KECK GEOLOGY CONSORTIUM

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

April 2011
Union College, Schenectady, NY

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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 MCATEE*, 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.

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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.

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Students: LYNN M. GEIGER, Wellesley College, KARA JACOBACCI, University of Massachusetts (Amherst), GABRIEL ROMERO, Pomona College.

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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

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.

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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, *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

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Project Faculty: JADE STAR LACKEY, Pomona College, STACI L. LOEWY, California State University—Bakersfield

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MARY BADAME, Oberlin College
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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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JESSLYN STARNES, Denison University
Research Advisor: Dr. Erik Klemetti

INTRODUCTION

Roof pendants engulfed between the granitoid plutons that comprise the Cretaceous Sierra Nevada batholith record the early history of Triassic-to-Jurassic arc volcanism in western North America. This study provides new U-Pb SHRIMP-RG ages of meta-rhyolites from the Mineral King roof pendant, as well as geochemical data, which document an extended and more complex early volcanic history in the southern Sierra Nevada than previous studies have suggested. Additionally, these new ages revise the existing relationship between the rhyolite units within the pendant and suggest that they may not share a common magmatic source. Zircon isotopic and trace element compositions suggest that these rhyolites may record the progressive involvement of continental crust in western North America.

GEOLOGIC SETTING

The Mineral King Roof pendant is a screen of late Triassic to early Cretaceous meta-volcanic and meta-sedimentary rocks located between two mid-Cretaceous granitic plutons in the Southern Sierra Nevada. The meta-volcanic units with the pendant represent early Sierran arc-volcanism related to the beginning of subduction along the western edge of North America (Busby-Spera, 1987). These units are interpreted as four large-scale rhyolite ash-flow tuffs (R_0, R_1, R_2, R_4), one smaller rhyolite ash-flow tuff (R_3), and a number of smaller andesite deposits (A_0-A_3) (Fig. 1). Previous work (Busby-Spera, 1983; Busby-Spera, 1986; Busby-Spera and Saleeby, 1987) proposed that a series of submarine caldera eruptions deposited the rhyolite tuffs at a range of water depths on a subsiding continental shelf. Within the pendant, calc-silicate units, marine shales, breccia-sandstone, and marbles are also present. Two faults run the length of the pendant, generally trending NNW. The Empire Fault acts as a boundary between R_2 and R_4, while the Farewell Fault runs down the center of the valley that divides the pendant. R_0 and R_1 lie to the west of this fault, and R_2, R_3, and R_4 lie to the east. The Eagle Lake quartz monzodiorite (QM) borders the pendant to the west, the Empire quartz diorite (QD) borders it to the north, and the Sawtooth Peak granite (Gr) borders it to the east.

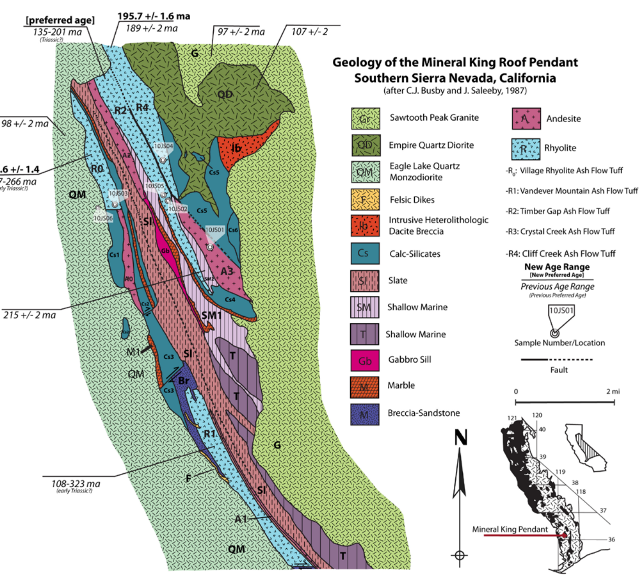

Figure 1 A map of the Mineral King Roof Pendant, with ages of important units listed. See legend for sources of data in map.

METHODS

Fieldwork for this project was conducted in the Mineral King area of Sequoia National Park during July 2010. During this time, samples were collected from units R_0, R_2, R_3, as well as A_3, and QM. Standard sample processing and zircon extraction procedures were performed, including crushing and pulverizing of the samples, and removal of zircons via the use of a gold table, Frantz magnetic separator and heavy liquid separation using facilities at Pomona College and California State University, Bakersfield. Whole-rock major and trace element compositions were measured in the Pomona College XRF lab. Zircon mounting and CL-imaging was performed at Stanford University. Zircon ages and trace element data were collected at the USGS/Stanford SUMAC lab using the sensitive high-resolution ion microprobe-reverse geometry (SHRIMP-RG). Oxygen isotopes of zircon splits were collected at the University of Oregon Stable Isotope lab.

SAMPLE DESCRIPTIONS

Field and Petrographic Descriptions

Four samples were collected from three different rhyolite units within the pendant:

10JS03 was collected from the Village Ash Flow Tuff (R_0) (Fig. 1) and is altered to a quartz sericite schist (Busby-Spera and Saleeby, 1987). The unit is intruded by the Eagle Lake Quartz Monzodiorite (QM) to the west, and calc-silicate units lie to the south and east. 10JS03 is extremely quartz-rich (~55%). The quartz grains are typically <0.05 mm, anhedral in shape, and comprise the majority of the matrix. Clusters of coarser grained quartz are also visible; these grains range in size up to ~0.25 mm and are interlocking, with highly irregular edges. Significantly altered plagioclase feldspar grains are also present, but they are eroded and "dusty", with finer quartz grains grown into the remaining crystal.

10JS04 was collected from the Cliff Creek Ash Flow tuff (R4) (Fig. 1). The weathering pattern on the outcrop is platy, and fresh surfaces have visible phenocrysts. The matrix is composed mostly of fine quartz and plagioclase feldspar grains. Small, rounded quartz grains are interspersed with the slightly larger, blocky plagioclase grains. Clusters of coarser quartz grains are also visible, as well as extremely weathered, rounded plagioclase grains. Some of the plagioclase grains are relict, and overprinted by the smaller quartz and feldspar grains that make up the matrix, as well as biotite mica.

10JS02 and 10JS05 were both collected from the Timber Gap Ash Flow Tuff (R_2) (Fig. 1). R_2 is extremely weathered throughout, with relict phenocrysts visible on the weathered surfaces but not visible on fresh surfaces. It has abundant mica, and grades west to east from a rhyolite tuff to a flow-banded rhyolite. 10JS02 represents the tuff, while 10JS05 is a sample of the flow-banded section. 10JS02 is composed of primarily quartz and plagioclase feldspar. The quartz grains are small and rounded and sometimes arranged in clusters, and the plagioclase grains that comprise the matrix are small and elongate. The matrix of 10JS05 is composed of fine-grained, subhedral to anhedral quartz and coarser, anhedral, angular and blocky quartz, which is sometimes arranged in clusters. There is a significant amount of muscovite, with lesser amounts of biotite. There are two varieties of plagioclase feldspar: highly altered, relict grains and smaller, less altered grains with visible twinning.

DATA

Zircon U-Pb age data

In-situ U-Pb ages of individual zircon were determined for two of the meta-rhyolites using SHRIMP-RG. Cathodoluminescence was used to image the zircons prior to dating, and zircons were selected for dating based on their appearance. Zircons from 10JS03 (R_0) are typically elongate, with oscilatory zoning patterns. Zircons from 10JS04 (R_4) are less elongate, with fine-scale zonation. Inclusions are visible in zircons from both samples but were avoided during analysis. Minimal resorption textures are visible (Fig. 2). Zircons (n = 12) from 10JS04 (R_4) yield a concordant age of 195.7 ± 1.6 Ma (Fig. 3). Individual zircon ages from this sample range from 191.2 ± 1.9 Ma to 198.7 ± 2.1 Ma (Table 1). Zircons (n = 11) from 10JS03 (R_0) produced no concordant ages, but yielded a median age of 135.6 ± 1.4 Ma (Fig. 3). Individual zircon ages ranged between 112.5 ± 2.0 and 140.7 ± 0.8 Ma, excluding one core (10JS03-5.1), which produced an age of 1.63 Ga ± 8.4 Ma. (Table 1). U-Pb data was collected from both the core and rim in many of the zircons, in order to pinpoint potential inherited cores or the presence of magmatic overgrowths, but no significant age difference was found for the majority of samples.

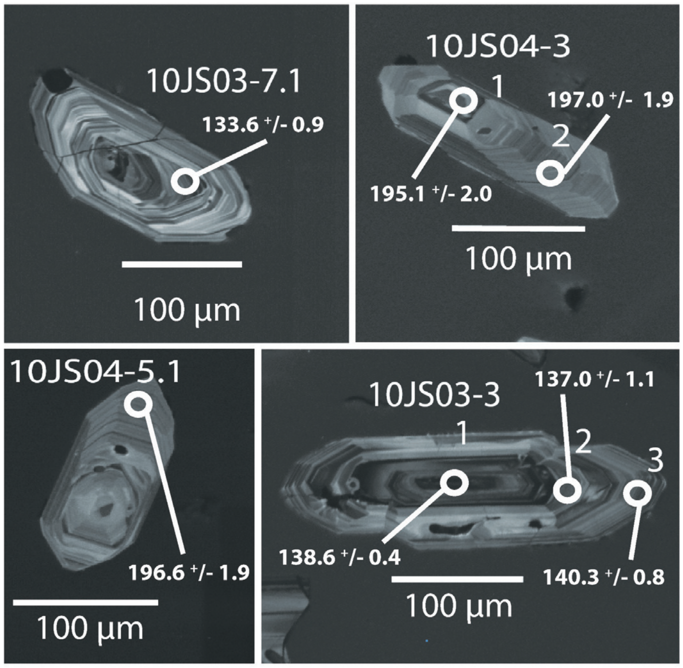

Figure 2 Cathodoluminesce images of zircon samples. Images show SHRIMP-RG spot analysis locations and U-Pb ages with 2σ error.

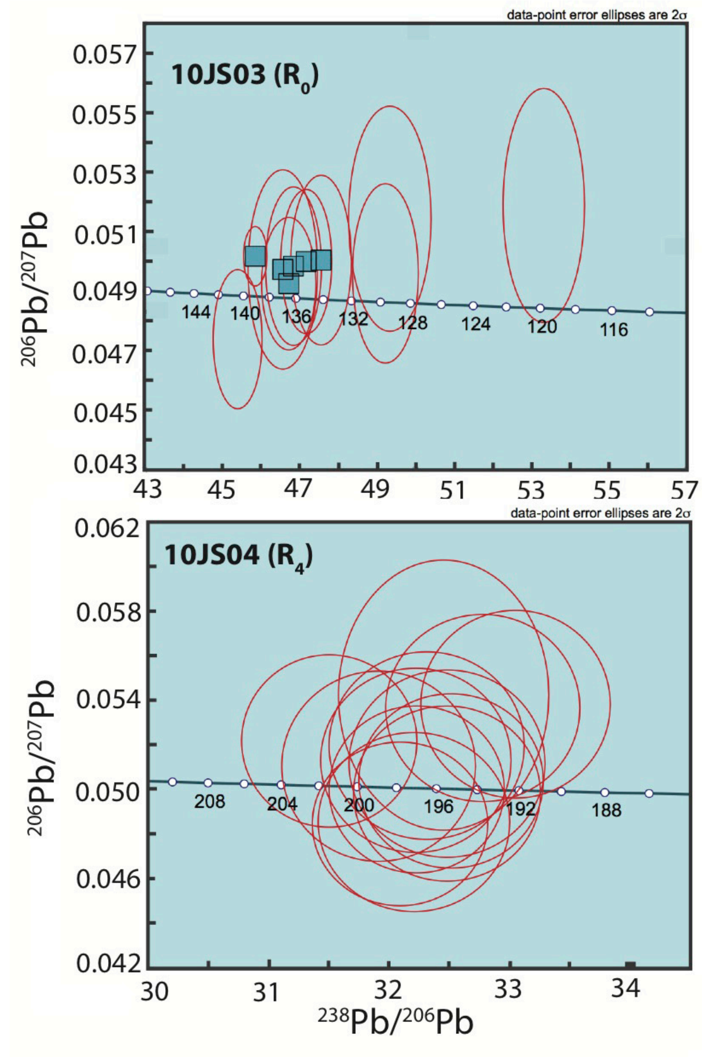

Figure 3 Concordia diagrams showing U-Pb age ranges and error ellipses of zircons from samples 10JS03 (R0) and 10JS04 (R_4). 10JS03 produced a range of ages between 112.5 ± 2.0 and 140.7 ± 0.8 Ma, and a median age of 135.6 ±1.4 Ma. 10JS04 produced a range of ages between 191.2 ± 1.9 Ma to 198.7 ± 2.1 Ma, and a concordant U-Pb age of 195.7 ± 1.6 Ma.

Zircon trace element composition

For 10JS03 (R_0), Hf concentrations range between 7708 and 11771 ppm, while Eu/Eu* values range between 0.06 and 0.48, and Th concentrations range between 95 and 1006 ppm. For 10JS04 (R_4), Hf concentrations range between 9474 and 10468 ppm, with Eu/Eu* values range between 0.22 and 0.28 (with the exception of a single value calculated at 0.55), and Th concentrations range between 54 and 84 ppm. When comparing the trace element distribution between the two different samples, it is apparent that 10JS04 (R_4) has more tightly clustered trace element compositions, while 10JS03 (R_0) trace elements values are more widely dispersed (Fig. 4).

Zircon oxygen isotopic composition

Values of $\delta^{18}O$ were collected from three of the samples at the University of Oregon Stable Isotope Lab. Sample 10JS03 (R_0) yielded average values of 6.78 ± 0.08‰, 10JS06 (QM) yielded average values of 6.70 ± 0.12‰, and 10JS04 (R_4) yielded a value of 5.33‰. The standard deviation for the standards used in the calculations was 0.09. Unknown values were corrected to an accepted value of UWG-2 of 5.80‰ (Valley et al. 1995). Replicate analyses of zircon samples were typically better than ± 0.12‰.

Whole-rock major and trace element composition

Whole-rock compositional data from each sample are typical for rhyolite: SiO_2 values are 69 to 74 wt. %, zirconium ranges from 187 to 233 ppm. Using these compositions and calculations of Watson and Harrison (1983) and Miller et al. (2003), R0 and R4 had zircon saturation temperatures of 831º C and and 795º C, respectively.

DISCUSSION

Previous work in this region (Busby-Spera, 1983,

Analysis	U (ppm)	Th (ppm)	$^{206}Pb/^{238}U$	Error (%)	$^{207}Pb/^{206}Pb$	Error (%)	Model age (Ma)	+/- error (Ma)
10JS03-6.1	690	339	0.022	0.6	.1970	5.6	112.5	2.0
10JS03-8.1	368	146	0.019	0.8	.0519	3.1	119.3	1.0
10JS03-1.2	377	214	0.020	0.9	.0514	3.0	128.9	1.2
10JS03-2.1	594	143	0.020	0.7	.0496	2.5	129.5	0.9
10JS03-7.1	443	116	0.021	0.7	.0500	2.3	133.9	0.9
10JS03-4.1	601	98	0.021	0.6	.0500	2.0	135.0	0.8
10JS03-2.2	788	120	0.021	0.6	.0498	2.2	136.0	0.9
10JS03-1.1	861	147	0.021	0.6	.0493	1.8	136.4	0.8
10JS03-3.2	343	142	0.021	0.8	.0497	2.8	136.8	1.1
10JS03-3.1	2989	1018	0.022	0.3	.0502	0.8	138.8	0.4
10JS03-3.3	709	183	0.022	0.6	.0474	2.0	140.7	0.8
10JS03-5.1	217	317	0.292	0.5	.1093	0.6	1636.3	8.4
10JS04-10.1	197	97	0.030	1.0	.0538	3.2	191.2	1.9
10JS04-4.2	162	67	0.031	1.0	.0536	3.2	192.8	2.0
10JS04-4.1	136	66	0.031	1.1	.0542	4.6	194.6	2.2
10JS04-8.1	195	85	0.031	1.0	.0504	3.2	195.2	1.9
10JS04-3.1	151	80	0.031	1.0	.0511	3.4	195.2	2.0
10JS04-2.2	171	73	0.031	1.0	.0498	3.2	195.5	1.9
10JS04-7.1	149	64	0.031	1.0	.0520	3.3	196.0	2.0
10JS04-3.2	153	66	0.031	1.0	.0513	3.3	196.7	2.0
10JS04-6.1	190	81	0.031	0,9	.0500	3.1	197.0	1.8
10JS04-9.1	193	87	0.031	1.0	.0485	3.4	197.5	2.0
10JS04-5.1	192	86	0.031	0.9	.0484	3.1	198.2	1.9
10JS04-1.1	148	56	0.031	1.0	.0510	3.4	198.7	2.1

*Table 1: Selected isotopic composition and elemental composition of zircon from 10JS03 and 10JS04. Total concentrations of U and Th in ppm, $^{206}Pb/^{238}U$, $^{207}Pb/^{206}Pb$, and calculated model age for each individual SHRIMP-RG spot analysis for zircons from 10JS03 (R_0) and 10JS04 (R_4). * denotes the sample was flagged for high ^{204}Pb and excluded from final age calculation.*

Busby-Spera, 1986), provided bulk U-Pb zircon age analyses for the Mineral King rhyolites. The Village ash flow tuff (R_0) and Vandever Mountain rhyolite (R_1) yielded discordant ages, but these units were tentatively considered to be Early Triassic in age based on their location within the pendant (Busby-Spera, 1983). Zircons from the Crystal Creek ash-flow tuff (R_3) produced concordant ages of 215 ± 2 Ma while the Cliff Creek ash-flow tuff (R_4) produced concordant ages of 189 ± 2 Ma. The Monarch rhyolite ash-flow tuff (R_2) was interpreted to be Late Triassic (Busby-Spera, 1983). Additionally, a meta-dacite fault sliver along the Empire fault yielded a U-Pb zircon age of 240 ± 7 Ma (Busby-Spera, 1987).

In this study, new *in situ* U-Pb single zircon age data are presented for the R_0 and R_4 rhyolite. Zircons from R_4 produced a tightly clustered range of concordant ages between 191.2 ± 1.9 Ma to 198.7 ± 2.1 Ma, and a median U-Pb age of 195.7 ± 1.6 Ma, which is close to Busby's (1983) value for the same unit (~189 Ma). Individual zircons from R_0, however, produced a range of ages slightly discordant ages between 112.5 ± 2.0 and 140.7 ± 0.8 Ma, and a median $^{206}Pb/^{238}U$ age of 135.6 ± 1.4 Ma (MSWD=1.6), making the new age of the unit early Cretaceous rather than the previously assigned early Triassic (Busby 1983). One possible explanation for the previous older ages (Busby 1983) is inclusion of much older inherited cores within the multigrain zircon dissolution analysis. As with any bulk analysis method, the existence of significantly older inherited cores (xenocrysts) within the sample would skew the resulting age data. This is supported by the inherited core found within zircon 10JS03-5.1, which yielded a core age of 1.636 Ga ± 8.4 Ma.

Previous studies of the Mineral King pendant suggested that the volcanic units of the roof pendant became older from east to west, and that the pendant records a continuous sequence of volcanic events that occurred over a time span ranging from the early Triassic to the early Jurassic (Busby-Spera, 1983; Busby-Spera, 1986). Our new ages suggest that R0 on the western edge of the pendant is actually early Cretaceous in age, out of sequence with the proposed eastward-younging pattern (Busby-Spera, 1983; Busby-Spera, 1986). Additionally, R_0 has experienced a much higher degree of alteration than other rhyolite units in the pendant. Combined with evidence of potential shearing, such as large, boudinaged quartz veins within the outcrop, and the unit's location west of the known Farewell Fault, it is possible that R_0 is a fault sliver which has experienced a significant amount of displacement along a shear zone, and is potentially not genetically related to the rest of the pendant.

The trace element and isotopic composition of zircon can be used to examine the magmatic sources and processes involved with the generation of the Mineral King pendant rhyolite units. Our data suggests varying degrees of crustal interaction for R_0 and R_4 based on $\delta^{18}O$ values and zircon trace element compositions with respect to sample age. Zircon from 10JS03 (R_0) have average $\delta^{18}O$ values of 6.78 ± 0.08‰ while zircon from 10JS04 (R_4) have an average value of 5.33‰. A typical mantle value is 5.3 ± 0.3‰ (Valley et al. 1998) while continental crust has higher $\delta^{18}O$ compositions (Faure, 1986) suggesting R_4 has little crustal input in comparison to R_0. Additionally, the significantly older 1.63 Ga ± 8.4 Ma inherited core found in R_0 potentially represents the assimilation of sediment derived from the interior of North America into R_0. Despite being the younger volcanic unit, R_0

exhibits a much wider range of trace element compositions (Fig. 4), suggesting a more diverse population of zircons than in R_4. When combined with the observation that R_4 zircon ages are much more tightly clustered than R_0 zircon (Fig. 4), this suggests that the R_4 rhyolite may represent the generation of rhyolite without significant influence of previously-existing continental crust, while R_0 may record more significant crystal recycling from the maturing arc continental crust. This is similar, albeit at a longer timescale, as to what is observed at other long-lived arc-related magmatic systems (Walker et al, 2010). Alternatively, the differences in trace element values may suggest that R_0 underwent a longer period of crystallization within the crust, and experienced a greater amount of fractionation than R_4 (Claiborne, et al. 2010).

Generally, the Th/U values tend to trend inversely to concentrations of Hf, such that samples with lower Th/U ratios have higher Hf concentrations, and vice versa. Using Hf values as a relative proxy for temperature, this indicates that zircons with lower Th/U ratios record higher temperatures, while zircons with higher Th/U ratios record lower temperatures. (Claiborne, et al. 2010). Additionally, the magnitude of the Eu anomaly (Fig. 4) increases with increasing plagioclase fractionation as plagioclase feldspar preferentially takes in Eu from the magma while crystallizing. Therefore, a lower Eu/Eu* value indicates higher degrees of fractionation. Analyzed zircons from both samples have low Eu anomalies (< 0.30). Values this low suggest that either a considerable amount of feldspars crystallized and were removed from the parent magma before zircons began crystallizing, or that the parent magma came from a feldspar rich source, which already had a significant Eu anomaly (Claiborne, et al. 2010). However, sample R_0 exhibits lower Eu/Eu* values than R_4, potentially implying the magmatic source for the younger R_0 was actually more fractionated than that of R_4. This further demonstrates the unlikelihood of a genetic relationship between R_0 and R_4.

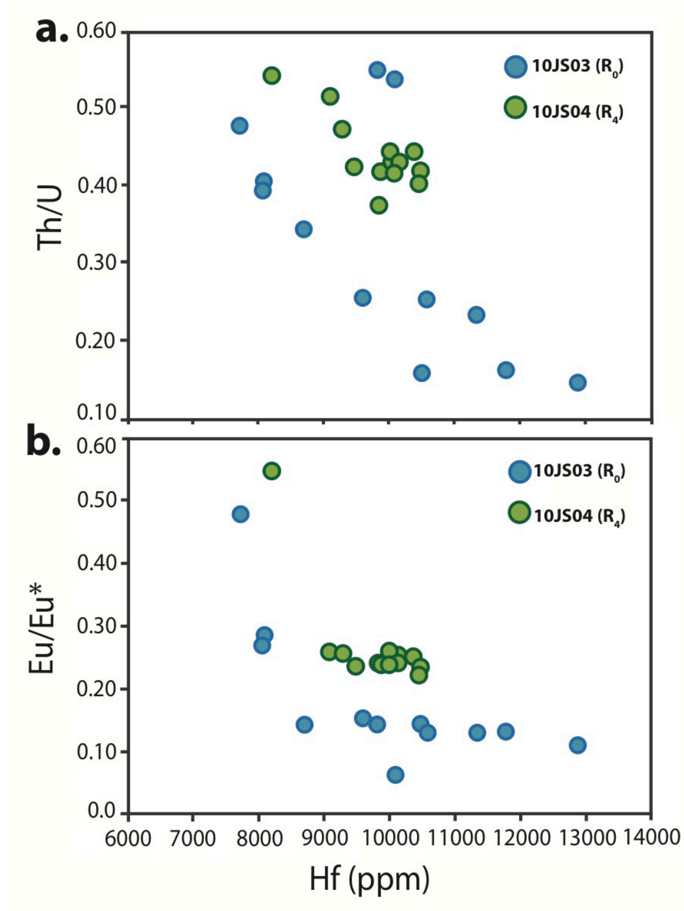

Figure 4: A. Hafnium concentration versus Th/U in zircons B. Hafnium concentration versus Eu/Eu (Eu anomaly) in zircons. Both diagrams show analyses from from 10JS03 (R_0) and 10JS04 (R_4). Note in both diagrams the contrast between the tightly clustered 10JS04 (R_4) values and the more dispersed 10JS03 (R_0) values.*

CONCLUSIONS

The determination of new, more accurate ages for the rhyolite units of the Mineral King pendant have demonstrated the potential for a more complicated volcanic history than previously thought. These new ages modify the age of R_0 to ~136 Ma, making it significantly younger than the ~196 Ma R_4. Additionally, differences in alteration and the presence of shearing structures within unit R_0 further suggest that the pendant is not a continuous sequence of erupted material, but rather a potential amalgamation of several fault slivers of varying age and origin. Combined with geochemical data suggesting that R_0 has potentially more crustal input, a more diverse population of zircons, and is less fractionated than R_4, it is unlikely that R_0 and R_4 were produced in the same magmatic conditions. Zircon trace element and isotopic compositions suggest that R_0 had more interaction with previously-existing continental crust (both igneous material and sediment). This change is likely related to the development of the western North American margin as arc volcanism progressed from the Triassic to Jurassic prior to the main pulse of plutonism related to the Sierra Nevada.

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