limit and increased the importance of small events that could be confused with buried or atmospheric nuclear tests. In anticipation of a CTBT, recent years have seen the development of an International Monitoring System (IMS) which will consist of a global deployment of four kinds of sensors - seismic, infrasonic, hydroacoustic and radionuclide. Researchers at Scripps are constructing stations in the IMS and are exploring ways in which these data can be used most effectively for treaty monitoring.

Surface and underground mining explosions are of interest to the treaty monitoring community as the largest involve more than a kiloton of explosives detonated sequentially for fracturing the rock to facilitate ore recovery. These large events might be confused with nuclear tests. Michael Hedlin is using physical modeling to better understand the processes at surface coal mining events that are responsible for signals that are recorded by stations in the IMS seismic network. Hedlin is using the modeling to develop techniques that use regional seismic recordings to discriminate these events from nuclear tests and earthquakes, and is working with scientists at the Los Alamos National Laboratory to better understand why some mining events do not detonate sequentially, as is planned, but detonate, in large part, simultaneously. Hedlin is assessing the utility of IMS seismic data to characterize these failed mining blasts and distinguish them from hybrid events in which a mining blast is being used to hide a nuclear test. The focus is on low-frequency signals that will allow us to characterize these events from mid- to far-regional distances.

In another aspect of CTBT monitoring, hydroacoustic sensors are in place to “listen” to oceanic sources. The ocean basins provide a very efficient waveguide for acoustic energy, thus underwater earthquakes and explosions can be observed on hydrophones thousands of kilometres away. Examination of a large waveform database from events in the Pacific has shown that T-phase signatures are dependent on the bathymetry in the source region. The Scripps group has shown that realistic T-phase codas can be synthesized assuming that seismic to T-phase coupling occurs by means of scattering at the seafloor. In related study, de Groot-Hedlin and Orcutt are examining factors affecting the coupling of ocean-borne T-phase to the seismic T-phase. Preliminary modeling efforts have shown that the coupling is strongly dependent upon both the slope of the seafloor and on the detailed seismic velocity structure at the coastline.

A shift in treaty monitoring means from acoustic to seismic occurred in the 1960’s as weapons testing operations moved underground in response to the Limited TBT in 1963. The reduction of yield limits to 150 kT (TTBT; 1974) and now to zero has led to a renewed interest in acoustic emissions although the focus is now on faint signals produced by small near-surface events rather than remote detection of large signals from unlikely atmospheric blasts. Currently the CTBT calls for a global infrasound network consisting of 60 ground-based stations. Currently, just one station (in Manitoba, Canada) is operating. Michael Hedlin, Jon Berger and Frank Vernon are conducting infrasonic site surveys to find locations for IMS infrasound stations on three islands in the Atlantic (Sao Miguel, Azores, Maio, Cape Verde and Ascension island). This group is currently conducting site surveys for two additional stations (in southern California at the Piñon Flat Observatory and in eastern Washington state). This team will establish the stations at these sites within the next year.

Schematic of a mine blast shot grid with a co-located clandestine nuclear weapons test.
Further research in infrasound is being carried out by Jon Berger and Mark Zumberge, who are developing a new type of infrasound sensor. As part of the International Monitoring System of the CTBT, infrasound signals in the band 0.02 to 4 Hz must be detected in the presence of ambient noise generated chiefly by wind. The effectiveness of acoustic filters employed in standard infrasound sensors is limited by pressure propagation and attenuation characteristics within the filter. To improve the signal-to-noise ratio, an optical fiber instrument for sensing the integrated pressure variations along a line has been designed. The sensor design consists of optical fibers wrapped around a long, compliant tube, deployed along the ground surface. Integrated pressure variations along the tube’s length are sensed by interferometrically monitoring changes in the optical path length of the fiber. The optical fiber sensor can average over kilometer-scale lengths of arbitrary geometry with an averaging bandwidth governed by the speed of light and thus should offer significant practical advantages in reducing the effect of wind noise, increasing the signal-to-noise ratio over a wide bandwidth.

Three photographs of a cast blast detonated in the Black Thunder coal mine on August 1, 1996. This delay-fired detonation of 3 million pounds of ANFO was used to cast overburden to expose a coal seam. The pictures were taken at 0.3 s, 1.7 s and 4.2 s into the blast sequence. The sympathetic detonation is clearly visible in the second and third photos.

Parabolic Equation simulations of transmission loss (in dB) of 1 Hz acoustic energy propagating through a stationary atmosphere (top) and one in which wind speed increases from zero at the ground by 1 m/s (left to right) with every 1 km of altitude. The energy is focused into a strong caustic downwind and is dispersed upwind.

Atmospheric Acoustics

The atmospheric acoustics group at IGPP, Jonathan Berger, Catherine de Groot-Hedlin, Michael Hedlin, and Mark Zumberge (http://l2a.ucsd.edu/), studies the generation of infrasound by man-made activity and natural phenomena, its propagation through our heterogeneous, highly time variant atmosphere, and methods for detecting signals from remote sources despite high levels of noise from atmospheric turbulence.

See also: http://www.inframatics.org/
**Planetary Science**

*Catherine Johnson*’s research encompasses several topics that can be grouped into two general fields: planetary science and terrestrial magnetism. Her work in planetary science has encompassed investigations of the structure and dynamics of planetary lithospheres using geophysical modeling of remotely sensed data sets (altimetry, gravity and radar image data) collected during the Magellan mission to Venus and the Mars Global Surveyor missions. In the future she anticipates working with data from new Mars missions and the Messenger mission to Mercury. Her work in terrestrial magnetism spans field, laboratory and numerical / theoretical analyses. In both areas of research she focuses on specific, well-defined, disciplinary research topics that collectively have contributed to, or initiated, broader multi-disciplinary studies. Her planetary research has contributed to multi-investigator, multi-disciplinary research pursued by the Magellan and Mars Orbiter Laser Altimeter science teams. Her research in geomagnetism and paleomagnetism has formed the backbone for a large, multi-institutional field, laboratory and modeling project.

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**Planetary Geophysics: Thermal and Tectonic Evolution of the Terrestrial Planets**

*Catherine Johnson*’s research in planetary science is funded through NASA’s Planetary Geology and Geophysics program. A sampling of past and future projects includes:

**Venus:** Global studies of gravity / topography admittance at coronae (quasi-circular features unique to Venus among the terrestrial planets, believed to be the surface manifestation of mantle upwellings) and rifts to investigate compensation of topography and lithospheric structure at these features. Also investigations of lithospheric thickness (a proxy for planetary heat flow) as inferred from topographic flexure associated with rift-like features and coronae. The results are used to construct regional and global thermal and tectonic evolution models for Venus. A variety of studies indicate that surface tectonic processes on Venus may have been closely coupled to the history of volcanism and climate evolution of the planet.

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**Magellan Mission**

**1989 - 1994**
Coronae on Venus

**Mars:** Examination of compensation of northern polar cap topography on Mars. The polar caps constitute significant loads on the martian lithosphere. Interactions between climate-driven changes in the polar caps and the time-dependent response of the venusian mantle have implications for the how the cap topography is supported (compensated), for the volume of the caps, for the temperature at the base of the caps, and for determining lithosphere structure in the polar regions. As for Venus, the interactions between interior, surface and atmospheric processes have been extremely important in the evolution of Mars.

**The Moon:** Recent gravity field data returned by the Lunar Prospector spacecraft combined with the high resolution Clementine altimetry data provide exciting new opportunities for lunar crustal and lithospheric studies.

**Planetary Magnetism: Geomagnetism and Paleomagnetism**

Catherine Johnson's work in planetary magnetism has to date focussed on studies of the terrestrial magnetic field and is motivated by the need for constraints on long-term properties of the geomagnetic field, in order to understand and model the geodynamo. Of particular interest is the behavior of the geomagnetic field over time scales of thousands or millions of years. Recent geodynamo simulations show that the pattern of heat flux through the core-mantle boundary (CMB) may have a profound effect on the dynamics of the outer core. The behavior of the field over the past few hundred years is well known and suggests that the effects of CMB conditions may be detectable in surface paleomagnetic observables. Are there persistent signatures in geomagnetic field "maps" that reflect the influence of long-lived lateral heterogeneities in the physical properties of the lower mantle on geodynamo processes? Why are there apparent asymmetries between normal and reverse polarity geomagnetic field configurations that are not predicted by dynamo equations, but are observed in paleomagnetic data? How can one characterize the temporal changes (secular variation) in geomagnetic field behavior over paleomagnetic time scales? Johnson's research is aimed at addressing questions such as these using an integrated approach of data collection, data analysis, the compilation of global data sets, and the generation and interpretation of geomagnetic field models based on these data. This work is done in collaboration with several other researchers at Scripps including Cathy Constable, Lisa Tauxe, Jeff Gee, and Bob Parker.
Multi-disciplinary Research – an Example from Geochemistry

A number of multi-disciplinary research opportunities are available at SIO. Geophysicists have benefitted by collaborating with other Scripps scientists working in physical oceanography, geology, remote sensing, fluid dynamics, acoustics, and atmospheric science. Cross-fertilization is being fostered by new research endeavors. In global warming, for example, key roles are played by atmospheric science, oceanography, and geophysics. The apparent rise in sea level seen in coastal tide gauges can be due to glacial melting, a rise in ocean temperature, a change in the pattern of coastal currents, or tectonic movement of the land to which the tide gauges are attached. Understanding the simple problem of sea level rise will require coordinated efforts by meteorologists, theoretical geophysicists, geodesists, acousticians, and fluid dynamicists—all disciplines well represented at Scripps Institution of Oceanography.

Earth is a complex chemical, physical and biological system, and many of the key advances in its understanding can be expected from research at the interface between traditional Earth science disciplines. A geochemistry project at Scripps provides an excellent example of such interdisciplinary topics. Research in marine and global geophysics is combined with geochemistry in the study of seamounts and submarine hydrothermal systems and the development of the Geochemical Earth Reference Model (GERM). This research also links with biologists to study the “Deep Biosphere,” in particular the biological mediation of chemical transport during water-rock interaction.

Seamounts provide a wealth of information for many different aspects of Earth sciences. Seamounts have a characteristic gravity anomaly that can be used to infer lithosphere thermal structure at the time of seamount loading. The correlation of shipboard gravity and bathymetry can be used to “predict” bathymetry from gravity data alone, as they can be obtained from satellite data. This technique can be used to estimate ocean floor bathymetry in regions that never have been charted by an oceanographic vessel. Seamount magnetization and age may be used to infer plate motion or the possibility of relative motion of hot spots. The geochemistry of seamounts and ocean islands reveals the composition of their vast mantle source regions. Ongoing seamount studies at Scripps by Hubert Staudigel and Anthony Koppers, involve all these aspects of seamount research, currently focussing on seamount chains in the Western Pacific.

Submarine hydrothermal activity on the ocean floor near ocean ridges and low temperature chemical exchange on the ridge flanks has a fundamental effect on the chemistry of the oceans and the chemical composition of

Oblique view of Vlinder Guyot, Western Pacific Ocean. Vlinder is a characteristic guyot with four radiating rift zones, an erosional platform, and a posterosional, submarine volcanic edifice that was built on the eroded summit platform after drowning.
The present-day Earth is composed of a set of chemically distinct reservoirs with chemical fluxes between them. Fluxes between reservoirs vary greatly in magnitude on long and short time-scales. These fluxes, and the resulting changes in reservoir compositions, established the “Earth System” over its 4.5 Ga history and sustain its current habitability. The understanding of this chemical and physical Earth System is critical to climate, the environment and natural resources. Progress in our understanding of Earth is greatly limited by the lack of a chemical reference model. Hubert Staudigel and Scripps coworkers Guy Masters, and Anthony Koppers, along with an international group of scientists, have founded the Geochemical Earth Reference Model (GERM) initiative that has the goal to establish such a model. Specific GERM efforts by IGPP geochemists includes the determination of chemical fluxes between Earth’s mantle and the oceans and the development of a “Geochemical Modeling Toolbox.” The latter will provide a tool chest within GERM that allows to simulate Earth geochemical evolution, and to perform global mass balance calculations for all chemical elements and their stable and radiogenic isotope ratios.

Microbial habitats on Earth extend into many deep and extreme environments that have been previously considered “barren.” Initial studies suggest that the “Deep Biosphere” may contain most of the global biomass and that it is likely that life originated there. Microbial activity results in chemical control on the composition of seawater, sediments, and probably deep aquifers and the oceanic crust as well. Scripps scientists are focusing on the extent and type of “biocorrosion” in silicate glass and minerals in the oceanic crust and the influence of microbial activity on chemical transport in hydrothermal systems.

**Biologically mediated Water - Rock interaction in thin section:** Fresh volcanic glass (“FG”) displays black channels (“B”) caused by preferential dissolution by colonizing microbes. Channels typically originate at the glass surfaces and end inside the fresh glass. Microbial DNA can be found in many of these channels.

### Spotlight on a the Newest Member of the SIO Geophysical Instructional Staff, Sofia Akber

Sofia Akber
Assistant Professor, IGPP
Research Interests: Geophysics and Mineral Physics

Sofia Akber received her PhD in Geophysics from UC Berkeley in 2003. Her thesis covered two subjects and was titled "A Theoretical Study of Perovskite Solid Solutions: Towards an Interpretation of Seismic Tomographic Data". She spent a year and a half as a Postdoctoral Scholar of Geophysics at the Geological and Planetary Sciences Division, California Institute of Technology. She has recently come to Scripps. Sofia describes her research in her own words:

As a theoretical/computational mineral physicist, I address fundamental questions in the earth sciences; What mineral assemblages account for the lateral heterogeneities or the radial discontinuities in density and seismic velocity in the mantle? How are radioactive and rare earth elements partitioned among mineral phases in the Earth (and what are the implications for heat flow and mixing in the mantle)? What is the nature of the D” zone and the Ultra Low Velocity Zone the core? What is the composition of the core and what is the structure of the iron alloy in the inner core? Most generally, is there a compositional Earth model satisfying all of the constraints provided by seismologists, geodynamicists and geochemists? The answers to these questions rely on comparisons of geological data with properties of candidate Earth-forming materials under the conditions of the Earth’s interior.

My research focuses on accurately predicting physical and chemical properties of diverse geologically relevant materials, by calculating energies and forces derived from a range of Hamiltonians: from simple, classical, interatomic interactions to sophisticated quantum mechanical electronic charge density functional theory. Such properties include pressure-volume-temperature equations of state, elastic velocities, equilibrium phase assemblages and phase boundaries, element partitioning, defect populations, and melting. Studies of these material properties should involve realistic Earth compositions, and these, in turn, necessitate advances in the computational theory of solid solutions.
Most of these properties are in principle measurable. However, the Earth imposes stringent requirements on experimental equipment: pressures up to 360 GPa, and temperatures which approach a substantial fraction of 10,000 K. Computations complement experiments by extending the pressure-temperature range of material studies; state-of-the-art theoretical models are increasingly showing very good agreement with observations (e.g., volumes, elastic constants, phase transition pressures) and can therefore serve as a reliable means to predict material behavior beyond the limits of experiment. Most importantly, theoretical frameworks help measurements inform our understanding beyond the particular, and necessarily limited, experimental context.

I have examined the chemistry and structure of the major phases of the Earth’s lower mantle, in order to provide constraints for interpreting seismically observed lateral and radial velocity heterogeneities. Using atomistic models, I investigated the effects of aluminum on the elasticity and defect population of lower mantle perovskites (MgSiO₃ and CaSiO₃), as well as the partitioning of aluminum in the lower mantle assemblage, at high pressures and temperatures. I also investigated the high-pressure structure and compressibility of CaSiO₃ perovskite, the third most abundant lower mantle phase, and the viability of a second-order phase transition in the lower mantle. Most recently, I have studied the effects of Al and Fe on a recently experimentally observed and theoretically predicted MgSiO₃ post-perovskite phase transition in the lowermost mantle. The thickness and depth of a phase transition near the core-mantle boundary would have important implications for the Earth’s heat budget. In addition, the post-perovskite phase may explain the puzzling negative correlation between shear and bulk sound velocities that has been observed seismically. My research also extends to the core with molecular dynamics simulations to compute the melting temperature of iron and its alloys at high pressures.
R/P FLIP, Scripps Floating Instrument Platform provides a stable base for conducting open-ocean experiments and measurements. The 108 meter long Research Barge is non-propelled and must be towed into position. Once it is on site, the ballast tanks that comprise most of its length are flooded in order to flip the research decks into operating mode. All on board accommodations are gimbaled to function either horizontally or vertically, when the walls become the floors and visa versa.

For further information on the graduate program in Geophysics, contact:

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http://www.siodgraddept.ucsd.edu/

The Geophysics Curricular Program at SIO: http://pfostrain.ucsd.edu/gpcirgr/gp.html

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