Research Opportunities in Geophysics at the Scripps Institution of Oceanography

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March 2003
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 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 ongoing 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 groundbreaking 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.

The existence of an axial magma chamber beneath the East Pacific Rise has been confirmed with ocean bottom seismic methods.
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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.

At the close of the decade, John Orcutt and Don Forsyth (Brown) shifted their attention toward the slow-spreading end of the accretionary spectrum with an OBS cruise to the southern Mid-Atlantic Ridge. The PLUME experiment was designed to study the bulls-eye pattern of gravity anomaly lows that appear, centered on individual spreading segments, in maps of residual mantle gravity. These gravity lows were thought perhaps to reflect the threedimensional nature of magma delivery at slow spreading ridges. However, an accurate calculation of residual mantle gravity depends on knowledge of the overlying crustal structure. The PLUME data revealed that, in fact, the bulls-eye pattern is associated with crustal thickening toward mid-segment, most likely as the result of focused mantle upwelling.

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

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.
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 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 researches to study details of the seismic structure of the lithosphere/asthenosphere system beneath the oceans. The SWELL pilot study provides the first clear seismic evidence for a geographically confined deep-rooted mechanism that is responsible for the Hawaiian Swell uplift.
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.

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

Four depth slices of the shear velocity structure beneath the SWELL pilot array. Shown are percentage variations with respect to a model of 52-110 Myr old lithosphere (reference velocities given at each panel). Note that low velocity anomalies that are typically found closer to the island chain fade out towards the center of the array. Also note that the lateral variation becomes stronger with increasing depth.
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 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 normal 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.

Scripps is also involved in the development of innovative new approaches for handling large data sets that involve automatic processing and stacking techniques. These

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.
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.

The infrastructure supporting research in global seismology at SIO is substantial. Researchers have access to a modern network of high-speed Sun and HP workstations and several large sets of online seismograms, containing records from 1976 to the present day. Jon Berger, Peter 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 contributes 36 stations with 4 more stations planned. The three newest IDA stations (Mbarara, Uganda; Sulawesi, Indonesia; and Kwajalein Atoll, Marshall Islands) 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 31 of our stations currently have telemetry capability to permit routine monitoring of data quality. One of the new stations (Mbarara) is the first IDA station to transmit all data recorded on site back to La Jolla via satellite. Future stations will include Global Positioning Satellite (GPS) receivers for geodetic measurements and orbit determinations, environmental monitors, and dedicated telemetry. 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 world wide web.
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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.

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 top panel is a splitting function derived from data from recent events (circa 1995), while the bottom 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 0.3deg/year. However, the average inner core rotation rate from the analysis of many such modes is essentially zero.
**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.

![Geologic cross section of the Santa Fe Springs anticline and fault segment with the relocated mainshock and aftershocks of the 1987 Whittier Narrows earthquake.](image)

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 is one of the oldest sciences tracing its beginnings to the first measurement of the size of the Earth by Eratosthenes (276-196 B.C.), the librarian of the great Alexandrian museum. Eratosthenes used measurements of the sun’s shadow at Alexandria in his computations, and ever since geodesists have been using space-based objects as an integral part of their discipline. Geodesists have made significant contributions to the understanding of Earth’s structure over the centuries; for example, they confirmed by direct measurement Newton’s model of an Earth flattened at the poles based on his laws of motion and gravitation, they were instrumental in the development of the theory of isostasy from triangulation measurements made by Everest at the Survey of India in the 19th century, they have contributed to the development of the elastic rebound hypothesis of Reid from geodetic measurements of crustal deformation in California, and they have recently provided constraints on the characteristics of the core-mantle boundary from improvement in nutation models derived from radio astronomical observations of extragalactic radio sources.

Several developments in the last three decades have breathed fresh life into geodesy which had become a rather obscure science by the middle of the twentieth century. The launching of artificial Earth satellites, developments in radio astronomy, manned missions to the moon, and computer technology ushered in the discipline of modern space geodesy. These technical developments were responsible for new measurement systems such as satellite laser ranging, lunar laser ranging, very long baseline interferometry, and satellite altimetry which have profoundly increased our knowledge of the Earth’s figure and shape, and its internal properties. NASA programs such as the NASA Geodynamics Program, the Crustal Dynamics Project (CDP), and the Dynamics of the Solid Earth program (DOSE) have been instrumental in the development of these new techniques and their application to geophysical problems. The acceptance of the plate tectonics paradigm coincided in time with the development of the new space geodetic methods, which began the increasingly harmonious symbiosis between geodesy and geophysics, creating a new discipline which has been called “Geophysical Geodesy.” It quickly became apparent that space geodetic techniques could be used to confirm present day global plate motion models, to detect small variations from these models and to monitor crustal deformation across plate boundaries.

The new space geodetic methods were very expensive though, involving huge radio telescopes and bulky laser ranging equipment which limited the amount of data that could be obtained and required government agencies to make the necessary measurements. The launching of the Global Positioning System (GPS) by the Department of Defense in the early 1980s rapidly accelerated the interest of geophysicists in space geodesy. GPS is a compact, inexpensive tool that can be used to measure the Earth’s figure over a wide range of spatial and temporal scales, and the measurements can be performed by university investigators. The ability of GPS to position dynamic as well as static geophysical platforms with high accuracy greatly broadens its scientific applications.

Scripps is at the forefront of research in space-based geodesy and its applications to a wide variety of geophysical problems, on land and at sea. Techniques to improve the accuracy of geodetic measurements, in particular for satellite orbit determination and high temporal sampling of crustal deformation, are being developed. A group led by Yehuda Bock is using GPS technology to measure crustal deformation across the North American - Pacific plate boundary in California, and across the Australian - Southeast Asia plate boundary in Indonesia. Scripps is the operational center of the Permanent GPS Geodetic Array (PGGA) in Southern California, a facility to monitor continuously crustal deformation for the purpose of earthquake hazards research. PGGA is a major component of a new multi-institutional initiative for a very large, dense GPS network in southern California. This project, the southern California integrated GPS network (SCIGN) aims to deploy as many as 250 permanent GPS sites in the region to look for details of the deformation pattern. The project is funded by NASA, the NSF, the USGS, and the Keck Foundation, and is currently managed through the Southern California...
Earthquake Center (SCEC). Scripps is the site of one of two data analysis centers for SCIGN (the other one is located at JPL), and supports the primary data archive facility. As part of this effort, Scripps geodesists are pioneering methods of geodetic data collection, analysis and archiving and are disseminating data to other investigators. GPS technology is being used to position precisely moving platforms in support of ocean acoustic tomography, sea-floor positioning, two-ship multichannel seismology, and marine gravity studies.

A relatively recent addition to IGPP’s activities in geodetic monitoring is airborne and spaceborne laser altimetry. Bernard Minster is leading a collaboration with NASA scientists to conduct repeated airborne laser altimetry surveys of Long Valley Caldera, a region of active seismicity and volcanism. These surveys, which use the NASA WFF aircraft and several laser profilers and scanners, make use of precise GPS navigation and INS attitude control of the aircraft. Supported by the NASA topography and surface change program, these experiments are a prelude to the Geoscience Laser Altimetry System (GLAS) mission of the Earth Observing System suite of instruments. Preliminary space flights involve a series of Shuttle Laser Altimeter missions, the first of which flew in January, 1996, on STS-72. With current launch date of 2001, GLAS will be a 5-year mission to monitor the mass balance of the ice sheets, as well as to provide precisely calibrated altimetric profiles on land.

Perhaps the most exciting development in space geodesy of the last decade is the advent of Interferometric Synthetic Aperture Radar (IFSAR) to study surface deformations. Of special interest are deformations associated with the various stages of the seismic cycle, and with volcanic eruptions. But SAR has been applied to quite a variety of problems, such as studies of the cryosphere (ice sheets, ice streams and temperate glaciers),
oceanography, measurements of soil moisture, analysis of vegetation and other land covers, and even analysis of the propagation of disease vectors. **David Sandwell, Yehuda Bock** and **Bernard Minster** have started a Scripps effort in the systematic use of SAR and GPS to study tectonic problems. The Scripps satellite facility is being upgraded to permit inexpensive down link of voluminous satellite data, in particular the European, Canadian and Japanese SAR satellites.

**Yuri Fialko** studies deformation, and heat and mass transfer associated with active tectonic processes operating within the Earth. In particular, he combines theory and observations to get quantitative insights into how magma is forcing it’s way up in volcanically active regions such as the mid-ocean ridges, “hot spots”, and large silicic calderas in the continental crust, how temperature increases due to friction on seismic faults affect the earthquake dynamics, how the Earth crust responds to stress changes due to major earthquakes, how the fractures propagate and interact in the Earth’s interior, and so on. **Yuri Fialko** is using space-based geodetic techniques such as the Interferometric Synthetic Aperture Radar, and Global Positioning System to image displacements of the Earth’s surface due to seismic and magmatic processes, and human activity. As more IFSAR satellites are launched into orbit, our ability to measure saddle (as well as large) surface changes will improve dramatically, and much will be learned about the occurrence and physical causes of active tectonic processes that shape the surface of our planet.

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*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.*
In addition to the growing program in space-based geodesy, SIO has continued to thrive in developing new land-based geodetic techniques. The flagship of the program is Cecil and Ida Green Piñon Flat Observatory, a facility in the high desert outside of San Diego between the San Jacinto and San Andreas faults. The site, directed by Frank Wyatt and Duncan Agnew, is a test-bed for a variety of geodetic instrumentation developed at a score of institutions around the globe. SIO operates state-of-the-art laser strainmeters, long-baseline fluid tiltmeters, and a number of borehole strain and tiltmeters. Records from these highly stable instruments have been critical to the evolution of crustal deformation monitoring. The records from lesser-quality instruments had previously been interpreted as indicative of true ground motion, whereas the Piñon Flat data showed that Earth is quite stable, and that some signals that had been considered as earthquake precursors were in fact instrument noise. The Piñon Flat instruments give a continuous record of crustal deformation of a quality unmatched anywhere else in the world. These data have yielded much new information about the behavior of the Earth’s crust and local faults, before, after, and between earthquakes. The data from this observatory will play a significant role in any attempt to issue short-term earthquake warnings.

The techniques perfected by the Piñon Flat group are now being applied in other settings. New strain-monitoring instrumentation has been installed by Wyatt and Agnew near the Salton Sea and the southern San Andreas Fault, and similar instruments are planned for the Los Angeles Basin. Both are sites of high potential for a great earthquake. A long baseline laser strainmeter is slated for installation at Yucca Mt., Nevada, to help assess the suitability of the site as a nuclear waste depository.

Another important geodetic program at SIO is the measurement of gravity. Absolute gravity is being used by Glenn Sasagawa to monitor vertical crustal deformations associated with volcanic activity in the Long Valley Caldera of California, and to calibrate relative gravity meters used in a number of geodetic projects. A new absolute gravity meter designed to be operated on the ocean bottom is being built by SIO (Zumberge and Sasagawa). Its completion represents one of the few tools available to detect cm-level deformation of seafloor crust.

**Seafloor Geodesy**

Seafloor deformation can be used to study both tectonic and volcanic processes. 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. Since deformation is a spatially varying process, it may result in a local surficial tilt. 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. Three principal types of seafloor deformation measurements are being studied at SIO: horizontal deformation, vertical deformation and tilt.

**Horizontal Deformation:** At the finest scale of observation, Mark Zumberge and coworkers are constructing a Fiber Optic Seafloor Strainmeter (FOSS) on a 500 m baseline. An optical fiber will be attached to benchmarks that firmly anchor it to the seafloor. Distances between the benchmarks will be measured by an optical interferometer with a precision of several mm. The FOSS will be self-recording at a few samples per day for one year deployments.

A second technique at the 1-km scale measures the travel time of an acoustic signal that propagates along a direct path between transponders separated by about 700 m. By knowing the speed of sound along the path, the distance between the transponders can be determined with 1-centimeter precision. Repeated measurements of a baseline are used to estimate the deformation. Normark, Morton and Reiss of the United States Geological Survey deployed a transponder net across the axial cleft of the southern Juan de Fuca Ridge. In collaboration with the USGS investigators, Dave Chadwell, John Hildebrand and Fred Spiess have collected measurements from 1994 to 1999 that show no significant extension (-3 ±5 mm/yr) across the axial cleft.

At a 10-km scale, horizontal deformation measurement are being conducted by Fred Spiess, Dave Chadwell, and John Hildebrand using precision acoustic transponders, with a 1-4 km spacing between acoustic array elements. These instruments are deployed so that they span the axial rift on the Juan de Fuca ridge. A towed survey vehicle is used to interrogate the transponders, allowing them to be placed at stations that do not have direct acoustic paths. A coded acoustic signal is used to provide greater timing accuracy and to eliminate uncertainty in transponder latency. The acoustic transponder array is revisited on an annual basis. This technique has position repeatability of 6 cm rms.

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 alongwith similar tracking onshore. At a site about 150 km west of Vancouver Island in 2.6 km deep water Spiess, Chadwell and Hildebrand have measured the convergence of the Juan de Fuca and North American plates. Preliminary results from measurements collected in 1994, 1995, and 1996 show the convergence of the Juan de Fuca and North American plates to be 1.1 ±2.6 cm/yr in the east component and 4.0 ± 0.9 cm/yr in the north component. This suggests
convergence in a more northerly direction than that predicted by geologic models. Measurements were repeated in 1999 and the data are being processed.

The horizontal deformation measurements to date on the Juan de Fuca Ridge and plate interior have implications for understanding Juan de Fuca plate motion on a regional scale. Given an expected full-spreading rate of 56 mm/yr, the ridge-centered data suggest that extension across the Cleft segment occurs only episodically within the narrow (~1 km-wide) axial valley floor. This contrasts to a nearly uniform present-day plate-interior rate of +41 ± 28 mm/yr at the one globally-located seafloor site (48°-10' N and 127°-10' W) on the Juan de Fuca plate. The different rates between the axial valley and the plate interior suggest that the crust is undergoing active deformation, probably within the ridges flanking the axial valley. Additional deformation measurements farther off axis should discriminate the partitioning of strain between episodic extension at the axial cleft to uniform motion nearer the plate interior. An expanded experiment is underway.

Vertical Deformation: In a tectonic setting, vertical deformation measurements provide a quantitative characterization of the displacement due to faulting events. Several of the standard techniques for measuring vertical deformation on land, leveling surveys and GPS satellite measurements, cannot be used underwater. Instead, 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 µGal/cm, therefore, a gravity meter must be capable of several µGal measurement accuracy for several cm depth accuracy.

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.
These measurements are conducted on seafloor benchmarks which will remain on the seafloor to be revisited periodically using an ROV or submersible to place a gravity meter at a fiducial level on the benchmark. A series of benchmarks spanning the southern Juan de Fuca ridge is currently being studied.

Zumberge and Sasagawa, building on previous collaborations with John Hildebrand, recently 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 gimbal frame for leveling. A small microcontroller executes the various sensor functions and allows a shipboard operator to control the system. The sensor, gimbal 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.

A commercial gravity sensor has been mounted in a gimbaled pressure case small enough to be handled by a remotely operated vehicle (ROV). The ROV positions the sensor on a concrete monument on the sea floor to facilitate accurate relocation of future observations. As the sea floor deforms, the associated gravity changes are monitored.
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.

Tilt: To study seafloor tilt due to tectonic deformation, bubble tiltmeters have been installed in existing ocean bottom seismographs by Frank Wyatt and John Orcutt. These instruments are self-recording and can be deployed and retrieved by ship. The combination of seismic monitoring and continuous measurement of tilt has been the most important means to monitor subaerial volcanic eruptions and to constrain their deformation and plumbing systems. Observations of this nature on submarine volcanoes will undoubtedly help us understand how new oceanic crust is emplaced at mid-ocean ridges and at seamounts.

**Seafloor Electromagnetic Sounding**

Electrical conductivity is one of the few properties that may be sensed remotely and is the only property besides elastic velocities that may be sensed using a man-made source. Electrical methods are therefore a vital tool in our exploration of Earth’s interior. Electrical studies of the oceanic crust and mantle are especially relevant to our understanding of lithospheric evolution, since electrical conductivity is primarily sensitive to porosity, melt content and temperature. Also, mapping of the continental shelf using EM methods has practical application to the petroleum industry.

*Below: Natural variations in Earth’s magnetic field interact with conductive rocks to generate secondary electric currents. Both magnetic and electric fields can be recorded at the seafloor to provide an electrical impedance as a function of frequency (a proxy for depth) and position. Inset: This method has been used to map salt bodies in the Gulf of Mexico, where seismic methods can sometimes have difficulty in determining the depth of the base of salt.*
Scripps has pioneered most aspects of marine electromagnetism and has always been the world leader in this field. Currently, Steve Constable is continuing a program of seafloor controlled-source sounding established in the late 1970’s by Chip Cox (of PORD). Seafloor instrumentation has been developed a great deal since then, and marine experiments have been supplemented by work on interpretational and inversion methods and also laboratory studies of rock and mineral properties, in order that field data may be used correctly to infer properties of the crust and mantle. This combination of various geophysical disciplines makes Scripps Institution of Oceanography a perfect environment for undertaking marine experiments with the appropriate support in the areas of interpretation and laboratory measurements.

Two basic methods are employed. In the magnetotelluric (MT) method, natural variations in Earth’s magnetic field are used to probe seafloor conductivity structure. In the controlled source EM sounding method, a man-made transmitter is towed close to the seafloor, broadcasting signals that are monitored by remote seafloor recorders. The MT and controlled source EM methods are complementary, as the former is primarily sensitive to conductive features and the latter to resistive structure.

One area of interest is the study of magmatic and hydrothermal systems at mid-ocean ridges using EM methods. An experiment on the Reykjanes Ridge in 1993, which involved joint interpretation of seismic and electromagnetic data collected on the same research cruise, produced the first compelling evidence for the existence of a slow-spreading ridge magma chamber, and puts strong constraints on its depth, size, melt volume, and relationship to the upwelling mantle below the ridge. A more recent pilot study on the East Pacific Rise (EPR) produced excellent images of the magma chamber with only four seafloor MT sites – Scripps has been funded to return to the EPR and collect 70 sites of seafloor MT and carry out a controlled source survey in early 2004.

In an innovative alliance with industry, Scripps has developed a technique for using marine MT and controlled source measurements to study structure on the continental shelves, with specific application to petroleum exploration. Surveys have been carried out in the Mediterranean Sea and the Gulf of Mexico, with as many as 100 deployments being made for a single study. The MT method is aimed specifically at areas in which the seismic method performs poorly, where structures such as carbonates, lava flows and salt sheets reflect and reverberate seismic energy and obscure potentially oil-bearing sediments below. The controlled source method has the unique capability of being able to discriminate between resistive targets, which may be oil and gas reservoirs, and conductive structure, which is likely simply water-saturated sediment.

A deep-towed transmitter radiates electromagnetic energy into the seafloor, which is then detected as a function of range and frequency by seafloor receivers. Most of the measured energy propagates through the seafloor rocks, as the more conductive seawater absorbs energy within a shorter range. Resistive rock, such as oil or gas (but also lavas and evaporites), increases the magnitude of the detected electric fields. Right: This method was first tested over an oilfield offshore Angola in 2000.
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, paleoclimatic 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, including proof that a viable self-sustaining geodynamo could exist in the core, pointing out 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 perhaps had the most far reaching effects on the whole subject of geomagnetism (and indeed all of geophysics). It is now widely recognized, for example, that the 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.

The development of computational and theoretical tools for the solution of such problems continues at SIO, and these are being 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. A new series of models satisfying the Kelvin constraints which require magnetostrophic force balance at the surface of the core is presently under construction; these will be useful for the derivation of core surface motions under the frozen-flux approximation.

Oersted, a new Danish vector magnetic satellite was launched in early 1999 and will provide excellent geomagnetic field coverage complementing that obtained by the first vector satellite, Magsat, which flew in 1980. With the prospect of new higher quality global magnetic data renewed interest has focussed on how to separate the core, crustal, and external contributions to the measured field. The crustal and external parts of the field, although intrinsically interesting on their own, are considered noise in the core field estimation problem. Techniques have centered on finding suitable statistical descriptions for the crustal and external parts of the field: for the crust these can be derived from theoretical models of crustal magnetization, or more directly from very long profile aeromagnetic surveys. Analyses by Bob Parker and coworkers have used spectral estimation tools to separate crustal magnetic signal from noise in long aeromagnetic profiles, and derive a global spatial magnetic spectrum typical of oceanic crust. Similar techniques are being applied to satellite observations, to provide estimates of the global spectrum at longer wavelengths.

The electrical conductivity structure of Earth’s mantle 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 collaborations with Al Duba at LLNL and Tom Shankland at LANL, by making 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 the expertise in core and crustal geomagnetic field modeling described above.
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. While it is generally agreed that every model based on observation is uncertain, quantification of the uncertainty is traditionally 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.

Recently the Mars Global Survey satellite observed a remarkable and quite unexpected pattern of magnetic anomalies on Mars. A rather crude contour map of the radial component of \( B \) at an altitude of about 100 km is shown in the map.

The discovery raises a number of difficult questions, such as why the fields are concentrated into a relatively small area of the planet which has no other distinguishing features. 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, in press, Feb, 2002].

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 volume on Earth.

*Radial component of the magnetic field* \( B \) *on Mars. The map shows contours of the average of raw observations taken at altitudes between 100 and 120 km height. Values in nanotesla.*
Paleomagnetism

On longer time scales geomagnetism is concerned with the evolution of the geodynamo during the course of geological time. This is the domain of paleomagnetic data, encompassing secular variation and reversals of the geomagnetic field. At SIO there is a strong paleomagnetic group involved in field and experimental studies and also in deriving global models for the paleomagnetic field and its long term secular variation.

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). The paleomagnetic group in collaboration with volcanologist, Hubert Staudigel, at Scripps is involved in sampling globally distributed lava flows erupted during the past 5 Myr to generate better datasets for resolving long-term structure in the geomagnetic field. On shorter time scales detailed models of the global magnetic field at 100 year intervals for the past 3000 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.

Paleomagnetic research at Scripps wanders throughout the broad field of paleomagnetism, including geological applications, experimental work on basic rock magnetism as well as 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.

Geological applications of paleomagnetism at Scripps include magnetostratigraphic studies. These are now focussed on the late Cretaceous/early Tertiary time scale. Attempts to obtain high quality radiometric and magnetostratigraphic data from sections whose biostratigraphy are well constrained are currently being made.

Another 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.

As a backdrop to all these 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.

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. Although 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), one of the most important contributions has been towards 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. The possibility now exists for deep-sea sediments to provide constraints on relative paleointensity variations.

SIO geophysicists are also contributing to the time averaged field project in a substantive way. Because much of the information in the existing paleomagnetic data base derives from efforts from several decades ago, a new generation of data based on modern laboratory work including paleointensity estimates is required to enhance the resolution of the time averaged geomagnetic field models. To this end, Lisa Tauxe, Cathy Constable and Catherine Johnson have spear-headed a new multi-institutional effort to obtain a pole-to-pole transect of high quality data for the last 5 Myr.

In the course of research, problems for which the usual statistical procedures are inadequate or inappropriate are frequently encountered, requiring 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.

**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 serpentinitized peridotites exposed at the Mid-Atlantic Ridge, and a variety of projects in the Troodos ophiolite (e.g., magma flow in dikes, timing of epidote alteration). Jeff Gee, Steve Cande and Bob Parker have 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.

For more research in Paleomagnetism, see section titled Spotlight on a Former SIO Geophysics Student, **Catherine Johnson**.

**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 satellite 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 decompresses 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
Research Opportunities in Geophysics at the Scripps Institution of Oceanography

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.

occur in the oceans. 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 focussed on applying the principles of nonlinear dynamics and complex systems to modeling the natural environment and to model-testing. 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. Systems with these characteristics often exhibit the property that they evolve to a small subset of the available set of states; a small number of variables predominate, and these variables interact through simply characterizable processes to give rise to rich interactions known as emergent behavior. The implication is that these systems can be modeled using a relatively small number of degrees of freedom and simplified, often rule-based, interactions. The general properties of nonlinear systems suggest that these simple models are best tested by perturbing the system from its natural state.
Models for surficial phenomena in arid, arctic and coastal environments are being developed and tested in the CSL, based on this complex systems approach. For nearshore waves, currents, sediment transport and bathymetric change, traditional approaches to prediction and modeling largely have been unsuccessful, because of the lack of simplifying principles for this highly nonlinear, nonequilibrium system. However, predictive, tractable models can be developed by first identifying dominant variables and processes through observation and description. For example, a simple model for an undulating pattern in the beach at the shoreline known as beach cusps, based on positive feedbacks between flow, sediment transport and bathymetry (an effect easily observable with a shovel on a steep beach), exhibits qualitative behavior similar to that of beach cusps on a natural beach. The model was found to be in quantitative agreement with measurements of flow and bathymetric change following modification with heavy equipment of an originally cuspatte beach. Current coastal research in the CSL is aimed at developing models for breaking, shoaling and low-frequency trapped waves, rip currents, sand bars and coastlines and at implementing new techniques for remote measurement of waves, currents and bathymetry.

The recurrent freezing and thawing of an active layer of stones and soil above the permafrost in the arctic gives rise to inhomogeneous thermal and mechanical properties and affects the stability of permafrost as a reservoir of organics and water. Segregation of stones and soil is pervasive, sometimes resulting in circular or linear stone patterns that exhibit convective-like soil circulation, despite the lack of fluidity. Rule-based modeling and fieldwork in West Spitsbergen are aimed at reproducing and interpreting the range of patterns and behaviors observed in frozen soils.

Both frozen ground patterns and surficial features of arid environments can serve as sensitive indicators of recent climate. The patterns of large sand dunes up to 20,000 years old provide constraints on the timing of major shifts in wind direction. Desert pavements, smooth, mosaicked monolayers of surficial stones formed on abandoned depositional terrain, might be the oldest surfaces on Earth. These surfaces are maintained through a complicated interaction of faunal, physical and chemical processes. Their sensitivity to climate is not well-established; however, the potential fragility of desert pavement surfaces was illustrated by their significant localized degradation accompanying a rodent population explosion in the deserts of California (approximately coinciding with a recent outbreak of hantavirus in the western U.S). Interpreting the record of recent surficial features requires quantitative models relating climate processes to surficial evolution, a challenge that will remain a prime goal of the CSL.
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. Several investigators at SIO are using waveform data from both hydrophone and island seismic stations to detect and locate hydroacoustic events such as suboceanic earthquakes or explosions at sea.

Catherine de Groot-Hedlin, Donna Blackman, and John Orcutt are currently conducting research into how seismic energy from abyssal earthquakes couples to acoustic, or T-phase energy which can be detected 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 a 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.
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.
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 the oceanic crust before it is recycled into Earth’s mantle. Submarine volcanism and hydrothermal processes provide a direct chemical pathway for chemical fluxes from the mantle to the oceans. The recycling of altered oceanic crust at subduction zones allows for a return chemical flux from the oceans into the mantle. Hubert Staudigel is studying these fluxes using materials from the Ocean Drilling Program and from ophiolites.
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.

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.

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.
Catherine Johnson received her PhD in Geophysics from Scripps in 1994. Her thesis covered two subjects and was titled "The Geomagnetic Field Over the Last 5 Myr From Lava Flows and Properties of the Venusian Lithosphere From Magellan Data". She spent a year as a Postgraduate Researcher at Scripps and then continued her research at the Carnegie Institute in Washington DC for several years. She has recently returned to Scripps. Catherine describes her research in her own words:

My research encompasses several topics that can be grouped into two general fields: planetary science and terrestrial magnetism. My 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 Mars Global Surveyor missions. In the future I anticipate working with data from new Mars missions and the Messenger mission to Mercury. My work in terrestrial magnetism spans field, laboratory and numerical / theoretical analyses. In both areas of research I have focus on specific, well-defined, disciplinary research topics that collectively have contributed to, or initiated, broader multi-disciplinary studies. My planetary research has contributed to multi-investigator, multi-disciplinary research pursued by the Magellan and Mars Orbiter Laser Altimeter science teams. My research in geomagnetism and paleomagnetism has formed the backbone for a large, multi-institutional field, laboratory and modeling project.

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

My 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.

**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**

My work in planetary magnetism has to date focused 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 imaps 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? My 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.
**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.

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