Research Experience for Graduates

Forty-three 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

Beth Pratt-Sitaula
Ph.D. Program, Douglas W. Burbank, advisor

Himalayan climate, ice, and education

PhD student, Beth Pratt-Sitaula, has been combining scientific research on climate and glaciers of the central Nepal Himalaya with educational outreach in both California and Nepal. The scientific focus of her work has centered on determining the timing and climatic controls on glacial advances in the Himalaya. Researchers have a good understanding of when continental ice sheets last covered large parts of North America and Europe, but the study of Himalayan glaciers is still in its infancy. Early work indicates that mountain glaciers likely behave quite differently than large ice sheets, but little previous research had been conducted in Nepal to assess this claim. Glaciers are very sensitive to climate change and have the potential to provide rare glimpses into high altitude climates of the past. Such glimpses will help calibrate global climate models for terrestrial locations and predict the effect of future climate change. Melting Himalayan snow and ice are crucial dry-season water sources for drinking, irrigation, and power generation for 100's millions of people, so understanding how this resource may change as climate changes is very important.

Using an exposure dating technique that measures the time since glacial boulders were last moved (hence the time since ice last left the area), Ms. Pratt-Sitaula established a detailed, remarkably self-consistent glacial chronology for the last ~15,000 years. This record clearly shows that glaciers in the central Himalaya have advanced under both cold/dry and warm/wet conditions. Hers is the most tightly documented example of this type of glacial response in the entire Himalaya. One of the glacial advances she identified occurred during the Younger Dryas cold snap at ~12,000-11,000 years ago. This colder drier period has been identified in marine and cave climate records throughout Europe and Asia, but had not previously been observed in the Himalayas.

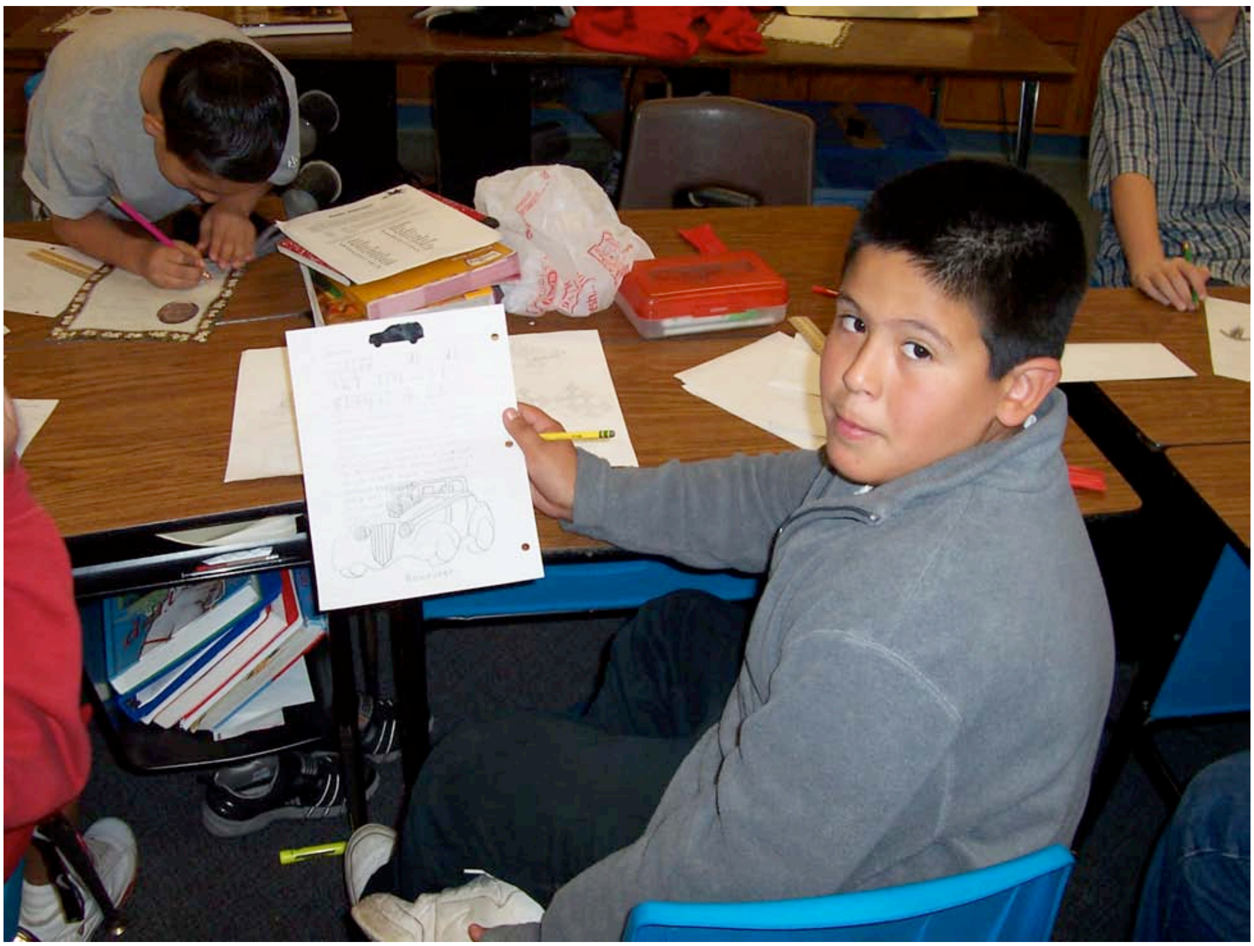
Using a computer model of glacial flow, she demonstrated that the altitude range of the glaciers plays an important role in the type of climate under which glaciers grow and neighboring glaciers experiencing the exact same climate can exhibit opposite behavior, solely due to their altitudes. Glaciers with limited altitude ranges can typically only survive in colder climates. Glaciers that have high altitude source areas can actually advance when the climate warms because warming is often accompanied by increased precipitation that falls as snow at high altitudes and provides increased nourishment to the glaciers.

She also combined modern weather records from the Marsyandi meteorological network with analysis of modern and past glacial extents to constrain possible climate variations in the past. She demonstrated that modern glaciers receive about half of their snowfall during winter months. Previously, researchers had assumed that most of the snow came during the summer monsoons that bring most (~85%) of the precipitation to the lower altitudes. This had led them to conclude that only changes in the summer monsoon system could control glacial advances. Now we know that variations in the winter weather systems must also be considered. The bulk of modern summer precipitation falls as rain at altitudes just below the modern glaciers (below 4000 m [13,000 ft]). Ms. Pratt-Sitaula shows that only 1-3ºC (2-5ºF) of cooling would convert a large amount of precipitation currently falling as rain to fall as snow, allowing glaciers to advance considerably more than the temperature change might suggest.

Snow station

Glacial overlook

In addition to pure research, Ms. Pratt-Sitaula has undertaken considerable educational outreach in both the USA and Nepal. She founded a non-profit organization to promote international improvements in education and cultural understanding (Oneworld School Project). Together with teachers, she organized letter writing between students in California and Nepal and facilitated discussions on cultural differences. The Nepali rural schools lack most of the facilities that Americans take for granted (dependable electricity, classroom materials, etc.), so at the request of the Nepali teachers and administration, Ms. Pratt-Sitaula and the Californian teachers and students organized a fund raising campaign to provide science educational materials for two Nepali schools. They successfully donated basic demonstration materials for biology, chemistry, physics, and earth science and have long term plans to help the school build classrooms dedicated to science.



Goleta elementary student writing to Nepalese school children.

Beth Pratt-Sitaula showing teachers the donated school supplies.

Scott Johnston
Ph.D. Program, Bradley Hacker, advisor

The demise of an ancient mountain range: the Norwegian Caledonides

Imagine a breathtaking mountain range, similar in size and grandeur to the Himalaya of Tibet or the Alps of Italy, collapsing into a series of relatively low-lying basins and ranges over the course of several million years. A million years may seem like a long time to the average human being, but for the average rock, a million years passes faster than the blink of an eye. To suggest that a mountain range of this size could collapse over such a short period of time is shocking to geologists, but with my advisor Brad Hacker, I have been working on an ancient mountain range in Norway that did just that.

The Norwegian Caledonides formed nearly 500 million years ago as the European continent rumbled westward toward North America. During repeated collisions between Europe and small island chains, the Caledonides began to form as highly deformed rocks under contraction were pushed together and stacked up on the European continental margin. Using single garnet crystals from across my field area, we have identified a mountain building event that began 425 million years ago. Fifteen to 20 million years later, the ultimate collision between Europe and North America forced European continental rocks over 100 km beneath the Earth's surface and created a mighty mountain range with peaks as high as Mt. Everest spanning from the northern tip of Norway to Georgia and Alabama. Then, around 400 million years ago, collision ceased and the Caledonides suddenly collapsed, causing rocks buried deep within the mountain range to rocket toward the surface.

The main focus of my research is the Nordfjord Sogn Detachment Zone, a major fault that stretches for several hundred kilometers across western Norway, and is thought to be one of the primary structures responsible for the collapse of the Caledonides. In contrast to the contraction experienced during the construction of Caledonides, during the collapse of the mountain range, extension was the dominant force, and the mountains were slowly pulled apart and flattened along the Nordfjord Sogn Detachment Zone. My geologic mapping and structural data suggest that this shear zone was much more complex than just a simple extensional fault, though, and was actually a composite structure with deformation styles that evolved dramatically from one incarnation of the fault to the next. Initially, the roots of the mountain range may have risen along the fault as a diapir, or a giant bubble of hot rock, toward the surface. Later, these same rocks moved closer to the surface as the rocks in the upper crust were dragged off the top of the range toward the west along the fault in a series of stages that started at 500ºC and gradually cooled through 300ºC. We have also used computer programs that calculate temperature gradients within the Earth's crust in conjunction with recently published paleo-temperature data from western Norway to develop a simple model for the generation of a series of folds that warped the surface of the evolving Nordfjord Sogn Detachment Zone. In contrast to published theories that require coeval displacement along large strike-slip faults, like the San Andreas Fault in California, with extension along the Nordfjord Sogn Detachment Zone, we have suggested that the folds formed as the result subtle variations in the rate of extension and uplift along the Nordfjord Sogn Detachment Zone (Fig. 1). This work has helped to put the pieces of the

Caledonian puzzle back into place, and has important implications for what the future holds for mountain ranges like the mighty Himalaya.

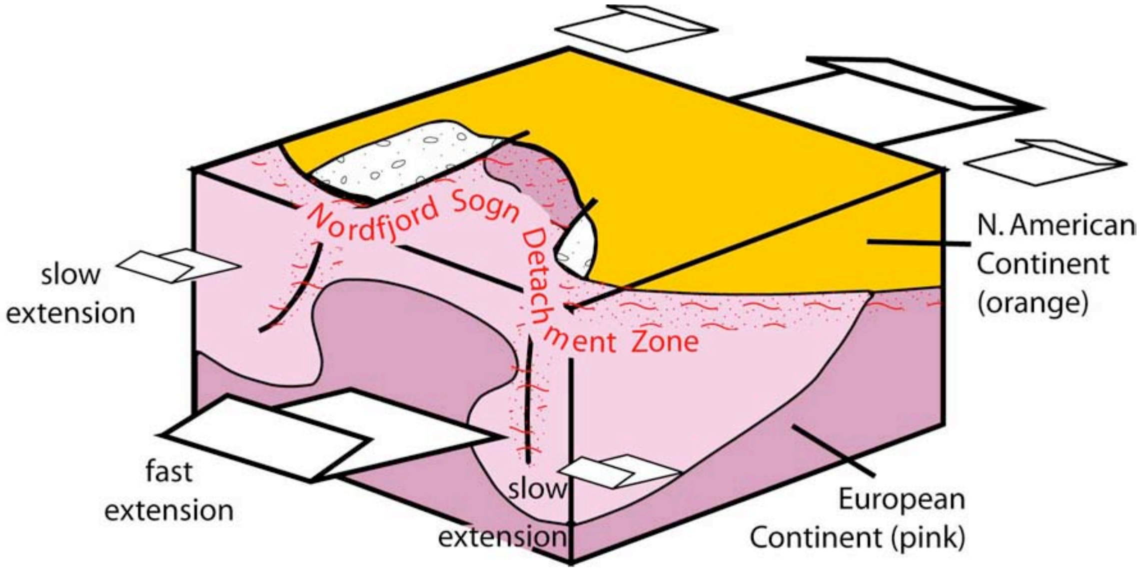


Figure 1. Our new model for the generation of folds on the surface of the Nordfjord Sogn Detachment Zone.

This past summer, in addition to more fieldwork in Norway, I also had the opportunity to visit Greenland and look at the North American side of the Caledonides. Recent work has indicated that the North American side of the mountain range reached similar depths of over 100 km within the crust, but with significantly higher temperatures of up to 1000ºC. It was a very successful trip: in addition to spectacular glaciers, icebergs (Fig. 2), and surprisingly warm weather (I even managed a quick swim in a lake near our camp), we found a series of high pressure and high temperature rocks that will provide me with plenty of work for the coming year. I am looking forward to getting started!

Figure 2. My collaborator, Luc Mehl, taking advantage of the midnight sun while working on a rock outcrop in Greenland with glaciers and icebergs in the distance.

Karen Blair
Ph.D. Program, Phillip Gans, advisor

Alluvial fans, giant lakes, rivers and volcanoes; A tale of Sahuaripa's geologic history

I am an honorary Arivecheña. My home away from home for the last four winters has been the Sahuaripa valley of eastern Sonora, Mexico, including the towns of Sahuaripa, Bamori, Valle de Tacupeto, and Arivechi. The hills and valley surrounding Sahuaripa preserve some of the oldest known rocks in the country in addition to structures and rock sequences that point to a long history of sedimentary basins and faulting. The minor amount of previous work in this area of Sonora had largely been focused on the descriptions and correlation of Neoproterozoic and fossiliferous Paleozoic through Early Cretaceous formations. The younger rocks had been all but ignored and are often lumped into Eocene/Oligocene rhyolites or the Tertiary "Baucarit" formation. This project was originally titled "Neogene Sedimentary Basin Development in east-central Sonora, Mexico". We intended to study these Tertiary basin-fill deposits partly to learn if extension that lead to the opening of the Gulf of California affected areas this far east. But, after the first field season's results we knew the scope of the project needed to evolve to also encompass some of the older structural and sedimentologic history of the area. The "recent" deformation here is generally older than the extension that affected the development of the Gulf starting ~12.5 Ma. Dip direction is rather consistent throughout the field area, though the dips decrease with the age of the rock. Gentle angular unconformities exist between the distinct packages of sediment. Instead of the expected short duration of mid-Tertiary extensional faulting, we have found evidence of at least four periods of tilting and deposition since the Early Cretaceous (about 100 Ma) lasting till not much after 15 Ma.

A period of deformation following deposition of Early Cretaceous limestone exposed the area's Proterozoic and Paleozoic rocks. These bedrock formations shed coarse limestone and quartzite clasts into alluvial and fluvial deposits over an angular unconformity. Today the bedded red-matrix conglomerates are over 200 m thick in some locations. Above the limestone-clast conglomerate is a very thick section of andesitic lava flows, volcaniclastic breccia and tuffaceous sandstone. The remarkable point to make is the very rapid conformable transition from beds of completely non-volcanic, limestone and quartzite conglomerate to entirely volcanic deposits. It looks as if the Paleozoic source area "turned off" completely while another completely volcanic source "turned on". In areas where this transition was sufficiently exposed there were only a few mixed-clast beds between the two very different conglomerate sequences. The structures controlling that basin develpoment may include a thrust fault in the eastern range, which juxtaposes Neoproterozoic rocks over Aptian fossiliferous shales. Previous K/Ar geochronology studies have dated some of the lavas from the volcanic section to be ~74 Ma. The deformation creating the basin occurred before this, probably around 80 Ma, and the limestone clast conglomerate would be about the same age.

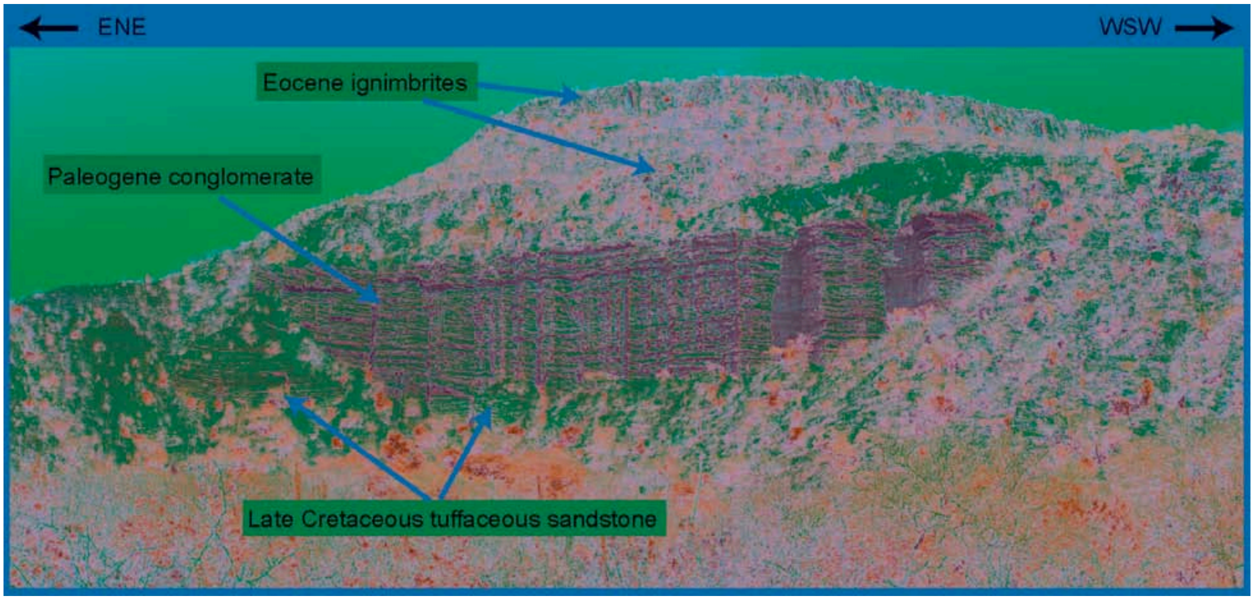
The previously mentioned lower, andesitic rocks can be correlated with the Tarahumara formation representing the late Cretaceous volcanic arc of central Sonora and much of western North America. The dark-colored volcanic and volcaniclastic sequence transitions vertically to thin bedded light-colored tuffaceous sandstone, siltstone and shale with horizons of limy shales and two- to five-meter thick crystal rich tuffs (see photo). In the Sahuaripa area the whole section is upwards of four kilometers thick! While the andesitic units were probably subaerially deposited, ripple marks, soft sediment deformation, disaggregated plant debris, load structures, thick sections of black shale and the lateral continuity of many of the beds indicate a lacustrine and deltaic depositional environment. While previous workers had described this section, they had not interpreted the depositional environment. A new $^{40}Ar/^{39}Ar$ sanidine age of one of the tuffs in this upper section is 73.7 ± 0.3 Ma and when analysis is completed on a couple additional samples we will have a better idea of the age range of the basin. While we do not know exactly how much sedimentary section is above those tuffs, what we do know is that hundreds of meters of volcanic material and sediments were deposited in a matter of just a couple million years based on the two existing ages. The Santonian-Maastrichtian Cabullona basin in northeastern Sonora is the closest correlation to the Sahuaripa section described in the literature. The Cabullona basin formed syntectonically adjacent to a thrust fault, which raised the Sierra Anibacachi, and the 2.5 km of sediments that filled the basin are fluvial-deltaic-lacustrine in origin. Here in the Sahuaripa area we have not located a distinct thrust fault which would satisfactorily explain the necessary accommodation space and transition of thick section of rock found, but thrust faults have been identified juxtaposing older Paleozoic formations above younger.

A second period of deposition following deformation is indicated by a rounded pebble to cobble conglomerate found unconformably above the east-tilted Late Cretaceous sediments. The clast assemblage is unlike any of the other clastic sequences and includes abundant milky quartzite, light colored porphyritic volcanics, and a distinct black chert against a generally light yellow-weathering deposit. Tilting and gentle folding of the Late Cretaceous sedimentary section, likely tied to continuted Laramide deformation, was followed by local incision by river systems, which deposited the conglomerate and interbedded fine-grained overbank sediments. In one modern arroyo wall a beautiful, large, U-shaped channel is exposed (see photo), which cut was into the thin-bedded Late Cretaceous section and filled with the stratified conglomerate! Up to 400 m of fluvial conglomerate and minor sandstone were deposited during the loosely bracketed Early Tertiary. Sediments of similar description are found in the Mogollon Rim area of Arizona filling canyons incised into Mesozoic formations and underlying mid- to late-Tertiary volcanic deposits. Paleogeographic studies of those gravels showed that they were deposited by large north-flowing rivers draining the Mogollon highlands. Clast imbrication near Sahuaripa indicates the paleocurrent flowed from the southwest and west. The early Tertiary gravels in Sahuaripa likely have their source in central Sonora, which had been uplifted during Laramide crustal thickening and include Paleozoic and early Mesozoic quartzite and chert bearing formations. The degree of rounding of the cobbles and pebbles indicates significant transport and/or high energy streams. The rivers may have drained to a basin similar to the large Eocene lakes of Wyoming and Utah. A crystal rich tuff was found in the section and we are waiting for the results of $^{40}Ar/^{39}Ar$ analysis to give us a more exact age of the early-Tertiary gravel.

The third identified period of eastward tilting occurred after the fluvial conglomerate was deposited and before a locally thick section of Eocene ignimbrites blanketed the area indicated by the 10-15° angular unconformity between the them. The northwest strike of the sedimentary beds implies that the active faults would have been NNW to NW trending compared to the modern basin bounding faults, which are closer to north-south. The ignimbrites and overlying basaltic andesites represent the western edge of the Sierra Madre Occidental volcanic province, which was active during the Eocene and Oligocene and is one of the largest silicic volcanic centers yet described. Four ignimbrites were sampled in Sahuaripa, whose ages range from 37.3 – 28.2 Ma and the basaltic andesites range from 28.6 – 25.0 Ma with one sample dated at 35.3 Ma. While the ignimbrite sequence seems to be rather consistent across the field area, the stack of basaltic andesite flows and breccias is thickest in the northern part of the area. Adjacent to the town of Sahuaripa the mafic flows total more than 300 m thick and contain horizons of cindery deposits and volcanic bombs. Clearly there was local volcanism concurrent with the larger volume explosive ignimbrite eruptions.

Lastly, the Basin and Range style normal-faulting, which defines the valley's present topography and caused the additional eastward tilts, occurred after the Eocene-Oligocene volcanism. This last phase of faulting was dominated by movement along a system of west-dipping normal faults along the valley's eastern edge. Additional faulting occurred in nearly the center of the basin causing isolated exposure of the Oligocene volcanics, but these faults are difficult to trace due to more recent beveling of alluvial surfaces and incision by the Sahuaripa River. Andesite flows covered some of the alluvial deposits between 19 and 15 Ma on the western side of the valley and alluvial fans built out over these flows on the eastern side. There aren't any younger volcanic units, valuable for geochronology, to help constrain the younger history of the basin, but because the sedimentary section above the 15 Ma andesites are tilted up to 20°, the basin must have continued to experience faulting after the lavas erupted. Sediments that interbed with and overlie the andesite flows consists of angular to sub-angular pebble to cobble breccias and conglomerate proximal to the highlands and grade to pebbly coarse- and medium-grained sandstone nearer the basin's center. The deposits represent the alluvial fans and axial river system of the half-graben basin. Nearly all of the clasts are from the Late Cretaceous volcaniclastic sandstone and siltstone units and are curiously absent of Paleozoic limestone clasts. The area has experienced significant erosion and river incision in the last 15 Ma considering that the young andesites cap 1600 m buttes in the southwestern part of the field area while the drainages below them are at around 700 m.

In summary the Sahuaripa area of eastern Sonora has seen a volcanic arc approach, a giant lake develop, a river system carve canyons, volcanics blanket everything, faults continually tilt the sequences eastward and alluvial fans build out into a basin. Each of the described sections of rock and segments in time are separated from the previous by tilting and erosion marked by their difference in eastward dip. Early in the Late Cretaceous a basin formed in the area of Sahuaripa into which Paleozoic limestones and quartzite clasts were shed. After the Late Cretaceous volcaniclastic breccias and thick deltaic and lacustrine section were deposited they were broadly folded and uplifted. Rivers carrying clasts from central Sonora carved new topography across the landscape and deposited gravels in channels. The area experienced faulting which tilted the beds eastward about 10°. Ignimbrites blanketed the region followed by more localized basaltic andesite flows. Additional eastward tilting of 10-15° occurred due to normal faulting followed by development of alluvial fans, andesite flows, and an axial river system. All in the last 100 Ma. The adventure of discovery did not end with just the geology, but I have also discovered in this enclave of Mexico, some of the warmest hearts and welcoming homes I have ever encountered. The local people were intrigued by the stories I shared about the history of the area's rocks, and I delighted in hearing stories about the history of the villages.



Caption of photo: Here we can see three of the described rock sequences. This is a magnificent view of a channel, cut into the moderately dipping yellowish-green thin-bedded Late Cretaceous tuffaceous sandstone, and filled with stratified early Tertiary gravels. This part of the gravel sequence is less well-bedded than in other exposures and, although they appear sub-horizontal, they are dipping away from the view. The sequence is then capped by at least two Eocene ignimbrites, the lower one includes the white ashy base and the second makes the resistant bed on the skyline.

Jill Wertheim
Ph.D. Program, Andre Wyss, advisor

Discovering unique fossil mammals in the Chilean Andes

South America was isolated from other landmasses for all but the final three of the last 75 million years (at which point it connected with Central and North America). The land mammals that became isolated in South America as it separated from Africa and Antarctica followed their own, idiosyncratic evolutionary pathways, leading to the origin of such peculiar modern groups as armadillos, sloths, and capybaras, and myriad other exotic extinct forms. Although paleontologists have been uncovering a rich fossil record in the high latitudes of Patagonia for over a century, dense vegetation and extensive volcanic cover have hindered collecting from much of the rest of the continent, leading to a highly skewed representation of actual diversity. The paucity of extra-Patagonian fossil material greatly restricts the reconstruction of South America's unique paleontological history; thus our research team's discovery (from UCSB, the Field Museum, and University of Chile) of abundant, well-preserved fossil mammals across a broad swath of the central Chilean Andes offers crucial new information about the history of land mammals in South America. Furthermore, these unusual fossil-bearing volcanigenic deposits permit radioisotopic analysis, allowing these new faunas to be precisely dated.

Mammal faunas recovered from the Laguna del Laja region of the Andean Main Range include rodents, marsupials, xenarthrans (e.g. armadillos), and various extinct herbivores (notoungulates). My research focuses on the rodents from these faunas (including early chinchillas, pacas, etc.). Rodents occur abundantly as fossils; this, coupled with their rapid pace of evolutionary change, makes them of particular interest paleontologically and especially useful as an independent age calibration tool. We have recovered at least 17 new rodent species from the area to date, and several new genera. The high degree of taxonomic novelty results from at least three factors: the region's geographic isolation from other roughly contemporaneous mammal-producing strata, the unusual volcaniclastic preservation of the Laja fossils, and our sampling of time intervals poorly represented by fossils elsewehere in South America. Evidence from the fossils and radioisotopic data suggest that these deposits span up to five South American Land Mammal "Ages" (SALMAs); more than two stratigraphically superposed SALMAs have been documented only once before in South America. This unique collection allows us to study evolutionary trends across several SALMAs, while documenting for the first time the taxonomic diversity of this region during the Miocene. Furthermore, comparison with these new, well-calibrated fossils will help us establish taxonomic and temporal context for the multitude of new Miocene fossil mammals our research team is currently uncovering elsewhere within the Main Range of central Chile.

Colin Amos
Ph.D. Program, Doug Burbank, advisor

My graduate research at UCSB focuses on interactions between active faults and river systems at the earth's surface over the last several million years. Such work is important to our understanding of how young mountain ranges evolve because it deals directly with the ongoing competition between tectonic forces that raise mountains and erosional processes that shape and reduce them back to the ground. Additionally, rivers and their deposits provide an excellent frame of reference for observing ground deformation associated with active faulting that, in turn, permits detailed examination fault growth and evolution. By focusing on several well-exposed fault zones in New Zealand's South Island, I hope to understand the style, timing, and magnitude of faulting and the potential contribution of such faults to the continually evolving form and topography of active mountain belts.

Initial stages of my work in New Zealand involved investigation of abandoned river channels preserved across folds that formed as a result of active faulting in the shallow subsurface. There, I looked at changes in the width of these channels to show that river narrowing may serve as a primary response to deformation at the earth's surface. Such a result is potentially significant because it reveals a detailed picture of how river channels adjust to folding and faulting and erode through zones of active uplift.

Currently, I am working on a series of deformed river terraces developed across these faults that reveal progressive folding and tilting as a response to the accumulation of fault slip or motion at depth. Such terraces mark the former bed of a river as it incises and adjusts to changing climate over the past several hundred thousand years. Relating the deformed shape of these terraces to the initial profile of the modern river allows us to see how deformation has progressed through time and permits construction of models for fault geometry in the subsurface. Despite challenges in deciphering the respective age of each terrace surface, the results of our ongoing fieldwork in the area should provide a robust dataset necessary for a quantitative reconstruction of fault zone evolution.

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

Rupture Model for the 2004 Mw6 Parkfield Earthquake

The San Andreas Fault (SAF) is the major fault in California that accommodates right-lateral motion between the Pacific plate, to the SW, and the North American plate, to the NE.

Different sections of the fault exhibit different seismic behaviors. The locked sections generate large earthquakes that repeat in large time intervals (Mw>7, recurrence period >150years). The creeping sections accommodate slip aseismically (plastic silent deformation, without production of earthquakes) and/or producing many frequent small earthquakes (M<3, recurrence period <1year). Parkfield is located between a creeping section (NW) and a locked section (SE) of the SAF (Figure 1). In historical times, it released 5 moderate size earthquakes (Mw6), approximately every 22 years. Bakun and McEvilly (1984) observed that ground motion recorded during the 1922, 1934 and 1966 Parkfield earthquakes was extremely similar. Only identical ruptures can generate similar ground motion. Thus Bakun and McEvilly (1984) advanced the concept of characteristic earthquakes – earthquakes of persisting features – they would nucleate at a same point, rupture the same fault patches, thus releasing the same amount of energy, and they would repeat regularly in time. According to Bakun and McEvilly's (1984) idea, the next Parkfield earthquake was due between 1983 and 1993. As a consequence of this prediction, several geophysical instruments were deployed in the Parkfield region to trap the next Mw6 event. The long awaited Mw6 Parkfield earthquake occurred on September 28, 2004, generating a seismic data set of unprecedented quantity, quality, and diversity.

The 2004 Parkfield earthquake exhibited two intriguing aspects: 1) even though it was only a Mw6 event, it generated very large peak ground motion (peak ground accelerations exceeded the value of gravity acceleration); and 2) the 2004 earthquake was not a characteristic event – it occurred 38 years after the previous Mw6 event, nucleated at a point 20km SE of the anticipated hypocenter, and ruptured the SAF from SE to NW, in a direction opposite from previous Mw6 Parkfield ruptures. In order to explain these two pertinent features of the 2004 Parkfield earthquake, we derive a time-space model for co-seismic slip on the fault. The rupture model is obtained through a non-linear inversion algorithm (Liu and Archuleta, 2004) that takes as inputs acceleration records from 43 near-fault stations and the velocity structure between the fault and the stations.

Rock material in the Parkfield region is extremely heterogeneous, as revealed by velocity structure studies (Michelini and McEvilly, 1991; Eberhart-Phillips and Michael, 1993; Thurber et al., 2003), magneto-telluric work (Unsworth and Bedrosian, 2004), and recent drilling at

SAFOD. The strong material heterogeneity suggests that the source signal recorded at individual surface stations may be severely distorted by non-linear effects and amplifications in the near-surface layers. Using records from the 1983 Coalinga earthquake we were able to assess the effects of local site conditions particular to each station. Figure 2 shows that the stations that recorded larger peak ground velocities in 2004 are those most affected by site effects. Thus site effects appear to be the most important factor in the generation of large peak ground-motion during the 2004 Parkfield earthquake.

After correcting for site effects, we computed 10 rupture models that explain the observed ground-motion equally well. The comparison between different models indicates the fault regions where the rupture model is robust (Figure 3). In order to assess the dependency of our models on dataset used, we inverted subsets of data; the derived rupture models are identical to the ones obtained by simultaneous inversion of all available data. We find that the hypocentral region (Zone A, Figure 1) produced the maximum amount of slip – 65 cm. A secondary region to the NW of the hypocenter (Zones B and C) also ruptured. Details of slip cannot be resolved in this secondary region. In 1994, Zone B generated a $M_W 5$ event; therefore it could be interpreted as a strong patch. After nucleating in a relatively quiet seismic region (Zone A), and breaking through the strong Zone B, the rupture continued to shallower depths, into zone C. The rupture did not proceed into the strong Zones D and E, which produced two $M_W 5$ aftershocks in the two days after the mainshock. Our model yields a highly heterogeneous rupture velocity distribution, which includes supershear (4.25km/s) in the SE rupture direction (YY' in Figure 3). This high rupture velocity probably contributes to the strong ground motion recorded towards the SE end of the rupture zone. Even though our time-space slip models show a zone of shallow slip towards the NW of the hypocenter, no surface break occurred at the time of the mainshock - the slow rupture velocities in the NW zone of shallow slip might explain the inexistence of surface break.

This research resulted in the submission of two papers, one to the *Geophysical Research Letters* and another to the *Bulletin of the Seismological Society of America*.

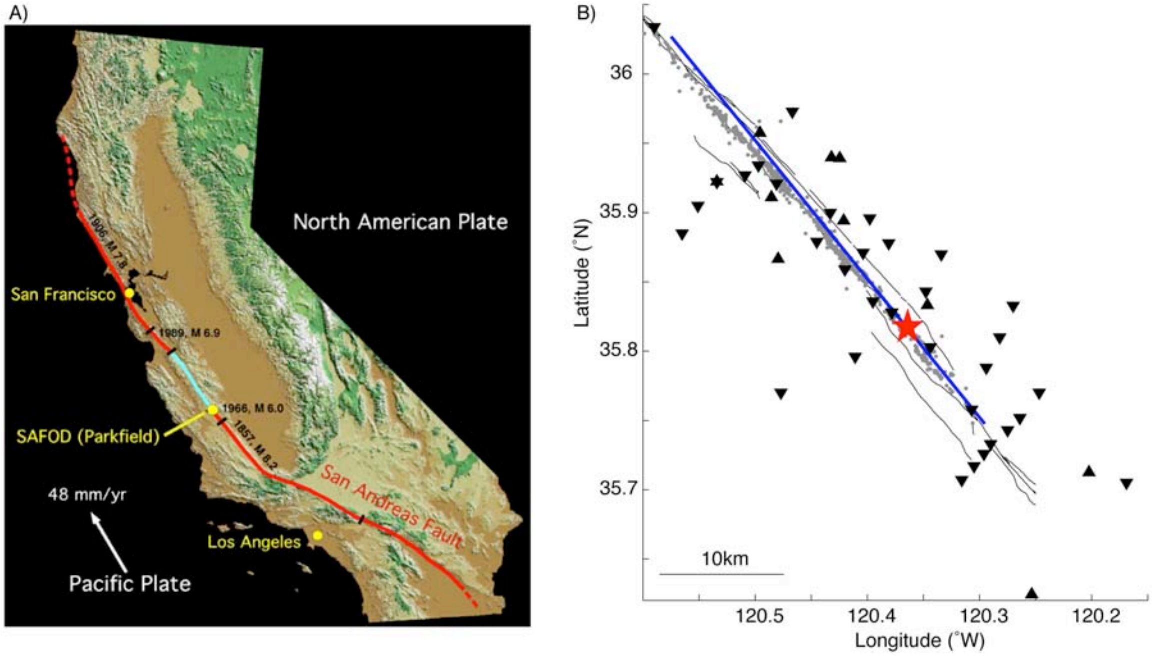


Figure 1 – A) Shaded relief map of California showing the location of Parkfield. Major historical earthquakes along the San Andreas Fault are shown, with the creeping section of the fault in blue. B) Map of the Parkfield segment of the San Andreas Fault. The 43 stations used to derive a rupture models are represented by: normal triangles - USGS stations; inverted triangles - CGS stations. 2004 Parkfield epicenter (red star); modeled fault profile (blue line); aftershocks located by Hardebeck and Michael [2004] (gray dots).

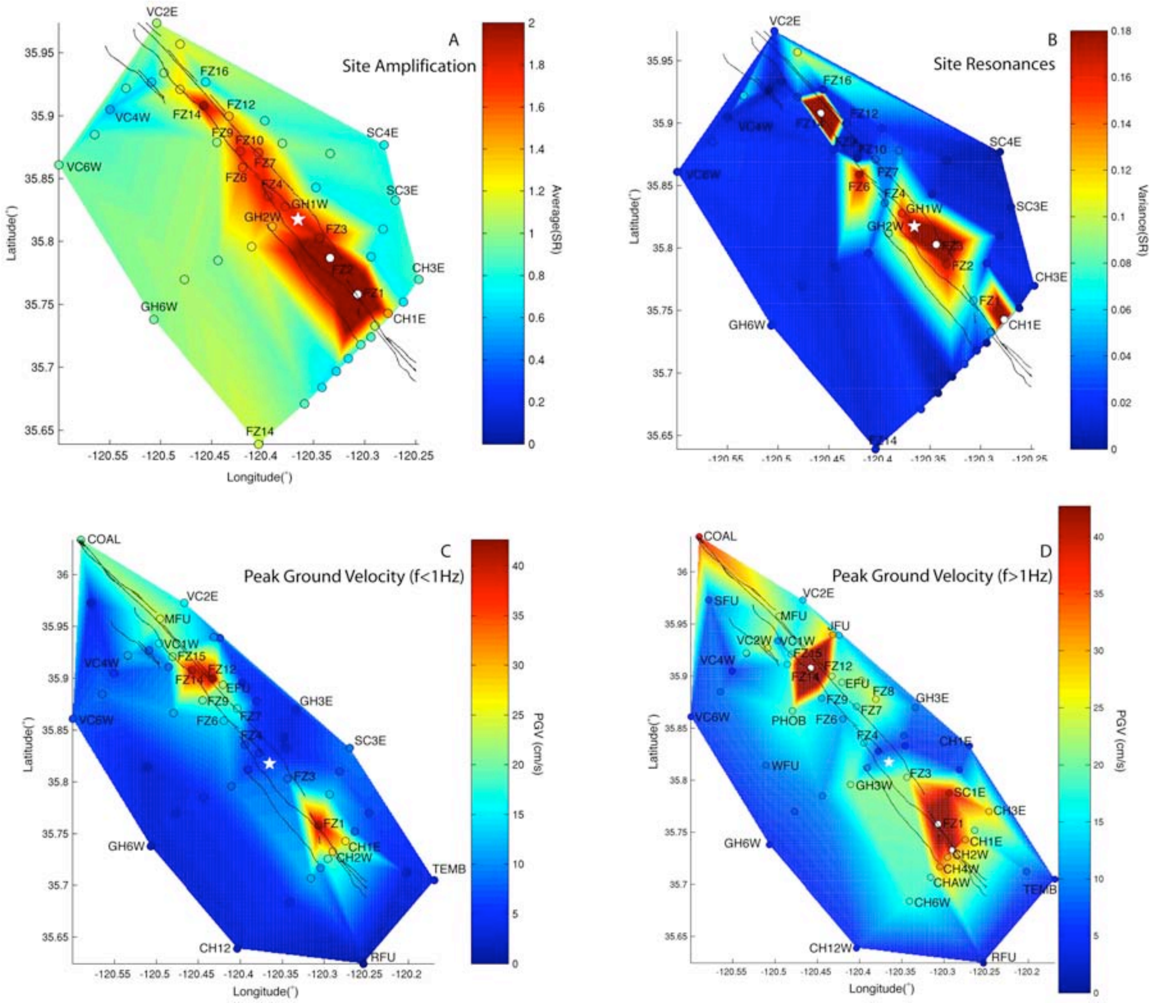


Figure 2 – Maps of the Parkfield region showing: A) Local amplification of ground-motion from a common source signal; B) Local ground-motion resonance - preferential amplification of specific frequencies; C) Peak Ground Velocity (PGV) at frequencies below 1Hz, observed during the 2004 Parkfield earthquake. D) PGV at frequencies above 1Hz, observed during the 2004 Parkfield earthquake. All maps were produced by linear interpolation between stations. Stations represented by white circles denote values that are higher than the color bar maximum. Most local amplification and resonances, as well as large PGV, take place on the fault-zone.

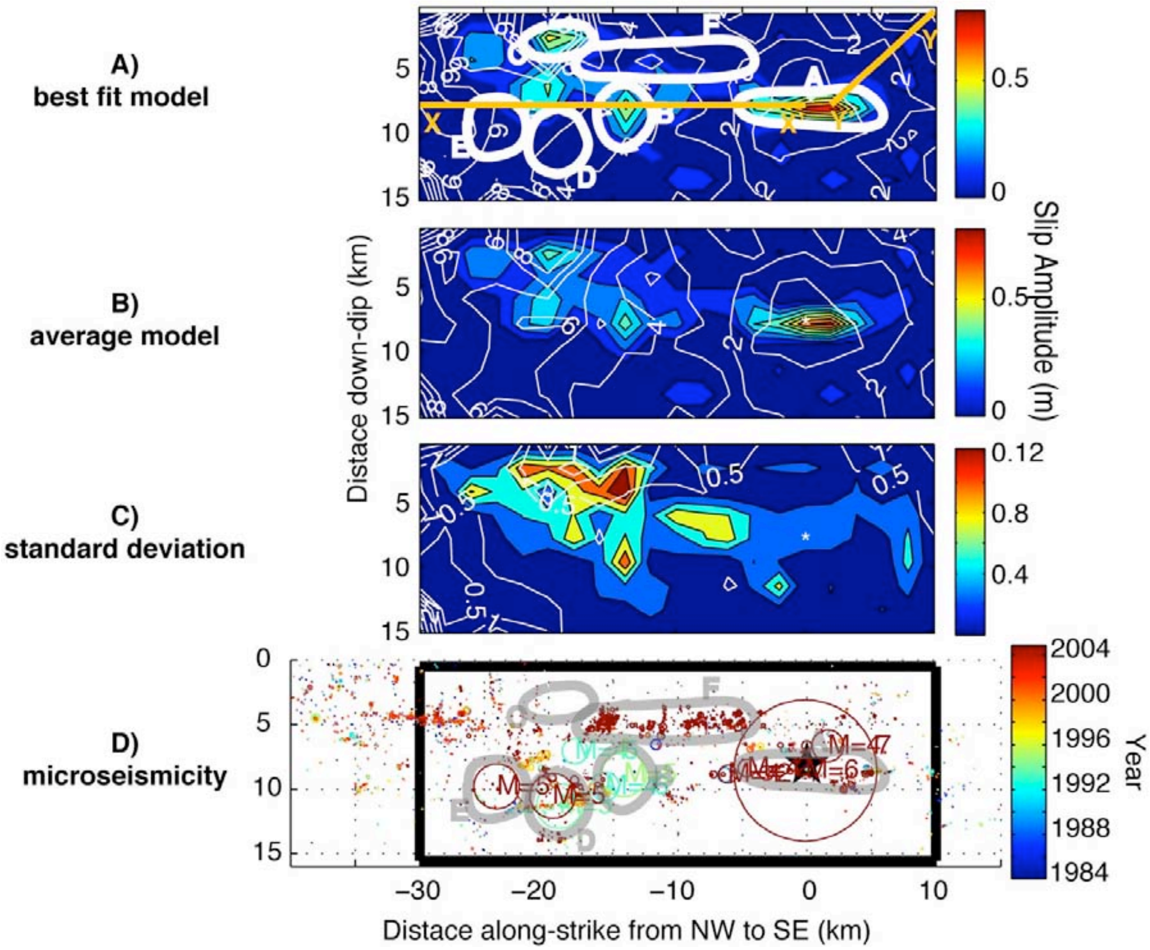


Figure 3 – A-C) Rupture models: slip amplitude (m) and rupture time (white lines are 1 sec contours). A) Rupture model that best fits the data. B) Average of 10 models that fit data identically well. The average retains only the coherent features from the 10 models. C) Standard deviation between the 10 models. Regions that present high standard deviation are not well resolved in our model. D) Seismicity before and after the 2004 mainshock (1984-2004) [Waldhauser et al., 2004; Hardebeck and Michael, 2004]. The area of the circles corresponds to the rupture area of each earthquake assuming a constant stress drop of 3MPa. The white asterisk marks the hypocenter. The three largest aftershocks in the hypocentral region, two Mw4.2 and one Mw4.7 events, took place on the edges of Zone A. Large slip (Zones A, B and C) occurred in zones of reduced no micro-seismicity. One of the two Mw5 aftershocks coincided with a the hypocenter of a 1993 Mw5 earthquake (Zone D). The other Mw5 aftershock (Zone E) coincides with the 1966 Mw6 hypocenter. Zones D and E did not slip during the mainshock but generated two Mw5 aftershocks in the two days after the mainshock. Zone F, which also did not slip during the Mw6 event, is delineated by several small aftershocks.

Mason Dykstra
Ph. D. Program, Ben Kneller and James Kennett, advisor

The Sedimentary Response of a Paleofjord to Rapid Climate Change in the Carboniferous Period (~320 million years ago) of South America

One of the projects I have been working on focuses on a succession of sediments in western Argentina deposited during the Carboniferous (Pennsylvanian – about 320 million years ago). These sediments were deposited on the continent when it became flooded after a large glacial epoch ended and sea-levels rose rapidly. During the middle-Carboniferous, the Earth had two major continents: Gondwana to the south, and Euramerica to the north. Gondwana consisted of the present continents of South America, Africa, Antarctica, and Australia, while Euramerica consisted of the modern continents of Eurasia and North America. Gondwana was located far to the south, with a large proportion of the continent in the South Polar Region. Because of its latitude, and because of the climate conditions at the time, large regions of polar and subpolar Gondwana supported continental glacier systems. These glacier systems waxed and waned in three major cycles that appear to record the progressive drift of Gondwana over the South Pole. The modern continent of South America hosted large, continentally-based glaciers during these glacial cycles. Because it is the nature of glaciers to carve deeply into the underlying rock and thus remove previously deposited sediment, the sedimentary record of these glaciations is most commonly limited to sediments deposited during the end of the last glacial cycle. This de-glacial sedimentary succession is fairly thick (up to about 1 km thick (3300 ft)), and consists largely of sediment thought to have been deposited quite rapidly (in only a few thousand to tens of thousands of years) following the end of the last glacial cycle in South America. Because such large volumes of sediment were deposited so rapidly, these sedimentary successions comprise very high-resolution records of the sedimentary response to rapid climate change of the depositional systems involved. Thus, by studying the record of these sediments, we can learn something about the response of the Earth in the distant past to climate changes similar to those that have been affecting the Earth in recent geologic history, and that continue today.

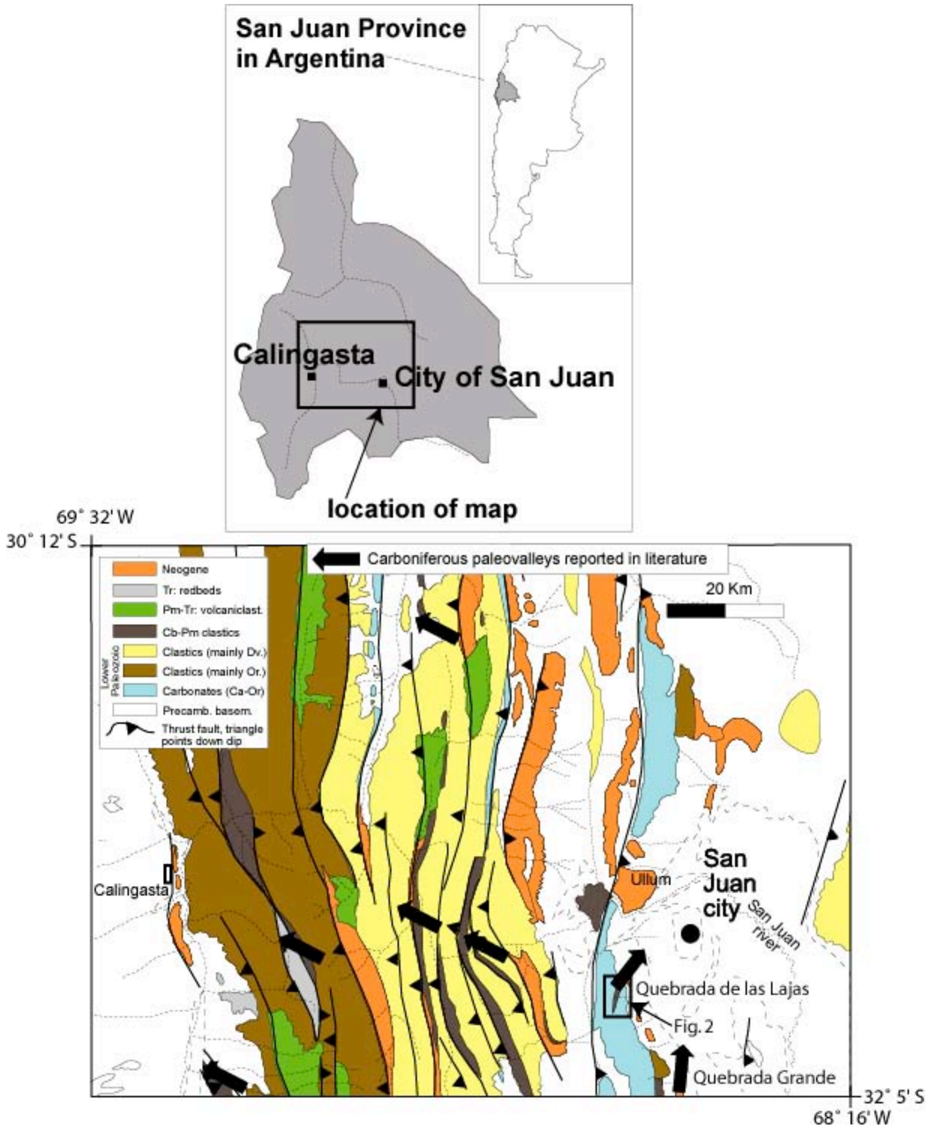


Figure 1 – Location map and geological map of the central portion of San Juan province, Argentina. The large arrows in the geologic map represent the location of large paleovalleys carved during the Gondwanan glaciations and filled rapidly during and after deglaciation. The multitude of thrust faults are the result of recent and modern tectonics, not from the Carboniferous. The paleovalley targeted in this research is exposed in Quebrada de las Lajas, SW of San Juan city.

The Carboniferous sedimentary basins of western Argentina include large epicratonic basins (basins situated on the continent), and a number of ancient valleys (paleovalleys) cut deeply into a mountain range or series of ranges that occupied approximately the same position as the modern Andes and Andean Precordillera mountain ranges (Fig. 1). That is, the mountain ranges were parallel with the western coastline of South America, and ran approximately North-South. The glaciations of Gondwana were large enough and lasted long enough, however, that the glacially carved valleys cut right across these mountain ranges and connected the interior continent to the coast. During climate amelioration and deglaciation, therefore, water levels in the Panthalassic Ocean (now the Pacific) rose, and flooded onto the continent through these valleys. For the next few thousand years (possibly much longer), a large area of the continental landmass was covered by fairly shallow seas (<~100 m (300 ft)) that only reached great depths (>~ 200 m (600 ft)) in the deeply carved valleys. It was during this period that the majority of the sedimentary record preserved for the Carboniferous deglacial succession was deposited.

The ancient valley presented in this study, Quebrada de las Lajas, was a relatively small glacially carved valley that became a fjord (seawater-filled, glacially carved valley) when the large glaciers that capped the continent (Gondwana) at the time melted. The valley was carved over 1000 m (3300 ft) down into the hard limestone mountains, and then filled by sediment. The sedimentary succession preserved in this ancient fjord includes a basal thin (< 10 m (30 ft)) veneer of sediment deposited by the overlying, actively moving glacier prior to deglaciation. When the glacier in the valley began to melt, sediment dumped by the glacier at its snout dammed the valley, which then filled with the melt-water, forming a relatively shallow (~30 ft deep) lake (Fig. 2). The lake became progressively deeper as the valley glacier continued to melt, helping to further 'float' the glacial ice and melt it more rapidly. This led to a very vigorous sedimentary system in the bottom of the lake, with numerous and common underwater sediment-gravity flows (currents composed of a dense mixture of water and sediment that hug the lake or ocean bottom and flow downslope), probably modulated by seasonal melting and thawing of the valley glacier.

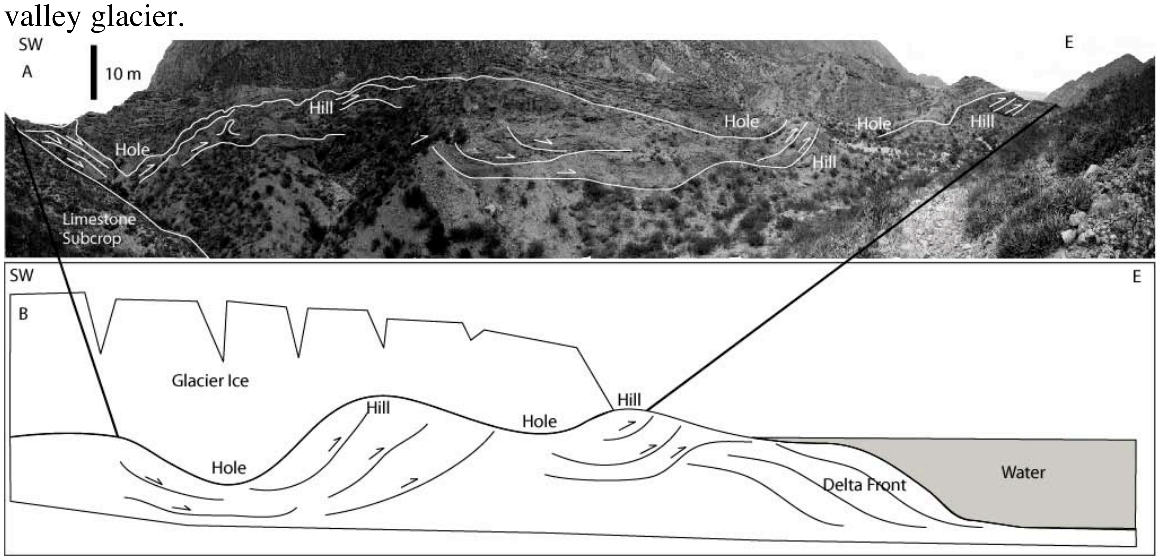


Figure 2 – A. Photograph and B. interpretive diagram of the early lake-fill sediments deposited in the glacial valley. The glacier was busy retreating, but would occasionally re-advance down the valley, which deformed the underlying sediment into depressions and high areas termed hill-hole pairs. In front of the valley glacier was a short river drainage that fed directly into a standing body of water (the lake). As the valley glacier melted further, the lake level rose and the bottom of the lake was able to host a 'healthy' (high sediment influx) deep-water environment.

Around this time the major continental ice-cap had begun to melt in earnest, and sea-levels rose significantly (up to ~120 m (400 ft)), flowing up the intra-montane valleys and into the local valley system. This rapid rise in sea-level may have helped further to 'float' the valley glacier in Quebrada de las Lajas and caused it to melt and retreat very rapidly up-valley. This event is recorded in the sedimentary record by a thick bed (stratum) of sandstone with dropstones and dump-out tills (rocks and boulders dropped by melting icebergs). After this event the valley was filled to a depth of at least 350 m (1000 ft) with the encroaching seawater, which effectively shut off the sedimentary delivery system to the valley. The succeeding hundred meters (~300 ft) of sediments are dominated by dark, fine-grained shales typical of a deep marine environment, and show evidence of marine life, as well as hosting spores, pollen, fossilized wood and plant casts from a nearby riparian forest that likely grew on the fjord slopes (Fig. 3).

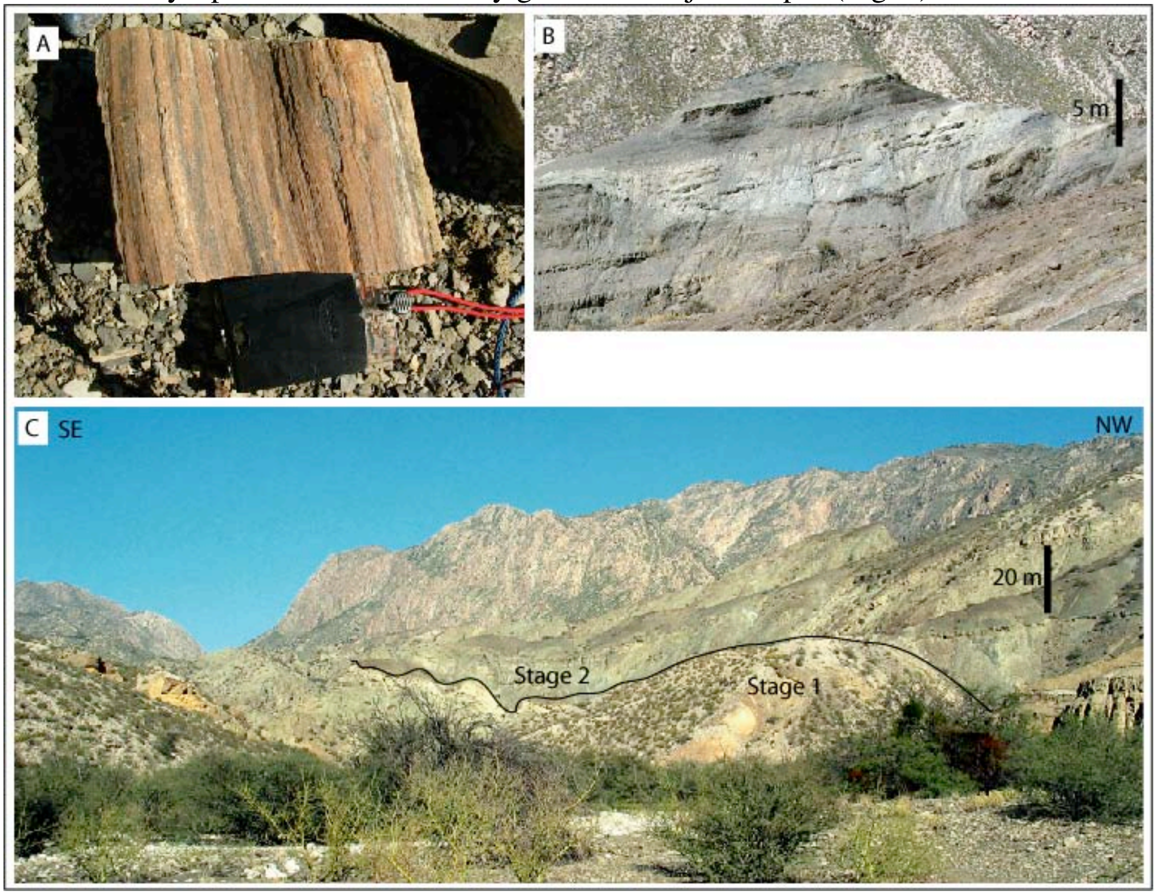


Figure 3 – A. A large piece of fossilized wood, B. the deposits of an under-water channel system, and C. the walls of the glacial valley in the background (buff-colored limestone) flanking the fill, which consists of the lake deposits (Stage 1) overlain by the deep-marine shales (Stage 2).

By examining the sedimentary record in Quebrada de las Lajas we can determine some of the potential effects of rapid climate change on both the sedimentary system and, with the fossil record, on the local ecosystem in subpolar fjord-type environments. Given the current state of flux of our planet, understanding the possible effects of climate change on depositional systems is critical to safely navigating into the future.

RESEARCH EXPERIENCE FOR UNDERGRADUATES

Twenty undergraduate students are involved in research administered through ICS.
Four undergraduate students are involved in administrative work through ICS.

Catherine Schindler 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 three 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.

- Karen Vasko participated in Professor's Burbank's research project on Geomorphic-Geodynamic Coupling at the Orogen Scale: A Himalayan Transect in Central Nepal. She assisted Graduate Student Researcher Beth Pratt-Situala for eight weeks with stratigraphic analysis, glacial geologic mapping, and cosmogenic radionuclide sample collection as well as how to operate a laser range finder, hand-held GPS, and inclinometer. During the last few weeks she developed a stratigraphic study of her own giving her the opportunity to apply her sedimentary and geomorphic knowledge to determine the genesis of the deposits and whether they display the same climate forcing mechanism found other regions.

- 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 two students are working on the seismic processing of multichannel reflection data and sea floor maps from multibeam bathymetry data.

Southern California Earthquake Center Interns

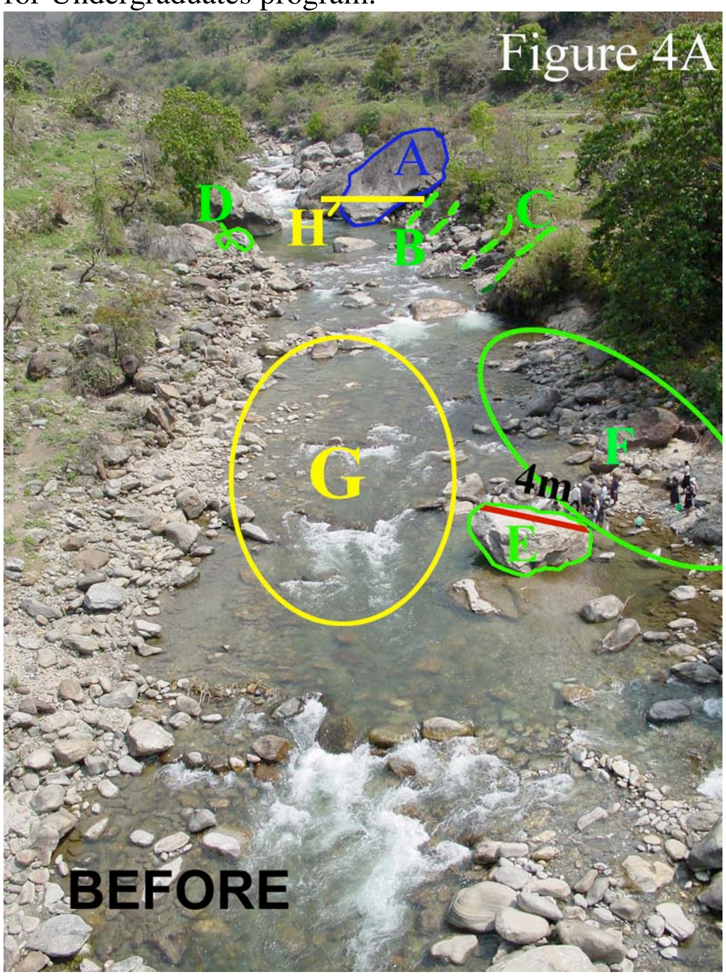
The SCEC intern we had this summer was Jack Tung, a geology student from Cal State Los Angeles. He worked on processing of the San Simeon earthquake aftershock data collected using the SCEC portable instruments and also assisted with a field experiment at the Garner Valley site

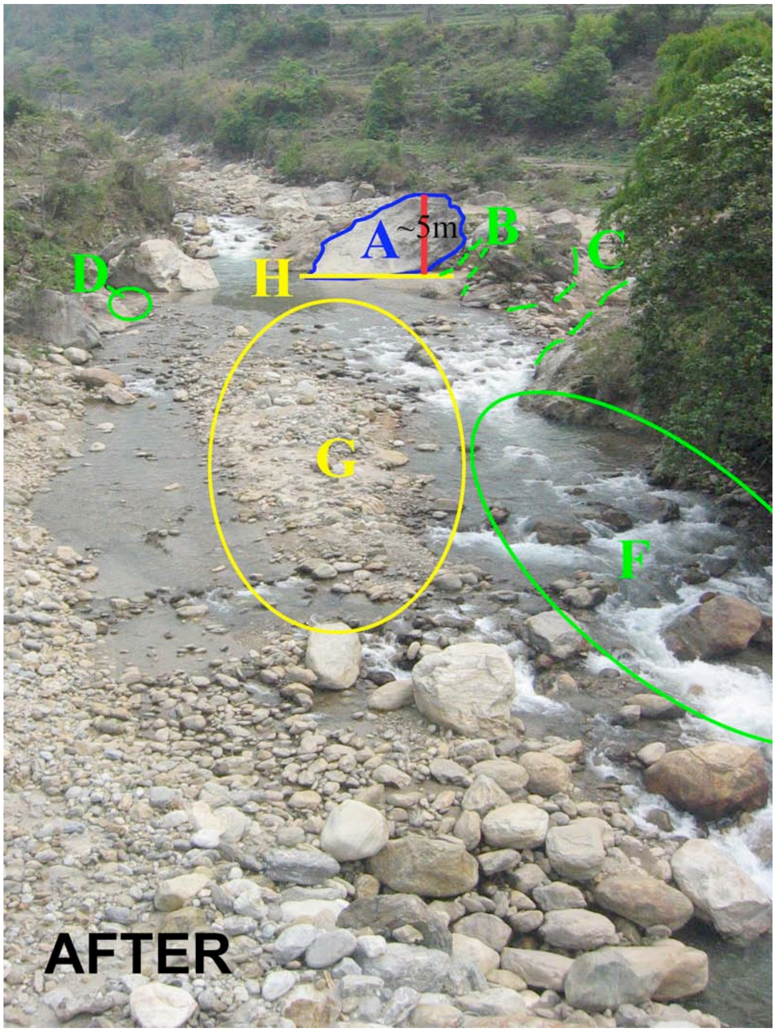
For the third year in a row the research projects administered at the Institute have been featured by the Office of Research publication on undergraduate research opportunities. This year's Office of Research Publication of Undergraduate Research featured professor Burbank's student in Nepal.

Undergraduate research on Himalayan Rivers

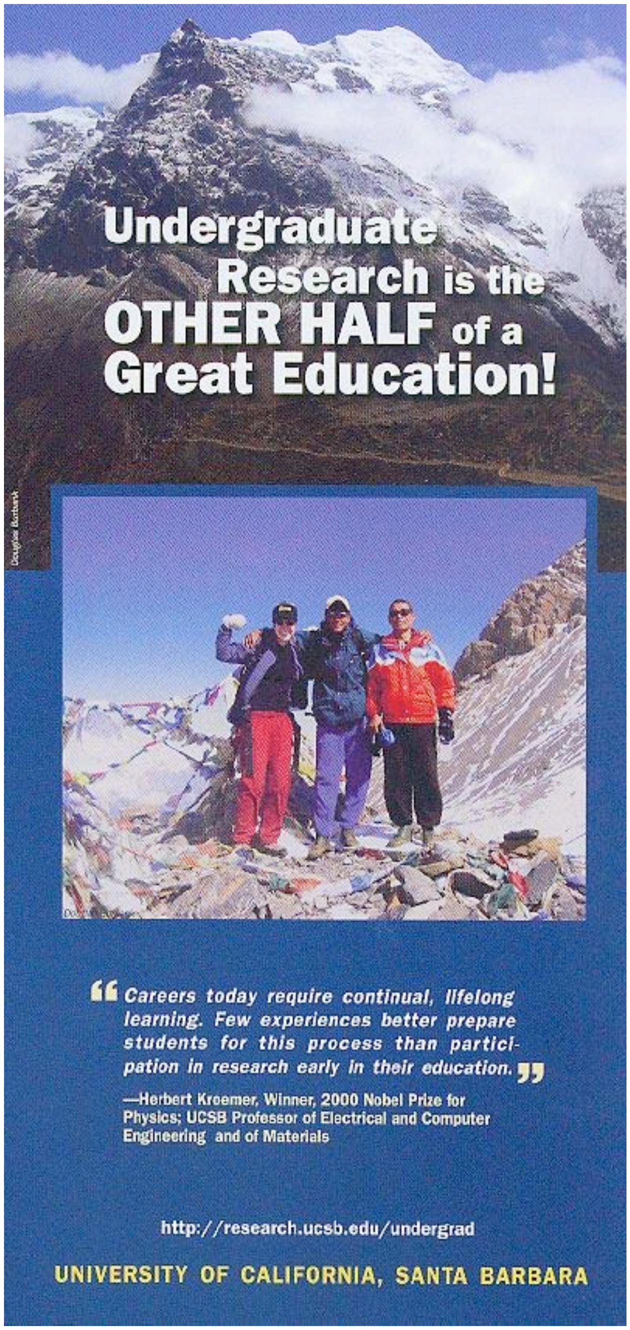
Two research projects on sediment transport in Himalayan rivers conducted by women undergraduates in the Geological Sciences Dept came to fruition in the last year. Michelle Garde coauthored a paper (which is currently in review) with graduate student, Beth Pratt-Sitaula, on the relative abundance of fine-grain and coarse-grain sediments in the Marsyandi River of central Nepal. Rivers draining the Himalaya carry a huge amount of sediments from the eroding mountains out into the oceans. However, measuring the actual amount of material -- especially the coarsest sediments that only move during large floods -- can be quite difficult. Most river monitoring programs only sample the fine sand and clay that is carried along suspended in the water and ignore the larger rocks that roll along the bottom of the channel. Ms. Garde analyzed the ratio between fine and coarse sediments in lake deposits preserved behind a large landslide that dammed the river and determined that ~33% of the material was coarse grained. This is considerably more than the <10% commonly assumed. Her work has important implications for anyone studying sediment transport in steep mountain rivers.

Undergraduate Karen Vasko studied the size of boulders that moved in exceptionally large monsoon floods. Armed with "before" pictures of river channels taken by other researchers, she revisited key river gauging sites along the Marsyandi River in 2004 and assessed the size of boulders that moved in the previous monsoon floods. Some of the boulders that moved were >4 m (12 ft) across. By analyzing the destruction along the adjoining banks, she was able to determine the depth and slope of the highest flood waters. Very little data exists on the water conditions that move these large rocks and her analysis provides some initial numbers that can be used to calibrate sediment movement equations for the very largest "sediments". Both undergraduate projects were funded by the National Science Foundation's Research Experience for Undergraduates program.

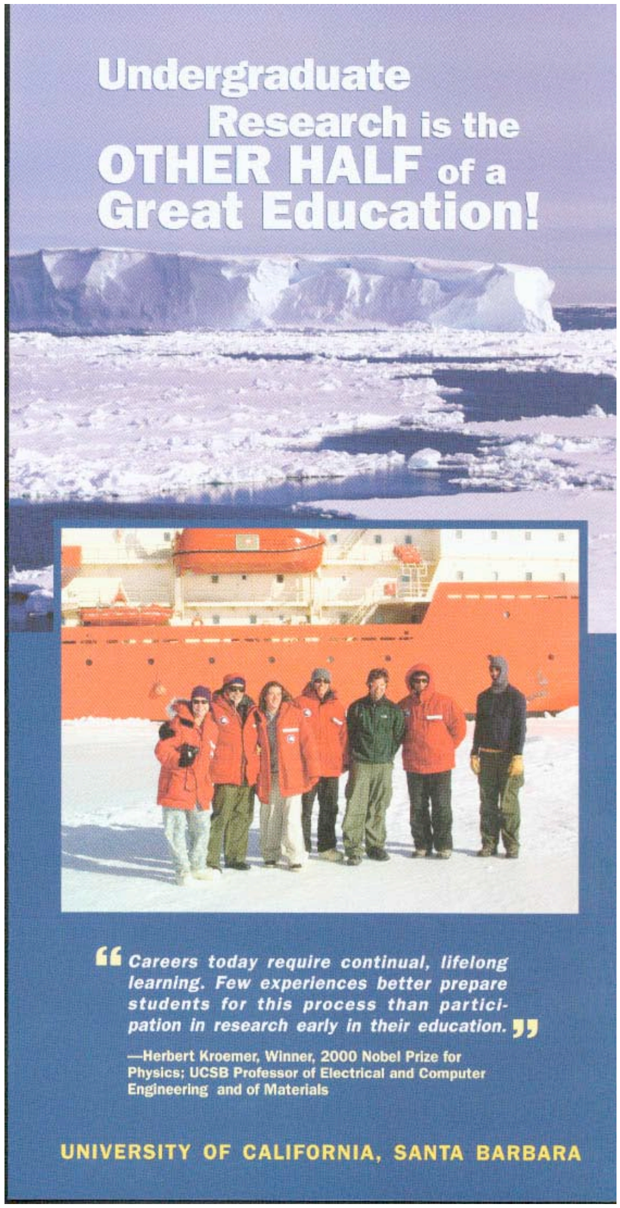




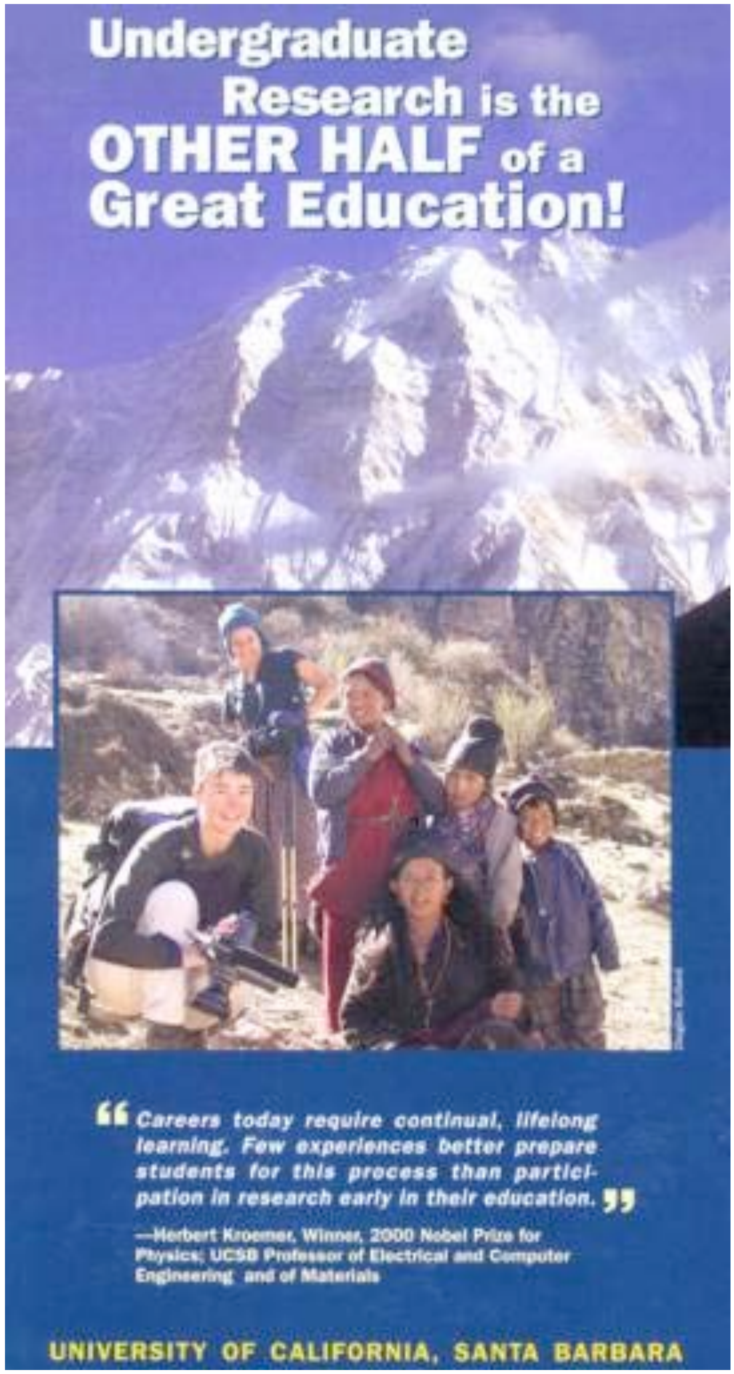
Before-and-after sequence from Ngadi Khola, Nepal analyzed by UCSB undergraduate, Karen Vasko, for flooding-caused sediment movement. Note the 4-m boulder completely removed from view and the 2-3 m of small boulders and cobbles that were deposited across the entire area as the flood subsided.



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.)