HIGHLIGHTS OF RESEARCH ACTIVITIES 1991-1992

1. Crustal Structure and Tectonics

Personnel: T. Atwater, N. Brown, C. Busby, S. Cisowski, R. Crippen, J. Crowell, J. Elliot, A. Hull, D. Imperato, E. Keller, D. Kimbrough, J. Lees, H. Loaiciga, **B. Luyendyk***, P. Molnar, R. Morris, C. Nicholson, B. Patrick, N. Pinter, W. Prothero, S. Richard, C. Smith, C. Sorlien, W. Stuart, A. Sylvester, D. Valentine, R. West. (* Agenda coordinator)

Projects under this agenda span the globe from Canada to Antarctica. In the Yellowknife mining district in Canada Dr. Richard Sibson and graduate student Norm Brown have been conducting an ICS project relating faulting, fluid movements, and fault zone mineralization. A similar project is underway in the Mother Lode of The Sierra Nevada by Dr. Sibson's graduate student James Elliot. In the southern Brooks Range, Alaska, the history of high-grade metamorphic rock is under study by Dr. Brian Patrick. In the Grand Tetons, Wyoming, ICS leveling surveys by Dr. Art Sylvester and his students have been measuring the uplift of this range.

In the area of southern California and the Mojave Desert, the tectonic history of Pacific-North American plate interaction is being studied on several fronts. These include studies of the San Andreas fault (Drs. T. Atwater and J. Crowell), the Ridge Basin (Dr. J. Crowell), tectonic geomorphology of the Los Angeles Basin (Dr. E. Keller and students), and crustal rotations in the northeast Mojave (Drs. Bruce Luyendyk and Stan Cisowski). Fault movements and seismicity are being monitored on the southern San Andreas fault by Drs. Nicholson and Sylvester. Dr. Sylvester is publishing a study on vertical strain along the Garlock fault in central California. Several projects have been and continue to be focused in southeast California and southwest Arizona. Researchers involved include Atwater, Crowell, Dr. Steve Richard, Rebecca Morris, Dr. Robert Crippen and Dr. William Stuart. These projects mostly concern Miocene tectonics here, including crustal rotations, extension and metamorphic core complexes, and link-up of faults in this area with the Eastern California Shear Zone in the Mojave Desert. The shear zone was the subject of a workshop held at ICS in September, 1991. Jurassic island arc rock sequences are being mapped in southern Arizona by Dr. C. Busby in order to understand the ancient western North America continental margin.

A multi-disciplinary, integrated study of basin development in the Central Great Valley, using mostly detailed subsurface well-log correlations is being conducted by graduate student Doug Imperato under the direction of Dr. Art Sylvester.

A hallmark of ICS research is the detailed, integrated, multi-disciplinary study that brings together a wealth of information from both geology and geophysics. An excellent example is the PhD work of Alan Hull, who combined detailed geologic field mapping, gravity and seismicity to resolve the seismotectonics and pull-apart basin geometry along the northern Elsinore fault in Southern California. This work was performed in collaboration with Drs. Craig Nicholson, Rick Sibson, and Art Sylvester, and documented the young age (<2.5 Ma), the small cumulative offset (<15 km), the oblique nature of fault slip, and the apparent evolution of basin geometry associated with the active fault zone. Two other major integrated studies are currently being conducted in the offshore regions of the California margin. These projects involve the detailed reprocessing of marine seismic reflection and refraction records, and analysis of well logs, gravity, seismicity and field mapping of adjacent onshore structure. The first involves a regional tectonic study of the offshore southern Santa Maria Basin and Western Transverse Ranges and constitutes largely the PhD work of Chris Sorlien under the direction of Drs. Craig Nicholson and Bruce Luyendyk. The second involves a comparison of shallow and deep offshore structure in the San Diego Trough using high-resolution seismic reflection, deep-penetration mutichannel seismic and earthquake data directed by Drs. Craig Nicholson and Mark Legg, a recent ICS Visiting Scientist. These projects have been funded by the Petroleum Research Fund and the National Science Foundation.

ICS researchers B. Luyendyk, D. Kimbrough, S. Richard and graduate student Christine Smith have spent two field seasons in Marie Byrd Land, West Antarctica, to study the fit of this piece in the Gondwana supercontinent, and to study the uplift of deep crustal rocks here. These researchers presented preliminary results of their work at the Sixth Antarctic Earth Sciences symposium in Ranzan, Japan, in September, 1991. Paleomagnetic study of rock samples obtained on the expeditions is being done by Luyendyk and Dr. Stan Cisowski. This work is in part an extension of research done in New Zealand earlier by Luyendyk and students. Gondwana research continues to occupy J. Crowell who is analyzing tectonics and past climates of the supercontinent. Dr. Crowell is in the process of writing a monograph on paleoclimate.

2. Crustal Materials

Personnel: C. Balzer, B. Cousens, A. Giacobbe, C. Hopson, C. Oldenburg, B. Patrick, A. Proussevitch, N. Rosenberg, **F. Spera***, D. Graham, D. Stein, G. Tilton, C. Smith, M. Todesco, A. Trial, A. Tumarkina. (* Agenda coordinator)

Research in this agenda is conducted by the groups headed by Drs. Brian Patrick, Clifford Hopson, Frank Spera and George Tilton. Patrick is studying the response of crustal materials at the regional scale due to the imposition of tectonic forces. In particular, his group is studying the deformation of crustal materials at depth in response to compressive forces along plate boundaries. The evolution of pressure and temperature fields through time are deduced by application of thermodynamics to mineral assembledges. He is conducting a study of the deep burial and exhumation of metamorphic rocks in the Kigluaik Mountains in northwest Alaska. This range has been subjected to granulite-grade regional metamorphism during Cretaceous time.

Hopson and Tilton's research is involved with application of geochronology and regional field geology to solve petrological problems bearing on the tectonic evolution of continental margins. By careful geochronological work, they have been able to document the behavior of the upper and middle crust along the continental margins of the Asian plate during the Paleozoic and Mesozoic.

Frank Spera's group is involved with studying the behavior of materials under conditions of pressure and temperature characteristic of the crust. Studies utilize numerical, laboratory and field techniques. Simulations have been made of the thermodynamic and transport properties of silicate melts utilizing the method of Molecular Dynamics. This enables one to visualize, at the atomic level, the dynamics of silicate liquids at various relevant environmental conditions. At the macroscopic level, simulations of convection in magmas undergoing phase change and in the flow of hydrothermal fluids in porous crustal rocks have also been undertaken. Laboratory studies of the rheologic properties of high temperature - multicomponent silicate systems is also on-going. Also, field studies of Italian volcanic structures (Mt. Etna, Roman Volcanic Province) are currently underway.

Crustal materials research at ICS spans a range of time and length scales from picoseconds to millions of years and from the atomic scale to the global scale. This is a diverse set of problems that all relate to the material behavior of the earth's crust when acted upon by forces due to tectonic processes.

3. Earthquakes

Personnel **R. Archuleta***, N. Brown, M. Campillo, R. Crippen, J. Elliot, A. Hull, D. Imperato, E. Keller, J. Lees, H. Loaiciga, G. Lindley, B. Luyendyk, A. Martin, P. Molnar, R. Morris, C. Nicholson, W. Prothero, P. Rodgers, S. Seale, B. Shaw, R. Sibson, L. Steck, J. Steidl, W. Stuart, S. Swain, A. Sylvester, A. Tumarkin, A. Tumarkina, C. Weiland. (*Agenda coordinator)
91-92 Report

Many ICS investigators have been concerned with the mechanical behavior of faults and the patterns of strain, fault slip and stress that have developed in California as a result of evolution of the San Andreas fault system. Dr. Rick Sibson developed models that explain how high-angle reverse faults can accommodate slip in unfavorable stress environments, and, in particular, the important role that fluids in the crust play in affecting the mechanical behavior of faults. This has lead to several studies, in collaboration with graduate students Norm Brown and James Elliott, on the evolution of structural discontinuities (such as fault jogs) that may control earthquake ruptures and the distribution of fault slip, as well as how fluid-fault interactions may be responsible for the location of mesothermal ore deposits of gold and other minerals. Sibson has since left ICS to become Chairman of the Department of Geology at the University of Otago, New Zealand.

Dr. Art Sylvester has established several long-baseline geodetic profiles across active faults in California to measure vertical displacements associated with the contemporary pattern of crustal deformation. This project is a multi-year effort funded through the National Earthquake Hazards Reduction Program (NEHRP). The exciting preliminary observations have resulted in a collaborative project that has just begun with Dr. Roger Bilham from the University of Colorado, to examine the phenomena of vertical fault creep. An ICS Visiting Scientist, Dr. Peter Molnar from the Massachusetts Institute of Technology, investigated the uplift and erosion of the Western Transverse Ranges to see if uplift rates may be controlled by climate change. Although preliminary results were inconclusive, Molnar was able to demonstrate that geodetic data, earthquake focal mechanisms, and geologic fault slip rates are consistent with the contemporary clockwise rotation of the Western Transverse Ranges at rates of rotation similar to the long-term tectonic rates inferred from paleomagnetic data by Luyendyk and his colleagues.

Dr. Craig Nicholson has participated in a number of ICS projects typically associated with either earthquakes in general, the distribution and seismic behavior of active faults in California, or the tectonic evolution of the Pacific-North American plate boundary. These projects have included the documentation of secondary left-lateral faults, detachments, and small-scale block rotation in accommodating a component of the contemporary crustal deformation in southern California; analysis of California earthquake precursory phenomena and the successful forecast of the 1987 M_S 6.6 Superstition Hills and the 1989 M_S 7.1 Loma Prieta earthquakes; the evaluation of earthquake hazards associated with deep-well activities involving either fluid injection or massive fluid or gas extraction; and seismotectonic studies of the Salton Trough area, the southern San Andreas fault, and the easternmost Transverse Ranges. A high-resolution tomographic study along the southern San Andreas fault in collaboration with Dr. Jonathan Lees revealed that 3-D velocity perturbations in the northern Coachella Valley correlate with the dynamic slip and most of the aftershocks of the 1986 North Palm Springs event, suggesting that tomographic techniques may be capable of imaging other sites (or asperities?) where future large earthquakes in California may nucleate.

A major ICS research effort of 1992 involved collaborative investigations of aftershocks from the 23 April M6.1 Joshua Tree and 28 June M7.4 Landers and M6.5 Big Bear earthquakes. These investigations were undertaken by several groups associated with the Southern California Earthquake Center (SCEC), including Caltech, UC Santa Barbara, USC, UC San Diego, SDSU, IRIS/Passcal and the USGS. The M6.1 Joshua Tree mainshock occurred at 21:50 PDT April 22 in the Eastern Transverse Ranges. Eleven portable instruments were deployed following the Joshua

Tree mainshock; the major deployment lasted from 23 April to 26 May, although 3 stations were still in operation on June 10. The M7.4 Landers earthquake occurred at 04:58 PDT about 10 km north of Yucca Valley along the southern extension of the Johnson Valley fault. The Landers mainshock ruptured unilaterally to the north along the Johnson Valley fault, then jumped to the Landers, Homestead Valley, Emerson and Camp Rock faults. Aftershocks extended from the Camp Rock fault at 34°N40', 116°W40' south to 33°N50', 116°W18' near the southern San Andreas fault—a distance of nearly 100 km. The M6.5 Big Bear earthquake occurred at 08:04 PDT about 35 km west of the Landers epicenter in the San Bernardino Mountains. The Big Bear aftershocks extend over an area about 30 km long, extending roughly NE between the San Andreas fault at Yucaipa to the Helendale fault.

Following the June mainshocks, four portable instruments were installed and operating within 12 hours, two in the San Bernardino Mountains near Big Bear, and the other two in the epicentral region of the Landers earthquake. By Tuesday, June 30, another 13 portable instruments were installed and operating. These instruments supplemented the regional network of permanent stations operated by Caltech/USGS, accelerometers operated by the USGS and CDMG, and temporary instruments deployed following the April M6.1 Joshua Tree earthquake and still in operation at the time of the June mainshocks. The portable equipment consists mostly of Reftek digital recorders using L-22 velocity and FBA acceleration sensors. Two sites employ Guralp broadband instruments, 3 sites use outputs from very broadband STS-2's, and 3 sites use digital SSR-1's. These instruments supplement 5 USGS GEOS instruments operating at the time of the Landers and Big Bear mainshocks. The SCEC data are 250 sps; several sites exhibit significant high-frequency (above 100 Hz) signal. Over 8 Gbytes have been collected; approximately 8,000 events are recorded by 2 or more stations.

The data sets collected on the 1992 Southern California earthquake sequence have formed the basis for an extensive series of studies conducted by ICS researchers. Craig Nicholson and Aaron Martin are actively involved in the data organization from both the Joshua Tree and Landers/Big Bear deployments. Ralph Archuleta and Michel Campillo, an ICS visiting scientist from the Université de Joseph Fourier in Grenoble, have inverted strong ground motion records for the long-period rupture history of the M7.4 Landers mainshock. They find that the earthquake largely involved two subevents on faults with different orientations, with a 1.0 second delay between the two events. Nicholson and Jonathan Lees, an ICS visiting scientist from Yale University, have inverted the earthquake arrival times from the 1992 sequence for the 3-D velocity structure of Southern California. They find that all three earthquakes (Joshua Tree, Landers and Big Bear) occurred in areas that exhibit high-velocity anomalies, similar to previous results using aftershocks from the 1986 M5.9 North Palm Springs event. In many cases, the dynamic rupture lengths of the earthquakes were controlled by the distribution of low-velocity anomalies, i.e., the earthquakes failed to propagate into or across these regions. Nicholson is also

1992 Southern California Aftershock Sequences

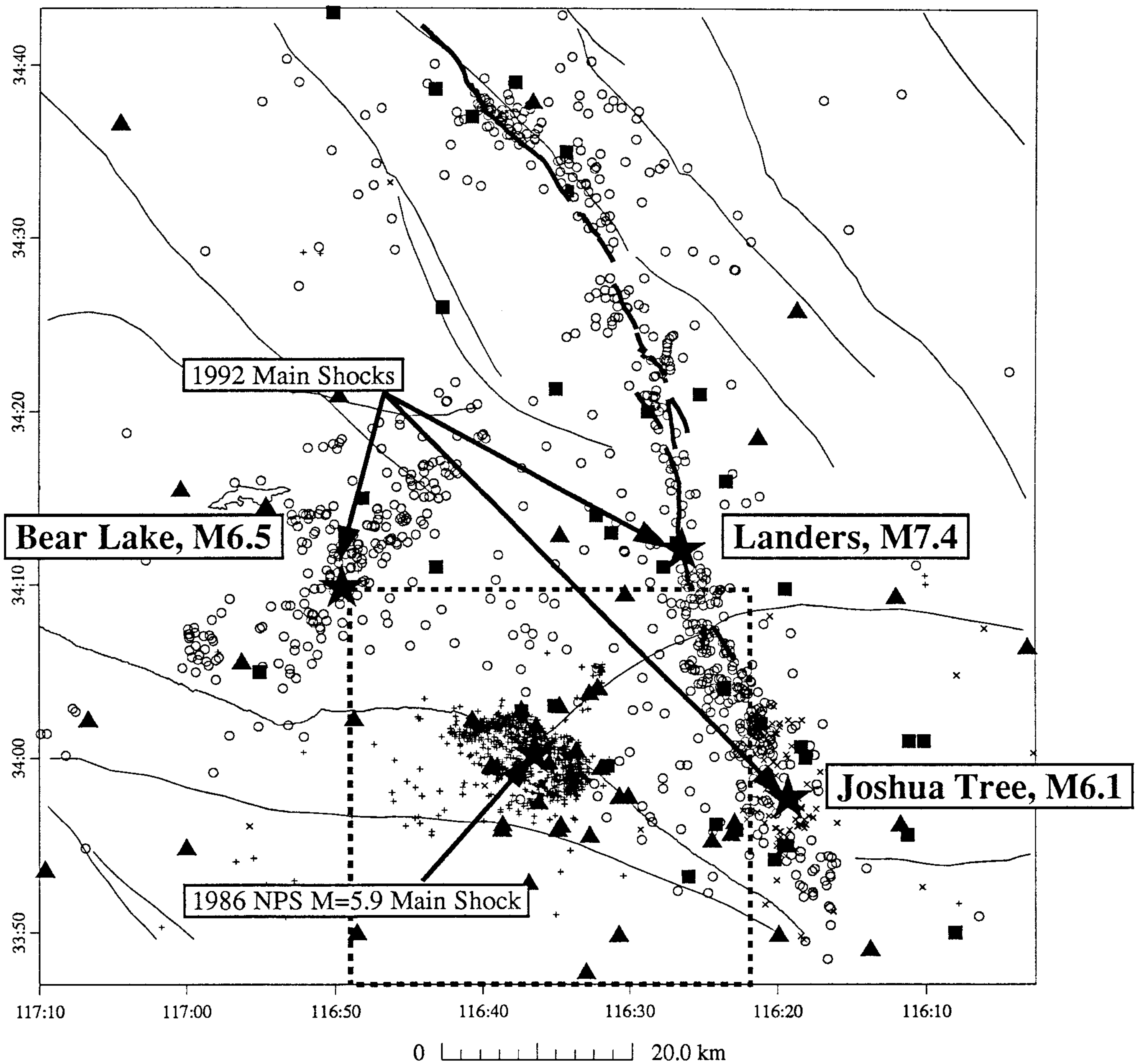

Figure 1. Aftershock sequence of three 1992 Southern California earthquakes. Circles represent preliminary epicentral locations of catalogued aftershocks in June and July, 1992. The Joshua Tree M=6.1 event occurred on April 22, 1992 and its aftershocks are represented by x-marks. The Landers and Bear Lake events ruptured on June 28, 1992. Triangles are permanent network stations and solid squares are locations of portable stations installed after the main shocks. The bold lines trending north and then northwest are mapped surface ruptures of the Landers fault. The dashed outline was the target area of a tomographic analysis of the 1986 North Palm Springs aftershock sequence (plus-marks) by Nicholson and Lees [1992].

collaborating with Egill Hauksson of Caltech on a seismotectonic analysis of the complex faulting involved in the M6.1 Joshua Tree sequence.

Art Sylvester, with the help of several graduate and undergraduate students, has established several leveling and geodetic arrays across the M7.4 Landers ground rupture. These geodetic lines were used to determine whether any near-surface post-seismic creep (or afterslip) occurred. No afterslip was found along the major surface breaks of the Landers mainshock, but small amounts of slip (at rates of mm/day) were found south of the Pinto Mountain fault where several major aftershocks have occurred. Thus, nearly everyone previously associated with ICS earthquake studies joined in the Joshua Tree/Landers/Big Bear investigations.

Ralph Archuleta, with graduate students and other ICS researchers, has continued to investigate the nature of strong ground motion (accelerations greater than 10 cm/s^2). His major 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. The data from the 1992 southern California earthquakes are currently being analyzed. Using data from aftershocks and foreshocks with M 4.6 Archuleta and his collaborators were able to predict the amplification for the larger M 6.1 mainshock.

Dr. Sandra Seale has spent most of her efforts examining the data from the array to determine the transfer function for the soil. A description of the Garner Valley instrumentation and preliminary data analysis are presented in a paper accepted for publication in the Bulletin of the Seismological Society of America. Seale has recently focussed her efforts on predicting ground motion in San Bernardino and Los Angeles in the event of a M 7.5 or greater earthquake on the San Andreas. She has begun to validate the method and provide initial constraints using data from the Landers M 7.4 earthquake.

Dr. Alexei Tumarkin, visiting from the International Institute for Earthquake Prediction Theory and Mathematical Geophysics in Moscow, and Archuleta have focussed their research on finding a small number of parameters that represent the fundamental features in strong motion accelerograms. Tumarkin, Archuleta and Raul Madariaga (Institute Physique du Globe, University of Paris VII) have prepared a paper that discusses the basic relations and conditions for describing an earthquake as the composite of many small earthquakes. They find that the most commonly held assumption about earthquake scaling is violated unless the subscale events are out of plane with the mainshock or that each subevent slips more than once during the mainshock.

Alla Tumarkina has established a database of strong motion accelerograms recorded in southern California. This database will make accelerograms readily available to SCEC scientists.

Graduate student Grant Lindley has systematically studied more than 10,000 earthquake spectra from aftershocks of the 1980 Mammoth Lakes, 1984 Coalinga and 1989 Loma Prieta, California, earthquakes. His results show that the attenuation of near-surface material is frequency dependent for soft rocks; large stress-drop aftershocks are generally at the base of the seismogenic zone or at the periphery of regions that experienced large slip during the main shock; scaling the spectra of different size earthquakes is only possible if attenuation is accounted for first. The results are published in the September 1992 issue of the Journal of Geophysical Research. Lindley has also finished a paper showing that large stress-drop earthquakes concentrate at the ends of faults that have previously ruptured. This paper clearly demonstrates that aftershocks are affected by the stress concentration generated by the mainshock.

In studying the Loma Prieta earthquake Lindley and Archuleta concluded that site effects are more dominant than topographic effects in influencing the ground motion. In his final stage of his PhD research, Lindley is investigating the differences between the spectra of the mainshock records and the aftershocks. The initial analysis indicates a different source spectrum for the mainshock compared to the aftershocks.

Jamison Steidl, a graduate student, and Archuleta completed a study to resolve major disagreement that arose in analysis of the geodetic data from the Loma Prieta earthquake. The fault that produced results most consistent with the geodetic data was offset by four kilometers from the fault delineated by the aftershocks. Steidl and Archuleta investigated this problem using the slip distribution found by inversion. They found that the data were strongly influenced by one station that was near a theoretical null point in the static field. This paper has been accepted for publication in the U.S. Geological Survey Professional Paper on the ground motion of the Loma Prieta earthquake.

Steidl, Tumarkin and Archuleta have been examining new methods to characterize the the amplification of seismic waves. They have found that by using a cross correlation spectrum method and the coherency between a reference site and the site being studied they can estimate the spectral amplification and assign errors to the estimate. This is a major improvement on the current method that is based on spectral ratio of soil site to a reference site.

Dr. William Prothero is continuing his research on the Kaokiki fault zone on the big island of Hawaii. This project is concerned with the origin of large earthquakes on this zone which are hypothesized to occur on a deeply buried sediment layer beneath the volcanic pile. Dr. Prothero's graduate student, Lee Steck, has recently completed his dissertation on the velocity structure beneath Long Valley caldera, California, using teleseismic ray paths and velocity anomalies.

4. Hazardous Waste Disposal

Personnel: S. Cullen, **L. Everett***, J. Kramer, M. Leipnik, H. Loaiciga, T. Robinson, D. Springer, J. Wells, I. Zekster. (* Agenda coordinator)

Hazardous waste disposal in the earth's crust is studied in the Vadose Zone Monitoring Laboratory (VZML) of the ICS. This laboratory's mission is to conduct research and educational activities on the subject of ground water protection, contaminant migration, and the monitoring of contaminant movement above the principal water table in the vadose zone. Through the efforts of the director Dr. Lorne G. Everett and Co-Principal Investigator Stephen J. Cullen, the VZML has emerged as the research backbone for the U.S. Environmental Protection Agency's newly-defined vadose zone monitoring strategy. National regulations require vadose zone monitoring at all hazardous waste land disposal units. Dr. Everett and Stephen Cullen are writing the guidance document to support this effort.

In addition to presentations at professional meetings and publication in scientific journals, VZML has conducted numerous short courses and workshops on vadose zone monitoring strategies and techniques around the country. Primary audiences included the U.S. Navy, U.S. Air Force, Department of Energy, Bureau of Reclamation, and various professional organizations.

Cooperative working agreements initiated in 1990-1991 with the Water Problems Institute, Russian National Academy of Sciences, Moscow and the Weizman Institute of Israel have expanded into discussions of potential VZML involvement in the World Lab project. The World Lab runs a number of activities, one of which is the Ettore Majorana Center for Scientific Culture in Erice, Sicily. This center has hosted almost 600 courses in the past 26 years which have been sponsored by the Italians and attended by 45,000 prominent scientists including 41 Nobelists. Discussions are now in progress involving the Italian government, the ICS director, and Dr. Everett of the VZML to formulate the basis for establishing an office of the World Lab at UCSB.

Efforts directed via Dr. Everett's chairmanship of the American Society of Testing and Materials Committee on Vadose Zone Monitoring have coordinated thinking and developments of both public agencies and private enterprise to formalize standards for investigative protocols in subsurface environmental studies.

VZML is developing new research initiatives and has been successful in obtaining funding from private, state, and federal sources to develop solutions to emerging environmental management issues. VZML is concluding a project using a Geographic Information System workstation to develop a fundamental understanding of subsurface contaminant migration at Vandenburg Air Force Base. The U.S. Bureau of Reclamation funded this research effort. VZML received the loan of a GIS workstation including workstation, digitizing table, and optical disk drive from Intergraph Corporation.

A research agreement is currently under active discussion between VZML and Lawrence Livermore National Laboratory. LLNL invited L. Everett, S. Cullen, and J. Kramer for discussions of vadose zone hydrogeologic research issues and to conduct a review of the vadose zone and ground water site environmental restoration project. Several research tasks were identified and VZML was invited to submit a proposal.

VZML has been visited by personnel from the U.S. Navy, Port Hueneme Naval Civil Engineering Laboratory (NCEL), Energy and Environment Department. NCEL has expressed interest in developing a "partnership" with UCSB which would include the funding of selected research projects and personnel exchanges in support of NCEL environmental programs. NCEL and VZML have tentatively agreed to co-host a national symposium on environmental problems associated with Underground Storage Tanks (USTs) in the spring of 1993.