# The SCEC Borderland Working Group: Science and Data Collection Objectives

September, 2002

# Preface

The problem of comprehensively understanding California Continental Borderland tectonics, structures, and seismic hazards is one that crosses traditional geoscience research group boundaries. Borderland research has largely been conducted by a loose group of collaborators with common or complementary research visions. The Borderland Working Group has just been formed as a part of the official organizational structure of SCEC in an attempt to focus and integrate research activities within the scientific mission of SCEC. Its purpose is to coordinate onshore-offshore southern California research activities, to archive and analyze existing data, and to plan new research activities including future experiments within the Borderland. This white paper will form the basis of the working group's science objectives and has been endorsed by the Borderland science community.

This document represents the ideas and contributions of many academic and USGS scientists who constituted a preliminary Borderland working group (see Appendix A). The ideas are based largely on discussions that took place at a SCEC Borderland Initiative workshop, March 8-10, 2002. Workshop participants submitted statements of interest that were to define major scientific issues, available data and current data collection efforts, prioritized lists of short-term and long-term objectives, and permanent instrumentation needs. The statements also served as a basis for workshop discussions. Speakers were invited to present ideas about the types of Borderland data-gathering and research activities they thought should be considered under the umbrella of the SCEC Borderland Working Group. Participants were encouraged to discuss the fundamental driving science questions behind a number of topics, the availability of existing data sets, and use of new technology. The white paper is organized according to the general themes that guided breakout groups and plenary sessions at the workshop. The key scientific questions listed within each of the sections summarize workshop discussions about what is still unknown about the Borderland. All workshop participants and working group members have reviewed this document, many of whom provided valuable input. The principal contributors to the white paper are D. Agnew, W. Berelson, D. Burbank, M. Fisher, G. Fuis, C. Goldfinger, T. Jordan, M. Kamerling, M. Kohler, V. Langenheim, M. Legg, A. Michael, C. Nicholson, W. Normark, D. Okaya, J. Shaw, P. Shearer, C. Sorlien, U. ten Brink, and M. Tolstoy. An online version can be found at www.scec.org/borderland. For information on the white paper, contact Monica Kohler, Department of Earth and Space Sciences; University of California, Los Angeles; Los Angeles, CA 90095-1567; Phone: (310) 206-1289; kohler@ess.ucla.edu.

Cover page: True-color image of southern California from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project, NASA/Goddard Space Flight Center, and ORBIMAGE (OrbView-2 satellite imagery).

# Executive Summary

The extension of the focus of SCEC scientific research from onshore to offshore regions is a natural evolution. SCEC has the mission of gathering new information about earthquakes in Southern California and integrating that knowledge into a comprehensive and predictive understanding of earthquake phenomena. It is inevitable that studies of the California Continental Borderland must eventually be included in SCEC's science framework. Major active faults and associated geological structures offshore southern California pose a serious threat to coastal populations and structures; however, many of these structures are not accounted for in the seismic hazard assessments or community science models that comprise SCEC research products.

The major elements of the Borderland Working Group science objectives summarized below are closely aligned with major objectives (in bold italics) outlined in the SCEC proposal to NSF and the USGS:

1. **Tectonic Architecture and Evolution**: to determine the ***plate-boundary tectonics*** of the offshore portion of the Pacific-North America plate-boundary system, including stresses, plate-motion distribution, tectonic history since 20 Ma, rheological environment, transition to onshore, and three-dimensional lithospheric seismic structures. Offshore three-dimensional crustal velocity structure will be necessary for deterministic strong ground motion predictions from offshore seismic sources by ***wave propagation*** methods in ***seismic hazard analysis*** studies.

2. **Active Fault Systems**: to determine the kinematics and dynamics of offshore ***fault systems*** in order to construct probabilities of earthquake occurrence in the Borderland. The fault system characteristics will be used in ***seismic hazard analysis*** to forecast the spatial and temporal dependence in offshore earthquake occurrence, recurrence, and statistical distribution. Associated hazards such as tsunami potential will also be the focus of studies in order to include them in comprehensive hazard assessments.

3. **Ocean Observatories for Sustained Monitoring**: to use existing and new sensing technology for new measurements to understand offshore features of ***plate-boundary tectonics***, ***fault systems***, and ***seismic hazard analysis***. This includes determining background seismicity levels, designing real-time seismicity monitoring experiments, and calculating crustal motions. The incorporation of additional complementary biological, environmental, and biogeochemical monitoring in the Borderland is consistent with the call for collaboration and synthesis across many disciplines.

The white paper was composed in order to begin addressing the scientific problems in a way that is consistent with the SCEC science framework. The SCEC science plan as defined in the NSF/USGS proposal specifies that the ***Community Velocity Model***, currently limited to the Greater Los Angeles region, will need to be extended to the offshore regions. Likewise, by the second year the ***Community Fault Model*** is to be broadened to include offshore and coastal faults that threaten coastal population centers from San Diego to Santa Barbara. Ultimately, the ***Unified Structural Representation*** will incorporate the complete three-dimensional offshore extensions of the community velocity and fault models. New and existing marine geophysics technology and research methods such as those discussed here will provide the necessary datasets.

# Tectonic Architecture and Evolution

The California Continental Borderland represents California's most extensive and complex continental shelf (Fig. 1). Understanding this shelf is critical to understanding the evolution of the Pacific-North America plate boundary. The region has experienced significant elements of Mesozoic to early Tertiary subduction and middle Tertiary oblique extension (transtension). It has also accommodated major strike-slip components associated with the evolving transform system. The accretionary and fore-arc rocks of the Borderland occupy a zone that is nearly twice as wide as any other location along the western edge of North America. The doubling of the Borderland province was the result of extreme continental extension in Miocene time and has been closely tied to the large-scale unroofing of the Catalina Schist terrane and the large (>90°) tectonic rotation of the western Transverse Ranges. The amount of displacement that took place during the extension has been estimated to be as much as 250 km. A major debate, however, concerns whether extension in the Borderland continued until sea-floor spreading occurred, how the process of extension was accommodated at different levels in the crust and upper mantle, how extension was related to the evolving transform plate boundary, and how closely the timing of extension was related to offshore oceanic plate motion and ongoing transpression.

The three-dimensional extent of geological and seismic structures in Borderland crust is not well understood. High-quality digital vertical incidence multichannel seismic reflection profiling data are available in some parts of the Borderland. But, few refraction/wide-angle reflection experiments have taken place. The 1958 surveys of Shor and Raitt, and the 1994 and 1999 Los Angeles Region Seismic Experiment (LARSE) are the only crustal-scale refraction experiments available. In the inner Borderland, thin crust with a low and fairly uniform average velocity is observed. The origin of the region has been interpreted as a metamorphic core complex underlain by a crustal-scale thickness of Catalina schist (Fig. 1) but a continuing tectonic evolution debate concerns whether a lower crustal layer of subducted oceanic crust is present. Almost nothing is known about the outer Borderland deep crustal structure.

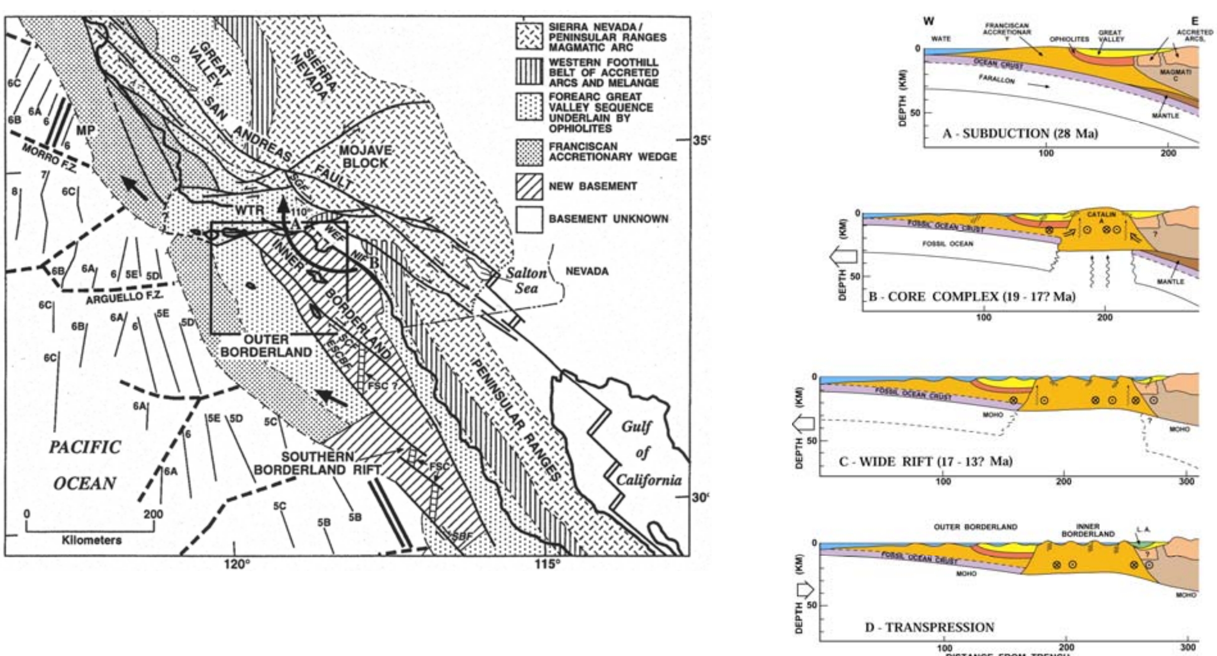


Figure 1. Left: Tectonic setting of California Borderland. Rectangle shows location of LARSE experiment, and arrows show translation and rotation of tectonic provinces. Right: Cross section diagrams showing an interpretation of southern California margin tectonic development based on analysis of LARSE refraction/wide-angle reflection data (both courtesy of U. ten Brink).

The lack of regional three-dimensional offshore geological and geophysical data has left a large number of unanswered questions regarding tectonic architecture and evolution of the Borderland region. The key questions associated with tectonic evolution are:

## Key questions

- What are the spatial and temporal patterns of tectonic stress within the Borderland? How are local tectonic regimes of extension, horizontal shear, and compression related to the large-scale evolution of the plate boundary?
- Are remnants of the early Tertiary megathrust visible beneath the Borderland with subducted oceanic crust below it? If not, is there evidence of a slab window or slab gap?
- How and where was Pacific-North America plate motion accommodated between 20 Ma to the present? What happened in the Borderland during the period 30 Ma to 20 Ma when the first interaction of the East Pacific Rise with the North America margin occurred?
- Did continental rifting in the inner Borderland progress to seafloor spreading? If so, where and how did the transition from continental rifting to seafloor spreading occur? If not, why not?
- Where did the Catalina Schist that underlies most of the inner Borderland at depth come from and how did it evolve? Are there large volumes of underplated mantle or subducted material within the inner Borderland?
- Does crustal structure in the Borderland support a model involving rotation of the Transverse Ranges away from the Peninsular Ranges, with core complexes forming in between?
- What is the source and mechanism of postulated Pliocene rifting and Quaternary volcanism in the Borderland if the chief Pacific-North America plate boundary was transferred to the Gulf of California at about 6 Ma?
- What is or has been the importance of the coastline in localizing and demarcating geologic structures? Why is the Borderland under water?
- How and why did large, long-wavelength (tens of km) folds in the basement and sediments develop in the Borderland?

## Data needs and collection techniques

The key questions can be addressed by determining the basic properties of rocks, as well as their geometries and relationships with other structures. This can be done most effectively by integrating detailed seafloor and land-based geologic studies with geophysical data. Properties of the major structural blocks and tectonic units that need to be determined include their geometries, chronology of motion and deformation history including rotations, major structural boundaries, and the major lithologic units (e.g., Catalina schist, Neogene sediments, oceanic crust, forearc strata, etc.). Measurements of the depths, shapes, sedimentation rates, and chronology of sedimentary basins will provide information on sedimentation history. Accurate measurements are needed of the ages of Borderland rocks and faulting. Petrological measurements of Catalina schist and other major rock formations which outcrop on the seafloor and islands will allow a better understanding of the structural and petrologic evolution of the deeper crust that would be imaged. Geochronology and geochemistry of volcanism, bathymetry, and geochronology of crustal extension will complement seismic studies. High-resolution images of two-dimensional and three-dimensional crustal seismic velocities, anisotropy, and crustal thickness variations are needed to determine present-day structures. Tectonic evolution models will also benefit from knowing Borderland fold properties such as thickness and lithology. Deformation rate data on low-stand shoreline locations and ages, and stream channel geometries can constrain vertical tectonic history.

The geophysical and geological data needed to answer the key questions can be obtained from a variety of measurement techniques. For example, many fundamental questions about the geodynamic evolution of the entire Borderland region could be addressed with near-vertical and wide-angle seismic imaging. The seismic data will provide information on how structures in the upper crust interact with or relate to structures in the deep crust and upper mantle, as the Moho may be as shallow as 12-18 km in the Borderland. The seismic character, structural geometry and seismic velocity of specific features could provide data about the tectonic and magmatic processes that have affected the region. One way to determine higher-resolution crustal seismic velocities and structural geometries is to collect additional, new Ocean Bottom Seismometer (OBS) airgun transect data. OBS arrays can record converted shear waves from active source experiments for additional information on constitutive parameters for material properties of the crust. Such transects can be collected coincident with existing multichannel seismic profiles such as USGS-128/LARSE-3, USGS-120, or LARSE-2 (Fig. 2) and will provide cross-sectional coverage from the continental slope through the outer and inner Borderland. This profiling can be designed to be complementary to a passive OBS experiment so that airgun sources can be used to contribute to three-dimensional tomography. Permitting of airgun sources is an issue that will have to be addressed.

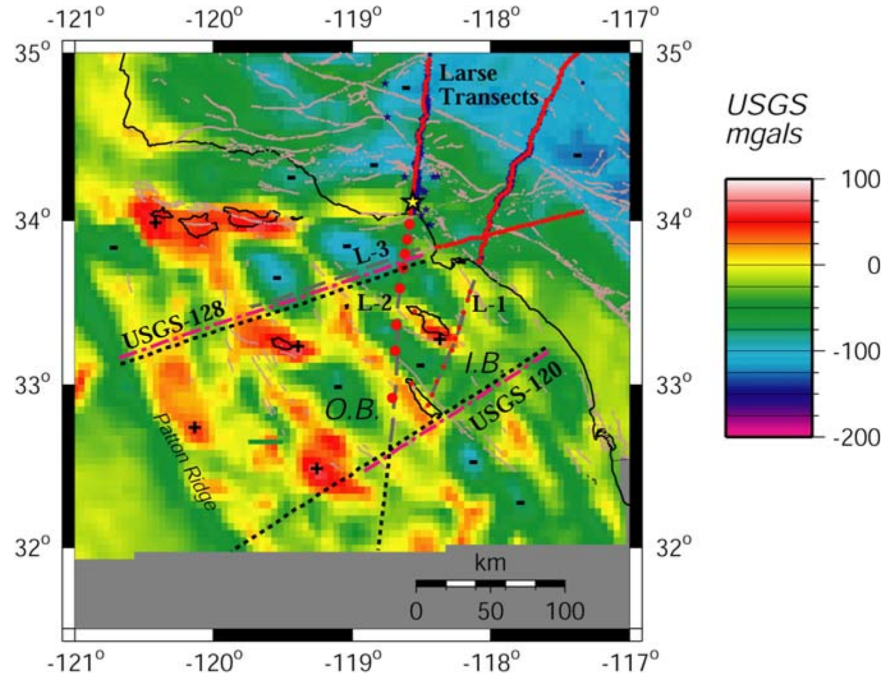


Figure 2. Location of possible OBS/airgun transects (courtesy of D. Okaya). Background Bouguer gravity anomaly structure reveals basins lows (-) and structural highs (+) that include the Channel Islands. Possible transects (black dotted lines) include those coincident with existing multichannel seismic profiles of USGS128/Larse-3, USGS-120, and Larse-2. Other routes are possible.

The southern and inner Borderland appear to represent an area where extreme crustal extension may have proceeded to nascent seafloor spreading, thereby completely exhuming the former subduction zone. Extreme extension has exposed a whole suite of crustal ophiolites in the southern Borderland south of the U.S.-Mexico border. Experiments to define seismic structures in the southern Borderland would provide data on the earliest stages of Borderland tectonic evolution. A possible experiment to delineate southern Borderland tectonic structure and history, where few data currently exist, could have two stages of investigation: a geophysical cruise to acquire deep penetration multichannel seismic, wide-angle reflection, swath bathymetry, gravity and magnetic data (Figs. 2 and 3), and a geologic cruise to sample the sea bottom and to acquire high-resolution seismic data for stratigraphic control, dating, and analysis of rock composition. A major wide-angle onshore-offshore seismic refraction experiment along two regional transects can also be incorporated into the multichannel seismic cruise. Ground truth sampling of deep crustal rocks that are likely exposed in the rifted inner Borderland is a critical element of a comprehensive Borderland research initiative. The volume and composition of volcanic rocks around the inner Borderland are consistent with formation in a continental extensional setting with high subcrustal temperatures. Heat flow values in the Borderland and coastal southern California are also unusually high for the continental crust (70-100 mW/m$^2$), however these measurements are sparse and provide little detail of the heat-flow structure. More measurements are needed.

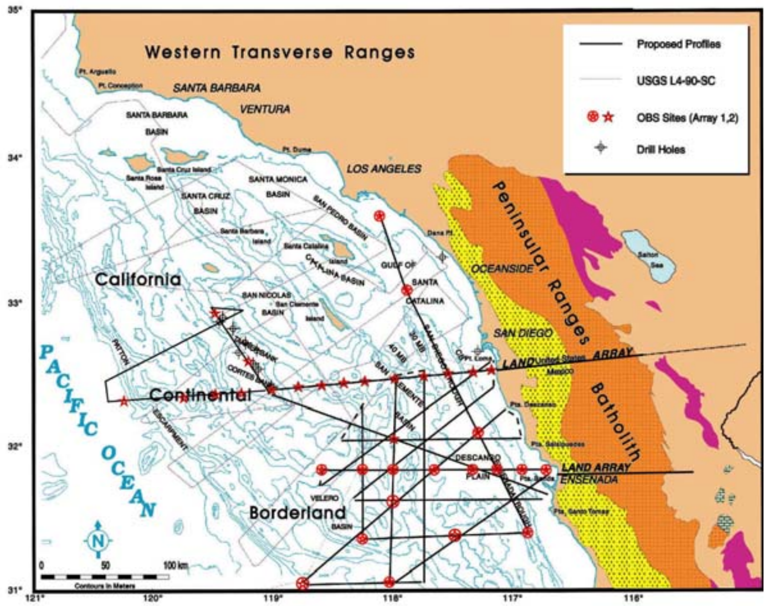


Figure 3. Preliminary ship tracks (heavy lines), OBS deployments (stars) and land arrays for proposed multichannel seismic, refraction, gravity, and magnetic data acquisition (courtesy of C. Nicholson and M. Legg).

Information about vertical tectonics in the submarine environment is elusive and limited to low-resolution micropaleontological studies of the preferred depths of benthic fauna. Onshore, marine terraces are evidence of sea-level still stands (intervals during which sea level is approximately constant) during Pleistocene glacial minima, and they record deformation over longer geologic intervals. Offshore, similar evidence exists along many of the world's continental shelves in the form of low-stand shorelines cut during glacial maxima. Sidescan sonar, swath bathymetry, high-resolution seismic reflection profiling, and submersible observations can allow the mapping of submerged lowstand shorelines. In addition, mapping of deformed stream channels, submarine fan valleys and depositional systems, and other deformed shelf and basin structures can lead to the determination of deformation mechanisms and rates.

One of the outstanding tectonic problems is how strike-slip faults of the Borderland intersect the thrust faults of the Transverse Ranges. The west-trending Western Transverse Ranges structural block lies along the northern edge of the Borderland. A major fold-and-thrust belt has developed and vertical tectonism is dominant at the northern boundary where the northwest structural fabric of the inner Borderland converges with the Western Transverse Ranges. It remains to be determined whether these faults are decoupled from the Transverse Ranges or if they interact with faults of the Transverse Ranges to cause rotation. The geometry of the Transverse Ranges and Borderland faults near their intersections is important to understand. Additional sidescan sonar, sub-bottom reflection profiles, and submersible observations of these faults and the submerged shorelines around them can be used in analyses of tectonic indicators.

Large-scale investigations of offshore plate boundary lithospheric structure can answer questions regarding structure and tectonic evolution of the Borderland such as its deep composition and rheology, the presence or absence of relict oceanic plates, and the nature of lateral changes to Pacific plate oceanic lithosphere on the west, and continental lithosphere on the north and east. Crustal and uppermost mantle velocity tomographic results are only good for the onshore regions where there is data coverage. There is a need for continuous waveform data collection from a passive offshore network that can be combined with onshore network data (e.g., TriNet). A long-term (12-18 months) seismic experiment involving a network of intermediate-band OBS's in the Borderland and extending out to Pacific plate oceanic lithosphere (Fig. 4) could provide earthquake data to fully model three-dimensional lithospheric structures. With a combination of offshore active and passive experiments, the SCEC Community Velocity Model can be extended offshore. This study could also serve as a three-dimensional backbone for complementary active-source experiments that seek to refine crustal velocities.

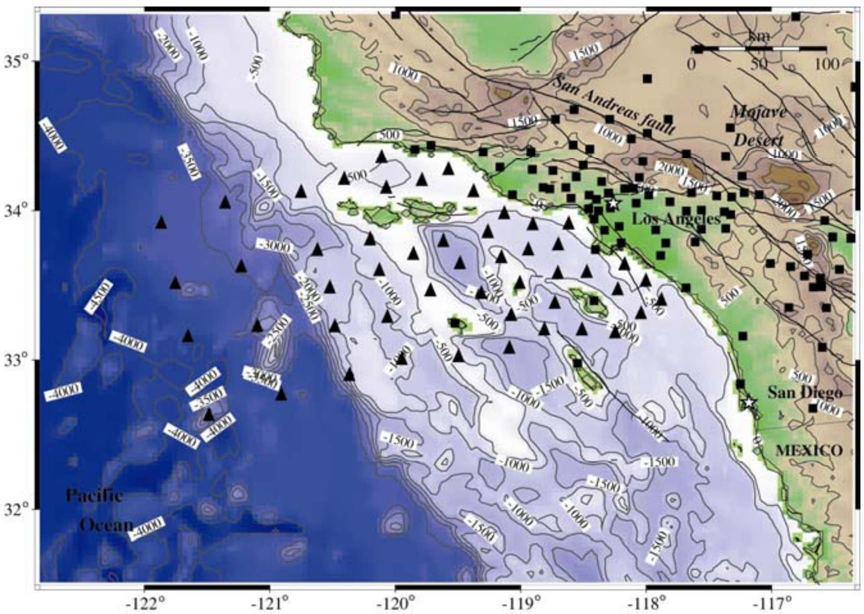


Figure 4. Relief map showing potential locations of future OBS's (triangles) and existing TriNet stations (squares) (courtesy of M. Kohler). Bathymetry/topography values are from the two-minute Smith and Sandwell catalog.

Mantle anisotropy is used as an indicator of mantle flow directions. Shear-wave splitting directions on land in the southwestern U.S. suggest regional east-west oriented mantle flow even west of the San Andreas fault where recent geodetic (GPS) monitoring shows Pacific plate surface movement to the northwest. The transition from the southwestern North America mantle flow to a regular Pacific flow direction may occur under or to the west of the Borderland. Little modern three-component seismic data has been collected within the Borderland except for at the Channel Island stations of TriNet. As a result, the anisotropic structure of the Borderland crust and upper mantle is not known. The crust of the inner Borderland has been interpreted to be underlain by vast amounts of Catalina schist based on limited geophysical evidence and tectonic models involving block rotations and associated extreme (metamorphic core complex) extension which exhumed the Catalina schist. Positive evidence for the widespread distribution of this schist is lacking. Although there have been no direct petrophysical measurements, the schist should exhibit strong seismic anisotropy based on its mineralogy. Active-source refraction/wide-angle reflection profiles using airguns and three-component OBS's can be collected in orthogonal directions relative to the Catalina schist tectonic orientations. Additionally, a comprehensive program of petrophysical measurements should be carried out on Catalina and other major rock formations which outcrop within the Channel Islands and surrounding coastal regions in southern California.

Many of the major structural and tectonic elements in the southern California Borderland are well expressed in the gravity and magnetic fields (Fig. 5), providing an opportunity to define the composition and structure of the middle and upper crust. Quantitative analysis of various faults and geologic contacts across which there are physical property contrasts can be made by potential-field modeling. Examples of features that may be pertinent to a Borderland study are 1) large-amplitude gravity lows of the offshore Ventura and Santa Monica basins, and smaller-amplitude lows associated with the Santa Cruz, San Nicolas, and Catalina basins, and the San Diego trough (Fig. 5); 2) a 150-km long belt of aeromagnetic highs oriented NNW-SSE bisects the southern California Borderland suggesting the existence of mafic rocks; and 3) the absence of magnetic highs in the Catalina terrane suggesting that the magnetic data can be used to map the extent of the Catalina schist. A potential-field study of the Borderland is viable because of the limited geologic exposure and the existence of suitable regional gravity and aeromagnetic datasets. The USGS Geophysical Unit

Menlo Park has compiled gravity and aeromagnetic datasets for the southern California Borderland with the purpose of characterizing the regional geophysical setting. This characterization could be enhanced by constructing quantitative three-dimensional models of the region based on the analysis of gravity and magnetic anomalies supported by geology, drill hole data, seismic reflection and refraction interpretations, and other available data. An arsenal of computer software exists for the interpretation of derivative maps with the goal of determining crustal structure and unraveling the tectonic history of the Borderland (e.g., by quantifying amount of slip, location and geometry of faults and basins). Existing gravity data are sufficient for regional studies (>5 mGal), but are not adequate for detailed studies. Recent advances in airborne and shipborne gravimeters and the advent of Global Positioning System (GPS) make it possible to design high-resolution (<1 mGal) gravity surveys offshore. Possible study areas could include the offshore Palos Verdes peninsula, offshore San Diego, and the Santa Monica basin: areas of interest for both the USGS Earthquake Hazards Team and USGS Coastal and Marine Geology Team programs.

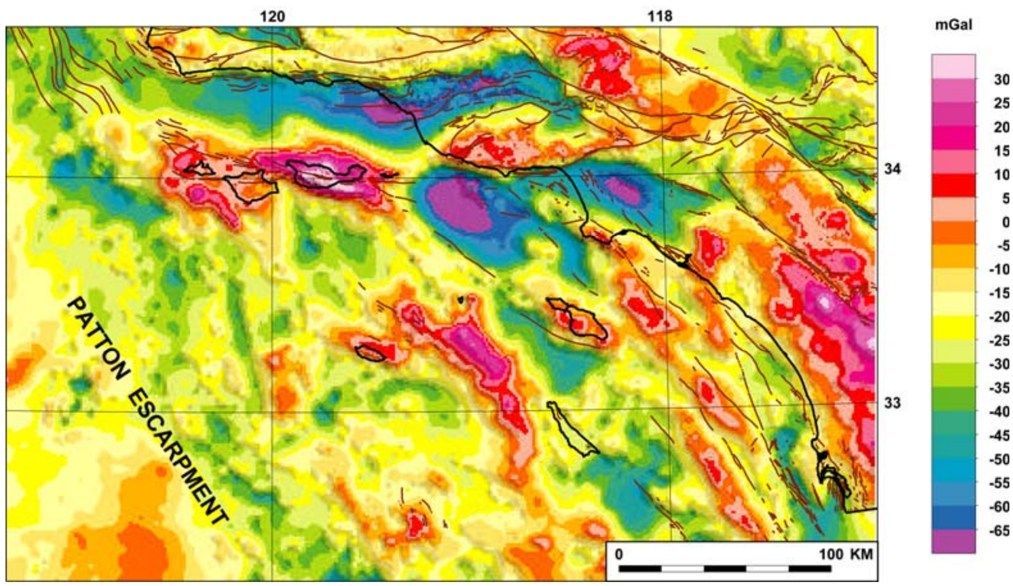


Figure 5. Isostatic gravity field (courtesy of V. Langenheim). The offshore gravity data are from a 2-minute gridded dataset of shiptrack data.

A combination of geophysical and geological data can answer the outstanding scientific questions using a variety of techniques. The following is a summary of the new data that are necessary to determine three-dimensional offshore tectonic architecture and evolution:

## New Data Needed

- OBS/airgun, multichannel seismic reflection data for three-dimensional coverage, including offshore Baja California;
- wide-angle reflection/refraction transect data;
- obtaining, archiving, and processing oil industry seismic reflection and oil-well data;
- large increase in number and density of heat flow measurements;
- swath bathymetry, side-scan sonar, submersible observations of tectonic structures exposed at the surface;
- continuous teleseismic and local earthquake waveform data from a long-term (12-18 months), backbone, three-dimensional, OBS network;
- anisotropy measurements from passive and active seismic source data;
- petrophysical measurements from island and surrounding coastal region outcrops;
- high-resolution gravity (<1 mGal) and magnetic surveys over offshore basins and faults;
- deep-penetration cores of Borderland basins;
- chronologic studies of the sedimentary and volcanic record.

# Active fault systems

Major active faults offshore southern California pose a serious threat to coastal populations and structures. These faults are modestly well known, though they are often not considered in tectonic models and seismic hazard assessments because their Holocene activity and slip rates are unknown. For example, two of the largest and most continuous offshore faults, the San Clemente Fault and San Diego Trough Fault, have not been included in past seismic hazard maps due to lack of data on recency of motion and slip rate. Yet because of their great lengths (300-500 km) and well-defined character, the faults have the potential to generate large magnitude (M>6.5) earthquakes that would be destructive to heavily populated coastal areas including San Diego, Los Angeles, and Orange Counties. Indeed, these faults are closer to the southern California coast than the areas of severe damage from the 1989 Loma Prieta earthquake (Marina district of San Francisco, Cypress freeway structure in Oakland) were to the epicenter. Moreover, the kinematics and dynamics of faults immediately offshore of Los Angeles from Malibu to San Clemente are not well understood.

The inner Borderland is characterized by active strike-slip and blind-thrust faults. In many cases, these fault systems come in contact with each other in the seismogenic crust. The nature of the cross-cutting relationships dictates the geometry and style of faulting in the earthquake source region. The Borderland provides an ideal laboratory to study these fault interactions, as the structures are commonplace and the fault junctions often occur at relatively shallow depths (<10 km). The structures are often expressed in the topography of the seafloor and can be imaged by techniques such as high-resolution seismic profiling and swath bathymetry. The seafloor exposures of fault-related folds above blind-thrust systems provide targets to constrain the slip rates on the faults. In contrast, the onshore counterparts of the fault-related folds are typically eroded or modified substantially by urban development.

The Borderland provides an excellent laboratory to study aspects of fault behavior that are relevant to both onshore and offshore seismic hazard assessment. The critical scientific questions related to active fault system studies are:

## Key questions

- Where are the active faults? What are their faulting histories?
- How do faults interact (e.g., NS strike-slip with EW reverse) and does slip partitioning take place either in time or space? How do the faults interact at depth?
- What is the seismic potential offshore? What is the largest possible magnitude of earthquake that can occur in the Borderland?
- What are the possible tsunami-producing structures in the Borderland, whether from faulting, folding, or steep-slope failure? What is the expected frequency and size of tsunamis that might be produced? What is the tsunami history?
- What are the changes in slip rates and styles of active systems, and how do they compare with geodetic data and syntectonic sedimentation records?
- How does the distribution of historic and catalog earthquakes relate to the active structures?
- How has reactivation and/or inversion of pre-existing structures occurred?
- How do fault slips relate to geodetic measurements and the Pacific plate reference frame? What drives the outer Borderland Quaternary deformation?
- What new techniques for high-resolution underwater paleoseismology can be developed here and then used to study other underwater faults worldwide?
- How do bends and offsets in major strike-slip fault systems control long-term deformation and fault segmentation during large earthquakes?

## Data needs and collection techniques

To answer the key questions, new data on the properties of offshore faults are necessary. At the most basic level, data are needed to allow identification of faults and whether or not they are active. Measurements need to be made of offshore fault slip rates, earthquake recurrence intervals, and past and potential earthquake sizes, especially on blind-thrust systems. The history of fault interactions can be obtained from records of sedimentary sequences. Fundamental fault property data that are needed include their locations, geometries (including crosscutting patterns), seafloor offsets along the faults, identification and dating of piercing points, and fault-related fold geometries. Age-related measurements that are also required include dates of specific earthquakes, history of offsets, changes in slip rates, and timing of submarine slide events. Seismicity measurements will also help constrain fault geometries through determinations of earthquake locations, maximum depths, dimensions of past and potential rupture zones, and the relationships between current seismicity and fault activity (see also next section). A large area of seafloor topography and deformed seafloor sediments remains to be mapped. The general interplay of sedimentation will be understood with new measurements of sedimentation rates from submarine fans and low-stand shorelines, and data from sediment cores. New high-resolution maps of past and potential submarine landslides, fault scarps, interactions within strike-slip fault systems, and evidence of past tsunamis will provide input for hazard assessments. Measurements of rock structure geometries, as well as restraining bend and pull-apart basins will provide new information for tsunami hazard assessment as well as fault activity. Rates of subsidence, uplift, and tilting should be determined for restraining bends. Spatial and temporal variations in deformation style such as evidence for reactiviation need be obtained from both on-fault and off-fault structures.

One way in which three-dimensional geometry and long-term slip history of fault systems can be defined is through high-resolution seismic reflection and borehole data studies. Major oblique- and strike-slip systems in the inner Borderland that are of concern include the Newport-Inglewood, Rose Canyon, San Diego Trough, and Palos Verdes faults. Two large Miocene detachment surfaces that were reactivated as blind-thrust faults (Oceanside and Thirtymile Bank) are the focus of ongoing mapping work using reflection and borehole data. These fault systems deform near-seafloor sediments, and have been associated with the 1986 Oceanside ($M_L$= 5.3) earthquake and coastal uplift patterns. Given their sizes, the faults may be capable of generating large earthquakes (M=7.1 to 7.6). The magnitude of slip in past events is unknown on these and most other Borderland faults. Delineation of the strike-slip component of displacement is a particular challenge because piercing points need to be identified and dated. The sources of the blind-thrust 1979 and 1989 Malibu Earthquakes ($M_L$=5.0) in Santa Monica Bay have been attributed to a similarly reactivated detachment surface. OBS deployments to improve offshore earthquake locations and to record microseismic activity will contribute directly to structural analyses that define three-dimensional fault geometries, including those that address high-angle and low-angle fault interactions.

Collaborations with the USGS will boost research in fault identification and characterization since the USGS has the goal of imaging faults and related structures along the highly populated urban corridor in the southern California region. The USGS has been actively involved in offshore imaging and has a repository of valuable reflection data, some of which are available for analysis. In 1997, the Coastal and Marine Geology Program of the USGS initiated a project to identify the active fault zones and areas of submarine landslides in the inner Borderland between the US-Mexican border and Santa Barbara. The study is generally limited to an area from the inner coastal zone to about 50 km offshore. Fig. 6 shows the tracklines for the work completed to date; the area from Point Dume to Santa Barbara will be surveyed in 2002. High-resolution multichannel seismic reflection profiles using small airgun acoustic sources have been obtained along many of the tracklines illustrated in Fig. 6. These data have a high spatial resolution because the common-depth-point interval is 5 m. The small airgun data are revealing upper crustal structure to an average depth of 2 km below the seafloor.

The data collected during the current USGS project still require interpretation. Examples of key issues currently under investigation include the transition from strike-slip to compressional structures along the northeastern edge of Santa Monica Basin; the character of the Palos Verdes fault zone in the Santa Monica shelf area; and the strain distribution across the multiple fault systems in the San Diego Trough area. Ongoing studies are showing that one set of reverse faults that are part of the Palos Verdes fault zone is presently active as shown by seafloor deformation. A second group of faults has been inactive, probably throughout the Quaternary, as indicated by undeformed rocks of this approximate age that onlap or cover these faults. The region of the southern California Borderland between San Diego and Dana Point is deformed by a minimum of four active, predominantly strike-slip faults: the Newport-Inglewood-Rose Canyon, Coronado Bank, San Diego Trough, and San Clemente fault zones. How slip is partitioned between these faults, and how slip is transferred from these to faults to the north (such as the Palos Verdes fault zone) are critical questions related to the understanding of the kinematics of the area. Additional high-resolution seismic reflection data combined with long sediment cores are needed to determine fault ages in the area near the northern ends of both the Coronado Bank and San Diego Trough fault zones where previously acquired data coverage is sparse. The kinematics of the area are also complicated by the probable presence of thrust faults at depth. For example, earthquake relocations of the 1986 Oceanside sequence show a thrust plane dipping to the northeast. A deep-crustal study of the area is needed to better determine how these deep-seated faults interact with strike-slip faults mapped near the surface. A multichannel seismic reflection survey using a large air-gun source array combined with tomographic studies would help resolve fault interactions at seismogenic depths.

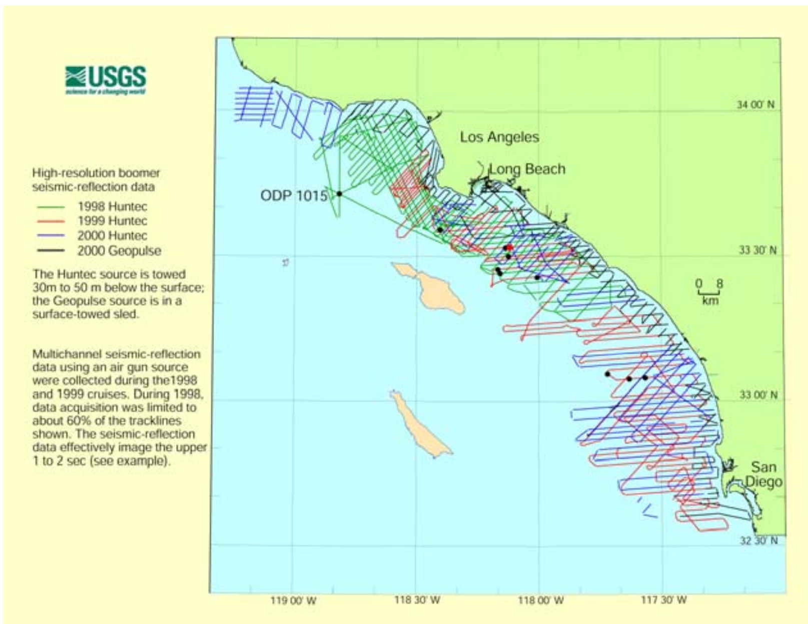


Figure 6. USGS high-resolution seismic reflection data tracklines for earthquake hazard study, 1998 to present (courtesy of W. Normark).

Petroleum seismic reflection and wellbore data can also contribute to structural and seismologic studies in several ways. Structural (i.e., velocity and fault) models derived from these data will support additional experiments by defining structural targets and providing velocity descriptions near stations and/or sources. In addition, fault maps and models based on industry reflection data (Fig. 7) will provide context for seafloor or shallow subsurface imaging (side-scan sonar, high-frequency seismic) and sampling (coring) experiments that seek to define slip rates and rupture histories.

Efforts have only just begun to rescue valuable old oil company data in order to make them publicly available to the scientific community. For example, Chevron-Texaco is offering tens of thousands of 9-track tapes of offshore west coast seismic reflection data. The majority of the data are from the Borderland and offshore southern-central California. Costs to archive the data include storage of the tapes and transcription of the data onto newer media devices. There is a mix of high-resolution and deep-penetration data, and some three-dimensional data. Most lines were shot in the 1970’s and 1980’s, and include airgun, watergun, sparker, and other sources. Chevron-Texaco also has potentially useful stack and migration film data. Similar issues are present for the retrieval and archival of Caldrill hole data which may be invaluable for stratigraphic or upper crustal studies.

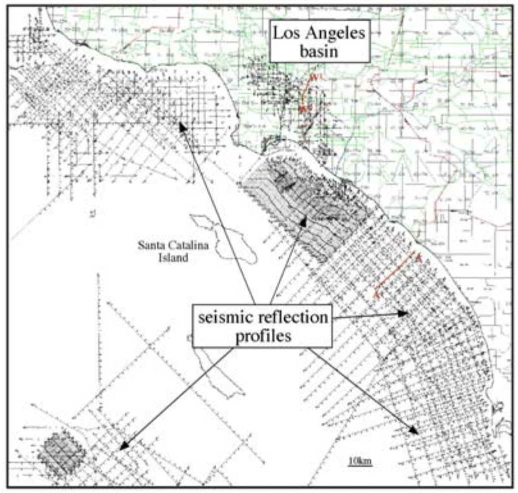


Figure 7. Petroleum industry seismic reflection data coverage in offshore southern California maintained in the Harvard database (courtesy of J. Shaw).

Bathymetric data also provide an accurate delineation of fault geometry and character, and illuminate numerous piercing point offsets on a variety of scales. Sample results can be found in recently collected data from the major portions of the two largest faults within the inner Borderland offshore southern California: the San Clemente and the San Diego Trough fault zones, as well as parts of the Palos Verdes-Coronado Bank Fault (Fig. 8). Combined with a dense grid of existing high-resolution single-channel seismic reflection data and observations from the submersible ALVIN, these data are sufficiently detailed to allow a first-order estimate of rates of deformation. Seafloor offsets along the faults provide input for new, detailed maps of the faults. The maps will, for the first time, allow an accurate assessment of fault segmentation and the relationship between fault morphology and seismicity. However, while near-shore coverage is good in some regions (Fig. 9), most of the Borderland, except for specific focus areas, is poorly mapped by multibeam methods. A comprehensive bathymetric dataset that includes recent high-resolution multibeam bathymetry and NOAA hydrographic data offshore southern California and northern Baja California needs to be compiled.

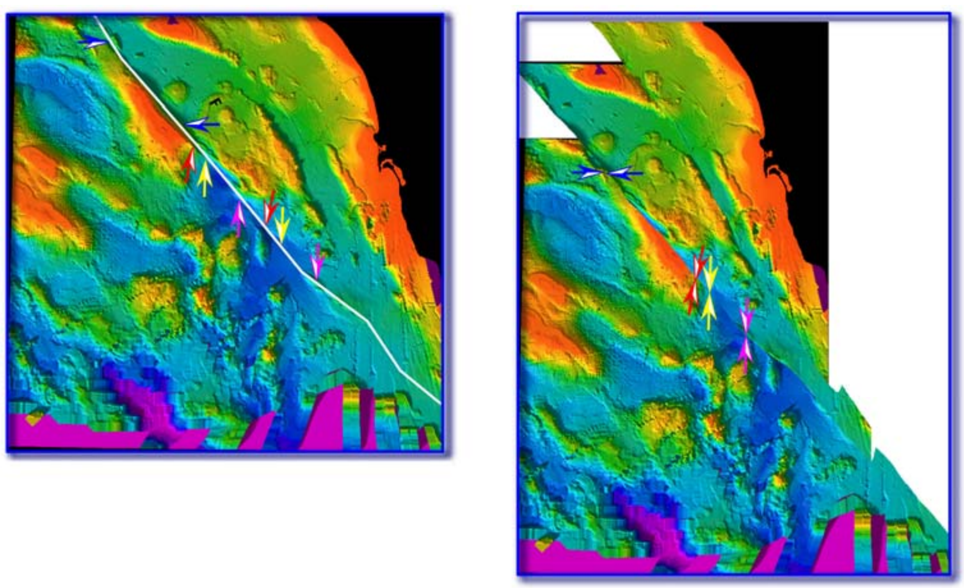

Figure 8. San Clemente fault before (left) and after (right) reconstruction, showing an average offset of 58 km (courtesy of C. Goldfinger). Colored arrows show matching points before and after fault motion. New multibeam bathymetry mapping merged with older data and existing soundings now allows reconstruction of major faults of the southern Borderland.

Many coastal areas are in close proximity to active submarine slides and faults. Seismic activity on these features pose considerable risk to coastal populations in the form of tsunamis. A modest earthquake may generate a large submarine slide and associated tsunami that is out of proportion to the earthquake magnitude. Understanding the tectonics and the associated earthquake and tsunami hazards of the Borderland will require a variety of approaches. One key avenue will be to acquire multibeam bathymetry for much of the unsurveyed Borderland region (Fig. 9). Borderland topographic highs ringed by submarine slides are now being revealed by new multibeam mapping. In basement rock areas, the dominating strike-slip faults are difficult to resolve with reflection profiling, but can be mapped with detailed bathymetry from which piercing point offsets and slip histories can be reconstructed. Bathymetry will also allow examination of the low-stand shorelines, which in turn reveal the Quaternary vertical motion. The vertical motion history can show deformation details such as the behavior of restraining bends and pull-apart basins, and the slip rates of the Transverse Ranges frontal fault system.

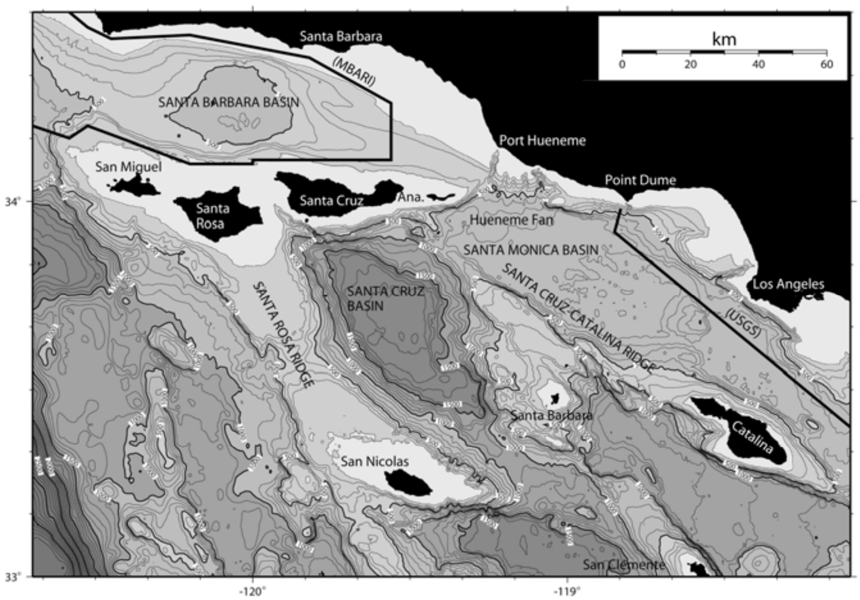


Figure 9. California Borderland bathymetry map showing approximately which regions have been surveyed using multibeam methods by the Monterey Bay Aquarium Research Institute (MBARI) and the USGS (courtesy of C. Sorlien and M. Cormier).

Paleoseismology observations from acoustic imaging and coring are useful for looking back through many earthquake cycles. They can be used to improve estimates of the statistical distributions that best describe the variability of earthquake occurrence and recurrence. Seismic reflection data are used to establish a detailed seismic-stratigraphy (‘acoustic trenching’). To determine the history of offsets and timing of submarine slide events it is necessary to obtain sediment cores to provide age control. Conventional wire-line piston cores are of limited use for age control because of the lack of penetration in the silty sand and mud deposits common in the inner Borderland basins. Although the current Ocean Drilling Program (ODP) coring technology is ideally suited for obtaining the necessary cores, the scientific research vessel JOIDES Resolution is not commonly used for nearshore, relatively shallow-water drilling work. As a result, future detailed stratigraphic analysis in the Borderland will need to explore the capabilities of alternate coring systems. Two currently under consideration are the GLAD800, which is capable of obtaining ODP-style piston cores 20 to 200 m long in water depths less than 800 m, and the PROD system, which is a carousel-style remotely-operated coring system that is lowered to the sea floor by cable. The GLAD800 system is operated from a barge with the coring rig and was designed for use in lakes. Its applicability to the marine environment is currently being tested. The PROD system can be used from a conventional research vessel with an A-frame and deck space for the winch and supporting equipment. The coring studies may be more successful offshore because the sediment record is more complete there than it is onshore. The new tools will make it easier to obtain 50 to 100 meter deep cores. There may also be a number of unexplored biological and geochemical markers for dating past earthquakes.

Offshore studies will contribute directly to regional seismic hazards assessment through contributions to the SCEC Community Fault Model and related database efforts (e.g., Southern California Fault Activity Database). Three-dimensional digital structure-contour mapping (e.g., GOCAD software package) of fault surfaces and deformed strata will need to incorporate offshore faults using new and existing academic, USGS, and industry seismic and oil-well data. New techniques such as laser line scanner, chirp seismic, and coastal lidar are promising sources of high-resolution images. The following is a summary of the new data needed for analysis of active fault systems:

## New Data Needed

- OBS deployments for improved offshore earthquake locations and microseismic activity recording;
- high-resolution seismic reflection data in offshore areas with no previous coverage;
- release and archival of existing petroleum company seismic reflection and Caldrill core hole data;
- high-resolution multibeam imaging of unmapped areas;
- shallow coring and seafloor sampling to provide chronostratigraphy;
- deep-tow and remotely operated vehicle high-resolution seafloor and sub-bottom imaging;
- acoustic imaging of Holocene strata associated with active faults.

## Ocean Observatories for Sustained Monitoring

The California Continental Borderland is seismically active and has the potential of producing earthquakes that can cause onshore damage. Some heavily populated coastal communities lie closer to active offshore faults than to the nearest onshore faults. Earthquakes that occurred on faults with offshore traces or folds during the last three decades include the 1973 Point Mugu ($M_L$ =6.0; $M_w$ =5.8), 1979 Malibu ($M_L$ =5.0), 1978 Santa Barbara ($M_L$ =5.1; $M_w$ =5.9), 1981 Santa Barbara Island ($M_L$ =5.3; $M_w$ =6.0), 1986 Oceanside ($M_L$ =5.3; $M_w$ =5.8), and the 1989 Malibu ($M_L$ =5.0) earthquakes (Fig. 10). Large offshore fault structures have been identified that could produce much larger earthquakes. Efforts to obtain accurate hypocentral parameters for the offshore events have been hampered by a lack of seismic stations west of the coastline. Only a handful of regional network (most recently TriNet) stations exist on permanent island locations and even those are too limited to produce hypocenters or focal mechanisms with reasonable uncertainties. In addition, island stations are affected by surface noise. For most offshore earthquakes, the moment magnitude is substantially larger than the local magnitude. The systematic understatement of offshore magnitudes by using the local magnitude scale understates the hazard to coastal cities from large offshore earthquakes. The magnitude difference leads to questions regarding seismic strain release on Borderland structures.

One way to circumvent the problem of limited station coverage in hypocenter computations has been to use more sophisticated earthquake relocation techniques such as the double-difference, joint hypocenter-velocity inversion, or waveform cross-correlation methods. These have produced locations (e.g., Fig. 10) that better define causative faults and fault plane solutions, though uncertainties are still higher than for onshore earthquakes. Of course a reliable master event location is still needed in these techniques. No offshore stations are capable of real-time telemetry necessary for producing data within minutes of the earthquake, further hampering seismic hazard assessment.

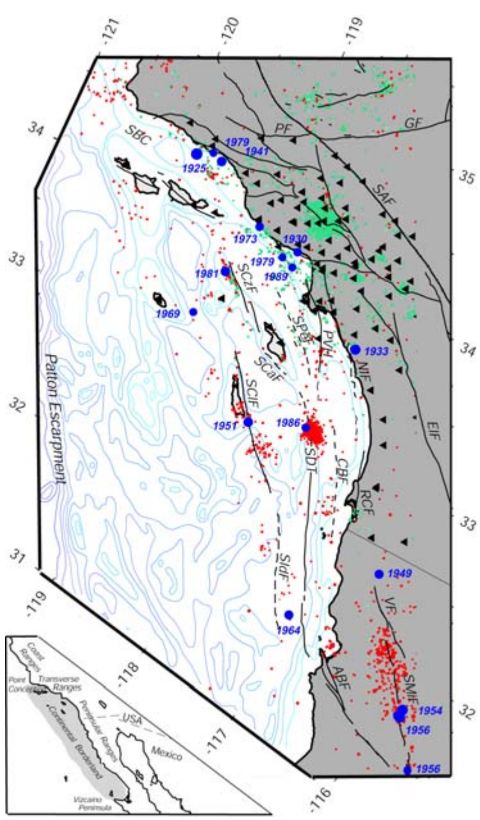


Figure 10. Borderland tectonic structures and seismicity (courtesy of P. Shearer). Dark circles show epicenters of $M_L \geq 5.0$ earthquakes from 1920 to 1997. Green and red dots indicate good and poorer quality earthquake locations from the Southern California Seismic Network catalog since 1981.

As with seismicity, offshore plate motion estimates are limited to where there are island stations. Earthquake hazard assessments are often most effectively based on balancing the deformation from expected earthquakes against the loading imposed by tectonic plate motions. The total Pacific-North America Plate motion is relatively well constrained but the amount of motion that takes place offshore is not well known. Resolving the debates over how the deformation is distributed could make a difference of approximately 20% in onshore probabilistic seismic hazard assessments. Currently, all offshore geodetic measurements have been made on the offshore islands, both by occasional occupations (survey-mode GPS) since 1986, or more recently using continuous stations. Fig. 11 shows the resulting velocities for island sites relative to one site (CAT1) on Catalina island. This map shows several obvious features. There are more than 5 mm/yr of north-south contraction across the eastern Santa Barbara Channel with the motion becoming more of a simple shear farther to the west. There are also about 5 mm/yr of shear across the inner Borderland area, from San Clemente and Catalina Islands to the mainland. In addition, there are 1-2 mm/yr of motion between the inner islands and those in the outer Borderland such as San Nicholas. Joint analysis of Borderland and Pacific plate GPS sites shows that, after correcting for strain accumulation on nearby faults, there appears to be about 3 mm/yr of motion for San Nicholas Island relative to the Pacific Plate. This suggests motion on an unspecified fault or other structure farther west than the islands.

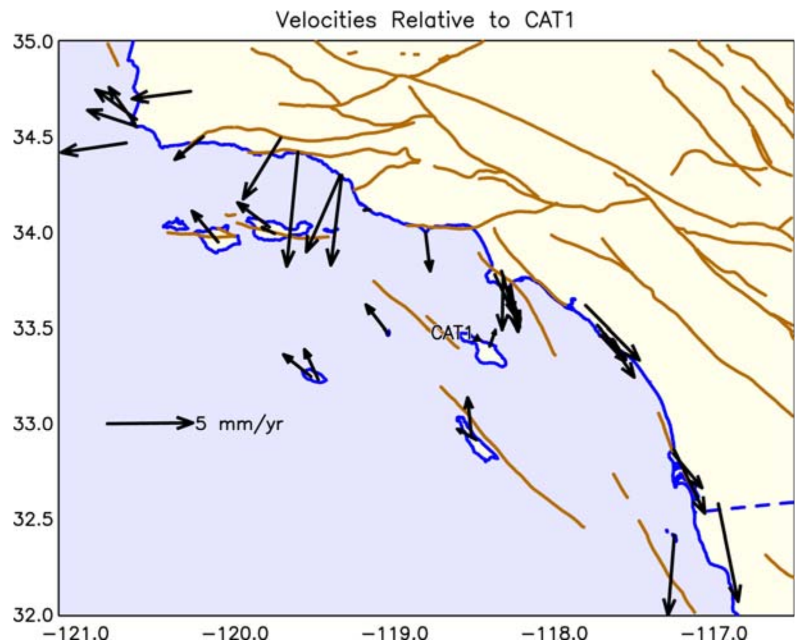


Figure 11. Plate velocities for island sites, relative to one site (CAT1) on Catalina Island; values come from Version 3 of the SCEC Crustal Motion Model (a preliminary release, courtesy of D. Agnew) and have errors of about 1 mm/yr.

Seismicity and plate motion monitoring are just two examples of data collected from networks where offshore coverage has been limited to island stations. Because decades of data are needed for accurate calculations, it is effective to think about solving certain scientific problems using data from ocean observatories. In practice, a sustained ocean observatory can incorporate a large number of multi-disciplinary sensor monitoring programs that have the potential of complementing existing networks, as well as each other. The key questions that should drive ocean observatory monitoring science have been identified as:

## Key Questions

- What is the percentage of plate motion taken up in the Borderland? How does this affect estimates of probabilistic seismic hazard assessments?
- If geological estimates of slip rates on major offshore faults differ from strain measured by geodesy, how well do decade-long geodetic measurements measure longer-term tectonic strains?
- If offshore earthquakes have relatively greater long-period energy release, do they have greater slip per event, lower stress drops, or larger source dimensions?

- How do the characteristics of offshore background seismicity define the activity level and three-dimensional geometries of faults?
- What is the relationship among rupture zone size, hypocenter, and known fault geometry?
- What is the stress transfer between earthquakes?
- Why do some offshore earthquake sequences have negligible aftershock sequences, others have extraordinary sequences (e.g., 1986 Oceanside), and still others appear to be swarm-like?
- Should offshore or near-coast onshore aftershock sequences be studied with temporary OBS deployments, given logistical limitations?
- What is the design array for real-time monitoring of offshore earthquakes?
- How might geological structures, fault systems, and seismicity be studied by complementary biological, geochemical, or environmental sensing?

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## Data needs and collection techniques

The concept of Borderland ocean observatories came about with the realization that several types of data needed to answer key science questions about seismic hazards, faults, and tectonics required sustained monitoring. For example, offshore geodetic and seismicity surveys would be best carried out over a period of years or decades. Survey-mode plate motion measurements on islands is one type of new sustained monitoring data needed. Additional measurements on both sides of the Santa Barbara Channel would provide a greater density of points to elucidate motions in a region of very inhomogeneous strain. Offshore seismicity needs requiring data collection over time spans of years include improved hypocenters, magnitudes, and focal mechanisms. The resulting offshore seismicity catalog will in turn provide an estimate of the variations in seismogenic thickness of the Borderland. Statistical seismic parameters needed include those associated with offshore background seismicity rates and the Gutenberg-Richter distribution. Related calculations required include relocations of earthquakes once the master events are known, slip per event, stress drop, and source dimensions. An ocean observatory is also the obvious place to test the feasibility and usefulness of new sensing technologies.

In order to resolve debates about how deformation is distributed throughout the Borderland, improved models of the tectonic development of the Borderland region are needed to constrain the fault slip rates of offshore faults. Improving tectonic models will require improved offshore GPS measurements and improved images of offshore geologic structures and their rheological properties. Even though all the islands are (or soon will be) the locations of continuous GPS sites, additional Borderland geodetic work is needed. Specifically, methods are being developed for making geodetic measurements on the ocean floor using acoustic links from GPS-referenced surface ships and buoys. The relatively large errors in these methods (1-2 cm) mean that they cannot be used to estimate velocities over times shorter than decades; but the sooner they are begun, the sooner the results will be known. Borderland research should thus include first-epoch measurements of a number of seafloor sites. In addition, higher precision and accuracy should be possible for these acoustic methods in relatively shallow water. Several shallow banks exist in the outer Borderland and measurements at these would clarify the source of the Pacific Plate discrepancy mentioned above.

Seismicity measurements can be made by a passive broadband OBS network such as that discussed in the section on tectonic architecture and evolution. The local seismicity recorded by a network would produce an accurate offshore hypocenter catalog that can be used to identify spatial relationships between background seismic activity with mapped offshore faults, as well as faulting types identified by focal mechanisms. Temporary OBS deployments can provide seismic monitoring data for small-scale background seismicity or microseismicity activity. A broadband OBS network could also supply data about aftershock source parameters for offshore and onshore earthquakes in a Rapid Array Mobilization Program (RAMP) type capability. Such deployments would require partnerships with appropriate organizations in order to be able to acquire instrumentation on short notice. Temporary network data are most useful if they can be rapidly integrated with existing earthquake catalogs, and this may require the development of new database tools for rapid data integration. Local earthquake data from a sufficiently dense OBS deployment would also provide additional raypath coverage necessary to produce three-dimensional velocity models with which to obtain more accurate hypocenters. Because many moderate offshore earthquakes have short-lived aftershock sequences, it would be beneficial to setup a cooperative agreement with the U.S. Navy for rapid deployment of sonobuoys to record the aftershocks within the first few hours of a moderate to large offshore earthquake. With Navy support and quick response, the problem of sonobuoy navigation is reduced providing important near-source aftershock coverage in the first few post-mainshock hours.

Real-time monitoring is a basic requirement for hazard mitigation applications where the data must be delivered to a processing facility and decision-making body so that measures may be taken to minimize losses in the event of a disaster. The technology for establishing shallow water moorings with real-time data telemetry via radio modem has been developed at the Woods Hole Oceanographic Institution, as has the technology for acquiring high-fidelity seafloor seismic data. These two technologies can therefore be combined to monitor submarine features that pose seismic hazards to nearby coastal population centers. The California Borderland is a suitable area for deployment of a Real-Time Offshore Seismic Monitoring Station (Fig. 12) network because it includes many banks shallower than 200 m water depth that are located as far as 150 km from the mainland, and several mountainous islands where onshore antennae can be mounted. The Real-Time Offshore Seismic Monitoring Station is a coastal mooring design for long term, continuous high bandwidth telemetry from bottom-mounted seismic sensors. It is designed for applications in water depths up to 300 m, at sites that are within the range of low power, line-of-sight radio links to shore (typically 20 to 50 km, depending on the height of the shore antenna). The complete system is designed for maintenance-free operation for periods of one year or more to minimize the costs associated with long-term monitoring programs. The cost of a station is estimated to be ~$70,000-$100,000.

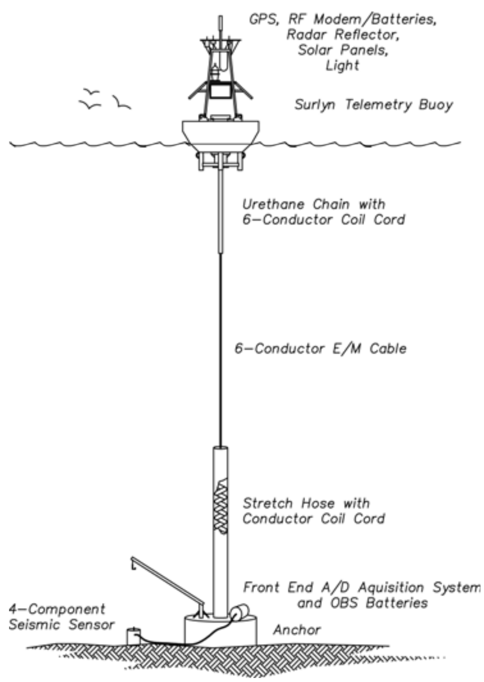


Figure 12. Real-Time Offshore Seismic Monitoring Station (courtesy of U. ten Brink).

The use of military communication cables is another potential new use of technology to further real-time monitoring in southern California. The U.S. Navy's SOund SUrveillance System (SOSUS) has been used by C. Fox at NOAA's Pacific Environmental Laboratory since 1991 to detect and located submarine earthquakes within the northeast Pacific Ocean. Originally used for detecting submarines, these hydrophone arrays can detect very small magnitude earthquakes at great distances using their t-wave (water-borne) arrivals. P-wave, converted S-wave and other seismic arrivals are also recorded for larger events. Similar SOSUS cables exist offshore on the western side of San Nicholas Island, and may soon be reactivated through the NOAA Ocean Exploration program (C. Fox, pers. comm.).

Biological, environmental, or biogeochemical sensors would complement the array of geophysical analyses and provide linkage to other funding agencies and scientific collaborations. For example, biogeochemical sensing may be applied in direct association with fault zone exploration and reconnaissance. Fluid expulsion through the sediments around a fault zone may be detected with in situ sensors for dissolved solutes and gases. These measurements plus discrete water samples could supply information concerning fluid residence times within fault zones and the depth of circulation. The presence or absence of methane in the water column has been used as a tracer for fault zone location. A methane 'sniffing' survey can be performed from a ship traversing the region and sediment disturbance structures (blow-outs), also indicative of fluid and gas escape around a fault zone, may be detected via side-scan or high-resolution seismic during such a survey. Biogeochemical tracers are useful stratigraphic markers and provide an excellent time-horizon for paleoseismicity studies conducted in marine sediments. Biogeochemical and meteorological moorings coupled to geophysical devices would provide information concerning phytoplankton blooms (including harmful algal blooms), vertebrate migration patterns, ocean circulation and chemical/pollutant dispersion. The adaptation of telephone and power cables between Los Angeles and Catalina Island for scientific use is being studied, particularly for a benthic observatory which would be equipped with water and sediment sampling, and sensing devices. The access to electrical power and the immediate data availability make this type of network particularly favorable for geophysical application.

A scientific benefit to ocean bottom seismic monitoring in the Borderland region would be the recording of whale songs. Of particular interest in this region is the Blue whale, an endangered species, which is known to frequent the Borderland region. Also endangered and seen in this area is the Fin whale. Both the Blue and Fin whale have songs within the frequency range appropriate for seismic instruments. Different species have different characteristic patterns and frequencies that can be identified on the hydrophone and seismometer channels of an OBS, and with appropriate instrument locations the whale can be tracked as it travels through the array. The type of close array studies required for the seismic objectives in the Borderland region should allow for excellent coverage of whale movements. This information would be of great use in studying a number of issues critical to the survival of these endangered species, including population estimation, impact of various noise sources including shipping, and migration studies

Complementary monitoring studies using ocean observatories can lead to multi-disciplinary research programs. The data needed to complete the understanding of offshore systems should come from a variety of sensor types. The following is a representative summary of new data that should be considered as part of the Borderland Working Group's sustained ocean observatory monitoring objectives:

### New Data Needed

- continuous waveforms from real-time offshore seismic monitoring station prototype(s);
- development of permanent, real-time, seismicity monitoring capability;
- temporary three-dimensional OBS deployment background seismicity data;
- use of temporary OBS deployments in RAMP-type aftershock studies;
- northern Borderland island GPS measurements;
- first-epoch acoustic geodesy measurements of seafloor sites;
- complementary biological, environmental, and biogeochemical monitoring data.

## Summary

This document has been an attempt to outline the most widely discussed, high-priority science objectives but is not meant to be exhaustive. Moreover, the focus of the objectives is likely to change as the number of Working Group participants and body of Borderland research grows. The white paper should exist as a living document that will be modified on a regular basis as SCEC Borderland science and data collection goals are met and updated.

As complementary experiments to collect offshore data are developed, they should be designed to take advantage of similar needs (e.g., ship time, temporary OBS network). Some experiments could conceivably be conducted in a piggy-back fashion (e.g., deploying sonobuoys during an active-source seismic experiment, making gravity measurements during an OBS deployment). This approach to exploring the Borderland will provide the greatest wealth of new data to investigators to attack the complex scientific problems from a broad front. It will also reduce the net costs of permitting, mobilization, and ship time. The Borderland Working Group recognizes that an overarching research plan should not be composed of a number of independent, small-scale experiments pieced together. In an initiative such as this, the whole effort should far exceed the sum of the individual parts.

It is expected that the largest potential sources of Borderland research funding will be the National Science Foundation (NSF) Earth Sciences, Ocean Sciences, and Continental Dynamics divisions, the U.S. Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA). New collaborations between the NSF Earth Sciences and Ocean Sciences programs will be explored. SCEC-endorsed proposals are likely to be collaborative, multi-institutional, multi-disciplinary submissions with future projects designed to build on related concurrent or preceding projects. Related Borderland efforts will include the exploration of potential new partnerships with or endorsements from the NSF MARGINS program, the USGS Earthquake Hazards Team, the USGS Coastal and Marine Geology Team, NOAA, and the Minerals Management Service. NASA programs for geodesy and space-based imaging (Western North America Interferometric Synthetic Aperture Radar: WInSAR) may also provide significant research funding for related projects in this important offshore area. Borderland studies will be further enhanced by collaboration with international colleagues, particularly earth scientists from Mexico who are actively engaged in Borderland research.

# Appendix A

March 8-10, 2002 workshop and preliminary working group participants

| | |
|---|---|
| Agnew, Duncan | Scripps |
| Babcock, Jeff | UCSD |
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| Berelson, Will | USC |
| Broderick, Kris | UCSB |
| Burbank, Doug | UCSB |
| Chaytor, Jason | Oregon State |
| Clayton, Rob | Caltech |
| Driscoll, Neal | UCSD |
| Fisher, Michael | USGS |
| Fletcher, John | CICESE |
| Francis, Robert | CSULB |
| Fuis, Gary | USGS |
| Goldfinger, Chris | Oregon State |
| Gonzalez Garcia, Javier | CICESE |
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| Henyey, Tom | USC |
| Hey, Richard | Hawaii |
| Hogan, Phil | URS Corp. |
| Janik, Aleksandra | U. of Miami |
| Jones, Lucile | USGS |
| Jordan, Tom | USC |
| Kamerling, Marc | UCSB |
| Kent, Graham | UCSD |
| Kohler, Monica | UCLA |
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| Magistrale, Harold | SDSU |
| Michael, Andy | USGS |
| McRaney, John | SCEC |
| Muller, Jordan | Stanford |
| Nicholson, Craig | UCSB |
| Normark, William | USGS |
| Okaya, David | USC |
| Orcutt, John | UCSD |
| Perry, Sue | SCEC |
| Ponti, Dan | USGS |
| Ross, Stephanie | USGS |
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| Sorlien, Chris | UCSB |
| Stock, Joann | Caltech |
| Ten Brink, Uri | USGS |
| Tolstoy, Maya | Lamont-Doherty |
| Uhrhammer, Robert | Berkeley |
| Wong-Ortega, Victor | CICESE |