Research Experience for Graduates

Thirty-nine graduate students are involved in research administered through ICS. These students are involved in field research both locally and internationally. Many have presented their research with talks or posters at professional meetings: e.g., American Geophysical Union, Geological Society of America, Seismological Society of America, annual Southern California Earthquake Center. In addition to the abstracts presented, ICS graduate students are also involved as co-authors on articles in referred journals.

Highlight of Graduate Student Research

Susana Custodio
Ph.D. Program, Ralph J. Archuleta, advisor

The Parkfield Section of the San Andreas Fault, California: Characteristics or Complementary Earthquakes?

The San Andreas Fault is the major fault in California; it accommodates the lateral (northwestward) motion of the Pacific Plate with respect to the North American plate. Different sections of the San Andreas Fault accommodate the plate motion in seismically different ways – while some sections of the fault are locked (they slip only during large ~M8 earthquakes; e.g.: the 1857 M7.9 Fort Tejon earthquake, the 1906 M7.8 San Francisco earthquake), others sections of the fault creep (they accommodate all the relative plate motion by permanent very slow slip; this is the case of the San Juan Bautista – Cholame segment). Parkfield marks the transition between a creeping and a locked part of the San Andreas Fault. In the historical period (post 1850's) it has generated at least five ~M_w6 earthquakes. Based on similarity of ground motion from the 1922, 1934 and 1966 Parkfield earthquakes, Bakun and McEvilly (BSSA 1984) proposed the idea of characteristic earthquakes: a given fault segment would always rupture repeatedly in earthquakes of the same magnitude, which would nucleate in the same hypocenter and generate slip on the same areas of the fault (asperities). Characteristic earthquakes would furthermore happen in regular time intervals. The concept of characteristic earthquakes has important consequences for seismic hazard: if the asperities (i.e., the regions of the fault that generate most slip during an earthquake and therefore cause most damaging shaking) are persistent, then we can easily predict the regions where future earthquakes will cause more shaking, simply by studying past earthquakes. Furthermore, predicting the time of occurrence of an earthquake will also be a relatively simple task. Due to the implications of the hypothesis of the characteristic behavior of earthquakes, it is important to assess its validity. In order to do so, we used the Parkfield dataset; we studied two consecutive earthquakes that ruptured the same fault section. Unlike previous Parkfield earthquakes, the 2004 Parkfield earthquake did not nucleate at the previously observed common epicenter and further did not rupture to the SE. Instead, it nucleated 20 km SE of the previous common epicenter and then ruptured NW. Despite these differences, do the 1966 and 2004 slip distributions look similar, i.e., did the 1966 and 2004 earthquakes rupture the same fault patches (asperities)? We computed rupture models for the two Parkfield earthquakes that were instrumentally recorded (1966 and 2004). The datasets available for the two earthquakes have very different qualities and resolutions. After performing a series of resolution tests, we were able to eliminate the hypothesis that the 1966 and 2004 Parkfield earthquakes had identical slip distributions. Our results contradict the existence of persistent asperities (that is, asperities with remain through several seismic cycles).

Custódio, S. and Archuleta, R.J., submitted. *Parkfield earthquakes: characteristic or complementary?* Journal of Geophysical Research.

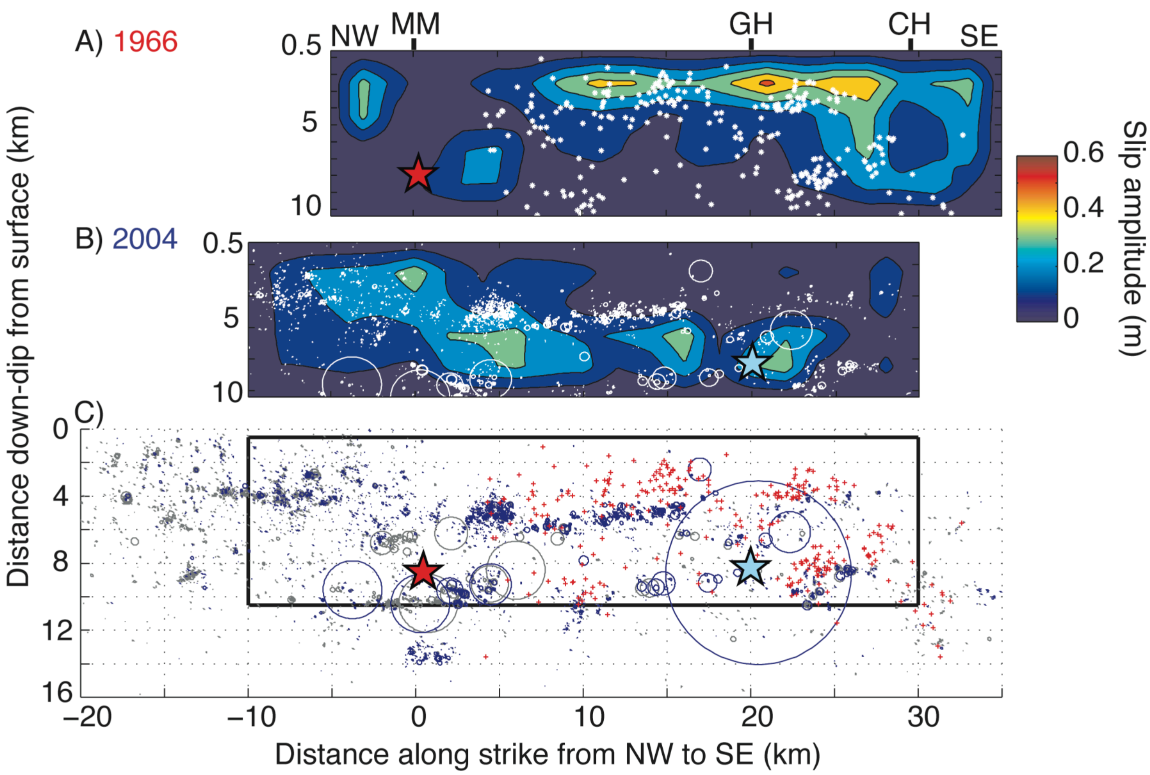


Figure 1 - Comparison between the rupture models for the 1966 and 2004 Parkfield earthquakes and microseismicity. According to our modeling of strong-motion seismic data, the two most recent Parkfield earthquakes (1966 and 2004) ruptured complementary parts of the fault plane. A) Slip amplitude and aftershocks of the 1966 earthquake. B) Slip amplitude and aftershocks of the 2004 earthquake. C) Aftershocks of the 1966 earthquake (red crosses), aftershocks of the 2004 earthquake (blue circles) and background seismicity from 1984 to the 2004 earthquake (gray circles) (Thurber et al., 2006). The size of the aftershocks (circles) is computed assuming a 3~MPa stress drop in a circular region. In the absence of information on the magnitudes of the 1966 aftershocks, we cannot compute their size; these aftershocks are represented by crosses. The rectangle indicates the position of the fault plane modeled for the 2004 earthquake. The red and blue stars mark the 1966 and 2004 hypocenters, respectively. MM - Middle Mountain; GH - Gold Hill; CH - Cholame.

Grace Giles
Ph.D. Program, James Boles, advisor

Geochemical signatures of rapid carbonate crystallization in well scales

Scale is an undesirable and damaging mineral deposit that commonly occurs in oil field production tubing, but its man-made environment provides a great resource for studying the effects of rapid crystallization on carbonate geochemistry. Rapid CO_2 degassing and calcite precipitation occurs in production tubing (and other natural settings) due to large pressure drops as formation water moves from confined spaces into the open well bore.
My work is particularly focused on the magnesium content and carbon and oxygen isotopic composition of Los Angeles Basin and San Joaquin basin oil field calcite scales.
Oxygen and carbon isotopes and trace element substitution in carbonates are widely used for paleotemperature studies of the oceans and for interpreting carbonate veins in faults. The effect of rapid (disequilibrium) crystallization on scale composition is not well understood. Calcite scales and their respective waters have been collected and analyzed for geochemical and isotopic composition. Reservoir data (including hydrostatic fluid levels, pressure, temperature, depth, perforation locations, etc.) is incorporated for calculating isotopic fractionation and trace element partitioning. Preliminary conclusions are that well scales show isotopic disequilibrium and highly variable magnesium content, apparently due to rapid crystallization.

Several parameters indicate isotopic disequilibrium and rapid CO_2 degassing for the well scales. The precipitated calcite is relatively more enriched in the heavier ^{18}O isotope than is anticipated for equilibrium fractionation. This deviation from the expected fractionation factor related to temperature and pressure is linear, indicating that greater precipitation rates (i.e. larger pressure differentials) increase isotopic disequilibrium. Rapid CO_2 degassing preferentially strips the lighter isotopes from the water, leaving precipitated calcite enriched in ^{13}C. Most of the scale samples have positive $\delta^{13}C$ values which suggest rapid CO_2 degassing. Assuming a constant input fluid composition, a positive correlation of carbon and oxygen isotopes is evidence of rapid crystallization. Vertical sample sets from different depths of the tubing and horizontal sample sets from transects of thick samples were analyzed for isotopic composition. All scales show positive $\delta^{13}C/\delta^{18}O$ slopes and are intermediate of experimentally determined ranges of slopes for rapid crystallization.

Preliminary analyses of calcite scales formed around 50-70°C show large variation of magnesium content from 4 to 16 mole percent. Past studies conclude that incorporation of Mg into calcite is independent of rate and rather, dependent on temperature and the saturation state of the starting solution. These samples come from waters with low $[Mg^{2+}]/[Ca^{2+}]$ ratios and wells with minimal temperature and fluid composition change, suggesting that precipitation rate instead is controlling the Mg content of the scales. The frequency of Mg variation in the scales positively correlates with the growth banding thickness in the scales.

Richard Heermance
Ph.D. Program, Douglas W. Brbank, advisor

Evolution of the Tian Shan foreland basin, western China

The Kashi foreland basin is located between the Pamir and Tian Shan mountain belts at the westernmost corner of the Tarim Basin in central Asia, and contains deformation and sedimentary deposits related to uplift, convergence, and erosion of the adjacent ranges. The arid climate of western China and recent tectonic deformation have exposed and preserved vertical sections of the stratigraphy that allow for a unique view of folding, faulting and the 3-dimensional architecture of the sedimentary facies relationships. We used magnetostratigraphy (magnetic reversals preserved in the sedimentary rocks related to the past changes in the Earth's magnetic field) to date the entire sedimentary sequence. Eleven magnetostratigraphic sections representing ~13 km of basin strata provide a 2- and 3-dimensional record of continuous deposition since ~ 19 Ma. The distinctive Xiyu conglomerate caps 8 of 11 magnetostratigraphic sections within the basin and has basal ages ranging from ~15.5 million years (Ma) in the north, ~8.6 Ma in the center, and 1.9 Ma in the south where it is found near the top of the basin sequence. These data indicate the Xiyu Conglomerate is syn-tectonic (formed during faulting and uplift of the Tian Shan) highly time-transgressive and has prograded south since just after initial uplift of the Kashi Basin Thrust (KBT) at 18.9 ± 3.3 Ma. These results are in contrast to previous work from the Tian Shan that suggested the Xiyu Conglomerate was very young (<2.5 Ma) and represented simply a change to a drier, colder climate at that time.

Our magnetostratigraphic age control of basin deposits constrain the timing of uplift for specific structures where growth strata (fanning dips that represent syn-tectonic deposition above active folds) are observed. These data combined with sedimentation rate changes indicate stepped migration of deformation into the Kashi foreland at 16.3, 10.5, 3.9, 1.4 and 1.3 Ma. Migration of deformation in the foreland causes i) uplift and reworking of basin-capping conglomerate, ii) a decrease of accommodation space and hence sedimentation rate above the active structure, and iii) an increase in accumulation on the margins of the structures due to increased subsidence and/or ponding of sediment behind the growing folds.

Besides the geochronologic history of the Kashi foreland, our mapping provides data to determine total contraction across the basin due to range-front deformation. At least 10 km of shortening is apparent in the foreland deposits in the eastern side of the basin, and this number gradually increases to >20 km in the west. Geometric modeling suggests that the observed westward increase in shortening magnitude results from the oblique collision between the Pamir and Tian Shan and subsequent closure from west to east of the Kashi foreland. Over time the Pamir mountain front with its foreland converge north with the Tian Shan, and its trailing edge migrates eastward as a function of the shortening rate between the two ranges. Thus shortening is most in the west where the range forelands have collided for the longest period of time, and decreases towards the east.

This research from the Kashi Basin highlights the complexity of foreland basin evolution and illustrates the need for thorough, 3-dimensional datasets when reconstructing the structural and depositional history of a region.

Caption:
"Core of a syncline (concave up fold) in Miocene (24-5 million years) sandstone and shale from the western Tarim Basin, China. Ongoing research by Dick Heermance, Doug Burbank, and Chinese collaborator Chen-Jie (shown in photo) has used magnetostratigraphy to date sedimentary rocks in order to constrain the initiation of uplift and deformation rates along the southern margin of the Tian Shan mountain range. Folding and faulting has migrated southward in pulsed episodes at ~18 million years (Ma), ~11 Ma, and from 3 Ma to present and has accounted for at least 20 km of shortening across the range front. These data have provided new insight into the evolution of the Tian Shan and the variable sedimentation patterns in an actively deforming foreland basin."

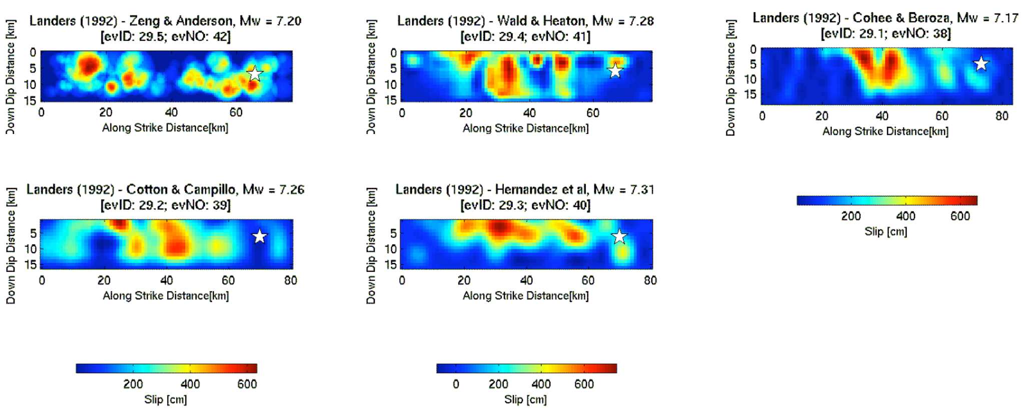
Morgan Page
Ph.D. Program (Physics Department), Jean Carlson, advisor

Resolution of Earthquake Source Inversions

Many of the interesting problems in geophysics can be formulated as inverse problems. Determining the structure of the earth from wave propagation data is one example. I am interested in the earthquake source inverse problem, which is to determine when and how much different parts of an earthquake fault slip during an earthquake using seismic recordings of the shaking on the surface.

These source inversions are often termed "kinematic" inversions, because they don't take into account the dynamics (and thus the true physics) of earthquake rupture. This is a necessary simplification to make the problem tractable, but it leaves out the biggest constraint we have in the inverse problem: the slip distribution in space and time must be one that could dynamically rupture, given that all the forces of the problem (that is, the true physics) are taken into account.

Below are five models of the 1992 Landers earthquake. These images show final slip on the fault plane. Each image is to the same scale. Why are they so different? There are a number of reasons, but the two most important are: 1) different researchers parameterize the inverse problem in different ways, and 2) this problem is very underdetermined, which means there are an infinite number of models that fit the data equally well. This is problematic because there is clearly a correct answer - but since we cannot more directly image slip at depth we don't know what it is. Still, the differences in these models beg the question, what can we believe in kinematic inversions? What features are robust? What are the "error bars" in these models?

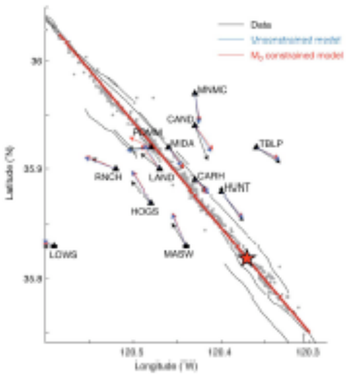


Source: Martin Mai's Database of Finite Source Models
http://www.seismo.ethz.ch/staff/martin/research/srcmod/srcmod.html

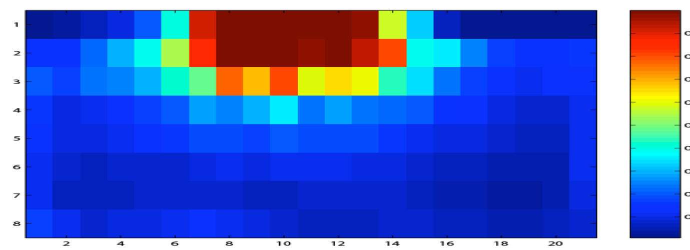
In recent work with Susana Custódio, Ralph Archuleta, and Jean Carlson, I have looked at the resolution of GPS data from the 2006 M_w6.0 Parkfield earthquake. The Parkfield earthquake sequence is extremely important for testing ideas of earthquake recurrence and predictability. Historically the Parkfield earthquake series was the impetus for formulating the "characteristic earthquake" hypothesis which still today has great impact on ideas used in seismic hazard analysis. By comparing kinematic inversions of past earthquakes at Parkfield we can determine to what extent these earthquakes are truly “characteristic” (the same), and thus, to what extent ideas developed in this region can be extrapolated to future seismicity on the San Andreas Fault. In order to compare the source processes of different earthquakes, a quantitative measure of the uncertainty between different inversions is needed.

To this end, we analyzed the resolution of the GPS data from the Parkfield earthquake. Below the station locations are shown in map view; the section of the San Andreas believed to have ruptured in the earthquake is shown in red. Notice that there are no GPS stations near the edges of the fault segment. The resolution on different parts of the fault plane is shown on the right. Except for a relatively small region near the surface and the center of the fault segment, the resolution is very poor.

GPS Station Locations



Diagonal elements of Resolution Matrix



Inversions of this earthquake using GPS data by different researchers do place slip in parts of the fault that are not well resolved. How should this slip be interpreted? We have found through synthetic tests (in which we generate simulated data, invert it, and compare our model to the initial model) that in the inversion process it is easy to generate apparent structure even from random input models. In underdetermined inversions, it is easy to generate areas of slip not well supported by data. Furthermore, conventional techniques to determine error bounds in the model (such as bootstrapping), fail in these inversions to produce reliable estimates of error. As such, much of the structure shown in GPS inversions of Parkfield, and other highly underdetermined source inversions, is highly uncertain.

RESEARCH EXPERIENCE FOR UNDERGRADUATES

Nineteen undergraduate students are involved in research administered through ICS.
Eight undergraduate students are involved in administrative work through ICS.

Undergraduates worked for the Portable Broadband Instrument and the Santa Barbara Array, which has nine operational stations throughout the city of Santa Barbara.

The Institute administered two National Science Foundation sponsored Research Experiences for Undergraduates (REU). Research Experiences for Undergraduates grants fund travel costs and stipends for undergraduates while engaged in research:

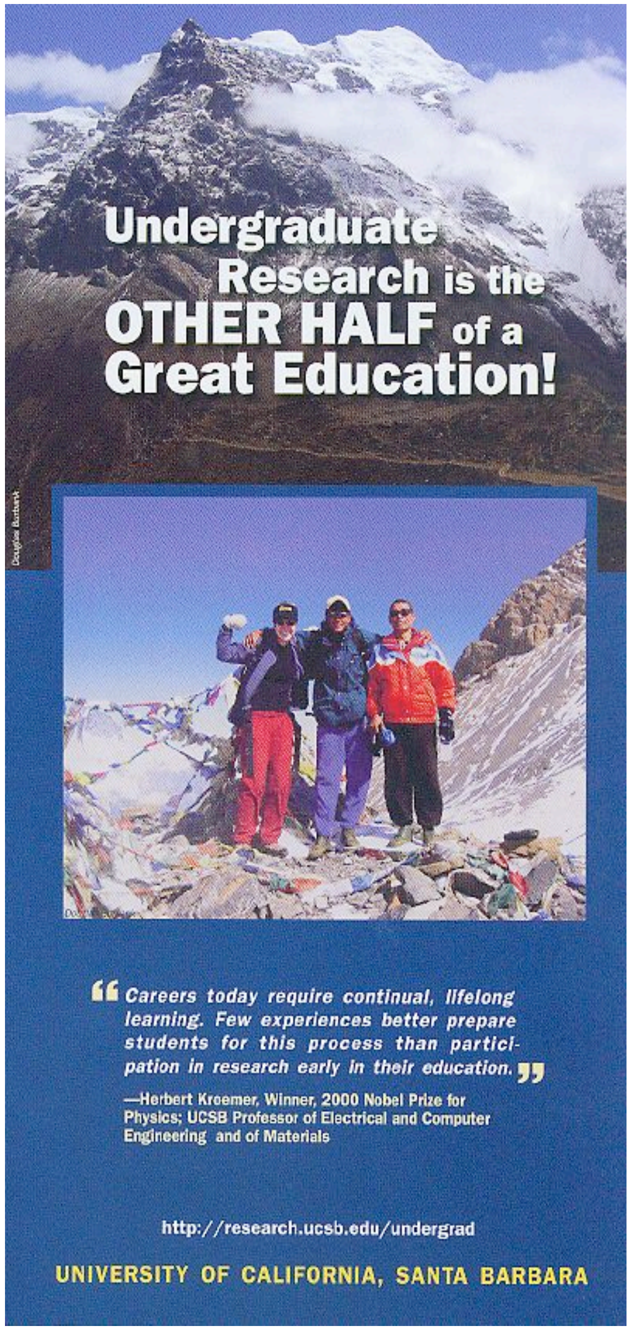
- Professor Burbank secured an REU research project on Scaling and Displacement for Thrust Fault in New Zealand. Undergraduates will assist Professor Burbank and Graduate Student Researcher Colin Amos with field research in the Southern Alps of New Zealand. Study changes in fault scarp morphology along a thrust front and use a differential GPS survey tool to make detailed 3-D images of the fault.

- Professor Luyendyk secured an REU for six undergraduates to gain experience with a marine geology and geophysical investigation in the eastern Ross Sea. This undergraduate research experience took place last year in Antarctica aboard the RVIB Nathaniel Palmer, the cruise will last for twenty eight days and Professor Luyendyk's team will attempt to acquire single-channel and multi channel seismic, piston cores, multibeam and deep towed chirp sonar and side scan sonar. This year students are continuing working on the seismic processing of multichannel reflection data and sea floor maps from multibeam bathymetry data.

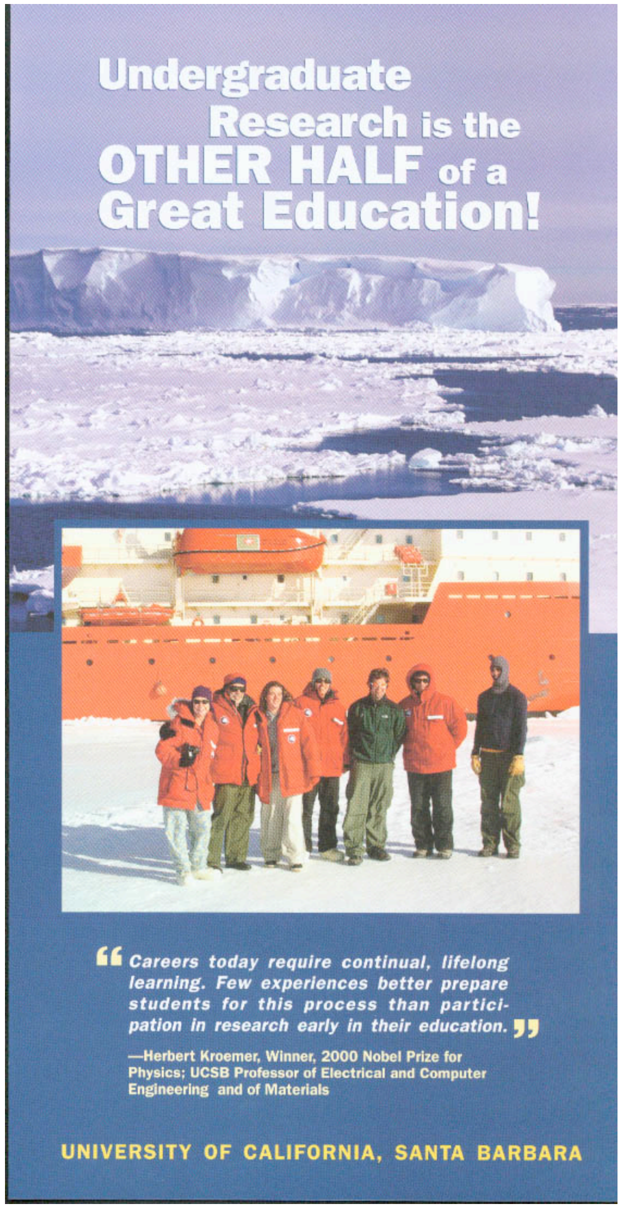
Southern California Earthquake Center Interns

The SCEC intern we had this summer was Jack Tung, a geology student from Cal State Los Angeles. He worked on processing of the San Simeon earthquake aftershock data collected using the SCEC portable instruments and also assisted with a field experiment at the Garner Valley site

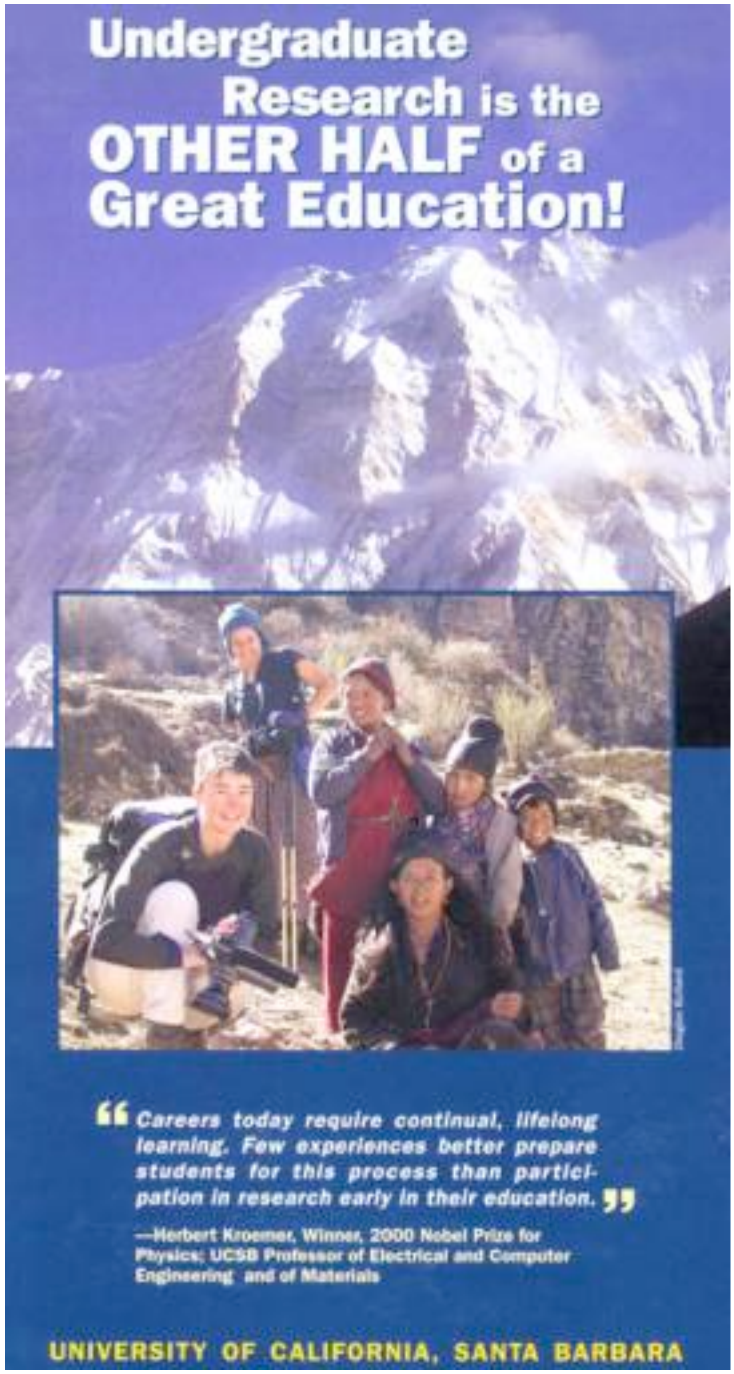
For the past three years 2002-2005 the research projects administered at the Institute have been featured by the Office of Research publication on undergraduate research opportunities. This year's Office of Research Publication of Undergraduate Research featured professor Burbank's student in Nepal.



Cover: Awesome research Monsoon-drenched Himalayan gorges and wind-swept alpine desert on Tibet's southern plateau were natural laboratories for undergraduate Karen Vasko in spring 2004. The senior's research project documented effects of the previous year's catastrophic flood, which displaced boulders more than 15 feet in diameter. Vasko also was field assistant to Beth Pratt, \a graduate student mentored by UCSB geology professor Douglas Burbank, director of the Institute for Crustal Studies. Burbank leads an eight-university team studying interactions between climate, erosion, and mountain building in the world's highest mountains. As Vasko helped install devices to monitor river flow, sediment loads, snow melt, and air temperature, she went from tropical rivers to glaciers at 18,000 feet. (Inset: Karen Vasko and two Nepalese assistants reach an alpine pass festooned with prayer flags.)



Cover: Extreme Research Very cool by any measure, a four-week expedition to Antarctica gave five undergrads, two graduate students and their faculty mentor a chance to explore new areas of the ocean floor in the minus 15-degree Antarctic summer of January 2003. Prepping for National Science Foundation-supported research in the coldest, windiest, highest, driest continent on earth included medical exams, full dental tune-ups, and a mandatory geophysics course. Led by Bruce Luyendyk, professor of Geological sciences and principal investigator in UCSB's Institute for Crustal Studies, the research team prepared for drilling from the Ross Ice Shelf that will answer questions about the evolution of the East and West Antarctic ice sheets, Antarctic climate, global sea level, and tectonic history of the West Antarctic rift system.



Cover photo: ***7,8000-Mile Field Trip*** Nepal's Annapurna mountain range in the Himalayas was junior Michelle Garde's research lab for eight weeks in spring 2002. Garde (left, in back) was field assistant to Beth Pratt (left, foreground), graduate student working under the supervision of Douglas Burbank, geology professor and director of the Institute for Crustal Studies. Burbank is leading an eight-university team studying inter actions between climate, erosion, and mountain building in the world's highest mountains. Garde also did her own research, which produced "valuable information on the history of a colossal, 5000-year-old landslide and rates of erosion in this mountainous region," according to Burbank. (The family in this photo was herding sheep near Tibet where the researchers were camping.)