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A REVIEW AND REVISION OF LATE MESOZOIC TO CENOZOIC PLUTON CHRONOLOGY IN THE RICO MOUNTAINS, SOUTHWESTERN COLORADO

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Abstract—Latest Mesozoic to Cenozoic plutonic rocks have had a profound influence on the landscape, mineralization, and uplift history in the Rico Mountains. This record is defined by emplacement of numerous stocks, sills, and dikes of felsic to mafic intrusive rocks. Plutons of diorite to monzonite porphyry emplaced in a narrow span of time at ~68 Ma dominate the record. The preservation of 1748 to 1381 Ma xenocrystic zircons in the ~68 Ma plutonic rocks provides further evidence for the involvement of Proterozoic basement in the generation of Laramide magmas in the western San Juan Mountains. Hypabyssal monzonite plutons were emplaced at ~4 Ma in the Rico Mountains, contemporaneous with a period of elevated geothermal gradient accompanied by production of a deep-seated stock with porphyry Mo mineralization. The Pliocene plutons formed in an interval marked by intrusion of 7 to 4 Ma alkaline mafic rocks along an incipient zone of extension that extends from Rico to Placerville. The 68 to 4 Ma plutonic events in the Rico Mountains mimic a long-term shift to more bimodal magmatism in the western San Juan Mountains. Injection of mantle melts from 25 to 0.6 Ma during incipient crustal extension accompanied elevated thermal gradients over the region, as evidenced by resetting of cooling ages in some Laramide intrusive rocks. The higher geothermal gradient and Pliocene magma production in the western San Juan Mountains marked the continued involvement of mantle melts in the production of crustal magmas.

INTRODUCTION

Numerous plutons of latest Mesozoic to Cenozoic felsic to mafic intrusive rock are exposed throughout the western San Juan Mountains (Fig. 1). Emplacement of plutons from 75 to 4 Ma caused localized uplift that had a major influence on landscape evolution in the area, and often were linked to zones of mineralization (Gonzales, 2015).

Subduction-driven magmatism in the Laramide (75-60 Ma) generated alkalic monzonite to gabbro that were emplaced as laccoliths and stocks on northeast trends along crustal-scale zones of weakness with Proterozoic ancestry (e.g., Warner, 1980; Karlstrom et al., 2005). The transition from Laramide subduction to slab rollback and delamination was marked by incipient regional extension and emplacement of alkaline mantle magmas accompanied by the semi-continuous intrusion of shallow felsic to mafic plutons from 27 to 4 Ma (Gonzales, 2015). Oligocene plutons are mostly peripheral to 29-27 Ma caldera complexes that formed over a regional subvolcanic batholith. The Rico Mountains are the only site in the western San Juan Mountains where ages of intrusive

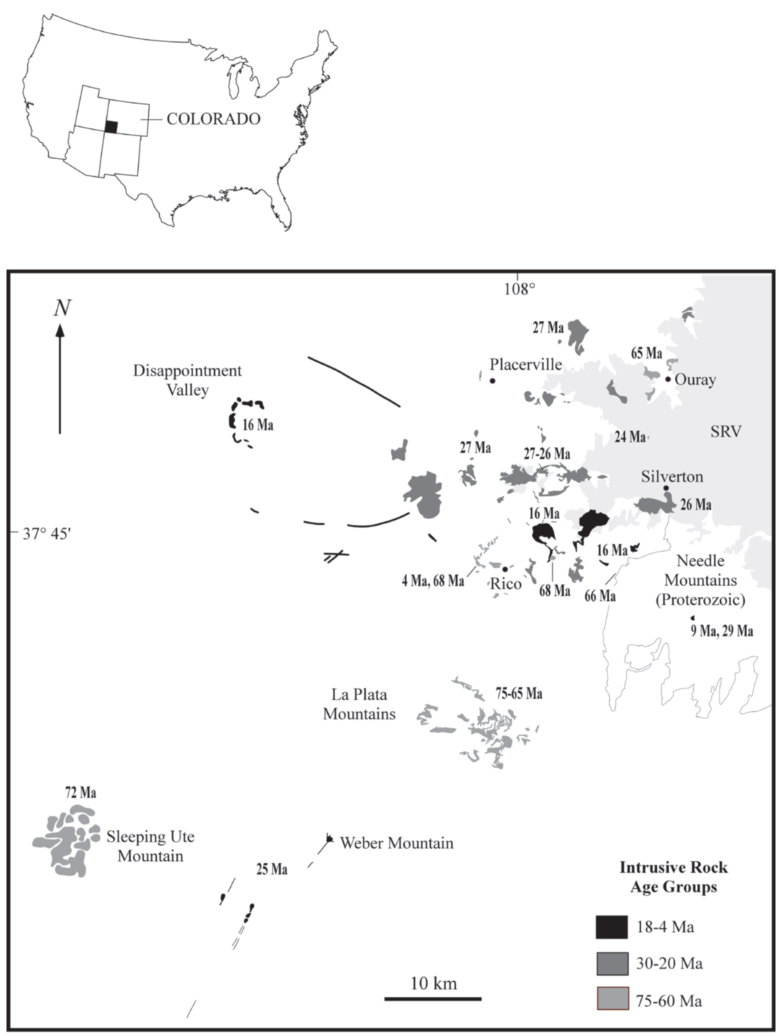

FIGURE 1. Generalized geologic map showing the distribution of 75 to 4 Ma intrusive rocks in the western San Juan Mountains. The numbers on the map are the accepted ages (millions of years) for plutonic rocks in an area from various methods (K/Ar, Ar/Ar, and U-Pb zircon) (summarized in Gonzales, 2015). Black rectangle in the map of the United States shows the approximate location of the map area.

rocks bracket the extremes of the Late Cretaceous to Pliocene plutonic record (75-4 Ma), and where 6 to 3 Ma mafic dikes and felsic plutons are spatially related. The plutonic record in the Rico area is marked by the noted absence of 27 to 16 Ma intrusive rocks that are widely exposed to the north and east (Fig. 1).

Latest Mesozoic to Cenozoic plutons in the Rico Mountains are exposed (Fig. 2) over an eroded landscape with nearly 1000 meters (~3300 feet) of relief. Previous K/Ar (whole rock, pyroxene, biotite) and fission-track (zircon, sphene, apatite) analyses on these plutonic rocks (Armstrong, 1969; Naeser et al., 1980; Fig. 2) constrained their emplacement between the Laramide and Pliocene, but there was wide variation in reported ages, even for rocks from the same pluton. These data also revealed a major thermal disturbance ~4 Ma that caused partial resetting of radiogenic systems (K/Ar and fission-track). New U-Pb zircon analyses were conducted in this investigation as part of an ongoing regional study (Gonzales, 2015; Gonzales and Lake, 2016) to constrain the timing and history of the Late Cretaceous to Pleistocene magmatic record in the western San Juan Mountains. These data redefine previous age constraints and establish that plutonic activity in the Rico area was restricted to narrow time spans at ~68 Ma and ~4 Ma.

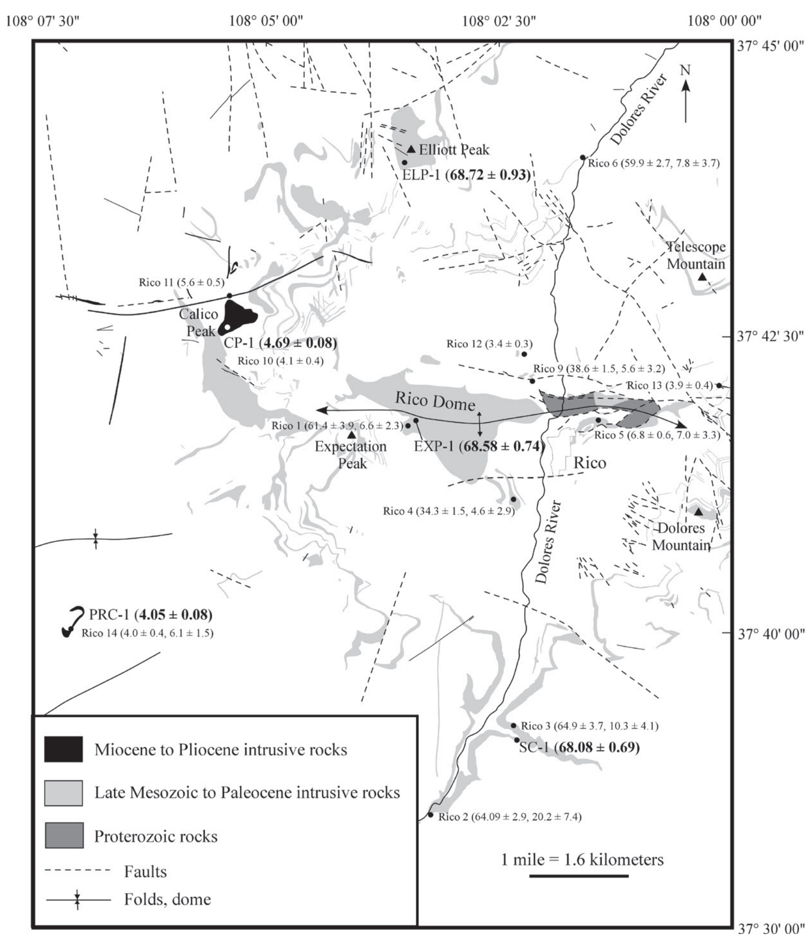

Figure 2. Generalized geologic map showing the distribution of Paleocene and Pliocene intrusive rocks in the Rico Mountains. The locations and ages (reported in millions of years, Ma) of samples for U-Pb zircon analyses are noted, as well as the fission track zircon and apatite ages determined by Naeser et al. (1980). Figure modified after map published by Pratt et al. (1969).

GEOLOGIC SETTING

Rico, Colorado (Fig. 2) is shrouded by rugged 12,000-foot peaks (~3700 meters) that distinguish the Rico Mountains, situated near the boundary of the Southern Rocky Mountains and Colorado Plateau. The principal geomorphic feature in the area is the Rico dome, an east-west trending elliptical uplift (5 km x 2 km) that is cut by a series of east-west, northeast-southwest, and northwest-trending normal faults (Fig. 2). North and east of Rico, the east- and northeast-trending faults define a horst block cored by Proterozoic “greenstone” and “metadiorite”, and rocks of the Uncompahgre Group (Pratt et al., 1969; McKnight, 1974; Fig. 2). Devonian to Late Cretaceous sedimentary rocks are exposed on the flanks of the dome. The strata are intruded by numerous mafic to felsic intrusive rocks that were emplaced in dikes, sills, and stocks. The largest exposed mass is a stock of augite monzonite exposed west of Rico within the core of the dome. The dome is incised by the southward-flowing Dolores River (Fig. 2) which is flanked by steep valley walls exposing nearly 900 meters (~3000 feet) of geologic record.

Laramide plutonic rocks exposed in the Rico Mountains consist of hornblende diorite porphyry and augite monzonite (Table 1). These rocks are similar in age and composition to those exposed in the La Plata Mountains, Sleeping Ute Mountain, and The Blowout stock in Ouray (Fig. 1). The Pliocene intrusive igneous rocks in the Rico area are porphyritic to aphanitic quartz-bearing biotite-hornblende monzonite (“latite” of Pratt et al., 1969). These rocks are exposed in an altered stock at Calico Peak, dikes at Johnny Bull Mountain, and a 10-meter thick sill at Priest Creek (Fig. 2). These are the youngest felsic plutonic rocks in the western San Juan Mountains (Fig. 1). Notably absent in the Rico Mountains are 27 to 16 Ma monzonitic to dioritic intrusive rocks that are widely exposed to the north and east (Fig. 1; Gonzales, 2015). Alkaline mafic dikes emplaced from 7 to 4 Ma (Gonzales, 2015; Gonzales and Lake, 2016) in the Rico Mountains are part of a swarm that extends N-NE from Rico to Placerville.

The pluton production and emplacement in the Rico Mountains over the past 70 Ma contributed to local uplift of a kilometer or more, modified the landscape, and influenced the paths of local drainage systems. Thermal metamorphism and related skarn mineralization of sedimentary strata is widespread within the contact zones of the plutons. The relationship of base- and precious-metals mineralization to intrusive rocks in the area is well documented (Farish, 1892; Rickard, 1897; Cross and Spencer, 1900; Ransome, 1901; Cross and Ransome, 1905; Pratt, 1968; Pratt et al., 1969; and McKnight, 1974; Larsen, 1987; Wareham, 1991; Cunningham et al., 1994; Larsen et al., 1994a, b; Wareham et al., 1998). The principal mineral production in the Rico district was zinc, lead, copper, silver, and gold from veins and replacement deposits in limestones of the Ouray, Leadville, and Hermosa formations that contain a variety of ore and gangue minerals (Barnes, 1985). It is reported (McKnight, 1974; Cameron et al., 1986) that between 1879 and 1968 the mines of the district produced 83,847 tons of Pb (76,064 metric tonnes), 82,717 tons (75,309 metric tonnes) of Zn, 5,637 tons of Cu (5,114 metric tonnes), 14,513,288 ounces of Ag, and 83,045 ounces of Au. In 1893 alone, 3 million ounces of silver were mined and produced (Barnes, 1985). Uranium-vanadium ores were also mined from deposits in the Entrada Sandstone east of Rico. Anaconda Minerals Company discovered and explored the Pliocene Silver Creek porphyry Mo deposit in the eastern part of the Rico district in the late 1970's to early 1980's. This porphyry system was drilled at depths of 1.5 kilometers (~0.9 miles) southeast of Rico near the southern edge of the horst block (Fig. 2). A drilling campaign on the stock indicated a reserve of ~40 million tons of 0.31% Mo with a potential reserve base of 200 million tons (Cameron et al., 1986). Larsen et al., (1994b) argued that precious and base metal deposits formed along the margins of the hydrothermal plume related to the porphyry Mo stock at ~4 Ma (Larsen, 1987). The elevated geothermal system present beneath Rico over the past 5 million years is in part the result of emplacement and crystallization of mantle melts at depth, as revealed by mantle He signatures of gases released by modern thermal springs in the area (Easley and Morgan, 2013).

DESCRIPTION OF SAMPLES

Five plutons exposed in the Rico Mountains were sampled in this investigation (Fig. 2, Table 1). Intrusive rocks suspected to be latest Mesozoic to Cenozoic were collected at Elliott Peak (ELP-1), north of Expectation Peak (EXP-1), and Scotch Creek (SC-1). All of these samples are distinguished by 1- to 7-mm phenocrysts of hornblende and plagioclase set in a fine-grained groundmass. The rocks preserve varying degrees of deuteric alteration with hornblende showing partial alteration to chlorite, and plagioclase to sericite.

Pliocene intrusive rocks were sampled from the Calico Peak stock (CP-1) and the sill on the west side of Priest Creek (Fig. 2, Table 1). These rocks were called "latite" by Pratt et al., (1969), but herein are described as monzonite to quartz monzonite (Table 1). They are characterized by porphyritic-aphanitic textures with phenocrysts of quartz + orthoclase + plagioclase set in fine grained to microcrystalline groundmass. The sill at Priest Creek contains a higher proportion of plagioclase and orthoclase phenocrysts than rocks exposed at Calico Peak. Whole-rock chemical analyses for samples from Calico Peak (63.47 wt. % SiO_2, 2.68 wt. % K_2O, 0.76 wt. % Na_2O) and Priest Creek (57.58 wt. % SiO_2, 3.34 wt. % K_2O, 3.59 wt. % Na_2O) reveal that the rocks are calc alkaline to shoshonitic.

U-PB ZIRCON ANALYSES

Zircon separates were obtained from ~20-pound samples of the different plutons (Fig. 2) at The University of Arizona LaserChron Center by standard separation methods; an in-depth discussion of these methods is at https://drive.google.com/file/d/0B9ezu34P5h8eTU9PaUczTGc5elk/view. Zircon separates were mounted onto a 1-inch diameter epoxy puck along with fragments or loose grains of Sri Lanka, FC-1, and R33 zircon crystals that were used as primary standards. About 50-high-quality grains were selected and mounted with the standards. The surface of the epoxy mounts was sanded down to a depth of ~20 microns, polished, imaged using a Gatan

TABLE 1. Summary of geochronologic data for U-Pb analyses on zircons from Cenozoic plutonic rocks in the Rico Mountains.

Plutonic Unit	Sample ID	Longitude (N)	Latitude (W)	Pluton Form	†Rock Type	Weighted Mean Age in Ma (± 2σ)	MSWD	Comments
Pliocene intrusive rocks								
Calico Peak	CP-1	37.72443	108.07922	stock	quartz monzonite	4.69 ± 0.08	1.6	
Priest Creek	PRC-1	37.66902	108.11697	sill	quartz monzonite	4.05 ± 0.08	0.95	
Late Mesozoic intrusive rocks								
Elliott Peak	ELP-1	37.73158	108.05997	stock	diorite	68.72 ± 0.93	1.03	Analyzed 11/32 zircon cores with ages of 1748-1402 Ma
Expectation Peak	EXP-1	37.69728	108.06119	stock	monzonite	68.58 ± 0.74	0.39	Analyzed 5/28 zircon cores with ages of 1575-1381 Ma
Scotch Creek	SC-1	37.65259	108.04023	stock	diorite	68.08 ± 0.69	0.44	Analyzed 4/28 zircon cores with ages of 1616-1382 Ma

†Rock names listed are those determined from modal analyses by author.

Chroma cathodoluminescence (CL) detector coupled to a Hitachi S2400 scanning electron microscope, and cleaned prior to isotopic analysis. The cathodoluminescence (CL) images were used to identify zonation in crystals, potential inherited xenocrysts and antecrysts, and mineral inclusions. U-Pb analyses of zircon crystals were conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008; Gehrels and Pecha, 2014). The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 microns at selected points. Data for 25 to 30 zircons were used to define weighted mean ages generated by isoplot (Ludwig, 2008). Inheritance in zircon crystals was assessed in each population by comparing the ages of cores and rims. All of the samples of Laramide intrusive rock contained a proportion of inherited Proterozoic zircons. Ages obtained from xenocrystic zircons were not included in the final age calculations, but a summary of the number of inherited grains and their range of ages are provided in Table 1. A complete set of U-Pb zircon age data is available in the NMGS data repository.

RESULTS

Late Cretaceous intrusive rocks

Armstrong (1969) reported the first age constraints on Laramide plutonic rocks in the Rico Mountains. K/Ar analyses on “altered hornblende diorite” exposed south of Rico yielded ages of 179 Ma (pyroxene) and 61.3 Ma (whole rock). Fission-track analyses on zircons produced ages of 61.4±2.9 Ma for the monzonite (Rico 1) in the Rico dome (Naeser et al., 1980) while ages of 64.9±2.9 (Rico 2, near Dutch Creek), 64.9±3.7 (Rico 3, Scotch Creek) and 59.9±2.7 (Rico 6, north of Rico) were determined for samples of hornblende diorite porphyry (Fig. 2). Several fission-track analyses of zircon from Laramide hornblende diorite yielded ages of 38 to 34 Ma (Rico 4 and 9). Apatite fission-track cooling ages of 20 to 5 Ma were documented in all analyzed samples (Armstrong, 1969) (Fig. 2), and were attributed to thermal disturbance and partial resetting of isotopic systems in Laramide plutonic rocks due to later magmatic events and hydrothermal alteration (Armstrong, 1969; Cunningham et al., 1977; Naeser et al., 1980; Cunningham et al., 1994).

Three samples of hornblende diorite porphyry were collected in the Rico area (Fig. 2, Table 1). Within analytical errors, all yield similar U-Pb zircon ages at ~68 Ma (Fig. 3, Table 1). These data indicate that Laramide plutons in the Rico Mountains were emplaced in a narrow range of time, and are similar in age to dioritic to monzonitic intrusive rocks in the La Plata Mountains and Ouray area (Gonzales, 2015). The ~68 Ma intrusive rocks in the Rico Mountains (Fig. 3, Table 1) contain 34% to 14% xenocrystic zircons with ages ranging from 1748 to 1381 Ma. An inherited zircon component is evident in many of the Laramide intrusive rocks in the western San Juan Mountains (Gonzales, 2015), indicating magmatic recycling of Proterozoic basement (Gonzales, 1997; Gonzales and Van Schmus, 2007).

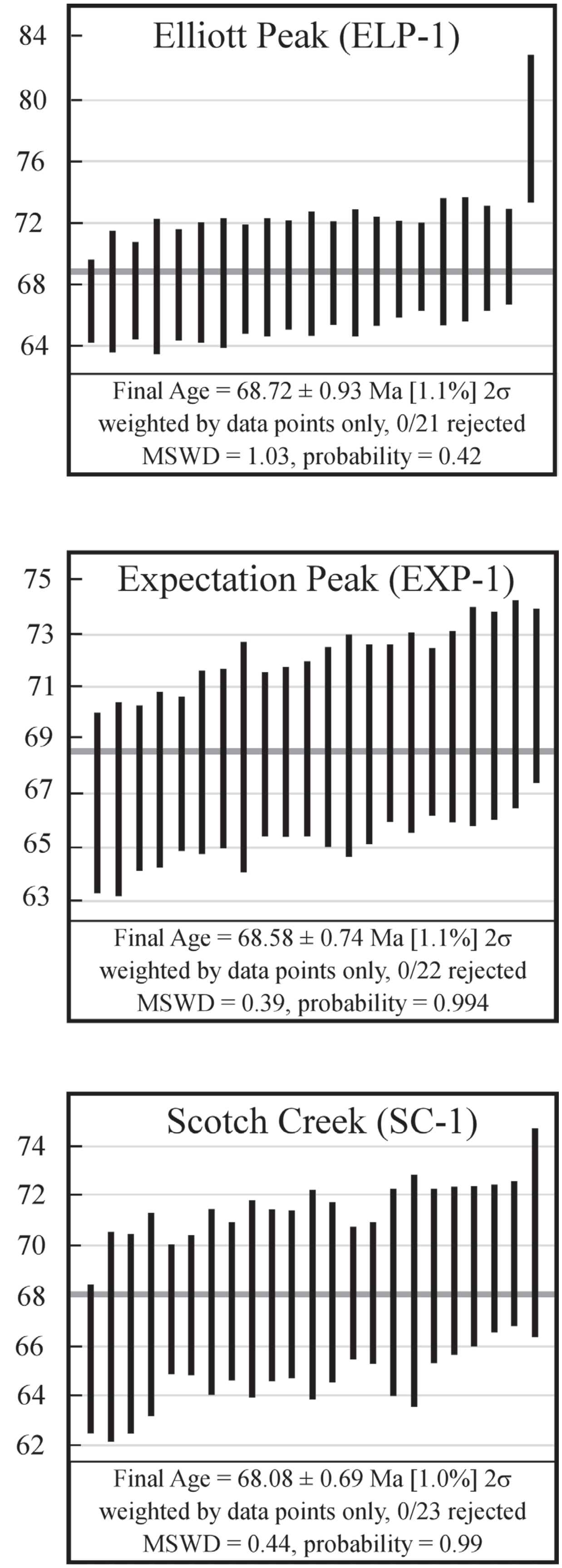

FIGURE 3. Weighted mean-age diagrams generated from U-Pb analyses on zircons from intermediate to felsic intrusive rocks in the Rico Mountains with assigned ages of ~68 Ma.

Early Pliocene intrusive rocks

Previous fission-track ages of 4.1 ± 0.4 Ma (Rico 10, Calico Peak), 5.6±0.5 Ma (Rico 11, dike at Johnny Bull Mountain), 4.0±0.4 Ma (Rico 14, Priest Creek sill), and 6.8±0.6 Ma (Rico 5, east of Rico) were determined for granitic to quartz monzonitic intrusive rocks (Armstrong, 1969; Fig. 2). Fission-track ages on zircon of 3.4±0.3 Ma (Rico 12) and 3.9±0.4 Ma (Rico 13) were also determined for samples of alaskite porphyry in the area (summarized in Gonzales, 2015). Apatite fission track analyses for Rico 14 yielded an age of 6.1±1.5 Ma (Fig. 2).

U-Pb zircon analyses for the Calico Peak sample gave an age of 4.69±0.08 Ma while the sample from the sill at Priest Creek yielded an age of 4.05±0.08 Ma (Fig. 4, Table 1). These age constraints are similar to previously published ages for rocks at these locations (Armstrong, 1969). No xenocrystic Proterozoic zircons were identified in the ~4 Ma intrusive rocks.

DISCUSSION

The 68 to 4 Ma intrusive rocks in the Rico Mountains are endmembers in the chronology of Late Cretaceous to Pliocene plutons in the western San Juan Mountains (Gonzales, 2015). The Paleocene intrusive rocks belong to the generation (Fig. 1) of potassic, calc-alkaline to alkaline intermediate to felsic rocks (± rare gabbro) that were emplaced in laccolithic complexes from 75 to 60 Ma (Fig. 1). The similarity of U-Pb zircon and previous fission-track zircon ages (Naeser et al., 1980) for Laramide plutons near Rico shows that magmas crystallized over a relatively short interval of time after emplacement and cooled quickly through ~110°C. The common occurrence of inherited Proterozoic zircons (Table 1; Gonzales, 2015) in most Laramide intrusive rocks in the western San Juan Mountains reveals that there was a significant contribution of 1.8-1.35 Ga crust to magmas produced during subduction of the Farallon slab.

The period after 25 Ma in the western San Juan Mountains was marked by the episodic intrusion of mantle melts, the youngest of which was the eruption of the Specie Mesa basalt at ~614±5 ka (Gonzales and Lake, 2016). Pliocene hypabyssal rocks in the Rico Mountains comprise the youngest plutons in the region, and are related to formation of the Silver Creek porphyry Mo deposit. The emplacement of Miocene to Pleistocene mantle melts in the western San Juan Mountains (Gonzales, 2015; Gonzales and Lake, 2016) were the catalyst for crustal melting and production of the small-volume plutons at ~4 Ma. This interval was marked by an elevated geothermal gradient revealed by 8 to 4 Ma apatite fission track ages in ~68 Ma intrusive rocks in the Rico Mountains, and thermal disturbance in K-Ar systems and fission tracks in zircon and apatite in Laramide plutons at Rico and Ouray (Armstrong, 1969; Cunningham et al., 1977; Billings, 1980; Naeser et al., 1980; Cunningham et al., 1994). The emplacement of widely distributed Miocene and Pliocene plutons coincides with the waning stages of magmatism in the San Juan Mountains and defines a transition to bimodal magmatism associated with regional extension and formation of the Rio Grande rift (Lipman et al., 1970; Lipman and Mehnert, 1975; Thompson et al., 1991).

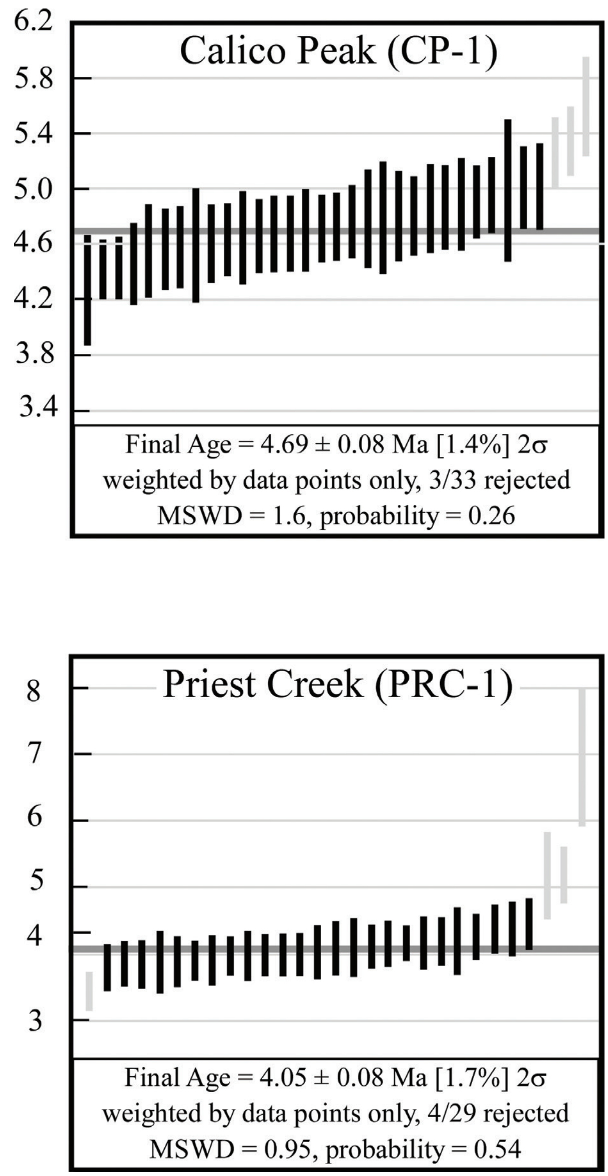

FIGURE 4. Weighted mean-age diagrams generated from U-Pb analyses on zircons from intermediate to felsic hypabyssal intrusive rocks in the Rico Mountains with assigned ages of ~4 Ma. Bars shown in lighter gray were not included in the final age determation.

Felsic to mafic plutons (Fig. 1) emplaced from 27 to 16 Ma in the western San Juan Mountains (Gonzales, 2017) are conspicuously absent in the Rico Mountains. Oligocene to Miocene intrusive rocks are widely exposed 5 to 10 kilometers north of Rico (e.g., Black Face-Mt. Wilson), but no Pliocene plutons are documented in this area. The reason for this distinct shift in pluton ages is uncertain, but magma production and high-level emplacement at ~4 Ma in the Rico Mountain was apparently linked to a unique set of magmatic-tectonic controls.

The plutonic record in the Rico Mountains (Fig. 2) encapsulates the influence of latest Mesozoic to Cenozoic magmatism on the geologic record in the western San Juan Mountains. Plutons emplaced in the Rico Mountains affected uplift and drainage patterns, and produced rich zones of mineralization in skarns, veins, and porphyry deposits. Continued production of geothermal springs at Rico distinguished by He signatures enriched in mantle gases reveals an ongoing contribution of magmatism to geologic processes in the region.

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REFERENCES CITED

Armstrong, L.A., 1969, K-Ar dating of laccolithic centers of the Colorado Plateau and vicinity: Geological Society of America Bulletin, v. 80, p. 2081-2086.

Barnes, R., 1985, The mines and minerals of Rico: The Mineralogical Record, v. 16, p. 203-247.

Cameron, D.E., Barrett, L.F., and Wilson, J.C., 1986, Discovery of the Silver Creek molybdenum deposit, Rico, Colorado: American Institute of Mining, Metallurgical, and Petroleum Engineers Transactions, v. 280, p. 2099–2105.

Cross W., and Spencer, A. C., 1900, Geology of the Rico Mountains, Colorado: U.S. Geological Survey 21st Annual Report, pt. 2, p. 7-165.

Cross, Whitman, and Ransome, F. L., 1905, Description of the Rico quadrangle [Colorado]: U.S. Geological Survey Atlas, Folio 130, 20 p.

Cunningham, C.G., Naeser, C.W., and Marvin, R.F., 1977, New ages for intrusive rocks in the Colorado mineral belt: U.S Geological Survey Open-File Report 77-573, 5 p.

Cunningham, C.G., Naeser, C.W., Marvin, R.F., Luedke, R.G., and Wallace, A.R., 1994, Ages of selected intrusive rocks and associated ore deposits in the Colorado Mineral belt: U.S. Geological Survey Bulletin 2109, 31 p.

Easley, E., and Morgan, P., 2013, Fluid, gas, and isotopic variation of thermal springs in the Southern Rocky Mountains, Colorado: Geothermal Resources Council Transactions, v. 37, p. 385-392.

Gehrels, G.E., Valencia, V., Pullen, A., 2006, Detrital zircon geochronology by Laser-Ablation Multicollector ICPMS at the Arizona LaserChron Center, *in* Loszewski, T., and Huff, W., eds., Geochronology: Emerging Opportunities, Paleontology Society Short Course: Paleontology Society Papers, v. 11, 10 p.

Gehrels, G.E., Valencia, V.A., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: Geochemistry, Geophysics, Geosystems, v. 9, 13 p., Q03017, doi:10.1029/2007GC001805.

Gehrels, G., and Pecha, M., 2014, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, v. 10, no. 1, p. 49-65.

Farish, J. B., 1892, On the ore deposits of Newman Hill, near Rico, Colorado: Colorado Scientific Society Proceedings, v. 4, p.151-164.

Gonzales, D.A., and Van Schmus, W.R., 2007, Proterozoic history and crustal evolution in southwestern Colorado: Insight from U/Pb and Sm/Nd data: Precambrian Research, v. 154, p. 31–70, doi: 10.1016/j.precamres.2006.12.001.

Gonzales, D.A., 2015, New U-Pb zircon and $^{40}Ar/^{39}Ar$ age constraints on the late Mesozoic to Cenozoic plutonic rocks in the western San Juan Mountains: The Mountain Geologist, v. 52, no. 2, p. 5-14.

Gonzales, D.A., and Lake, E.T., 2016, Geochemical constrains on mantle-melt sources for Oligocene to Pleistocene mafic rocks in the Four Corners region, USA: Geosphere, v. 13, no. 1, p. 1-26.

Karlstrom, K.E., Whitmeyer, S.J., Dueker, K., Williams, M.L., Bowring, S.A., Levander, A., Humphreys, E.D., Keller, G.R., and the CD-ROM Working Group, 2005, Synthesis of results from the CD-ROM experiment: 4-D image of the lithosphere beneath the Rocky Mountains and implications for understanding the evolution of continental lithosphere, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere (Tectonics, Geochemistry, and Geophysics), Geophysical Monograph Series 154, p. 421-441.

Larsen, P.B., 1987, Stable isotope and fluid inclusion investigations of epithermal vein and porphyry molybdenum mineralization in the Rico mining district Colorado: Economic Geology, v. 89, p. 1769-1779.

Larson, P.B., Cunningham C.G., and Naeser C.W., 1994a, Large-scale alteration effects in the Rico paleothermal anomaly, southwestern Colorado, Economic Geology, v. 89, p. 1769-1779.

Larson, P.B., Cunningham C.G., and Naeser C.W., 1994b, Hydrothermal alteration and mass exchange in the hornblende latite porphyry, Rico, Colorado: Contributions to Mineralogy and Petrology, v. 116, p. 199-215.

Lipman, P.W., Steven, T.A., and Mehnert, H.H., 1970, Volcanic history of the San Juan Mountains, as indicated by potassium-argon dating: Geological Society of America Bulletin, v. 81, p. 2329-2352.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 119-153.

Ludwig, K.R., 2008, Isoplot 3.6: Berkeley Geochronology Center Special Publication 4, 77 p.

McKnight, E.T., 1974, Geology and ore deposits of the Rico district, Colorado: U.S. Geological Survey Professional Paper 723, 100 p.

Naeser, C.W., Cunningham, C.G., Marvin, R.F., and Obradovich, J.D., 1980, Pliocene intrusive rocks and mineralization near Rico, Colorado: Economic Geology, v. 75, p. 122-135.

Pratt, W.P., 1968, Summary of the geology of the Rico region, Colorado, *in* Shomaker, J. W., ed., San Juan, San Miguel, La Plata Region (New Mexico and Colorado): New Mexico Geological Society, Field Conference Guidebook 19, p. 83-87.

Pratt, W.P., McKnight, E.T., and DeHon, R.A., 1969, Geologic map of the Rico quadrangle, Dolores and Montezuma Counties, Colorado: U.S. Geological Survey Map GQ-797.

Ransome, F. L., 1901, The ore deposits of the Rico Mountains, Colorado: U.S. Geological Survey 22d Annual Report, part 2, p. 229-397.

Rickard, T. A., 1897, The Enterprise mine, Rico, Colorado: American Institute of Mining Engineers Transactions, v. 26, p. 906-980.

Thompson, R. A, Johnson, C.M., and Mehnert, H.H., 1991, Oligocene basaltic volcanism of the northern Rio Grande rift: San Luis Hills, Colorado: Journal of Geophysical Research, v. 96, p. 13,577-13,592.

Wareham, C.D., 1991, Isotopic and geochemical studies of a Pliocene porphyry-Mo system, Rico, Colorado [Ph.D. dissertation]: Aberdeen, Scotlan, Aberdeen University, 288 p.

Wareham, C.D., Rice, C.M., Boyce, A.J., and Rogers, G., 1998, S, C, Sr, and Pb sources in the Pliocene Silver Creek porphyry Mo system, Rico, Colorado: Economic Geology, v. 93, p. 32-46.

Warner, L.A., 1980, The Colorado lineament, in Kent, H.C. and Porter, K.W., eds., Colorado Geology: Rocky Mountain Association of Geologists, p. 11-21.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2017002