KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
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Faculty: *KELLY MACGREGOR*, Macalester College, *CATHERINE RIIHIMAKI*, Drew University, *AMY MYRBO*, LacCore Lab, University of Minnesota, *KRISTINA BRADY*, LacCore Lab, University of Minnesota

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Students: *BRIANA BERKOWITZ*, Beloit College, *DAENA CHARLES*, Union College, *MELLISSA CROSS*, Colgate University, *JOHN MICHAELS*, North Carolina State University, *ERDENEBAYAR 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.

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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 Geology Consortium: Projects 2010-2011
Short Contributions— Sierra Nevada Mountains

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

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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

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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 Kpg 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.

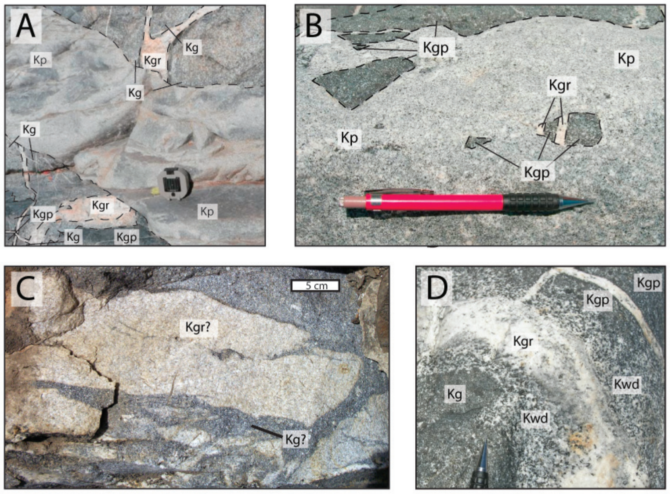

Figure 2. Field relationships shown for Kgp, Kg, Kwd, Kgr, and Kp at the Kaweah River site. Kpg is not shown. A) Kp is shown cross cutting all Stage 1 lithologies (Kgp, Kg, Kwd, Kgr). B) Angular xenoliths of Kgp are within Kp. One inclusion has preserved the original cross-cutting relationships of Kgr and Kgp. C) Mutually cross-cutting relationships initially identified by Ross (1958) are identified at the General's Highway site, 100m away from the Kaweah River site. Here, what appears to be Kg cross-cuts what appears to be Kgr. D) Gradational contacts define Stage 1 lithologies.

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 Kpg 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 ($Li_2B_4O_7$) 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 Kgp, Kwd, Kp, and a sample from the interior of the Fry's Point pluton (Kfp). The first two were chosen to constrain the timing of the Stage 1 intrusion event, assuming Kgr 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, Kgp 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 Kgp, no more than 100 µm in length with oscillatory zoning. Kwd 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. Kgp, Kwd, Kfp 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.

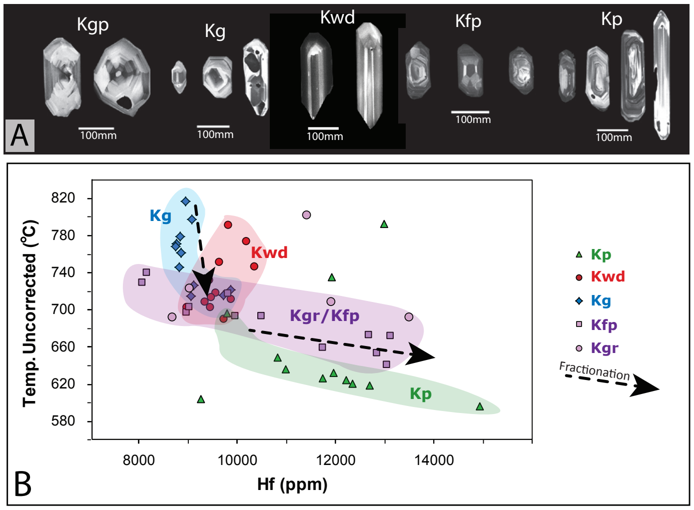

Figure 3. Zircon geochemical results for select trace and rare earth elements. A) Cathodoluminescence imaging reveals internal structure of zircons from primary samples. Stage 1 zircons are more pristine, generally lacking inclusions and inherited cores, and Stage 2 zircons contain significant melt inclusions and inherited cores. B) 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 Kwd cooled quickly, allowing little fractionation of Hf and Kgr, Kfp and Kp cooled slowly, allowing more fractionation of Hf.

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, an indicator of the extent of fractionation for all units except Kgp (Fig. 3), based on the Ti-in-zircon thermometer of Barth and Wooden, 2010). The highest temperatures recorded by the thermometer were zircon values from Stage 1 units Kg and Kwd, which display patterns consistent with rapid cooling and fractionation (steep slopes). In contrast, the maximum temperature of units Kgr, Kfp and Kp are equal to or lower than the lowest temperatures of Kg and Kwd, supporting relatively slow cooling and fractionation for Stage 2 units. Zircon geochemistry indicates the higher temperatures of units Kg and Kwd and their lack of fractionation (specifically of Hf) and rapid cooling, and the relatively low temperatures of Kgr, Kfp and Kp, as well as their greater fractionation and slower cooling history. This may indicate that units Kg and Kwd were quenched by the intrusion of Kgr.

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_2O_3 diagram displays a relatively low concentration of Al_2O_3 at low SiO_2 values that initially increases with increasing SiO_2 content then decreases with increasing SiO_2 content at SiO_2 values above ~55%, consistent with no significant plagioclase fractionation up to ~55% (positive slope), followed by plagioclase fractionation at values above 55% SiO_2 (negative slope).

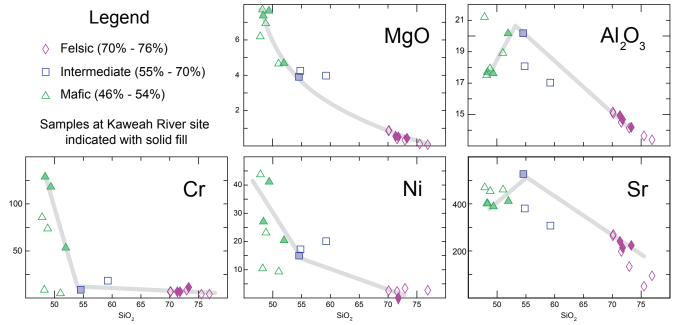

Figure 4. Select whole-rock major and trace elements are shown versus SiO_2. Major elements are normalized to 100% based on dry rock (Smith and Leeman, 2004). Light grey lines indicate hypothetical fractionation trends of AMC units.

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 ~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_2O_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.

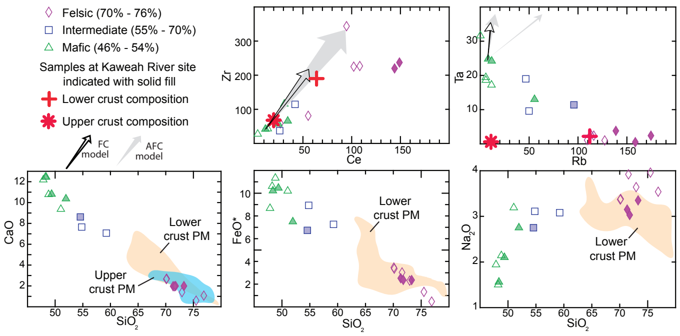

Figure 5. Trace element compositions are plotted for individual samples where data points are coded according to SiO_2 content. FC trends displayed on the Zr vs. Ce trend represent 80% fractionation of each mineral. AFC trends are displayed with two arrows on the Ta vs. Rb trend and FC trends display 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 Na_2O (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).

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