Highlights of research activities 1992-1993

1. Crustal Structure and Tectonics

Personnel: T. Atwater, C. Busby, S. Cisowski, R. Crippen, J. Crowell, D. Imperato, E. Keller, J. Lees, H. Loaiciga, M. Legg, **B. Luyendyk***, C. Nicholson, B. Patrick, W. Prothero, C. Smith, C. Sorlien, L. Steck, A. Sylvester, Toshiro Tanimoto, J. Um, C. Weiland (* Agenda coordinator)

Development of Basins and Calderas in Extensional to Transtensional Arc Settings (C. Busby)

This project comprises the study of volcanoplutonic arcs, including sedimentology, process volcanology, structural geology and geochronology. This integrated approach resulted in (1) formulation of a now widely-cited tectonic model for the origin of thick, continuous belts of continental arc strata, and (2) recognition of the effects of oblique subduction on the stratigraphic, structural and metamorphic evolution of basins and plutons within arcs. Although more focused in scope, an Article in press in *Science* should put an end to a long-standing debate with important process volcanological implications, because it documents and presents a model for deep-marine eruption and welding of ignimbrite. Most of Busby's work in volcanoplutonic arcs has been in extensional settings, both continental and oceanic, but she has recently begun to characterize the effects of transtension on subsidence patterns within arcs. This project targets well-exposed, little-altered and barely deformed rocks that show the interrelations of grabens, calderas and basement structures in a transtensional arc setting. Work in progress documents sinistral transtension along the Sawmill Canyon fault zone in southern Arizona contemporaneous with the Jurassic opening of the Gulf of Mexico and sinistral displacements along the Sonora-Mojave megashear system. The project will analyze the fault-subsidence styles of transtensional graben systems present immediately before and during caldera development, and examine ways in which caldera collapse and filling are influenced by regional structures.

Terrane Analysis in Baja California: Campanian to Eocene Tectonics and Sedimentation of the Vizcaino Terrane (Busby)

The goal of this project is to constrain Late Cretaceous through Paleogene plate tectonic reconstructions of the eastern Pacific, and test published paleomagnetic results bearing on the paleogeography of the Late Cretaceous convergent margin of southern and Baja California. Field and laboratory work focus on detailing the motion/accretion history of the Vizcaino terrane, Santa Ana terrane, and North America. The following specific questions are being addressed via a detailed study of the Upper Cretaceous through Eocene strata exposed on the southern margin of the Vizcaino Peninsula: (1) When was the Vizcaino terrane accreted to North America? (2) When were the Santa Ana and Vizcaino terranes amalgamated? (3) Can the instantaneous or average latitudinal velocity of the Vizcaino terrane be used to constrain reconstructions of Middle Cretaceous through Eocene Pacific/Farallon/Kula plate motions?

Ancient intensity of the Earth's magnetic field studied by the isotope Beryllium 10 (Cisowski)

Research detailing the behavior of the earth's magnetic field during it's last polarity reversal, which took place about 700,000 years ago, has recently been completed at UCSB's Paleomagnetic Laboratory. The most recent work involved measurement of an isotope of beryllium (10Be) from a sediment core which was deposited in the North Pacific during this last change in magnetic polarity. Since this beryllium isotope is formed in the upper atmosphere due to the interaction of the solar wind and the atmosphere, and as the magnetic field acts to shield the earth from the solar wind, the abundance of the isotope should reflect the strength of the field during the polarity reversal. These new results are in agreement with previous results obtained from a study of the strength of the magnetic signal recorded in these same sediments, and confirm that the earth's field suffered dramatic fluctuations in intensity for several thousand years prior to it's polarity transition. Because the intensity of the magnetic field may have some bearing on global climate, paleomagnetic intensity studies such as this could result in a better understanding of long term changes in the earth's weather patterns. The beryllium analysis was done in collaboration with Dr. D. Lal of Scripps Institute of Oceanography at UCSD, Dr. J. Southon and Dr. R. Finkel of Lawrence Livermore National Laboratory, and Dr. D. Lea of the Geological Sciences Department, UCSB, and was funded by the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory. Preparation of the samples for analysis was done by J. Athanassopolous as part of her doctoral thesis work at UCSB. The beryllium work represents the culmination of a research project begun in 1986 by Dr. Cisowski following his participation in Leg 126 of the Ocean Drilling Program, from which the studied samples were obtained.

Subsurface structure and stratigraphy at the Elk Hills Reserve, California (Imperato, Crowell)

Bechtel Petroleum Operations, Inc. and the Department of Energy have provided support for a research effort to better understand the results of recent deep drilling at Elk Hills Naval Petroleum Reserve No. 1, in the southwestern San Joaquin Valley less than 15 miles from the San Andreas fault. Three deep tests, including the deepest well drilled in California (24,426 feet), more than 500 shallower wells, and previously unreleased seismic-reflection sections provide the basis for an analysis of structural and depositional history of Elk Hills and vicinity. A primary goal of the research is to compare depositional and structural styles prior to, during, and after initiation of the San Andreas transform plate boundary. Deformation at Elk Hills conforms to a model of fault-propagation folding related to an imbricate thrust system. Southwest-directed thrust faults "die out" up section, and shortening is taken up by folding of the shallower rocks. Thrusting probably began during subduction tectonics and this same deformational style continued after initiation of the San Andreas transform plate boundary, with a major period of deformation beginning in the latest Pliocene and continuing today. Strike-slip faulting is restricted to an area less than 3-4 miles northeast of the San Andreas fault, consistent with strain partitioning models recently proposed for the San Andreas fault.

Post-early Miocene clockwise rotations in the northeast Mojave Desert, California (Luyendyk, Cisowski)

Paleomagnetic, structural, and geochronology data suggest that about 60° net of post-early Miocene clockwise vertical-axis crustal rotation has occurred in parts of a broad area of the northeast Mojave Desert. The region includes Fort Irwin military reservation; it is bounded by the Garlock fault on the north, the Avawatz Mountains on the east, and the Goldstone Lake fault on the west. The southern boundary is uncertain and the western boundary may be slightly further east. The Neogene-age predominant structural grain comprises a set of east-west striking sinistral faults. Volcanic rocks are dominantly early Miocene basalts and andesites, and minor late Miocene-early Pliocene basalts. Rocks as young as 16 Ma are offset by the faults the same amount as Mesozoic and Paleozoic markers; Pliocene through Holocene rocks are also offset an uncertain amount. Paleomagnetic data show NNW and ENE deflected declinations in early Miocene rocks; the younger rocks may record an excursion of the field. The NNW directions are believed to be secondary, and are possibly related to past hydrothermal activity in the region. One possible interpretation is that elongate blocks defined by the east-west faults were rotated from NNE to E-W orientation after ~16 Ma. Younger fault offsets permit the rotation to be much younger. The rotation was accompanied by sinistral faulting and local dilation in the region. However, fault offsets predicted by the rotation of elongate blocks do not match field observations, which suggests that small crustal pieces are involved. The rotation detected here is younger than those in the Mojave extended terrains which occurred from 22 to 18 Ma. It may correlate with the post 14 Ma rotation of the Cady Mountains and the post Miocene rotation of the Eastern Transverse Ranges south of here.

Geological and geophysical studies in Marie Byrd Land, West Antarctica (Luyendyk, Smith)

Luyendyk and Christine Smith took part in an expedition to Marie Byrd Land supported by the seventh German National Antarctic Expedition (GANOVEX VII), operating off the Norwegian-registered, ice-strengthened ship, *Polar Queen*. King Edward VII Peninsula (KE7), western Marie Byrd Land (MBL), is a largely ice-covered, domal feature containing the sparsely exposed and widely separated rock outcrops of the Rockefeller and Alexandra Mountains and outlying nunataks. The primary objectives for the 1992-93 season on KE7 were to extend gravity coverage over apparent gravity features detected in an earlier survey, to obtain samples for paleomagnetic study to augment existing data from the northern Ford Ranges in MBL, and to explore the relationship between the Fosdick Metamorphic Complex of northern MBL and the Alexandra Complex of KE7. Ancillary observations of glacial and volcanic features were taken in the northern Ford Ranges. Brief echo sounding surveys offshore from the Ford Ranges were also made. We visited all outcrops in the Alexandra and Rockefeller Mountains obtaining samples of Cretaceous Byrd Coast granite and early Paleozoic Swanson Formation. Seven paleomagnetic sites were made in the granite. Thirty gravity stations were established using GPS control.

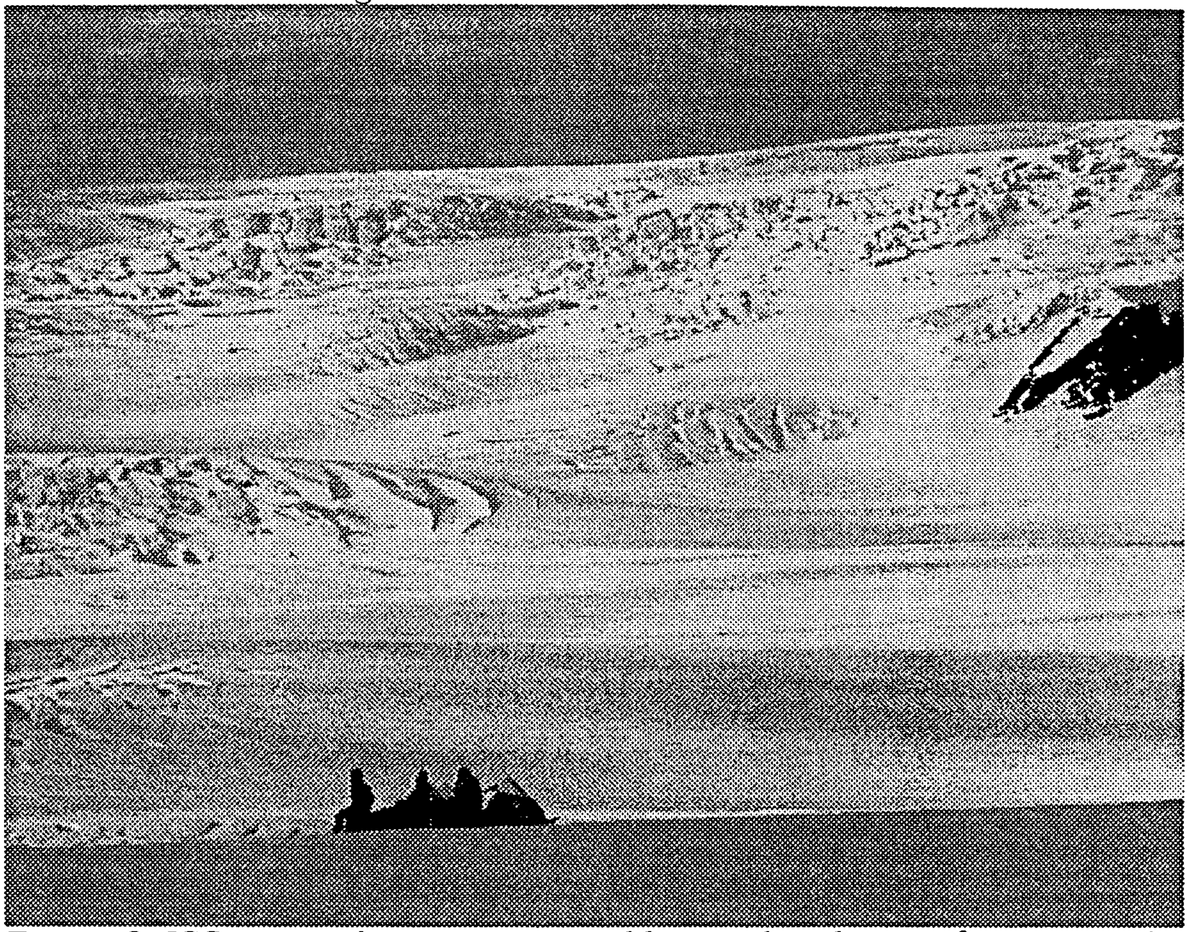

Figure 6: ICS researchers on snowmoblie on the slopes of Mount Erebus, Antarctica. Photo by Steve Richard.

Crustal Imaging And Extreme Miocene Extension Of The Inner California Continental Borderland (Nicholson, Sorlien, Legg)

In 1990, nearly 2800 km of seismic reflection data were collected across the offshore margin of southern California. We have analyzed over 250 km of these data to help resolve the nature of active faulting and tectonics in the Inner Continental Borderland, including parts or all of USGS lines 112, 113, 114 and 118. The data were severely contaminated by water-bottom and pegleg multiples. Particularly difficult were steeply-dipping multiples; however, *f-k* filtering in shot and CDP space proved somewhat effective. The most significant feature along the eastern part of Line 114 is the newly identified NE-dipping 30-Mile Bank detachment. Along line 112, this low-angle fault is traceable up onto 30-Mile Bank beneath Miocene volcanic rocks, and is offset by a high-angle fault that controls the steep NE-flank of 30-Mile Bank. The detachment forms the floor of the sedimentary basin in the western San Diego Trough, is traceable as far east as Coronado Bank, and exhibits a flexurally-rotated geometry characteristic of large-scale extension. High-angle faults of the Coronado Bank fault system occur above the major E-dipping normal-separation Coronado Bank fault, whose near-surface dip decreases northwards. The dominant tectonic style of the region consists of back-tilted crustal blocks, forming horsts and half-grabens that define local basins, ridges, and islands. This structure evolved mostly during early-to-middle Miocene time above low-angle detachments that expose high-grade metamorphic rocks of the Catalina terrane. Line 118 exhibits considerable evidence for extreme extension, including gently dipping faults and severely back-tilted blocks whose dips are too steep to image. This extensional structure was subsequently dissected, over-printed, and in places, re-activated and folded by oblique right-slip associated with the evolving transform plate boundary—with components of oblique slip varying in both space and time from transtension to transpression as a result of changing plate-motion vectors and local fault geometry. The more recent oblique strain appears to be largely partitioned into high-angle faults that accommodate lateral motion, that merge with, or in places offset, the older, more gently-dipping extensional faults that have been reactivated with reverse or oblique-reverse slip.

Miocene Collapse of the California Continental Margin (Nicholson, Sorlien, Luyendyk)

Late Oligocene and Miocene development of the California margin has long been thought to include major lateral displacement on offshore strike-slip faults. Recently reprocessed and interpreted deep multichannel seismic reflection data however, image many of these supposed Miocene transform structures as broad families of gently-dipping faults with normal separation. Major faults that exhibit Miocene extension include the southern Santa Lucia Bank fault and related Ferrelo fault, East Santa Cruz Basin fault, 30-Mile Bank detachment, and Coronado Bank fault. Beneath the Inner California Borderland, pre-rift and syn-rift sediments are severely back-tilted, while post-rift sediments fill the resulting half-grabens. Additional near-vertical faults cut the post-rift sediments and in some places, offset or merge with underlying detachment faults. Basin inversion initiated at the end of Miocene time, but more important shortening is probably post-early Pliocene. The post-Miocene transpression appears to be largely partitioned between steeply dipping hanging-wall strike-slip faults and reactivation of detachments as thrusts or oblique faults. This suggests a revised tectonic model in which offshore Neogene dextral motion may be limited to 250 km or less. Monterey and Arguello plates continued to subduct beneath the present offshore south-central and southern California margin through much of early Miocene time. The end of subduction resulted in relaxation of the compressed N. American plate margin and collapse of the upper crust;

this collapse was enhanced by capture of the partially subducted Monterey plate by the Pacific plate. The resulting extension, combined with components of transform motion, facilitated the rotation of the Western Transverse Ranges, and nearly doubled the width of the offshore California Continental Borderland. Extensional strain across the Borderland may have been at rates of cm/yr, creating sediment-starved basins and Basin-and-Range topography. More recent transpression has produced regionally continuous folds in WNW-trending basins, while in NNW-trending basins, important folds are typically localized to restraining bends of strike-slip faults.

New Analysis Tools for Subsurface Imaging of 3-D Fault Structure and Material Properties (Nicholson, Lees)

Improved techniques for the analysis of earthquake data are developed to enhance the subsurface imaging of 3-D fault structure, velocity structure and attenuation structure. In areas where dense clusters of earthquakes occur, an interactive computer processing program allows for the display of earthquake hypocenters in both map and cross-section view, combined with subsurface information from well logs and seismic reflection or refraction profiles. In addition, individual earthquake focal mechanism information can be plotted using either nodal planes, stress-axes orientations or single fault planes, with individual focal mechanisms colored according to rake angle. This allows for proper identification of active subsurface fracture networks, and the recognition of subsurface fault slip and strain patterns in 3-D. We have also developed the capability to perform joint high-resolution 3-D tomographic inversions using combinations of seismic, attenuation, and gravity data and to enable comparisons between different tomographic images using independent data sets. These tools are initially applied to data acquired from the 1992 Southern California earthquake sequence, with particular emphasis on the detailed fault structure active in the Joshua Tree area before and after the large M7.4 Landers mainshock of June 1992. We also investigate the relation between active faults, regions of high and low seismic velocity, and variations in heat flow in an active geothermal region.

Project Aloha: Imageing the crustal structure of the island of Hawaii (Prothero)

A passive seismic field experiment was carried out to image the major discontinuities in structure beneath Hawaii, with the primary aim of testing the hypothesis that major earthquakes occur along a subhorizontal buried sediment layer (BSL) at the interface between the volcanic pile and the underlying ocean crust. This was a cooperative project between W. Prothero, of UCSB, and C. Thurber, of Univ. of Wisconsin. We applied array techniques to S to P and P to S converted seismic waves from deep local earthquakes to image the volcano-ocean crust and crust-mantle interfaces beneath the southeast flank of Mauna Loa volcano. The former ranges in depth from 8.5 to 12 km, consistent with the depth distribution of thrust earthquakes, whereas the latter ranges in depth from 15 to 18 km, in conflict with previous flexure models. The thickness of the BSL is estimated to be 1 km. Ground motions in a low frequency band (0.1 to 10hz) were also recorded at a 5 station array to test whether receiver function analyses could be used to recover deep structure. In spite of high coherence at frequencies of 1 hz and below (at station spacings of 5-7 km), large scale heterogeneity beneath the array and high microseismic noise resulted in a null result for this portion of the experiment.

Structure beneath the Long Valley Caldera, California (Steck, Weiland)

Our study seeks to image the low velocity zone (LVZ) underlying the Long Valley Caldera. The presence of strong vertical and lateral heterogeneity in magmatic environments compounds the problem of adequately modeling wave propagation, as raypaths will undoubtedly be highly 3-dimensional. The consequence of ignoring diffracted raypaths in tomographic inversions is to underestimate the size and amplitude of the perturbing feature, so it is particularly important in terms of volcanic hazard assessment. We employ a more realistic model of wave propagation than has been used in previous teleseismic travel time inversions at Long Valley. This technique provides particularly accurate travel times and raypaths in the presence low velocity volume compared to other techniques. Our non-linear scheme has been tested using synthetic velocity models and yields better results in terms of travel time errors and model simplicity than a standard, straight ray approach, especially when the low velocity zone is greater than a few (~5) percent. Our model of the Long Valley Low Velocity Zone is consistent with previous results showing a large body between 7-15 km depth, centered beneath the resurgent dome section of the caldera.

Nearfield investigation of strain across faults in southern California (Sylvester)

During the contract period we resurveyed our existing leveling lines and trilateration arrays in the region of the 1992 Landers earthquake to determine if post-seismic slip has occurred along the faults since Christmas 1992. The answer is a qualified "no." We measured no changes of significance across parts of the surface rupture where we had not measured post-seismic slip in the period a few hours after the earthquake to Christmas 1992. Arrays at the south end of the surface rupture slipped as much as 40 mm after the earthquake, however, and continued to slip into 1993 at a logarithmically decaying rate. We also resurveyed all of our leveling lines in the creeping section of the San Andreas fault, that is, between Parkfield and San Juan Bautista. We have been surveying the lines for 8 to 18 years, so now we begin to have a significant period of time to observe and compare changes. We find significant vertical displacements in Cholame Valley (15 mm in 18 years), Lewis Creek on the Monterey/San Benito County line (20 mm in 8 years), and at San Juan Bautista (80 mm in 15 years). Lines near Parkfield, where horizontal creep is about 13 mm/yr, have very little associated vertical displacement. Therefore we have the first evidence that vertical creep accompanies the well-known horizontal creep along several parts of the fault.

Studies of mantle and crustal structure from seismic tomography (Tanimoto, Um)

Seismic waves provide not only the information about earthquakes that generated them but also about the Earth's interior structure through which they propagate. Two NSF grants supported research to improve our understanding of Earth structure, which will eventually help us to understand what kind of tectonic motions are occurring in the deep interior. One project supports research to understand the dynamics of the whole mantle while another aims to study the shallow structure in more detail. For example, differences in two types of upwelling motions in the Earth, namely ridges and hotspots, are becoming clear in seismic velocity maps, improving our understanding on how materials are welling up from the deep interior. Constraints on the large-scale motion of the mantle are also becoming clear through our efforts. Invited papers based on these research efforts were presented at Fall and Spring meetings of the American Geophysical Union, GEOSCOPE 10th anniversary meeting in France (September, 1992), and a meeting on geodynamics in Japan (March, 1992).

Investigations in areas of subsidence in the onshore fold and thrust belt of the Cascadia Subduction Zone (Keller, Valentine)

Stratigraphy within synclines associated with a fold and thrust belt in northern California, contains evidence for multiple paleoseismic events. We hypothesize that the stratigraphy is formed in part by repeated submergence of lowland surfaces near sea-level as subsidence occurs within the synclines during great earthquakes.

During the 1992 field season, three large earthquakes occurred near the Mendocino triple junction (MTJ) on April 25th and 26th Cape Mendocino earthquakes (Mw 71, 6.4, and 6.7). In conjunction with Angela Jayko of the USGS, and Gary Carver and Wen Hoa Li of Humboldt State University, we collected data on the mortality of intertidal organisms along the coast which we used to infer up to 1.2 meters of coastal coeismic uplift. The data was collected following the earthquake, and again in September of 1993. In August of 1993, with the assistance of researcher Paul Bodin from CIRES at the University of Colorado, Boulder, we releveled 21 benchmarks emplaced and surveyed in the weeks following the Cape Mendocino Earthquake.

Latest Pleistocene to Holocene rupture history of the Santa Cruz Island Fault (Keller, Pinter)

Latest Pleistocene to Holocene displacement and assumed paleoseismicity on the Santa Cruz Island Fault (SCIF) in southern California suggest that future seismicity is likely, and the fault represents a significant hazard to millions of people living in southern California. Research objectives are:

- Establish the late Pleistocene to Holocene chronology of displacement on the SCIF based on identification and dating of the deposits at the west end of the island where we have evaluated a natural exposure of the fault.
- Calculate the magnitude and extent of the seismic hazard associated with the SCIF. This includes age of most recent ruptures, slip rate, and maximum magnitude of earthquakes expected.
- Better understand how the SCIF system is related to other major geologic structure, including the Transverse ranges and the San Andreas Fault.

Progress in 1992-93:

- Field work to locate potential site for evaluating the displacement history of the Santa Cruz island Fault (SCIF).
- Excavation and logging of site exposed in a small gulley at the west end of Santa Cruz Island.
- Collected Material for radiocarbon dates to help define a rupture history of the SCIF

2. Crustal Materials

Personnel: L Ames, A. Blythe, C. Balzer, A. Giacobbe, C. Hopson, C. Oldenburg, B. Patrick, F. Raia, N. Rosenberg, **F. Spera***, D. Stein, G. Tilton, C. Smith, A. Trial, W. McClelland (* Agenda coordinator)

Molecular Dynamics and Experimental Rheology (Spera, Raia, Stein)

The liquid state, especially an understanding of the relationship between fluid structure at the atomic level and its thermodynamic and transport properties is relevant to a range of energy and material resource problems. In our work, we are systematically applying the method of Molecular Dynamics to study the properties of H_2O at elevated pressures and temperatures as well as the properties of melts at superliquidus temperatures in the system $NaAlSiO_4$-SiO_2. Here, we emphasize the completed work on silicate melts

We have studied, by experimental methods the rheological properties of six liquids in the system $NaAlSiO_4$-SiO_2 (Stein and Spera, 1992). These melts behave as Newtonian fluids (linear shear stress - shear rate relationship) in the range of temperatures (1050-1400°C) and shear rates (10^{-2} to 10 s^{-1}) explored. We find that as $NaAlO_2$ is added to SiO_2, both the viscosity of the melt and its arrhenian activation decreases systematically. Because all melts in this system are network tetrahedral fluids, the decreased activation energy and viscosity cannot be ascribed to the formation of non-bridging oxygen upon addition of $NaAlO_2$. Instead, we interpret these data according to the coupled substitution [Na+Al=Si]. The longer and weaker Al-O bond relative to the Si-O bond and the polarizing effects of Na serve to increase the fragility of melts across the join $NaAlSiO_4$-SiO_2.

In order to make the link between the macroscopic and atomic worlds, we have performed Molecular Dynamics simulations on $NaAlSiO_4$-SiO_2 melts at high temperatures and pressures. The goal is to see if a simple effective pair potential of the Born-Mayer type can be used to predict structural, thermodynamic and transport properties (Spera and Stein, manuscript in preparation). We have shown that, indeed, the MD technique can make decent predictions of many important transport and material properties. The MD simulation technique therefore offers a method significantly cheaper than laboratory studies to estimate properties of silicate liquids at conditions relevant to crustal geothermal and hydrothermal systems. Obtaining estimates of properties by MD simulations requires long MD runs (100 ps) with many (several thousand) particles. These are computationally demanding calculations that could not have been accomplished only a few years ago.

Three additional studies germane to magma properties have been carried out during the funding period. The first is an assessment of two widely used methods for calculating the viscosity of natural silicate melts. This was done by comparing the predictions of the two methods (Bottinga and Weill, 1972; Shaw 1972) against measurements made in our laboratory at UCSB. We found that the Shaw algorithm produces the more reliable estimate of melt viscosity as a function of temperature (Stein and Spera, 1993).

Secondly, in a contribution recently published in Science, (Spera and Trial, 1993) we have verified the validity of Onsager's Reciprocal Relations in the system CaO-Al_2O_3-SiO_2. Although previous experimental tests of the ORR for aqueous and metallic solutions have been made, our work is the first to report conformity with the ORR for a molten silicate solution. That is, we have verified the symmetry of the phenomenological matrix relevant to isothermal multicomponent chemical diffusion in the system CaO-Al_2O_3-SiO_2. This opens up the door to the possibility of using Molecular Dynamics simulations to predict the chemical diffusion matrix (not to be confused with tracer or self-diffusion) of multicomponent fluids including aqueous brines and natural silicate liquids.

Finally, a study has been made of the rheological properties of dilute germanate emulsions containing 1 to 5 volume percent vapor at high temperatures and variable shear rates (Stein and Spera, 1992). The emulsions are pseudoplastic (shear thinning) fluids described by a relative viscosity $h_r=1+13\emptyset$. Normal stress coefficients amounting to several percent of the total shear stress were also determined. An understanding of the non-Newtonian properties of a common geomaterial (magma) is important from both a practical and fundamental point of view. Because H_2O is a common component, virtually all natural magmas contain vapor bubbles. These impart a significant degree of non-Newtonian behavior. We are studying this behavior in the laboratory.

Thermohaline Convection in Sedimentary Basins and Hydrothermal Systems (Spera, Balzar, Oldenburg, Rosenberg)

Since the discovery of double-diffusive convection in the late 1950's it has become recognized that this phenomenon occurs widely in nature (e.g. oceans, groundwater, hydrothermal systems, magma bodies). Sometimes referred to as double-diffusive convection (DDC), the instability derives from the fact that chemical diffusion is slower than heat diffusion and because the density of a fluid depends on both its temperature and composition. Although a fair amount of work has been done on DDC in viscous fluids, very little work has been done to investigate DDC in porous media. The objectives of our study are to investigate the fundamental dynamics of thermohaline convection in porous media with application to hydrothermal systems and sedimentary basins. In both these geologic environments, saline solutions are known to occur. Because virtually no previous simulation work has been done, we have focused on developing a basic understanding of the role played by the key parameters (thermal Rayleigh number (Ra), salinity Rayleigh number (Rs), porosity of medium (Ø), and diffusivity ratio, Le) on controlling the nature of heat and mass transport in these systems. We have undertaken detailed simulations of thermohaline convection (Rosenberg and Spera, 1992a, 1992b). Because of the heterogeneous and anisotropic nature of permeability in geological systems, we have also studied thermal convection in anisotropic and/or layered porous media (Rosenberg and Spera, 1993). We have found that the character of the solutions to the governing conservation equations depends markedly on the parameter values. Unlike double-diffusive convection in clear (viscous) fluids, in porous media thermohaline convection, the ratio of advective heat transport to solute transport is proportional to $Ø^{-1}$ since fluid, unlike heat, can only be transported through connected porosity. This feature dramatically effects the stability of subcritical thermohaline flows and gives rise to behaviors unlike classical viscous DDC. At large Ø, such as in a poorly consolidated sediment, as Rr increases at fixed Ra, the style of flow changes from steady convective to chaotically convection and finally to stably stratified (static) when Dirichlet conditions on T and C are applied along the horizontal boundaries. For small values of Ø such as in a fractured lithologic unit, the region of chaotic flow in the Ra-Rr plane diminishes. An approximate relationship amongst the critical parameters that demarks the boundary between stable stratification and convective chaos is $Ra = 4p^2 + 200(1-Ø) + 150Rr$ valid for $0.05 < Ø < 1$, $0 < Ra < 600$ and $0.1 < Rr < 1.5$. For flows in poorly consolidated sedimentary environments and in some hydrothermal systems we find that chaotic solution may prevail. This means that, for example, the concentration of salt in the fluid at a fixed location will vary aperiodically. This is consistent with patterns of brine concentrations trapped in fluid inclusions as well as complex patterns of diagenetic alteration observed in some exhumed basins. It is also possible that this chaotic behavior is relevant to observed temporal changes in hydrothermal vent fluid compositions. These calculations are relevant to myriad geological, hydrological and environmental problems including heat extraction from continental geothermal regions, the origin of hydrothermal ore deposits and the dispersions of contaminants in groundwater systems.

Magma Dynamics (Spera, Giacobbe, Trial)

We have recently completed detailed calculations modeling the hydrodynamics of the withdrawal of magma from density and viscosity stratified reservoirs. From examination of the stratigraphic record of pyroclastic deposits at many geothermal sites (e.g., Long Valley, Valles Caldera, Katmai-Valley of Ten Thousand Smokes, Yellowstone), we know that zoned magma bodies are very common. This is an especially interesting problem because less dense (more silicic) magma is also more viscous. Details are presented in Trial, Spera and Yuen (1992).

High temperature metamorphic rocks from the Kigluaik Mountains, Alaska (Patrick, Ames, Blythe, McClelland)

Patrick's group is studying the temporal, thermal and kinematic evolution of crustal materials during a period of crustal deformation associated with Mesozoic convergent-margin tectonics in northwestern Alaska. Field work in the summers of 1992-93 focused on determining the direction of large-scale crustal movement associated with high temperature metamorphism in the Kigluaik Mountains of Seward Peninsula. Structural data indicate that this crustal block was plastically flowing to the west at ~105 million years ago (determined by U-Pb geochronology of the high-temperature metamorphism). This high-temperature flow contrasts sharply with crustal movements determined for lower-temperature metamorphic rocks flanking the Kigluaik Mountains. The lower-temperature rocks flowed northward at >120 million years ago (determined by $^{40}Ar/^{39}Ar$ geochronology). These earlier crustal movements were associated with profound crustal thickening. The complex thermal and structural history of the Kigluaik Mountains is most satisfactorily explained by a progression from deep burial by island arc-continent collision (N-S compression) followed by thermal reequilibration of this buried crust which led to partial melting and late-stage magmatism. Buoyant uplift of this hot mass occurred during E-W compression associated with post-collisional extrusion tectonics. The results of this project have implications regarding the origin of high-temperature metamorphism in convergent settings and the time scale of thermal equilibration of thickened continental crust.

3. Earthquakes

Personnel: Ralph Archuleta*, Michele Campillo, Jonathan Lees, Grant Lindley, Aaron Martin, David Oglesby, Craig Nicholson, Peter Rodgers, Sandra Seale, Jamison Steidl, Scott Swain, Jess Taylor, Alexei Tumarkin, Alla Tumarkin (*Agenda coordinator)

Research in seismology has been expanded into many different areas because of support from the Southern California Earthquake Center (SCEC).

Portable Broadband Instrument Center (PBIC) (Martin, Nicholson, Rodgers, Archuleta)

PBIC recorders and sensors were deployed for the three principal earthquakes that occurred in 1992: 22 April Joshua Tree: M6.1 Earthquake and 28 June Landers: M7.4/28 June Big Bear: M6.5 Earthquakes. Five PBIC and six PASSCAL DAS's (Data Acquisition System, DAS) were deployed within two days of the Joshua Tree mainshock. The array was maintained until early June and collected about 5-6 Gb of raw data. The PBIC corrected timing and performed event association of the 3-4 Gb of data left after reduction. Following the Landers/Big Bear earthquakes nine of the PBIC DAS's were deployed for this aftershock sequence. PASSCAL supplemented the SCEC array with 10 DAS's in the days following the mainshock. SCEC member institutions worked together to deploy and maintain the array: once fully deployed, consisted of 18 sites (see Figure 1) including 3 STS-2 and 2 CMG-3 broadband sensors. Approximately 15 Gbytes of data were collected in the six weeks following these earthquakes.

In other SCEC Experiments, the PBIC recorders have been deployed in Southern California almost continuously during the last year. The majority of recorders have been deployed, under different projects, in the LA Basin, with the remainder being deployed in the Cajon Pass and Keenwyld areas. Recorders have also been used in lab tests to calibrate sensors and evaluate noise characteristics of long cable segments.

The PBIC is currently working on methods of systematically calibrating sensors. Using software developed at LLNL, calibration pulses recorded from different sensors can be analyzed to produce accurate information about free period response and damping factors. The PBIC is also stressing the importance of deconvolving collected data to correct for instrument response.

Over the next several years the PBIC intends to expand the current instrument base to 25 DAS's, 20 FBA-23's, 25 L4C-3D and 4 STS-2's. DAS's acquired in future purchases will be equipped with GPS subsystems and many will have 24 bit digitizers. The high bandwidth of the 24 bit DAS's will allow user to collect very high quality data that covers the complete range of many of the sensors that are available.

Strong Motion Database (SMDB) (Tumarkin (Alla), Tumarkin, Archuleta)

The Strong-Motion Database **SMDB** was designed for the Southern California Earthquake Center to provide a fast and easy access to the strong-motion data. The SMDB database now contains the information about 85 earthquakes, 374 stations and 1911 components. The database combines the following features:

- it has a menu-driven user-friendly interface;
- both parametric and time-series data are available from the database;
- the parametric data are accessed through the network database model;
- the time-series are stored on-line in SAC format.

The major possibilities of the database include:

- performing various types of queries;
- processing time-series by means of SAC;
- obtaining maps of events and stations.

SMDB and its manual (the SMDB User's Guide) are available for the users of Sun 4 workstations via Internet. We are continously correcting and updating the database.

Maps of Site Amplification in LA (Tumarkin, Archuleta)

Site response studies should use both spectral and time-domain approaches. The analyses in the frequency domain (spectral ratio method, cross-spectrum method, etc.) have an obvious limitation of completely disregarding such an important engineering factor as the duration of shaking. At the same time the response spectral ratio method takes more care of duration, but in a not very explicit manner. That necessitates finding a way to incorporate duration-content information into site-response studies.

Our new method provides the amplification factor associated with signal's envelope. A direct comparison of envelopes of two recordings of ground motions at different sites seems impossible. Our idea is to rearrange amplitudes to produce an "equivalent" envelope, preserving absolute duration of shaking above an arbitrary amplitude threshold. Each given value *A* of the ordinate (observed amplitude) of this equivalent envelope corresponds to the value of the abscissa *D*, representing the total duration of shaking with amplitude greater than *A*. For equally spaced time-series this is easily achieved by sorting the initial envelope's amplitudes in a descending order. The resulting duration-amplitude graph represents an inverse function to the cumulative amplitude-frequency distribution (Schenk, 1985). Now we have a tool to study the amplification of envelopes of seismic signals by comparing amplitudes of ground motions with the same duration.

Our studies show that in the range of duration of a prime engineering concern (0.1 - 10 s), the envelope amplification between stations with different site geology is approximately constant. This fact allows us to introduce a time-domain measure of a gross amplification of ground shaking as the average ratio of sorted envelopes between 0.1 and 10 s. The comparison of envelope ratios with response spectral ratios (5% damping) shows that the envelope method is not so sensitive to site and/or source resonances, at the same time providing amplification values consistent with those inferred from the response spectral method. We have used this method to produce a map of gross strong ground motion amplification factors for the Los Angeles Basin.

Empirical Green's Functions (Tumarkin and Archuleta)

One of the most promising and widely used methods of simulating a heterogeneous mainshock rupture is the multiple event model, e.g., self-similar models of complex rupture, the specific barrier model, as well as some empirical Green's function methods (EGFM). The raison d'être of the EGFM is that it naturally accounts for the path and site propagation effects by using observed records of the subevents—small earthquakes co-located with the rupture areas of the simulated mainshock. The major difficulty with this approach is deciding how to sum the subevent records within the entire frequency bandwidth in a manner consistent with observed scaling relations between large and small earthquakes.

The current research is developing and validating an empirical spectral prediction satisfying three critical conditions:

- The prediction must be consistent with the entire observed seismic spectrum from the lowest to the highest frequencies.
- Source models must incorporate the basic scaling relations between source parameters and spectral parameters. The multiple event rupture model will allow for any distribution of subevent sizes (fractal, Gaussian, etc.)
- The prediction must allow for any subset of the available data, i.e., the predictor will allow for any number of recorded empirical Green's functions.

With these conditions met the spectral prediction will be internally self-consistent. It will account for the complexity of the source while maintaining the basic seismic scaling relations and the complexity of the path/site effects without being dependent on the characteristics of a single empirical Green's function. The practical output will consist of spectral predictions at characteristic sites for scenario earthquakes in Southern California.

LA Basin (Steidl, Chin-USC)

In the Spring of '93, Steidl began an experiment in site-specific hazard assessment in the Los Angeles metropolitan region. This work is a collaboration between Southern California Earthquake Center research groups at USC and UCSB. Dr. James Chin of USC and Steidl of UCSB, along with support from the SCEC/PBIC, have instrumented CDMG, USGS, and USC strong-motion sites with weak-motion instruments to examine and compare site response based on the two types of ground motion. One of the project goals is to create a site amplification map for the Los Angeles Basin based on seismic data, which can be used for earthquake hazard mitigation.

Landers Earthquake (Campillo, Archuleta, Steidl, Lindley)

Dr. Michel Campillo, a visiting professor from Joseph Fourier University, Grenoble, France, and Archuleta determined a set source parameters that correctly modeled the low frequency recordings of the Landers mainshock. The basic elements of the model is that the Landers earthquake consisted of two distinct segments, 20 and 30 km long, respectively. Rupture on the first segment causes slip of 3.5 m; the second segment 5.2 m. The rupture is delayed for one second between the first and second segment.

Following the 1992 Landers earthquake, two dense arrays of accelerographs were deployed in the epicentral region to examine the variation of ground motion over small distances and between soil and rock site conditions. Steidl looked at different methods for quantifying site amplification, concentrating on spectral ratio and cross-spectrum estimates of site response in this particular study. Steidl's analysis and subsequent paper based on these data resulted in his winning the student paper competition sponsored by the Earthquake Engineering Research Institute (EERI). Steidl was invited to talk at the EERI annual meeting in Seattle and publish his paper in the EERI journal Earthquake Spectra.

High-Frequency Modeling (Archuleta, Taylor)

Although the basic character of the low-frequency ground motion might be reproduced by a relatively simple model of faulting, the high-frequency ($f > 1$ Hz) ground motion requires a more complicated faulting model. In order to understand how the faulting occured on short time and length scales, Archuleta and Taylor have been using a numerical method, isochrons, to simulate the high-frequency radiation from a propagating fault. There is overall agreement between synthetics and data. Moreover the faulting model used for the high frequency radiation is not significantly different from the faulting model used for the low frequencies (thank goodness).

While SCEC has provided a major impetus to the seismological research, there are significant research programs underway independent of SCEC.

Garner Valley Downhole Array (GVDA) (Archuleta, Steidl, Tumarkin)

This project is downhole accelerometer array studies at Garner Valley, California, sponsored by the Office of Research, U. S. Nuclear Regulatory Commission, the French Commissariat à l'Energie Atomique and by the Electrical Power Research Institute. This project was started in 1987 and was recently funded through 1994. It involves the installation, maintenance, data acquisition and analysis of 10 dual-gain accelerometers, of which five are placed in a downhole array to a depth of 220 m and five placed in a linear surface array. The basic objective is to understand how the near-surface geology affects the amplitude and duration of seismic ground motion, especially strong motion. To date 737 earthquakes have been recorded at GVDA, including 88 with magnitudes greater than 4.0.

A second borehole with a depth of 600 m has been proposed to supplement the downhole array at Garner Valley. This deep hole would have accelerometers, pressure transducers and a borehole deformation gauge all within the same hole. It appears that this project will be funded and started in the Fall of 1993.

In the Fall of '92, Steidl began collecting data from boreholes and surface sites in the vicinity of the Garner Valley Downhole Array (GVDA) to examine the variation in the bedrock "reference" motion. Many studies of seismic zonation consider the site amplification at a particular location with respect to some "reference" site, usually a bedrock site. An assumption is made that the site response of the bedrock site is negligible, unity amplification over all frequencies of interest. Steidl has been collecting borehole data at GVDA as well as Pinon Flat, approximately 30 km from GVDA, and at Keenwild, approximately 7 km from GVDA, as well as surface bedrock sites to examine this critical assumption.

Extreme Accelerations (Archuleta, Ogelsby)

A puzzling attribute of some earthquakes is that extremely high ground accelerations (~1-2 g) may be recorded at certain accelerometers, yet nearby accelerometers record accelerations not nearly so high. The 1985 Nahanni, Canada and 1992 Petrolia, California, earthquakes are recent examples of this phenomenon. Archuleta had previously suggested that these anomalously high peak accelerations are due to the seismograph station being located in a position at which seismic waves from a large area arrive in phase and thus interfere constructively. David Olgesby and Archuleta have investigated this hypothesis by simulating seismograms from stations in the vicinity of an imploding fault zone, using the isochron method. Preliminary results from this method have produced localized extreme accelerations that differ by factors of two or more between stations separated by less than 0.5 km, and by factors of 5 or more between stations separated by 1 km. The locations of these points of extreme acceleration are determined by the competing influences of proximity to the fault and the degree of seismic wave coherence. This analysis is being applied to the accelerograms from the Petrolia earthquake to determine whether the observed variations in accelerations can be explained.

Aftershock Source Parameters (Lindley)

The study of the earthquake source is being conducted using recordings from TERRAscope stations (run by Cal Tech) and using recordings of earthquakes from portable instruments deployed by the Southern California Earthquake Center. Recordings of the 1992 Landers, Big Bear, and Joshua Tree earthquakes and associated foreshocks and aftershocks are being studied to determine source parameters. This research has indicated that the main shock source processes are significantly different from the aftershock source processes. In particular, the stress drops of the main shocks have been found to be approximately a factor of ten greater than the aftershock stress drops. This research has also found significant variation in measured source parameters from event to event indicating a complex variation of source processes from one earthquake to the next. This research is important in understanding the fundamental physical processes that occur during earthquake rupture. This research also has important implications for predicting the ground motion that is expected to occur from a given earthquake.

The second area of analysis studies the decay of seismic waves in the earth's crust. This analysis uses tomographic techniques to determine the three-dimensional nature of attenuation of seismic waves in the crust. This research has been successful in identifying regions of changing rock type. This research has also found differences between the decay of P- and S-wave radiated energy that has implications for properties of earthquake fault zones such as the pore fluid pressure, which may in turn play a key role in our understanding of earthquakes.

The April 1992 M_L 6.1 Joshua Tree Earthquake Sequence: Seismotectonic Analysis and Implications. (Nicholson)

The M_L 6.1 Joshua Tree earthquake of 23 April 1992 04:50 GMT occurred at 33°N 57.7', 116°W 19.2' about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault. It occurred at a depth of 12 to 13 km. The earthquake was preceded by a foreshock sequence that included a M_L 4.6 event at 02:25. The mainshock was followed by over 6,000 aftershocks recorded by the Southern California Seismic Network and an 11-element portable network deployed by the Southern California Earthquake Center. No surface rupture for the sequence has yet been found. The seismic moment is estimated at 2¥10^{25} dyne-cm. From the distribution of aftershocks and directivity effects, the mainshock ruptured unilaterally to the north along a fault about 15 km long. The focal mechanism indicated right-slip on a plane striking N14°W, dipping 80°W, with a rake of 175°. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures, similar to the cross-shaped or 'winged-shaped' pattern of events following the 1979 M_L 5.5 Homestead Valley earthquake. Many of these off-fault earthquakes occurred on structures either sub-parallel to the mainshock plane or on secondary left-lateral faults that strike at high angles. Aftershocks continued to migrate to the north and south following the mainshock, and ultimately extended from the southern San Andreas fault near the Indio Hills to the Pinto Mt fault. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. The 1992 Joshua Tree sequence occurred in the area of the 1940 M_L 5.3 Covington Flats earthquake—part of the premonitory activity leading up to the 1948 M_w 6.2 Desert Hot Springs event. The 1992 sequence was part of an accelerated moment-release rate that began in 1985–86 and which culminated in the M7.4 Landers event that initiated north of the Pinto Mt fault. The Landers earthquake caused continued aftershock activity along the fault responsible for the Joshua Tree mainshock. Seismicity on nearly all the secondary structures active during the Joshua Tree sequence, however, ceased in the hours prior to the M7.4 Landers event, and has not yet resumed.

Changes in Attitude - Changes in Latitude: What Happened to the Faults in the Joshua Tree Area Before and After the M7.4 Landers Mainshock? (Nicholson)

The M6.1 Joshua Tree earthquake of 23 April 1992 was followed by over 6,000 M>1 aftershocks. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the Landers earthquake on June 28. From the distribution of aftershocks and directivity effects, the mainshock ruptured unilaterally to the north along a fault about 15 km long. The focal mechanism indicated right-slip on a plane striking N14°W, dipping 80°W, with a rake of 175°. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. Aftershocks continued to migrate to the north and south following the mainshock, and ultimately extended from the southern San Andreas fault near the Indio Hills to the Pinto Mt fault. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June M7.4 Landers event, and did not resume. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. We investigated possible explanations for this change in the pattern of earthquake activity as a result of inferred stress changes induced by the Landers mainshock and some of its larger aftershocks.

Joint 3-D Tomography using Seismic and Gravity Data of the 1992 Southern California earhquake sequence: Constraints on Dynamic Earthquake Ruptures? (Nicholson, Jonathan Lees)

Linear tomographic inversion of P-waves from the recent 1992 Southern California earthquakes is used to produce 3-D images of subsurface velocity. The 1992 dataset, augmented by 1986 M5.9 North Palm Springs earthquakes, consists of 6458 high-quality events providing 76,306 raypaths for inversion. The target area consists of a 104x104x32 km^3 volume divided into 52x52x10 rectilinear blocks. Laplacian regularization was applied and the residual RMS misfit was reduced by ~40%. Significant velocity perturbations are observed that correlate with rupture properties of recent major earthquakes. Preliminary results indicate a low-velocity anomaly separates dynamic rupture of the M6.5 Big Bear event from the M7.4 Landers mainshock; a similar low-velocity region along the Pinto Mt fault separates the April M6.1 Joshua Tree sequence from the Landers rupture. High-velocity anomalies occur at or near the nucleation sites of all 4 recent mainshocks (North Palm Springs-Joshua Tree-Landers-Big Bear). A high-velocity anomaly is present along the San Andreas fault between 5-12 km depth through San Gorgonio Pass; this high-velocity area may define an asperity where stress is concentrated. To test model reliability, a joint inversion of seismic and gravity data was performed. Gravity data can be used by assuming a linear relation between density and velocity perturbations. Gravity may be important to subsurface structure because the Landers rupture follows a strong gravity gradient. Gravity also helps constrain near-surface regions of the model where incident rays are nearly vertical and seismic resolution is poor. The joint 3-D model is required to fit both seismic data and isostatic gravity anomalies to a specified degree of misfit. A joint tomographic inversion in which 40% of seismic data residual misfit and ~80% of the gravity anomalies are explained does not differ significantly from previous models. These results suggest that high-resolution 3-D tomography may be a more effective means of segmenting active faults at depths than near-surface mapping.

4. Hazardous Waste Disposal

Personnel: C. Campbell, S. Cullen, G. Deane, **L. Everett***, S. Everett, J. Kramer, M. Leipnik, H. Loaiciga, C. Ray, K. Rees, T. Robinson, S. Shu (*Agenda coordinator)

The Vadose Zone Monitoring Laboratory within the ICS, has had an exceptional year. The three year EPA grant (EPA CR816969-02) has been successfully completed and resulted in the drafting of a national guidance document on vadose zone monitoring for RCRA (Resource Conservation and Recovery Act), hazardous waste facilities throughout America. This document will result in a major philosophical change in the way hazardous waste sites are characterized and monitored. The concepts integrated into the Guidance Document were developed as the result of research conducted in the VZML and are anticipated to result in major savings of energy and dollars associated with future actual and potential contamination problems.

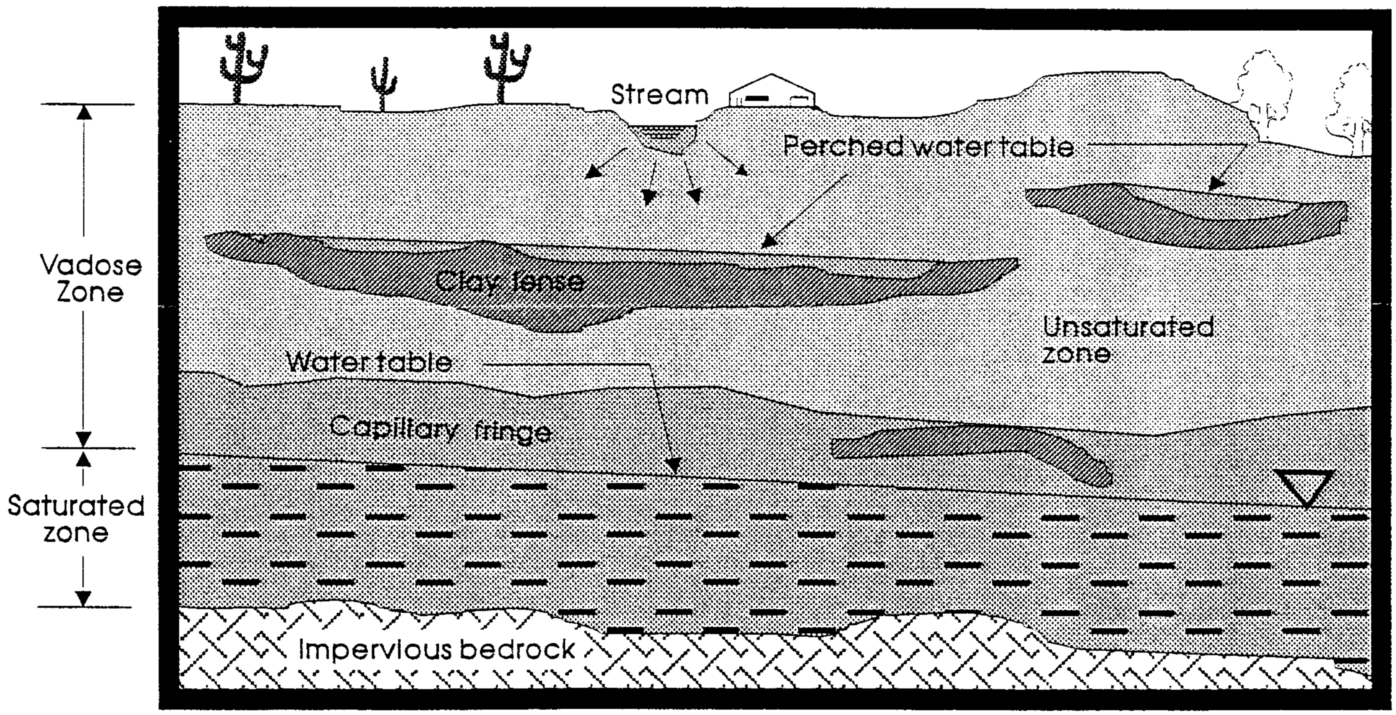

Figure 7: Scematic geologic cross section illustrating the relationship of the vadose zone, unsaturated zone, and saturated zone.

At the invitation of the United States Naval Civil Engineering Laboratory (NCEL), the Vadose Zone Monitoring Lab staff were asked to co-chair and provide tours of the VZML as a part of a National Underground Storage Tank Conference held at UCSB. At the end of the conference, Ms. Elsie Munsell, Assistant Secretary of the Navy, and Dr. Bill Powers, Program Manager within the NCEL initiated dialogue directed toward establishing a long term working relationship between UCSB and the US Navy. Dr. Everett served as co-chair of the Conference and Stephen Cullen served as Technical Advisor and Host for a multi-agency tour of VZML facilities.

The staff of the VZML has been very active in developing national standards related to vadose zone monitoring. In addition to Dr. Everett serving as chairman of the ASTM section D18.21.02, entitled "Vadose Zone Monitoring Standards," Stephen Cullen and other members of the laboratory have been involved in successfully completing soil pore liquid monitoring, soil core monitoring, major potential determination, soil gas monitoring, hydraulic conductivity monitoring, and a series of vadose zone definitions. Since the ASTM Standards process takes 3-5 years, VZML staff are responsible for the initiation of new standards on an ongoing basis. Standards which have been initiated and are currently in various stages of development cover topics such as neutron moderation, vadose zone water flux determinations, air permeability determination, field screening, soil moisture determination, and the use of dielectric methods.

Members of the vadose zone monitoring staff have been involved in numerous invited lecture series, including lectures for: the United Nations Environmental Program at San Jose, Costa Rica; the European Community's research facility at Espra, Italy; UCLA Extension Program, California Department of Toxic Substance Control; California Ground water Association at Los Angeles and San Francisco; Fundamentals courses on Ground Water Monitoring for American Ecology in Washington D.C.; US Department of Energy at Rocky Flats; the National Education and Environmental Program sponsored at Seattle, Washington; and the Santa Barbara County Environmental Health Program meeting scheduled for Santa Maria. At each of these presentations, professional papers developed at the Vadose Zone Monitoring Laboratory were presented. Stephen Cullen also lectured and instructed Geography 114, World Soils, for the Geography Department. Stephen also gave invited lectures and colloquiums in the Departments of Geography, Geology, and Mechanical and Environmental Engineering.

Intergraph, manufacturers of an engineering-based Geographic Information System (GIS) system, has loaned computer hardware/software valued at $500,000 loan to the VZML. This state-of-the-art GIS system has been used in the VZML activity at Vandenberg AFB and is scheduled to be a part of the forthcoming Navy activity.

The Troxler Electronics Corporation in Research Triangle Park, North Carolina, has developed a $100,000 probe and automated-winch system which it has loaned to the VZML to support ongoing research. This automated winch system was designed originally to be the second generation of equipment based on John Kramer's doctoral dissertation. The equipment, which is currently in use at the VZML outdoor experimental site, is scheduled to be a key part of the ongoing collaborative research with Sandia National Laboratories in Albuquerque. The Sandia project is directed toward developing a standard operating procedure for the United States Department of Energy for horizontal applications of neutron moderation. The VZML is uniquely identified with developing state-of-the-art technical insights into neutron moderation.

VZML staff have made special efforts to interact with members of the University of California System, UCSB faculty, other research universities and agencies, government regulatory entities, community members, and industry to insure the relevance of their applied research efforts. An example of this is John Kramer's collaborative interaction with the University of Arizona and Waste Management of North America, Inc. on solid waste landfill leachate release modeling;

VZML principal investigator Stephen Cullen is leading a research effort to assist the Environmental Restoration Division of Lawrence Livermore National Laboratory in developing an understanding of the operative contaminant transport mechanisms at LLNL. He has designed an interdisciplinary research approach which takes advantage of the resources and intellectual capabilities of the VZML and the Departments of Mechanical and Environmental Engineering and Geography. The project is attempting to measure diffusion coefficients for tritiated water vapor for the first time, identify and locate preferential flow pathways controlling contaminant transport in the subsurface at LLNL, and develop laboratory protocols for use by the Particle Characterization Laboratory for conducting hydrologic characterization of LLNL subsurface samples.

John H. Kramer, Stephen J. Cullen, and Lorne G. Everett were also awarded a patent during the past year for their efforts in designing a "wick-layer enhanced vadose zone monitoring system". The innovative system is designed to enhance contaminant release detection by increasing the sphere of measurement of subsurface contaminant detection sensors.