KECK GEOLOGY CONSORTIUM

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

April 2011
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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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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

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Research Advisor: Steve Wojtal

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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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STABLE ISOTOPE GEOCHEMISTRY OF MARBLES IN THE KINGS SEQUENCE, SIERRA NEVADA, CA

JULIANNE M. WALLAN, Colgate University
Research Advisor: William H. Peck

INTRODUCTION

SIERRA NEVADA

The Sierra Nevada batholith in central California has abundant granitoid plutons, with original wallrock, occurring as scattered roof pendants that preserve the contact metamorphic geologic history of the region. The Sequoia region contains metasedimentary lithologies of the Kings Sequence that include marbles, which are intruded by mainly Cretaceous high-silica granites. There is evidence of contamination at the margins of these granitic plutons, and localized migmatite complexes (see Lackey and Loewy, this volume). The purpose of this study is to determine peak metamorphic temperatures of the Kings Sequence in the Sequoia region of the Sierra Nevada batholith through use of calcite-graphite thermometry, and to evaluate fluid infiltration into country rock. Constraining thermal budgets associated with the process of recycling crust at convergent margin batholiths will add to our understanding of the mechanisms by which plutons are formed and the continental margin is modified by magmatism within the Kings Sequence. This enables the assessment of potential partial melting of schists in these rocks, and the contamination of Sierran magmas. Understanding the fluid and temperature record is useful to assess the fluid budget of the Sierran arc and evaluate the origins of mineral ore deposits like tungsten.

Marbles are good indicators of fluid and temperature history because of their preservation of carbon and oxygen isotopes during metamorphism. Metamorphic processes involving heat, fluid, and pressure alter original marine carbonate sediments to form marble. Organic material trapped in the sediments is recrystallized to form graphite within marbles. Although original $\delta^{13}C$ and $\delta^{18}O$ values of minerals in metasediments probably reflect sedimentary processes, both calcite and graphite respond to the conditions under which they were metamorphosed. This includes oxygen and carbon exchange with fluids as well as temperature-dependant exchange between calcite and graphite (Dunn and Valley, 1992). The evaluation of calcite-graphite carbon-isotope thermometry of marbles gives peak temperatures achieved during contact metamorphism, which may help constrain melting conditions and assist in evaluating the potential for partial melting of the Kings Sequence schists in the Sequoia region.

METHODS

Eighteen samples were collected from two proximal and similar locations of calcite marble north of the Potwisha campsite in Sequoia National Park and National Forest, CA, and one sample was collected just south of the entrance of the Potwisha campsite. Four more samples of calcite marble were obtained from similar localities near Crystal Cave and Monarch Lake, south and north of the main site, respectively, for comparison. Thin sections were made for petrographic analysis. Calcite and graphite samples were analyzed for isotope ratios at Colgate University. Calcite samples and standards were prepared for carbon and oxygen isotope analysis using the method of McCrea (1950), where samples are reacted with phosphoric acid in separate vessels and evolved CO_2 is purified using a vacuum line. To separate graphite, ground marble was dissolved in HCl and the residue was rinsed 2 to 3 times with distilled water. Very fine-grained graphite and insoluble residue was scraped from beakers and loaded with excess CuO into tin cups for combustion in an element analyzer (after Peck et al., 2005). Standards and samples were triplicated for precision and accuracy. The calibration of Dunn and Valley (1992) for calcite-graphite isotope fractionation was used to obtain temperature data:

Equation 1.

$$\Delta^{13}C_{Cal-Gr} = 5.81 \times 10^{6} \times T^{-2}(K) - 2.61.$$

As temperature of metamorphism increases in marble, the difference in the coexisting calcite and graphite $\delta^{13}C$ isotopic compositions gets smaller. These temperatures are useful for regional and local thermometry.

RESULTS

PETROGRAPHY

Thermometry samples are calcite marbles with very fine-grained but visible graphite. Some graphite-free samples were also analyzed for comparison. Most samples contain fine to coarse-grained (up to 2.5 cm) granoblastic calcite that often has a sugary texture (Figs. 1A-F). For almost every sample of calcite marble, there is approximately 90% calcite. Diopside occurs in every sample of calcite marble (Fig. 1B). Almost every sample contains graphite and plagioclase (Fig. 1F). Approximately half of the samples have mica, determined in some samples to be phlogopite. JW-05 has approximately 25% garnet, and 70% calcite (Fig. 1A). JW-01, JW-03, JW-05, and JW-18 contain rutile in thin section, not confirmed by SEM analysis.

Sample	Marble Body	Calcite		Avg Grain Size of Calcite	Graphite	Minerals Present				
		$\delta^{18}O$ (SMOW)	$\delta^{13}C$ (PDB)		$\delta^{13}C$ (PDB)	Di	Gt	Kfs	Mi	Op
JW-01	1	22.37	2.49	4mm	-2.71	T			X	X
JW-03	1	20.76	2.00	.5mm		T			T	X
JW-05	1	15.53	-2.11	.5mm		X	X	X	X	X
JW-07	1	24.36	3.53	2mm	-2.97	X		X		X
JW-11	2	18.31	0.92	1mm		X		X	X	X
JW-12	2	18.07	-0.26	.5mm		X		X		X
JW-13	2	20.53	0.62	1.5mm	-5.00	X		X	T	X
JW-14	2	18.63	0.85	1mm		X		X	X	X
JW-15	2	20.63	-1.60	1.5mm	-5.78	X		X		X
JW-16A	3	19.32	-1.75	2mm	-6.69	X		X		X
JW-18	ML			1.5mm		T		X		T
SH-6A	CC	18.37	-0.48	2mm	-8.57	T		X	T	X
SH-06A	CC	17.58	-0.71	1mm		T		X	X	

*Table 1. Summary of isotopic data and minerals present in each analyzed sample. Minerals identified from hand sample and thin section. All samples contain calcite and graphite. Samples where * with sample name indicates that the graphite in the sample was analyzed. Di= diopside, Gt= garnet, Kfs= k-feldspar, Mi= mica, Op= opaque.*

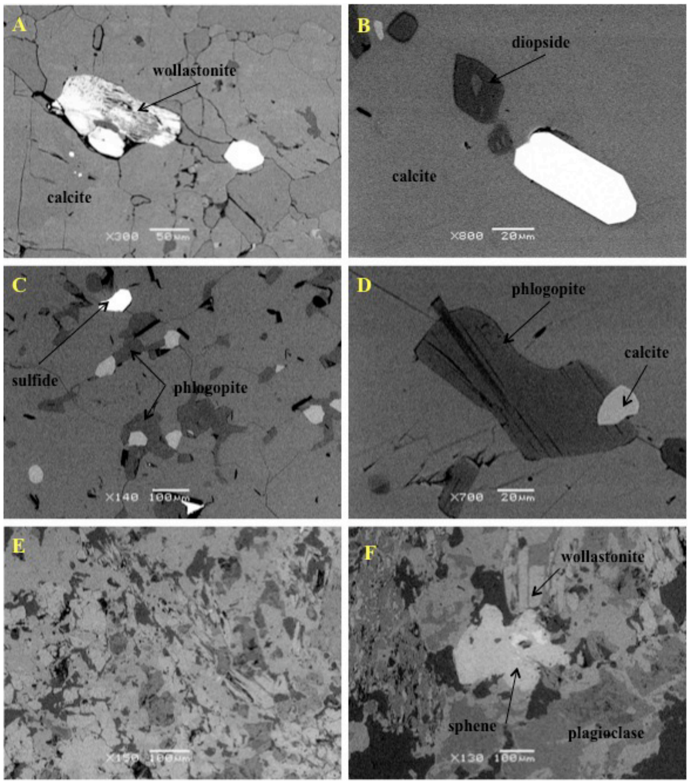

Figure 1. SEM images. A. JW-5 with sulfide and wollastonite. B. JW-1 with calcite, diopside, and sulfide. C. JW-14 with sulfide, calcite, and phlogopite. D. JW-1 with phlogopite grain and calcite. E. SH-06A from Crystal Cave with different composition than other sampled marble bodies with sugary textures. F. SH-06A with sphene, wollastonite, and plagioclase.

ISOTOPIC DATA

Measured $\delta^{13}C$ values for analyzed samples with coexisting calcite and graphite range from -1.75‰ to 3.53‰ (PDB) in calcite and from -1.75‰ to 3.53‰ in graphite. The temperatures calculated from these data range from 470°C to 650°C. Crystal Cave marble yielded the lowest temperature, but all other marble bodies have more or less very similar peak metamorphic temperatures. This indicates that these marbles were similarly formed under the same conditions. For samples of Marble Bodies #1 and #2, for which there are more than one sample to compare, there is no apparent difference in temperature between locations. In general, it seems that temperatures of contact metamorphism of ca. 600°C are associated with the Cretaceous Mike Ranch Peak granodiorite, both at its margin (body 3) and in large xenoliths in the center of the intrusion (bodies 1 and 2). The Crystal Cave marble is associated with surrounding schist and at the margin by the Cretaceous Giant Forest granodiorite of the Sequoia Intrusive Suite.

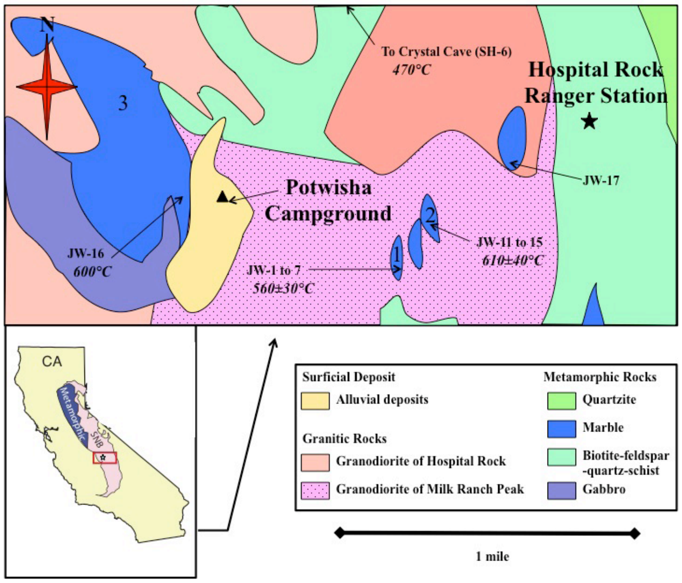

Figure 2. Giant Forest quadrangle map with sampling sites of the Kings Sequence marble body within the Milk Ranch granodiorite. Sample numbers are in bold and estimated temperatures from each marble body analyzed are in italics. 1,2 and 3 indicate is Marble Bodies discussed in text. No apparent pattern exists between the temperatures of each marble body, and temperatures are all relatively similar.

The $\delta^{13}C$ and $\delta^{18}O$ values of calcite from the Kings Sequence marble bodies #1, #2, #3, and Crystal Cave are lower than expected from primary marine carbonates, and reflect medium-grade alteration. The $\delta^{13}C$ values range from -2.11‰ to +3.53‰ (PDB) and $\delta^{18}O$ values range from 15.53‰ to 24.36‰ (SMOW). The data taken together have a positive slope on the carbon vs. oxygen isotope plot with an R^2 value of 0.57. The outline of $\delta^{13}C$-$\delta^{18}O$ field for skarn calcite from Pine Creek included in blue. Boxes showing average $\delta^{13}C$-$\delta^{18}O$ fields for marine limestone and "igneous" calcite shown are based on Bowman (1998). As described by Bowman (1998), igneous calcite is calcite in equilibrium with magmatic carbon, where $\delta^{13}C$= -5 to -8 per mil. Thick solid curves adapted from Bowman (1998) are $\delta^{13}C$-$\delta^{18}O$ trends for calcite produced by a progression of magmatic water and carbonate rock interaction, where fluids alter the calcite to different extents during metamorphism. Processes that could have produced the data array of Kings Sequence marble include exchange between calcite and graphite, decarbonation reactions, and most likely C+O altering fluids. Unaltered marine limestone exists in the "marine limestone" box in Fig. 3. The data from the Kings Sequence marble bodies is consistent with original Jurassic limestone that has been altered by magmatic fluids during metamorphism, with probably a minor role of calcite-graphite exchange and decarbonation reactions.

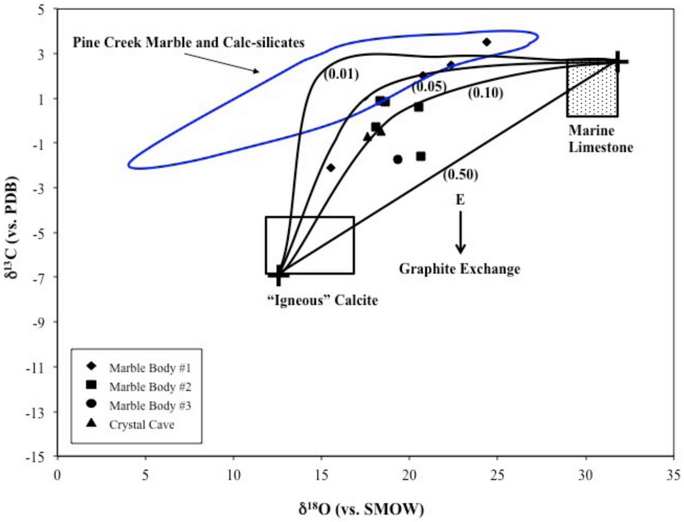

Figure 3. Plot of the $\delta^{13}C$ and $\delta^{18}O$ values of skarn-like calcite from the Kings Sequence marble bodies #1, #2, #3, and Crystal Cave. Outline of $\delta^{13}C$-$\delta^{18}O$ field for skarn calcite from Pine Creek included in blue. Boxes outlining the $\delta^{13}C$-$\delta^{18}O$ fields for marine limestone and "igneous" calcite shown are based on Bowman (1998). As described by Bowman (1991), igneous calcite is calcite and magmatic carbon in equilibrium, where $\delta^{13}C$= -5 to -8 per mil. Thick solid curves adapted from Bowman (1998) are $\delta^{13}C$-$\delta^{18}O$ trends for calcite produced by a progression of magmatic water and carbonate rock interaction, and the trend labeled E reflects the qualitative effect on the $\delta^{13}C$ values of calcite from exchange with graphite depleted in 13C. Values in () represent $X(CO_2)$ for water-rock interaction curves.

DISCUSSION

Data from this study are consistent with previous published descriptions of contact metamorphism in nearby locations. Bowman et al. (1998) summarizes similar temperatures for the Pine Creek skarn-hosted tungsten deposit of the eastern Sierra Nevada. The approximate carbon and oxygen isotope data for the Pine Creek marble are shown by the blue outline in Fig. 3, and closely follows the metamorphic alteration of the Kings Sequence marbles. However, the Kings Sequence marble trend is steeper than the Pine Creek marble, which could be a result of several processes. A minor component of graphite exchange and also of decarbonation reactions is the production of diopside; alternatively, altering fluids could have higher C:O. The range of error on the replicate samples is reasonable for within each marble body (Fig. 2).

Variations in the temperature of each marble body could be attributed to the sample proximity to the pluton. Crystal Cave temperatures are lower, but are still within range of medium-grade metamorphism. Overall, the temperature data reflect medium-grade metamorphism at amphibolite facies conditions. Temperatures of marble bodies within the Kings Sequence are reasonable when compared to the range of aluminosilicate temperatures in these rocks. Saleeby and Busby (1993) report anadalusite in many of the rocks in the area, with sillimanite occurring closer to pluton-wallrock contacts, giving a lower boundary of 500°C to metamorphism in the region. Lackey et al. (2006) discuss upper boundary qtz-sillimanite pairs in peraluminous granites that give oxygen isotope fractionation temperatures of approximately 650°C. The temperatures obtained from calcite-graphite thermometry are therefore consistent with the aluminosilicate-bracketed temperatures and suggest that the method provides a good measure of peak metamorphic temperature in marble bodies. These temperatures are also consistent with observed mineral assemblages and calcite-graphite fractionations in similar medium-grade marbles elsewhere (Kruelen and Van Beek 1983).

CONCLUSIONS

Temperatures from this study are generally similar to those described by Bowman (1998) of proximal marble bodies like Pine Creek in the Eastern Sierra Nevada. The $\delta^{13}C$-$\delta^{18}O$ trends for calcite in the Kings Sequence marble bodies sampled suggest that processes including graphite exchange, decarbonation, and C+O altering fluids metamorphosed the original marine carbonate. Data from marbles of the Kings Sequence show almost uniform temperatures within the surrounding pluton. However, more research should be done on marbles of the Kings Sequence to confirm these temperatures and determine any changes or patterns unobserved in this study.

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REFERENCES

Bowman, J.R., 1998, Stable-Isotope Systematics of Skarns: In Mineralized Intrusion-Related Skarn Systems (D.R. Lentz, ed.). Min. Assoc. Can. Short Course 26, p. 99-145.

Saleeby, J.B., and Busby, C.J., 1993, Paleogeographic and tectonic setting of axial and western metamorphic framework rocks of the southern Sierra Nevada, California: In G. Dunne and K. McDougall (eds), Mesozoic paleogeography of the western United States: Society for Sedimentary Geology (S.E.P.M.) Pacific Section.

Dunn, S.R., and Valley, J.W., 1992, Calcite-graphite isotope thermometry: a test for polymetamorphism in marble, Tudor gabbro aureole, Ontario, Canada: J. metamorphic Geol., 10, p. 487-501.

Kruelen, R., and Van Beek, P.C.J.M., 1983, The calcite-graphite isotope thermometer; data on graphite bearing marbles from Naxos, Greece: Geochimica et Cosmochimica, v. 47, p. 1527-1530.

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 plutons of the Sierra Nevada batholith: Contributions to Mineralogy and Petrology, v. 151, p. 20-44.

McCrea, J.M., 1950, On the isotopic chemistry of carbonates and a paleotemperature scale: J.Chem. Phys., 18, p. 849-857

Peck, W.H., DeAngelis, M.T., Meredith, M.T., and Morin, E., 2005, Polymetamorphism of marbles in the Morin terrane (Grenville Province, Quebec): Canadian Journal of Earth Sciences, v. 42, p. 1949-1965.