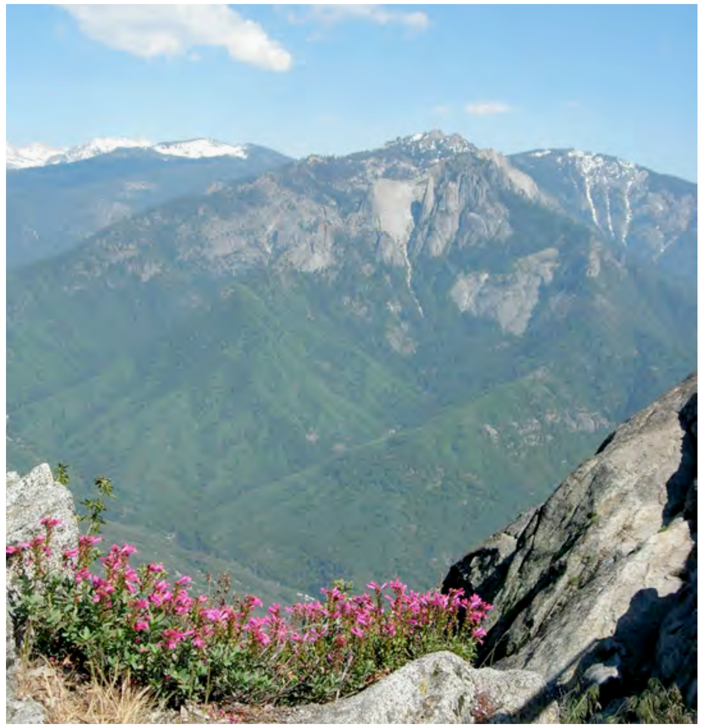
Pluton-Wallrock Interactions in the Sequoia Region: Evaluating Crustal Contamination in the Early Sierran Arc

A Proposal for a 2010-2011
Keck Geology Consortium
Research Project


Castle Peak and Kaweah River Valley from Moro Rock

Co-Directors:

Jade Star Lackey (Pomona College)
Staci Loewy (CSU—Bakersfield)

Project Details:

Number of students: 6
Approximate dates: July 1 – July 29, 2010
Locations: Sequoia National Park and National Forest, CSU-Bakersfield, Pomona College, and Stanford University

Introduction:

We are proposing a 6-student Keck project to investigate the interplay of magmatism and metamorphism in the west-central Sierra Nevada, CA. The project will be the first Keck project in the Sierra Nevada and takes advantage of the geologic diversity of the area as well as close proximity of the two co-Directors home institutions to allow a mix of field and laboratory research by student participants. In addition, we have reserved 3 days of beam time on the USGS-Stanford SHRIMP-RG at Stanford to conduct U-Pb geochronology as part of the 4-week project.

Geologic Background and Project Impetus:

The Sierra Nevada is renowned for its record of Mesozoic plutonism and metamorphism. Voluminous subduction-driven magmatism between 120 and 85 million years ago incorporated various amounts of mantle, arc- and crustal- rocks (Ague and Brimhall, 1988a; Bateman, 1992; Coleman and Glazner, 1998; Ducea, 2001; Saleeby et al., 2003; Coleman et al., 2004; Wenner and Coleman, 2004; Lackey et al., 2006; Lackey et al., 2008). The resulting batholith is a collage of plutons interspersed with remnant pendants and septa of pre-batholith metamorphic wallrocks (Fig. 1). In the Sequoia region, these plutons abut biotite schists, marbles, and other lithologies of the Kings Sequence (Fig. 1). The area has a number of high-silica granites, with associated gabbro and diorite stocks, which commonly abut steeply dipping pendants and septa of the Kings Sequence. Several of the high-silica granite are peraluminous and have evidence of contamination at their margins (Ague and Brimhall, 1988a,b; Lackey et al., 2006; Lackey et al., 2008), and migmatization of biotite schists has recently been documented in the Sequoia pendant, near the Fry's point pluton (Figs. 1 & 2D).

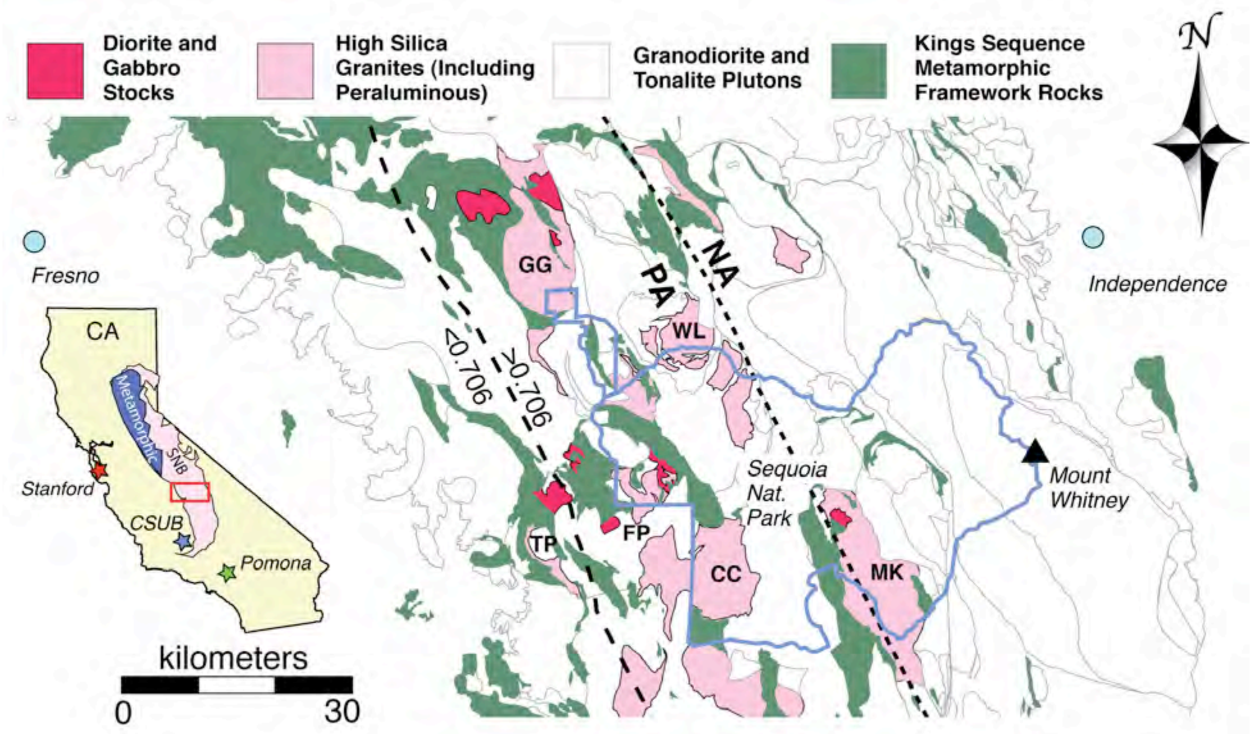


Figure 1. Bedrock Geology of the Sequoia region of the Sierra Nevada batholith. The project will focus on several of the high-silica granites, associated mafic intrusions, and migmatite complexes in the King Sequence. Initial $^{87}Sr/^{86}Sr$ = 0.706 boundary and the Panthalassan (PA)-North American (NA) boundaries are thought to represent major crustal breaks or basement sutures. Note locations of the CSUB, Pomona, and Stanford Campuses relative to the field area. Abbreviations: CC = Castle Creek; MK = Mineral King; FP = Fry's Point; TP = Tharps Peak; WL = Weaver Lake; GG = Grant Grove.

There is strong mineralogical evidence for pluton-wallrock interaction. For example, the Grant Grove pluton has a distinct garnet zone at its margin (Fig. 2A); locally, this garnet zone contains fibrolitic sillimanite and K-feldspar after muscovite (Fig. 2B) and gahnite (Zn)-rich spinel armored by muscovite (Fig. 2C). Adjacent Kings Sequence rocks contain sillimanite, as well, which is often in association with spinel. Sillimanite and spinel in the pluton are interpreted as refractory xenocryst assemblages derived from the adjacent schists. Oxygen and strontium isotope data for Grant Grove and other Sequoia region plutons suggest contamination in areas close to contacts with wallrocks (Chen and Tilton, 1991; Lackey et al., 2006). Additionally, the few "old" bulk zircon U-Pb analyses (Chen and Moore, 1982) for these plutons (mostly the granites), indicate considerable complexity and inheritance of diverse age populations of zircon crystals, which is consistent with assimilation of metasedimentary rocks.

The balance of evidence indicates that high-silica plutons in the Sequoia region are locally contaminated in response to partial melting of the Kings Sequence, and thus have veneers of superimposed contamination. Contamination and melting of metamorphic wallrocks is widely recognized in deeper exposures of the batholith (25–30 km) in the Southern Sierra (Saleeby et al., 1987; Pickett and Saleeby, 1994; Zeng et al., 2005), but mid-crustal (10–20 km; Ague and Brimhall, 1988a) contamination was largely unrecognized until recently and has not been studied in detail.

Hypothesis to be Tested and its Significance:

We hypothesize that as magmas (both felsic and mafic) ascended from source regions, they locally drove partial melting of Kings Sequence pendants. In this scenario, mafic magmas associated with the high-silica plutons are largely coeval and potentially supplied heat to drive partial melting of the metamorphic rocks. Migmatite complexes in the region may contain quenched former partial melts and therefore can be evaluated for melting reactions and potentially the "budget" of melt that they could produce. While the granites exposed at the current crustal levels are complex integrations of different source and contamination histories, crystal cargoes of inherited xenocrysts (zircon, garnet, aluminosilicate minerals, spinel, monazite) can be employed to begin to deconvolute this history.

The significance of testing this hypothesis is that it directly informs our understanding of the tempo and mode by which convergent margin batholiths recycle pre-existing crust (Kay et al., 1991; Ducea, 2001, 2002; Saleeby et al., 2003). Such constraints allow estimation of mass and thermal transport in such settings, which lends to understanding of the crustal growth and evolution. The findings can also shed light on ongoing discoveries regarding the mechanisms by which plutons are assembled and crystallize (Coleman et al., 2004; Glazner et al., 2004).

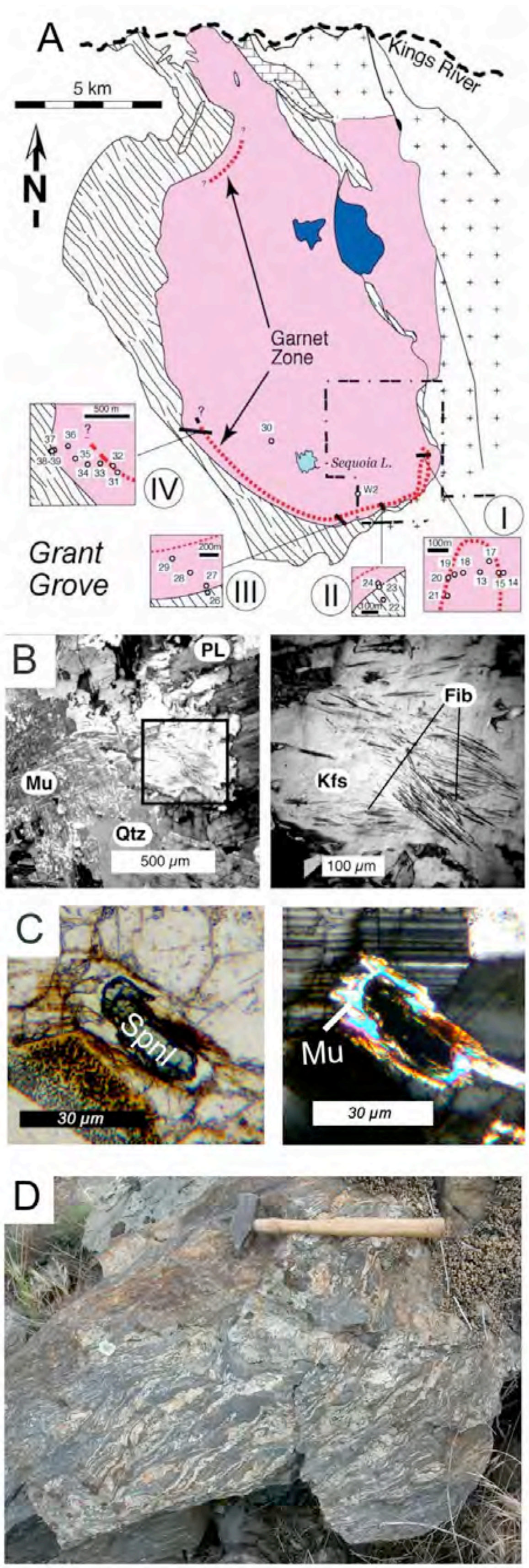


Figure 2. (A) The garnet zone of the Grant Grove pluton; (B) Sillimanite and K-feldspar after muscovite; (C) Zn-spinel with muscovite corona; (D) migmatites in the Marble Fork Canyon, Sequoia pendant.

Project Teaching and Learning Goals:

The Sequoia project will present students with a guided study of the dynamic interplay of magmatism and metamorphism in a magmatic arc setting. This complexity will provide them with exciting and challenging projects that blend several skills. During the project, students will gain experience:

- mapping igneous and metamorphic rocks and interpreting pluton-wallrock relationships
- recording field observations in notes and photographically
- representing field relations in maps
- developing and executing geochemical and geochronological sampling strategies
- preparing and analyzing geochronology samples by ion microprobe (SHRIMP)
- manipulating geochemical data

The project plan devotes half of the time to field work another quarter to laboratory preparation of samples, maps, and preliminary petrographic characterization. The remaining quarter will include preparation and analysis of selected geochronology samples during three days of beam time on the Stanford-USGS (SUMAC) SHRIMP-RG ion probe. This analytical component of the project takes advantage of the proximity of the field site to the SHRIMP lab and will give all students in the project a chance to experience, first-hand, one of the country's premiere ion probe labs. We think that the value of this experience merits the $1700/day expense. The lab produces high quality data and can analyze zircon, titanite, and monazite for U-Pb and trace elements and is therefore an ideal setting in which to obtain age constraints and thermometry information on the Sequoia rocks (see Wooden letter). While it could be argued that the instrument could malfunction during the project, there is as much likelihood of this occurring during the project as there would be during a later scheduled visit. In addition, SHRIMP beam time is reserved over a year in advance because of user demand, therefore taking all students early avoids scheduling conflicts during the academic year. Another benefit of conducting the analyses at this early stage of the project is that all students involved will benefit from the experience of conducting the analyses and interpreting the data. We will make all data accessible to all students so that they can integrate them into the studies that they continue at their home institutions.

Student Research Projects:

Students will test the overarching hypothesis by completing a number of related petrology and geochemistry projects. Each student project will include components of mapping (at scales ranging from plutons to outcrops), sample collection (students will be sent home with kg-sized hand samples for further analysis). Students will leave the project with a large body of geochronology and trace element data in hand and we anticipate additional petrographic and geochemical analyses to be conducted at their home institutions. An additional $464/student is budgeted for home campus laboratory expenses. Potential projects are listed below and can be refined depending on student interest and findings we make during the initial field work.

Partial Melting in Kings Sequence Schists (2 students)

Migmatitic rocks are exposed in several areas of the field area and present numerous opportunities to combine detailed petrography, phase equilibria, and geochronology to evaluate the conditions of melting and composition of melts. Monazite and detrital zircon dating in the schists would provide temporal constraints to test linkages of the migmatites with surrounding plutons. These migmatites have diverse mineralogy including index minerals such as garnet, cordierite, andalusite, gahnite-hercynite spinel, etc.

Grant Grove Pluton (1 student)

Prior U-Pb analyses of the Grant Grove Pluton have yielded complex age patterns suggesting extensive contamination (Chen and Moore 1982; Wenner and Coleman 2004). Several areas of the pluton have not been studied, particular northern areas where mafic stocks are associated with the pluton (Fig 1). This study would focus on the northern areas of the Grant Grove pluton to explore the relationship between the granite, mafic stocks, and Kings Sequence.

Mineral King Plutons (1 student)

The Mineral King, Castle Creek (Fig. 1) and other unnamed plutons in the southern part of the field area have not been studied in any detail. One student can investigate these plutons to evaluate if they have affinities with the plutons to the north.

Fry's Point Pluton (1 student)

The Fry's point pluton is a complex body with multiple mafic intrusions and associated migmatite complexes. A student can document the diversity of this pluton and work with the migmatites team to look for connectivity with the migmatite complex.

Mafic Stocks (1 student)

One student will be charged with evaluating and comparing the temporal and geochemical characteristics of the major mafic stocks in the area. The student will visit the different sites and map and sample these bodies as needed.

Preferred student background:

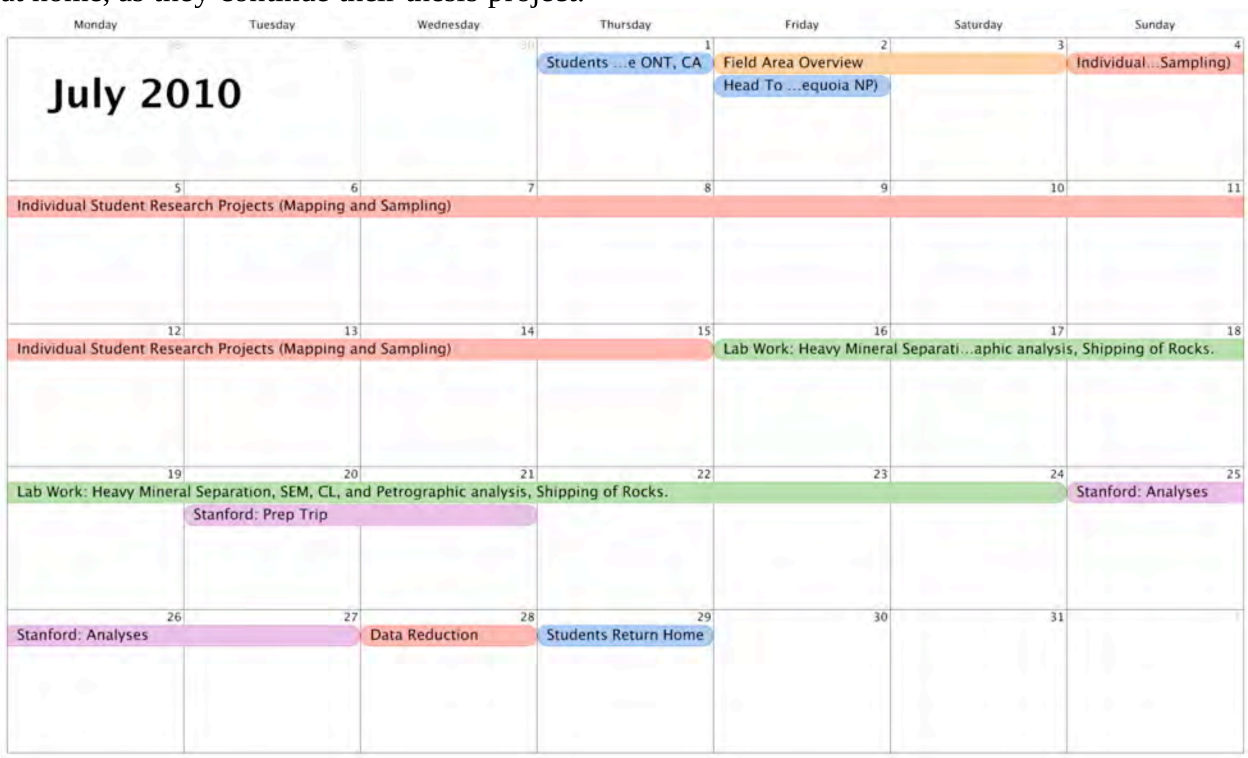
The field area is complex, so demonstrated ability in field methods is desirable. Students should also be prepared for working in challenging field conditions. Students should have taken core courses in, mineralogy, petrology, and structural geology.

Schedule:

The July 2010 calendar panel at the end of this section details the stages of the project from start to finish. The project will begin and end in Claremont, CA with the group members meeting on July 1 and departing for the field the next day. We will spend one night in Claremont for personal introductions and to organize our camping and field gear. From there, the whole group will head up through Bakersfield to the Sierra Nevada with stops along the way to gain an understanding of California Geology, the Mesozoic arcs, and other details. This overview will continue in the field the next day with students seeing the sites in detail. In the following days, students and faculty will work in groups of three or four to conduct field work with the intent of developing projects. We are not intending to assign particular students projects at this early stage, but instead to move students around so that they can feel out the field area. We anticipate that some students will have preferences for particular projects in advance and will work with them to refine the projects depending on the field findings.

Upon finalizing research projects and finishing fieldwork, we will head back to Bakersfield and/or Pomona to begin processing geochronology samples and to pool notes, sample data, maps, etc. The geochronology processing will be undertaken rapidly to guarantee that samples are ready to be mounted at the SHRIMP lab and imaged by SEM cathodoluminsescence at CSUB before the scheduled beam time. Depending on the particular needs for sample separating and processing, one contingent of students may work at Pomona for a few days and another will work at Bakersfield.

During the SHRIMP session, the whole group will be at Stanford working in shifts of 12 hours (the instrument runs 24 hours/day). During analyses, some students will help in the reduction of data results. Ages and other information obtained during this session will be made available to all students so that they can integrate the information into their own research projects at home, as they continue their thesis project.



Logistics:

Housing and Meals: lodging arrangements during fieldwork will involve a combination of camping, dormitories, and inexpensive motels. Quotes for lodging and meals differ for the two primary institutions (see budget notes); we will be camping for half of the trip which will cut meal and lodging costs significantly.

Vehicles and Field Equipment: The Pomona College Geology Department can provide a Suburban for fieldwork, field equipment (tents, hammers, bruntons, GPS, etc). A second vehicle will be rented during parts of the project where a faculty member and a large number of students will be moving locations. Roads in the field area are all 2WD accessible and lead to trails from which remote sights will be accessed on foot.

Laboratories: CSUB and Pomona both have a full complement of rock preparation facilities that will allow students to separate accessory minerals for SHRIMP and other analyses. CSUB has a modern SEM with live color cathodoluminescence, BSE, and EDS detectors. An ICPMS is currently being configured for laser ablation capability. An SEM with BSE, EDS, and conventional CL is available at Pomona and we have scanned and a desktop CL instrument. The individual requirements for each project will dictate which lab facilities students use.

Sampling permits: Lackey has obtained collecting permits for Sequoia-Kings Canyon over the past several years and Park officials (David Graber) have encouraged further research. In addition, we are in contact with Tom Sisson (USGS), who has mapped a substantial area of the Park and has encouraged this project.

Safety: Sequoia National Park emphasizes safety to the many visitors and participants in this project will likewise be informed of the potential hazards in the Park. Common natural hazards include terrane (cliffs, rock fall areas, and rivers), animals (black bears, snakes, scorpions, ticks), and plants (poison oak, cactus). Given that many people visit the Park and surrounding national forests, students will be instructed to be vigilant for human hazards. Only faculty will drive the vehicles.

Faculty Experience:

Lackey has over a decade of research experience in the Sierra Nevada and has led student research trips during 3 summers. He is trained as an igneous and metamorphic petrologist and specializes in stable isotope geochemistry to evaluate magma generation and diversification. He was a project faculty member on the Keck Nova Scotia project in 2006. Loewy has expertise in U/Pb, Pb-Pb, and Sm/Nd isotopic systems and applies these tools to address questions of plate tectonics, crustal evolution, and supercontinent reconstruction. She has a background in structural geology and petrology and considerable field experience, including leading students in the field in the Sierra.

Proposed Budget:

		Units	
Stipends			
Director (Lackey)	$5250.00	1	$5,250.00
Co-Director (Loewy)	$5250.00	1	$5,250.00
Students	$1,200.00	6	$7,200.00
Travel to California			
Faculty[1]	—	—	—
Students	$500.00	6	$3000.00
Travel in the Field: Two Vehicles + Fuel[2]			
Rental Vehicle	$50.00	20 days	$1,000.00
Pomona College Suburban	$600.00	duration	$600.00
Lodging (Camping + Dorms $280/person) [3]			
	$280.00	7 [4]	$1,960.00
Food ($22/person/day * 27 days = $594/person) [3]			
	$594.00	7	$4,158.00
Research Expenses (including sample shipping, thin sections, SHRIMP analyses, XRF analyses, consumable field equipment). [5]			
Stanford SHRIMP (3 Days)	$1700	3	$5,100.00
Student Research Budget	$464	6	$2,784.00
Total Research Budget:			$7,884.00
		Total	**$36,302**

Notes:

[1] Project Faculty are both on site.

[2] The Pomona Geology Department will make their Suburban available for the 4-week project for fuel cost only. Loewy in Bakersfield will rent a second vehicle as needed (probably only 3 weeks total).

[3] Lodging costs assume camping ~ 50% of the time and staying in dorms or motels the rest. Camping rates are based on estimates for renting campsites in National Forest (2 sites/night @ $18/night) = $4.50/person/night. Dorm rates are quoted from the college and university lodging estimates (PO = $11/day; CSUB = $25/day). Food on campuses: ($20/day at CSUB; $115/21 meals at Pomona).

[4] Faculty visiting each other's institution will stay with the other faculty member and therefore we foresee minimal expenses by sharing of private residences (including board) while on campus. The estimate of 7 instead of 8 units for meals and board accounts for this cost savings.

[5] Other expenses are to cover field gear if necessary. Otherwise, these funds will be used to cover research expenses for students to ship samples home and cover some research expenses at their home institutions.

References Cited:

Ague, J.J., and Brimhall, G.H., 1988a, Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: effects of assimilation, crustal thickness, and depth of crystallization: Geological Society of America Bulletin, v. 100, p. 912-927.

—, 1988b, Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California: with Suppl. Data 88-13: Geological Society of America Bulletin, v. 100, p. 891-911.

Bateman, P.C., 1992, Plutonism in the central part of the Sierra Nevada Batholith, California: U. S. Geological Survey Professional Paper, v. 1483, p. p 186.

Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotopic ages from the Sierra Nevada batholith, California: JGR Journal of Geophysical Research. B, v. 87, p. 4761-4784.

Chen, J.H., and Tilton, G.R., 1991, Applications of lead and strontium isotopic relationships to the petrogensis of granitoid rocks, central Sierra Nevada batholith, California: Geological Society of America Bulletin, v. 103, p. 437-447.

Coleman, D.S., and Glazner, A.F., 1998, The Sierra Crest magmatic event: rapid formation of juvenile crust during the Late Cretaceous in California, *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and environmental evolution of the Southwestern United States: the Clarence A. Hall, Jr. volume.: Columbia, MD, Bellwether Publishing, p. 253-272.

Coleman, D.S., Gray, W., and Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California: Geology, v. 32, p. 433–436.

Ducea, M., 2001, The California Arc: thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: GSA Today, v. 11, p. 4-10.

—, 2002, Constraints on the bulk composition and root foundering rates of continental arcs: a California arc perspective: Journal of Geophysical Research, B, Solid Earth and Planets, v. 107, p. ECV 15.1–15.13.

Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation from small magma chambers?: GSA Today, v. 14, p. 4-11.

Kay, R.W., Mahlburg-Kay, S., and Wedepohl, K.H., 1991, Creation and destruction of lower continental crust: International Journal of Earth Sciences, v. 80, p. 259-278.

Lackey, J.S., Valley, J.W., Chen, J.H., and Stockli, D.F., 2008, Evolving magma systems, crustal recycling, and alteration in the central Sierra Nevada batholith: the oxygen isotope record: Journal of Petrology, v. 49, p. 1397–1426.

Lackey, J.S., Valley, J.W., and Hinke, H.J., 2006, Deciphering the source and contamination history of peraluminous magmas using $\delta^{18}O$ of accessory minerals: examples from garnet-bearing granitoids of the Sierra Nevada batholith: Contributions to Mineralogy and Petrology, v. 151, p. 20–44.

Pickett, D.A., and Saleeby, J.B., 1994, Nd, Sr, and Pb isotopic characteristics of Cretaceous intrusive rocks from deep levels of the Sierra Nevada batholith, Tehachapi Mountains, California: Contributions to Mineralogy and Petrology, v. 118, p. 198-215.

Saleeby, J., Ducea, M., and Clemens Knott, D., 2003, Production and loss of high-density batholithic root, southern Sierra Nevada, California: Tectonics, v. 22, p. doi:10.1029/2002TC001374.

Saleeby, J.B., Sams, D.B., and Kistler, R.W., 1987, U/ Pb zircon, strontium, and oxygen isotopic and geochronological study of the southernmost Sierra Nevada Batholith, California: Journal of Geophysical Research, B, Solid Earth and Planets, v. 92, p. 10,443-10,466.

Wenner, J.M., and Coleman, D.S., 2004, Magma mixing and Cretaceous crustal growth: geology and geochemistry of granites in the central Sierra Nevada batholith, California: International Geology Review, v. 46, p. 880–903.

Zeng, L., Ducea, M., and Saleeby, J.B., 2005, Geochemical characteristics of crustal anatexis during the formation of migmatite at the southern Sierra Nevada, California: Contributions to Mineralogy and Petrology, v. 150, p. 386-402.

Stanford – USGS Micro-Isotopic Analytical Center (SUMAC)
School of Earth Sciences
Stanford University
Room 89, Green Earth Sciences Building
367 Panama Street
Stanford, CA 94305-2220
650-725-6536 (phone) and 650-724-6360 (fax)
http://shrimprg.stanford.edu

Center Directors
Dr. Marty Grove (Stanford) 650-721-5490 (mjgrove@ stanford.edu)
Dr. Charles Bacon (USGS) 650-329-5246 (cbacon@usgs.gov)

Senior Staff Scientist and External Use Coordinator
Dr. J.L. Wooden (Stanford) 650-725-6536 (jwooden@stanford.edu)

Jade Star Lackey
Department of Geology
Pomona College
185 East 6th Street
Claremont, CA 91711

April 9, 2009

Dear Jade Star,

There will be no problem providing time in July 2010 on the SHRIMP-RG for your proposed Keck project on Pluton-Wallrock Interactions in the Sequoia Region: evaluating Crustal contamination in the early Sierran Arc. You have supervised undergraduate students involved in a Keck project in the ion microprobe lab this year and are fully familiar with our operation here. We have always welcomed students in this lab and see one of our responsibilities as the training and introduction of students to analytical instruments and techniques and the principles of geochronology and geochemistry.

We are charging $1700 per day for use of the ion probe, and a day of analytical time is usually 22-24 hours. Our facility has excellent imaging capabilities which include digital reflected and transmitted light photographs plus CL, SE, and BSE pictures on our dedicated SEM. As you well know images are critical to aid the interpretation of the analytical data and are included in the analytical use fee. Significant modifications were made to the ion microprobe in Feb.-March, 2003 that improved both its transmission and mass resolution. These modifications allow even better quality data to be acquired in a shorter period of time for geochronology and trace element studies.

The SUMAC facility and staff have a great deal of experience with U-Th-Pb age studies of zircons, monazites, and titanites for geochronology and detrital provenance studies using the SHRIMP-RG. The minerals we use for age standards are all well tested and the procedures for data acquisition and reduction are fully established and tested. We continue to work with Ken

Ludwig on the development of SQUID II which will provide a much more flexible data reduction system for ion microprobe analysis.

We have been doing various trace element studies in a wide variety of minerals for many years. In 2005 we started more detailed trace element studies in zircon combined with using Ti concentrations for evaluation of temperatures of crystal growth based on the studies by Bruce Watson's group. These studies have proven to be very informative about zircon formation and magma and metamorphic histories. We had been concerned about a robust standard for trace elements in zircons and were uncomfortable with using glass standards that did not match the zircon bulk composition. As a result Frank Mazdab has grown synthetic zircons doped with trace element concentrations high enough to be measured accurately with the electron microprobe. CZ3, the gem quality zircon we have used for U and Th concentration calibration has been calibrated on the ion probe against these synthetic zircons and has proven to be homogeneous for most elements we measure. CZ3 and many of the other gem zircons used for U concentration and/or U-Pb age calibration (i.e. 91500, SL13) have low trace element abundances. We are testing other zircons to find one that is homogeneous and has much higher trace element concentrations and have one new standard (MAD) fully calibrated and in use in conjunction with CZ3.

We have expanded our U-Th-Pb analysis routines for zircon to include a variable number of trace elements at the same time. Hf and a set of 9 rare earth elements elements from La to Yb are now routinely included in all zircon U-Th-Pb analyses. Very little extra time is required for the trace element analyses and the contribution to data interpretation is significantly aided, especially for studies involving zircons grown or overgrown during metamorphism. We prefer to do the analysis for Ti concentration as a part of a package separate from U-Th-Pb analysis. Mass resolution of 10,000-12,000 is used to analyze approximately 30 elements from Li to U and requires about 15 minutes for 2 scans through the entire mass range. However, we have developed a U-Pb package that does Ti, Si P, Y (and Al, Ca, Fe for quality control) plus 9 REE and Hf. This routine takes about 20 minutes. We have found it particularly useful for work with metamorphic rim – igneous core pairs and zircon grown and/or recrystallized in metamorphic events.

We have expanded trace element studies to other minerals of interest for U-Th-Pb geochronology (titanite, monazite xenotime; apatite still in development) and for temperature control (quartz, titanite, rutile). We have an excellent titanite standard for trace elements now (BLR, our U-Th-Pb standard) and have begun detailed trace element studies on titanites. We have determined that titanites should be analyzed in thin section if at all possible in order to more clearly identify grain geometry and paragenesis. Early results indicate that trace element concentrations and REE patterns in titanites are more responsive to the conditions of formation than those in zircons. A good monazite standard (which can also serve as an age standard) and a usable xenotime have recently been identified (May 2008) and several gem quality apatite samples are currently being evaluated. These studies are proving to be very complementary to our traditional work in U-Th-Pb geochronology and should provide significant help with interpretation of U-Th-Pb age data in addition to helping to better understand mineral growth and petrologic processes. Please see abstracts (posters for most of these can be found at shrimprg@stanford.edu) by Wooden and others and Mazdab and others (2006 Goldschmidt, 2006 Fall AGU), Wooden and Mazdab and Mazdab and Wooden (2007 GSA Annual Meeting) and papers by Lowery-Claiborne (2006 Min. Mag.) and Grimes and others (2007 Geology) for early progress on the techniques, applications, and interpretations of trace element studies.

I look forward to having another opportunity to work with you and a new group of undergraduate students.

With best regards,

Joe

J.L. Wooden
Senior Staff Scientist and External Use coordinator
SUMAC, Stanford University