2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
Faculty: CHRISTINE SIDDOWAY, MEGAN ANDERSON, Colorado College, ERIC ERSLEV, University of Wyoming
Students: MOLLY CHAMBERLIN, Texas A&M University, ELIZABETH DALLEY, Oberlin College, JOHN SPENCE HORNBUCKLE III, Washington and Lee University, BRYAN MCADEE, Lafayette College, DAVID OAKLEY, Williams College, DREW C. THAYER, Colorado College, CHAD TREXLER, Whitman College, TRIANA N. UFRET, University of Puerto Rico, BRENNAN YOUNG, Utah State University.

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA
Faculty: TEKLA A. HARMS, JOHN T. CHENEY, Amherst College, JOHN BRADY, Smith College
Students: JESSE DAVENPORT, College of Wooster, KRISTINA DOYLE, Amherst College, B. PARKER HAYNES, University of North Carolina - Chapel Hill, DANIELLE LERNER, Mount Holyoke College, CALEB O. LUCY, Williams College, ALIANORA WALKER, Smith College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: DAVID P. DETHIER, Williams College, WILL OUMET, University of Connecticut
Students: ERIN CAMP, Amherst College, EVAN N. DETHIER, Williams College, HAYLEY CORSON-RIKERT, Wesleyan University, KEITH M. KANTACK, Williams College, ELLEN M. MALEY, Smith College, JAMES A. MCCARTHY, Williams College, COREY SHIRCLIFF, Beloit College, KATHLEEN WARRELL, Georgia Tech University, CIANNA E. WYSHNYSZYK, Amherst College.

SEDIMENT DYNAMICS & ENVIRONMENTS IN THE LOWER CONNECTICUT RIVER
Faculty: SUZANNE O’CONNELL, Wesleyan University
Students: LYNN M. GEIGER, Wellesley College, KARA JACOBACCI, University of Massachusetts (Amherst), GABRIEL ROMERO, Pomona College.

GEOMORPHIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA, U.S.A.
Faculty: KELLY MACGREGOR, Macalester College, CATHERINE RIIHIMAKI, Drew University, AMY MYRBO, LacCore Lab, University of Minnesota, KRISTINA BRADY, LacCore Lab, University of Minnesota.
Students: HANNAH BOURNE, Wesleyan University, JONATHAN GRIFFITH, Union College, JACQUELINE KUTVIRT, Macalester College, EMMA LOCATELLI, Macalester College, SARAH MATTESON, Bryn Mawr College, PERRY ODDO, Franklin and Marshall College, CLARK BRUNSON SIMCOE, Washington and Lee University.

GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA
Faculty: KARL W. WEGMANN, North Carolina State University, TSALMAN AMGAA, Mongolian University of Science and Technology, KURT L. FRANKEL, Georgia Institute of Technology, ANDREW P. deWET, Franklin & Marshall College, AMGALAN BAYASAGALN, Mongolian University of Science and Technology.
Students: BRIANA BERKOWITZ, Beloit College, DAENA CHARLES, Union College, MELLISSA CROSS, Colgate University, JOHN MICHAELS, North Carolina State University, ERDENEBAATAR TSAGAANNARAN, Mongolian University of Science and Technology, BATTOGTOH DAMDINSUREN, Mongolian University of Science and Technology, DANIEL ROTHBERG, Colorado College, ESUGEI GANBOLD, ARANZAL ERDENE, Mongolian University of Science and Technology, AFSHAN SHAIKH, Georgia Institute of Technology, KRISTIN TADDEI, Franklin and Marshall College, GABRIELLE VANCE, Whitman College, ANDREW ZUZA, Cornell University.

LATE PLEISTOCENE EDIFICE FAILURE AND SECTOR COLLAPSE OF VOLCÁN BARÚ, PANAMA
Faculty: THOMAS GARDNER, Trinity University, KRISTIN MORELL, Penn State University
Students: SHANNON BRADY, Union College. LOGAN SCHUMACHER, Pomona College, HANNAH ZELLNER, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION
Faculty: JADE STAR LACKEY, Pomona College, STACI L. LOEWY, California State University-Bakersfield
Students: MARY BADAME, Oberlin College, MEGAN D'ERRICO, Trinity University, STANLEY HENSLEY, California State University, Bakersfield, JULIA HOLLAND, Trinity University, JESSLYN STARNES, Denison University, JULIANNE M. WALLAN, Colgate University.

EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING
Faculty: JOHN CRADDOCK, Macalester College, DAVE MALONE, Illinois State University
Students: JESSE GEARY, Macalester College, KATHERINE KRAVITZ, Smith College, RAY MCGAUGHEY, Carleton College.

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KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION
Project Faculty: JADE STAR LACKEY, Pomona College, STACI L. LOEWY, California State University—Bakersfield

ORIGIN OF MIGMATITIC ROCKS IN THE SEQUOIA PENDANT, SIERRA NEVADA, CALIFORNIA
MARY BADAME, Oberlin College
Research Advisor: Steve Wojtal

PLUTON-WALLROCK INTERACTION OF THE EMPIRE QUARTZ DIORITE, SOUTHERN SIERRA NEVADA: IMPLICATIONS FOR SKARN FORMATION IN THE MINERAL KING PENDANT
MEGAN D’ERRICO, Trinity University
Research Advisor: Dr. Benjamin Surpless

TEMPORAL VARIATION IN PLUTON-WALLROCK INTERACTION IN THE SIERRAN ARC
STANLEY HENSLEY, California State University, Bakersfield
Research Advisor: Dr. Staci Loewy

THE PETROGENESIS OF THE ASH MOUNTAIN INTRUSIVE COMPLEX: IMPLICATIONS FOR SIERRAN MAGMATISM
JULIA HOLLAND, Trinity University
Research Advisor: Ben Surpless

EARLY SIERRA NEVADA MAGMATISM EXAMINED USING SHRIMP-RG U-PB AGES AND TRACE ELEMENT COMPOSITIONS OF ZIRCONS FROM THE MINERAL KING ROOF PENDANT RHYOLITE UNITS
JESSLYN STARNES, Denison University
Research Advisor: Dr. Erik Klemetti

STABLE ISOTOPE GEOCHEMISTRY OF MARBLES IN THE KINGS SEQUENCE, SIERRA NEVADA, CA
JULIANNE M. WALLAN, Colgate University
Research Advisor: William H. Peck
INTRODUCTION
The Sierra Nevada Batholith (Fig. 1; Lackey and Loewy, this volume) is marked by the presence of coeval high- and low-SiO$_2$ content intrusive rocks in close proximity, but the dichotomous petrogenesis of these bodies is not wholly understood. Country rock assimilation and fractional crystallization may account for the large compositional diversity in the SNB, although recent work in the Sierra Nevada presents mixing and mingling of magmas as primary causes of this compositional diversification (e.g., Frost and Mahood 1987; Ratajeski et al. 2001; Sisson et al. 1996).

The Ash Mountain Complex (AMC) in Sequoia National Park was initially described by Ross (1958), who documented enigmatic cross-cutting relations - ships between four distinct and compositionally diverse intrusive lithologies. This study defines two additional lithologies in the AMC, which consists of a series of mutually cross-cutting intrusive rocks ranging in composition from gabbro to peraluminous granite. The well-exposed relationships between high- and low-SiO$_2$ magmas of the AMC provide an opportunity to evaluate the relative roles of partial melting, mixing, mingling, and assimilation/fractional crystallization in the production of this compositional range. Research findings presented here have implications for the petrogenesis of these rocks in the context of the Sierran arc and crustal evolution.

GEOLOGIC SETTING
The Sierra Nevada batholith formed as the Farallon plate subducted below the North American continent (e.g., Dickinson, 1981; Wenner and Coleman, 2004). Arc magmatism lasted from the Triassic to the Late Cretaceous (e.g., Chen and Moore, 1982), and today, most of the volcanic rocks have eroded away, exposing the batholithic root of the Mesozoic arc. Based on known pluton ages, magmatism in the Late Cretaceous was primarily concentrated between 103 Ma (e.g., Ratajeski et al., 2001; Wenner and Coleman, 2004) and 88 Ma (Coleman and Glazner, 1997; Wenner and Coleman, 2004).

Cretaceous intrusive rocks surround the Ash Mountain Complex (AMC), although metamorphic wall-rocks are also common in the area, interspersed among the plutons (Fig. 1). The surrounding plutons are dominantly granodiorites with abundant mafic inclusions that range in age from 133 Ma to 97 Ma, and the schists that make up the wall rocks for these plutons range from Triassic to Cretaceous in age but predate nearby plutons (Fig. 1) (Sisson and Moore, 1994). Cretaceous diorite and marble are found in close proximity to the AMC (Sisson and Moore, 1994), and the Fry’s Point granite and the Milk Ranch Peak granodiorite are the largest adjacent plutons (Fig. 1).

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THE PETROGENESIS OF THE ASH MOUNTAIN INTRUSIVE COMPLEX: IMPLICATIONS FOR SIERRAN MAGMATISM

JULIA HOLLAND, Trinity University
Research Advisor: Ben Surpless

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Figure 1. Geologic map of Mesozoic plutonic and metamorphic rocks of the southwestern area of Sequoia National Park. Modified from Sisson and Moore 1994.
FIELD RELATIONS

Field relations between Ash Mountain Complex (AMC) intrusive units are most tightly constrained at an exposure along the Kaweah River and indicate a two-stage intrusion history. Stage 1 units are characterized by gradational contacts between units, suggesting that these units were approximately coeval and interacted prior to solidification. Stage 1 units include a gabbro porphyry (Kgp) and an equigranular gabbro (Kg), which crop out as massive intrusions, while a white diorite (Kwd) and a white granite (Kgr) appear more channelized, as dikes and sills that intruded prior to solidification of the more mafic units Kgp and Kg (Fig. 2). Kg is distinguished from Kgp in petrographic thin section by the presence of large clinopyroxene megacrysts, whereas Kg grains are equigranular. Kwd is marked by the presence of significantly less pyroxene, and Kgr marked by the presence of myrmekitic plagioclase. Stage 2 units include a granodiorite porphyry (Kp) marked by large dusty plagioclase crystals, and a granite pegmatite (Kgp), which have gradational contacts with one another, suggesting coeval intrusion. Stage 2 units display sharp contacts with Stage 1 units and include Stage 1 units as angular xenoliths (Fig. 2), suggesting that Stage 1 units were solid at the time of Stage 2 intrusion.

For regional comparison, samples were also collected from four other localities in and proximal to the Ash Mountain Complex, including samples from the General’s Highway, the Fry’s Point pluton (Kfp), and along Sycamore Drive (Fig. 1). At a site located along the General’s Highway, less than 100 m away, samples were collected based on apparent similarity to the Kaweah River lithologies. The field relationships between these samples are consistent with those identified at the Kaweah River, with the exception of the intrusion of a lithology resembling Kg into a lithology resembling Kgr, which is reversed relative to the sequence of Stage 1 intrusions documented at the Kaweah River outcrop (Fig. 2). However, this is consistent with the hypothesized coeval intrusions of Stage 1 units.

Therefore, field relationships strongly support a two-stage intrusion sequence for the Ash Mountain intrusive complex based on contact boundaries and cross-cutting relationships. Stage 2 units Kp and Kgp appear to have intruded simultaneously as dikes or sills into completely crystalline Stage 1 units.

ANALYTICAL METHODS

Samples were crushed using standard procedures at facilities at the University of California, Bakersfield. Fresh chips were chosen from the crushed samples for whole rock X-ray florescence analysis of 19 samples. These chips were pulverized using facilities at Pomona College, mixed with flux (Li2B4O7) at a ratio of 1:2 according to the procedure of Johnson et al. (1999). The remaining crushed samples were used to obtain zircons, which were separated through standard density and magnetic separation techniques using the facilities at University of California at Bakersfield. After magnetic separation, samples were picked using petrographic microscopes to choose zircons for analysis. Zircon separates were taken to the SUMAC SHRIMP-RG (sensitive high-resolution ion microprobe, reverse geometry) at Stanford University. Zircon grains were mounted and imaged for cathodoluminescence (CL) imaging on a Scanning Electron Microscope (SEM), and were also observed under
white light on a petrographic microscope to fully characterize internal structures and inclusions. Zircon grains were then analyzed in the SHRIMP RG with an ionized oxygen beam, releasing secondary ions from the zircons, and measuring concentration of U and Pb isotopes. Approximately 10 zircon grains were used for age analysis per unit. After collection of U-Pb data, grains were analyzed for major and trace element concentrations on the SHRIMP RG.

DATA

Zircon Morphologies and U-Pb dating
Samples chosen for U-Pb dating were from units Kg, Kw, Kp, and a sample from the interior of the Fry’s Point pluton (Kf). The first two were chosen to constrain the timing of the Stage 1 intrusion event, assuming Kg was similar in age to the Fry’s Point Pluton (as similar felsic units), and unit Kp was chosen to constrain the timing of Stage 2 intrusions. In CL, Kg zircons are large and characteristically “soccer ball” shaped or tabular with oscillatory zoning and displayed no inherited pre-magmatic cores or melt inclusions (Fig. 3A). Kg zircons are significantly smaller than those from Kg, no more than 100 μm in length with oscillatory zoning. Kw zircons are tabular, often longer than 200 μm with oscillatory zoning and no inherited cores. Kp zircons also show tight oscillatory zoning and commonly have inherited cores and melt inclusions. U-Pb ages were obtained through zircon age-dating procedures at the SUMAC SHRIMP RG facilities for four samples at the Kaweah River site. After data reduction, the four units yield concordant ages. Kg, Kw, Kf, and Kp yield ages of 105.1 ± 0.9 Ma, 105.5 ± 0.7 Ma, 105.5 ± 0.9 Ma, and 102 ± 0.7 Ma, respectively. These ages confirm the hypothesized two-stage intrusion sequence suggested by field relationships, with the coeval intrusion of all Stage 1 units at ca. 105 Ma and the intrusion of Stage 2 units at ca. 102 Ma. This also establishes that the interaction of these units is synchronous with intrusion of surrounding plutons, including the nearby Elk Creek gabbro. CL imaging shows Stage 1 units to have strong concentric zoning and generally lacking inherited cores while Stage 2 units are commonly mottled with inherited cores and melt inclusions.

Zircon Geochemistry
Rare earth element (REE) geochemistry was also obtained from zircons by elemental analysis at the SUMAC SHRIMP-RG for samples from the Kaweah River site. Crystallization temperature has been graphed against Hf to determine the cooling history of the units. Hf is an indicator of the extent of fractionation of minerals. Kg and Kw cooled quickly, allowing little fractionation of Hf, and Kp and Kf cooled slowly, allowing more fractionation of Hf.
Whole-Rock Major and Trace Element Geochemistry

Selected major and trace element Harker diagrams displayed in Figure 4 suggest that the chemistry of samples from the Kaweah River site is controlled in part by fractionation processes. Each shape represents a compositional range (triangles = mafic; squares = intermediate; diamonds = felsic), and elemental values of samples from the Kaweah outcrop are displayed as filled shapes. The MgO versus SiO\(_2\) diagram displays a negative slope, consistent with fractionation of ferromagnesian minerals such as olivine and pyroxene. The Al\(_2\)O\(_3\) diagram displays a relatively low concentration of Al\(_2\)O\(_3\) at low SiO\(_2\) values that initially increases with increasing SiO\(_2\) content then decreases with increasing SiO\(_2\) content at values above \(\sim 55\%\), consistent with no significant plagioclase fractionation up to \(\sim 55\%\) (positive slope), followed by plagioclase fractionation at values above 55\% SiO\(_2\) (negative slope).

The Ni versus SiO\(_2\) diagram displays a negative slope, consistent with concentrations expected due to fractional crystallization of olivine (high Ni partition coefficient), with a significant break in slope at SiO\(_2\) contents greater than 55\%, likely related to the absence of olivine in relatively felsic samples. The Cr versus SiO\(_2\) diagram also displays a significant change in negative slope at \(\sim 55\%\) SiO\(_2\), suggesting that the fractionation of clinopyroxene controlled Cr content at low SiO\(_2\) values (high Cr partition coefficient in clinopyroxene), with an absence of that mineral phase in high SiO\(_2\) samples. The Sr versus SiO\(_2\) diagram mimics the pattern observed on the Al\(_2\)O\(_3\) diagram, supporting changes in chemistry controlled by plagioclase fractionation processes (high Sr partition coefficient in plagioclase).

MODELING OF IGNEOUS PROCESSES

The trace element – trace element graphs displayed in Figure 5 do not reveal linear trends between mafic and felsic samples on all graphs, so mixing does not explain the origin of intermediate samples. However, modeling provides insight to possible differentiation processes that could generate the compositional diversity observed in the AMC. Modeling predicts how fractional crystallization and assimilation/fractional crystallization would affect melt evolution based on a chosen initial composition and thus can reveal a possible petrogenetic relationship between different AMC lithologies.

**Figure 4.** Select whole-rock major and trace elements are shown versus SiO\(_2\). Major elements are normalized to 100\% based on dry rock (Smith and Leeman, 2004). Light grey lines indicate hypothetical fractionation trends of AMC units.

**Figure 5.** Trace element compositions are plotted for individual samples where data points are coded according to SiO\(_2\) content. FC trends displayed on the Zr vs. Ce trend represent 80\% fractionation of each mineral. AFC trends are displayed with two arrows on the Ta vs. Rb trend and FC trends display fractionation to 30\%. Lower three graphs display fields based on partial melting experimental results for upper and lower crustal values with AMC units shown for reference.

FC Modeling

Select trace element – trace element diagrams were chosen for fractional crystallization (FC) modeling to explore the effects of olivine, clinopyroxene, and plagioclase fractionation on the evolution of melt. The composition of the most primitive sample from Stage 1, unit Kg, was used as the initial composition for all modeling. Melt evolution trends for FC modeling of olivine, clinopyroxene, and plagioclase plot along the...
same elemental trend for Ta versus Rb concentrations, incompatible with the production of any intermediate or felsic samples from the area (Fig. 5A). The Zr versus Ce melt trends for fractionation of the three minerals explain only one of the more felsic Kaweah River samples, but this requires 80% fractionation, an unlikely occurrence. This trend permits the evolution of mafic samples from other sites, but does not encompass the mafic samples from the Kaweah River site (Fig. 5). FC model trends for each mineral intersect one sample with Ba and Rb concentrations similar to the initial composition used for modeling, but none of the Kaweah River samples can be produced by mineral fractionation from a Kg-related source. Therefore, FC alone cannot explain the compositional diversity of the AMC.

**AFC Modeling**
Since FC modeling does not explain petrogenetic relationships between AMC units, assimilation – fractional crystallization (AFC) modeling was undertaken, modeling the same minerals and using upper (Taylor and McLennan, 1995) and lower (Rudnick and Fountain, 1995) crustal values as assimilants. Different R ratios were chosen, using values of 0.1, 0.5, and 0.9 (where R = assimilant/fractional crystallization). The Ta versus Rb AFC trend does not intersect any samples. The Zr versus Ce AFC model intersects one felsic sample from the Kaweah River site, but requires >50% fractionation. This modeling trend also intersects a number of samples from surrounding sites, although does not produce mafic samples from the Kaweah River site. The Ba versus Rb AFC modeling trend intersects no more than two samples at the Kaweah River site, but requires >50% fractionation to produce those samples. Under one of these circumstances the R value is so high that heat loss will be too great with the amount of assimilation that fractionation will likely not reach 50%. The trend intersects some samples at the surrounding locations, but not consistently or at a fractionation percentage that is plausible. AFC modeling suggests that AMC samples were not likely produced from the most primitive melt by AFC processes.

**PARTIAL MELTING EXPERIMENTS**
Because Mixing, and FC and AFC modeling do not explain the petrogenesis of AMC lithologies, samples were graphed against experimental results of partial melts from what are assumed to represent lower (Beard and Lofgren, 1991) and upper (Skjerlie and Johnston, 1993; Douce, 1997) crust. All felsic samples of the AMC fall within experimental ranges of the mafic partial melts of CaO, FeO, and Na₂O (Fig. 5). Available results from partial melting of felsic parent rocks (CaO) also produce compositions that encompass felsic AMC lithologies (Fig. 5). Rounded, inherited zircon cores and thin overgrowth rims of Stage 2 units may reflect partial melting and regrowth of zircons. All felsic AMC samples lie within the expected range of melt compositions produced by partial melting of lower and upper crustal samples.

**CONCLUSIONS**
Field relationships and zircon U-Pb age data indicate a two-stage intrusion history for the Ash Mountain intrusive complex (AMC), and zircon geochemistry indicates the rapid cooling of Stage 1 units Kbd and Kwd from high temperatures, while more felsic Stage 1 and Stage 2 units, Kgr and Kp, respectively, cooled more slowly. Although whole-rock major and trace element geochemistry suggest that the Kaweah River samples might be related by fractionation, FC and AFC modeling do not support a melt differentiation by any combination of crystal fractionation or assimilation, and mixing processes could not produce the diversity of compositions of the AMC.

Thus, based on the compositions produced by partial melting experiments and the aforementioned interpretations, it appears that the six AMC lithologies were derived from multiple sources. These sources are likely to include partial melts derived from greenstones and amphibolites, assumed representative of lower continental crust, and/or granitoids, assumed representative of upper continental crust. These results imply that a diversity of magmas can be produced by partial melting of pre-existing crust or lithospheric mantle without requiring significant mixing, FC or AFC processes. This result also suggests that recycling of crustal rocks may be an important process in continental arcs, possibly resulting in minimal or no net crustal growth over time (Ducea 2002; Sisson et al 2005).
REFERENCES

Barth, A. P., Wooden, J. L., 2010, Coupled elemental and isotopic analyses of polygenetic zircons from granitic rocks by ion microprobe, with implications for melt evolution and the sources of granitic magmas, Chemical Geology, v. 277, p. 149-159.


Sisson, T. W., Ratajeski, K., Hankins, W. B., Glazner, A. F., 2005, Voluminous granitic magmas from...
common basaltic sources, Contributions to Mineralogy and Petrology, v. 148, p. 635-661.


