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Inherited zircons in post-75 Ma igneous rocks of the western San Juan Mountains: Evidence for long-term involvement of Proterozoic lithosphere in magma production

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INHERITED ZIRCONS IN POST–75 MA IGNEOUS ROCKS OF THE WESTERN SAN JUAN MOUNTAINS: EVIDENCE FOR LONG-TERM INVOLVEMENT OF PROTEROZOIC LITHOSPHERE IN MAGMA PRODUCTION

DAVID A. GONZALES

Department of Geosciences, Fort Lewis College, 1000 Rim Drive, Durango, CO 81301; gonzales_d@fortlewis.edu

Abstract—Inherited zircons in 75–4 Ma mafic to felsic igneous rocks in the western San Juan Mountains offer a glimpse into the provenance and genesis of magmas. Inherited zircon populations together with trace element and isotopic signatures lend evidence for long-term involvement of Proterozoic lithosphere with arc signatures regardless of composition, age, or tectonomagmatic regime. Inherited zircons in the 32–30 Ma San Juan Formation and Cenozoic breccia dikes-pipes compose 8% to 95% of total zircon populations and show the greatest age range (2700–63 Ma). These rocks contain high proportions of 1800–1390 Ma zircons attributed to the melting of Proterozoic basement rocks along with contamination by detrital zircons from Paleozoic to Cenozoic sedimentary rocks. Most plutonic rocks emplaced during the intervals 75–60 Ma and 32–26 Ma contain 9% to 100% inherited 1800–1390 Ma zircons, with minor Archean and post–1300 Ma contributions. This is evidence that partial melting of 1800–1390 Ma crust was a major contributor in magma production. In contrast, most 23–5 Ma felsic rocks produced during incipient rifting and injection of mantle melts into the middle-upper crust contain only 0–10% inherited zircons, possibly due to a melt source devoid of inherited populations or changing melt conditions. The data reveal the legacy of accreted Proterozoic lithosphere in the production of igneous rocks in the region over the past ~80 million years. This is an important consideration in reconstructing the magmatic history and provenance of magmas under shifting tectonic regimes.

INTRODUCTION

The western San Juan Mountains on the boundary of the Colorado Plateau and Southern Rocky Mountains are a warehouse of latest Mesozoic to Cenozoic magmatic events (Figs. 1 and 2) linked to mountain building, landscape evolution, and mineralization (e.g., Burbank and Luedke, 2008; Gonzales, 2015; Gonzales et al., 2021). An understanding of the genesis and evolution of magmas over the past 75 Ma is fundamental to reconstructing the magmatic history, but only a limited amount of data are published to address these issues, especially the provenance of magmas.

Laser-ablation U-Pb zircon analyses on post–75 Ma igneous rocks (Fig. 1) and hydrothermal breccias in the western San Juan Mountains over the past decade (Gonzales, 2015, 2017, 2019; Gonzales et al., 2021) disclose inherited zircons of various ages that were previously undocumented (noted in Gonzales, 2015). These inherited zircons were entrained at depth in 75–4 Ma magmas, then brought to higher crustal levels in the latest Mesozoic to Cenozoic.

This paper presents the ages and proportions of inherited zircons in post–75 Ma igneous rocks in southwestern Colorado (Fig. 3; Table 1; Appendix 1), which lend insight into an enduring ancestry of 1800 to 1300 Ma lithosphere in melt production regardless of the tectonic regime. These findings are an essential consideration in unraveling the magmatic-tectonic history and geochemical traits of 75–4 Ma magmatic rocks, especially those that formed after 23 Ma and are distinguished by typical arc signatures (e.g., Glazner, 2022).

GEOLOGIC SETTING

A series of rugged peaks along the boundary of the Southern Rocky Mountains and the Colorado Plateau define the western San Juan Mountains. The oldest exposed rocks are 1800–1700 Ma metamorphosed arc assemblages in the Irving Formation and Twilight Gneiss, as well as 1730–1690 Ma syn- to post-orogenic granitic to dioritic plutons (Fig. 1; Gonzales and Van Schmus, 2007; Hillenbrand et al., 2023). This arc complex is overlain by thick successions of ~1705 Ma metamorphosed marine and fluvial deposits in the Uncompahgre Formation and Vallecito Conglomerate (Gonzales and Van Schmus, 2007; Karlstrom et al., 2017; Hillenbrand et al., 2023). A composite batholith of syn- to post-deformational granite to gabbro was emplaced from 1450 to 1400 Ma (Gonzales and Van Schmus, 2007). The Proterozoic basement is mostly covered by Cambrian to Cenozoic sedimentary rocks and 32–27 Ma volcanic rocks, except in the Needle Mountains (Fig. 1) and minor exposures near Ouray and Rico.

The latest Mesozoic to Cenozoic (75–4 Ma) record in southwestern Colorado is highlighted by generations of mafic to felsic plutonic rocks (Figs. 1 and 2; Gonzales, 2015, 2017, 2019; Gonzales et al., 2021). These rocks were emplaced on the southern extent of a northeast-trending regional zone of magmatism (i.e., the Colorado Mineral Belt), with peak events at 75–65 Ma, 35–23 Ma, and 18–4 Ma (e.g., Cunningham et al., 1977, 1994; Cappa, 1998; Chapin et al., 2004; Chapin, 2012).

Laramide magmatism involved intrusion of 75–60 Ma (Gonzales, 2015, 2017) alkaline to subalkaline mafic to felsic plutons into Paleozoic to Cenozoic strata (Figs. 1 and 2)

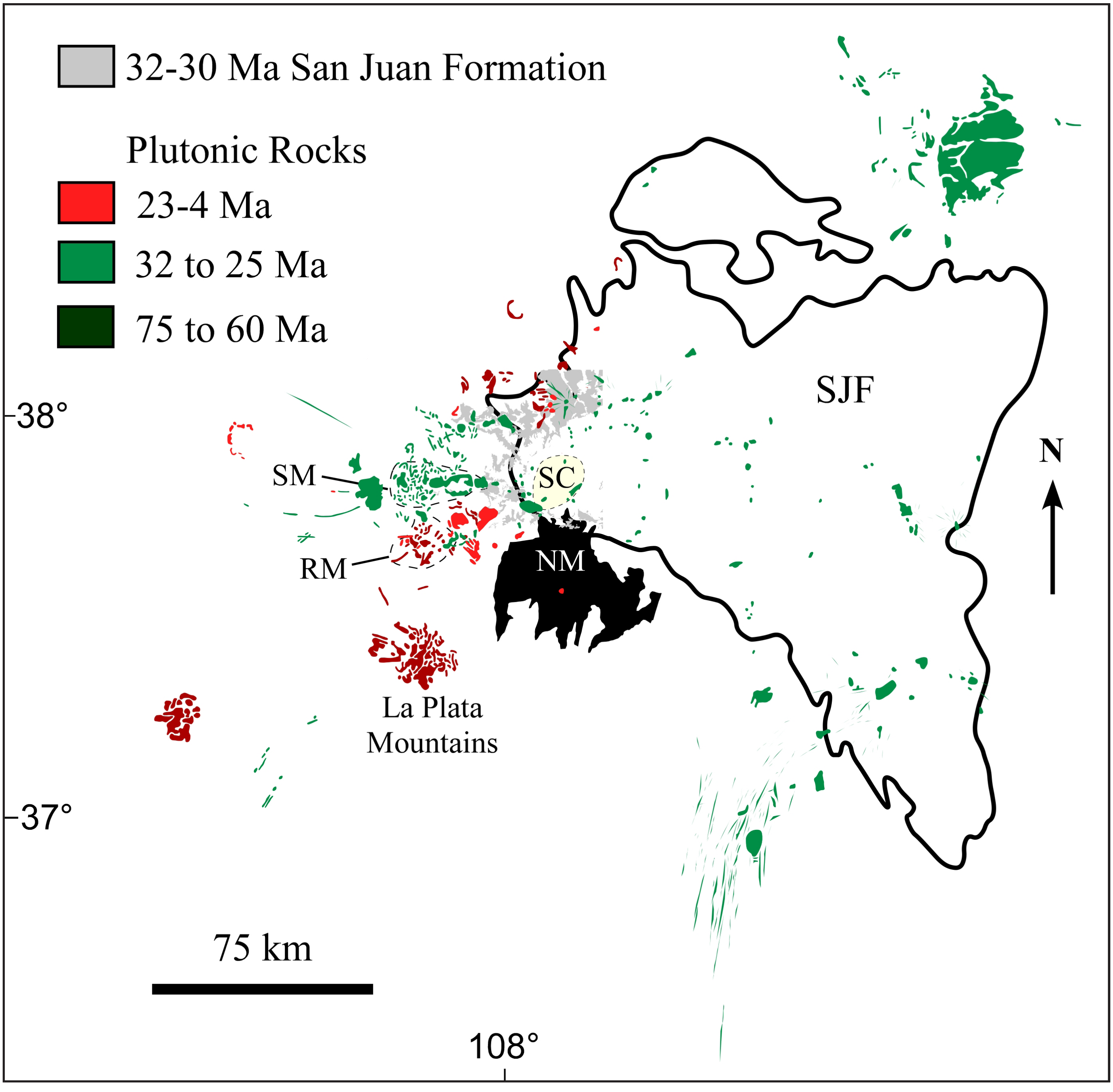
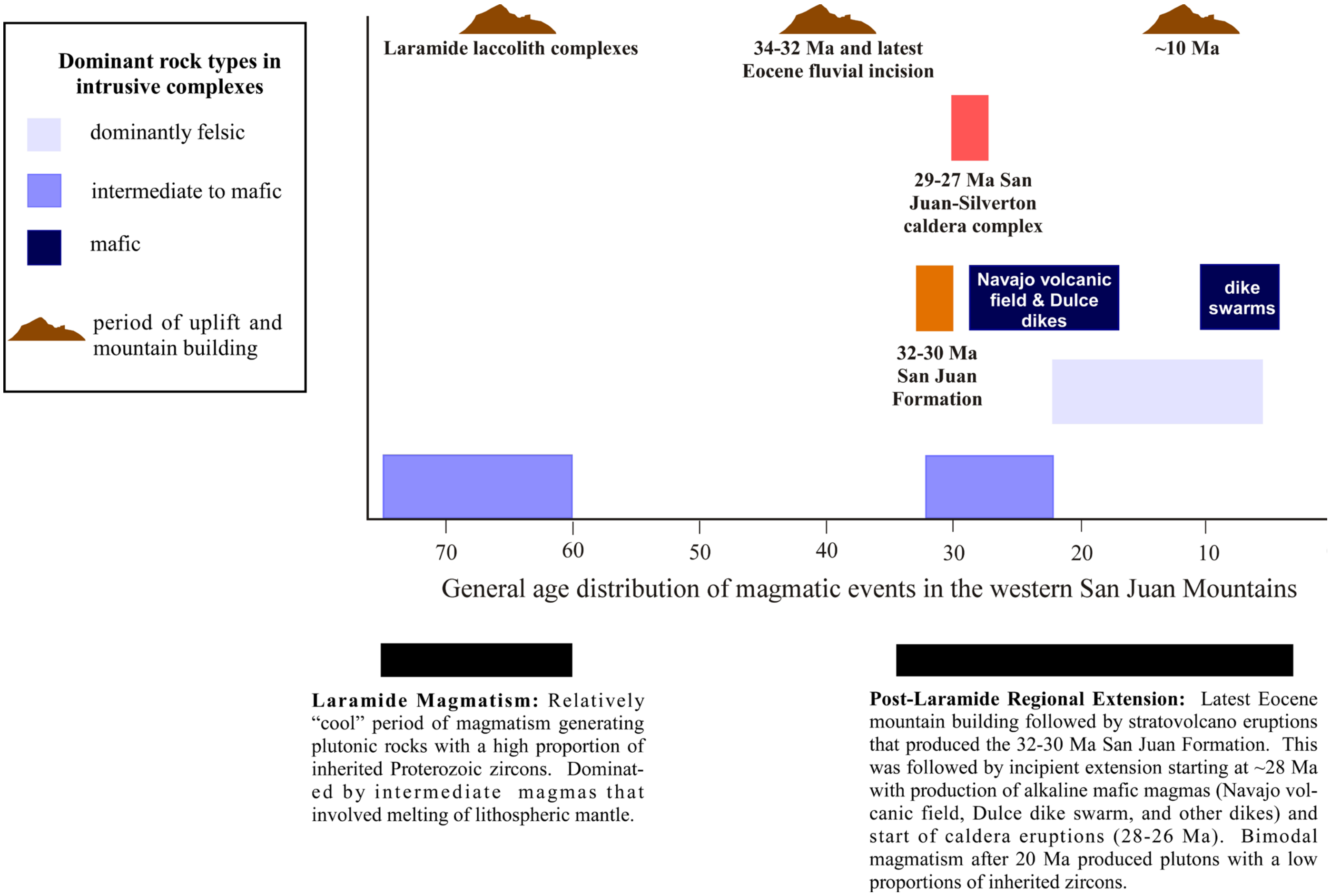


FIGURE 1. General distribution of latest Mesozoic to Cenozoic intrusive rocks (modified after Cunningham et al., 1994) and the Oligocene San Juan Formation in the western San Juan Mountains. The 28.4–27.6 Ma San Juan-Silverton caldera complex (SC; Lipman et al., 1973; Steven and Lipman, 1976; Lipman, 1989; Bove et al., 2001) is shown within the approximate the magmatic locus of the San Juan volcanic field (SJF). The Needle Mountains Proterozoic complex is indicated by NM. The approximate boundaries of the Rico Mountains (RM) and San Miguel Mountains are delineated with dashed lines.

producing domal complexes (e.g., La Plata Mountains, Rico Mountains). Emplacement of mantle magmas during the intervals of 28–18 Ma and 10–4 Ma produced alkaline mafic dike-diatreme complexes in the Navajo volcanic field and dikes across the northern San Juan Basin (Fig. 1; Roden et al., 1979; Laughlin et al., 1986; Nowell, 1993; Farmer et al., 2008; Gonzales et al., 2010; Nybo et al., 2011; Gonzales and Lake, 2017; Lipman and Zimmerer, 2019; McCormick and Gonzales, 2023). Mantle magmatism involved injection of asthenospheric melts into metasomatized lithospheric mantle and lower crust (e.g., Roden et al., 1990; Usui et al., 2002, 2003; Smith et al., 2004; Gonzales and Lake, 2017; McCormick and Gonzales, 2023). This happened in the transition from regional contraction to extension (e.g., Humphreys, 1995; Humphreys et al., 2003) with the influx of magmas along lithospheric-scale anisotropies (Warner, 1980; Karlstrom et al., 2005).

Mantle melts contributed to the production of crustal magmas and related volcanism during the period from 35–23 Ma (e.g., Lipman et al., 1973, 1978; Riciputi et al., 1995; Farmer et al., 2008; Gonzales and Lake, 2017; Lipman and Zimmerer, 2019). Eruptions of 32–30 Ma stratovolcanoes created thick successions of andesitic to dacitic lava flows and pyroclastic deposits with interbedded lahars in the San Juan Formation (Figs. 1 and 2). This volcanism closely followed latest Eocene uplift and erosion (e.g., Gonzales et al., 2021). The 28.4–27.6 Ma San Juan-Silverton caldera complex formed during the



Laramide Magmatism: Relatively "cool" period of magmatism generating plutonic rocks with a high proportion of inherited Proterozoic zircons. Dominated by intermediate magmas that involved melting of lithospheric mantle.

Post-Laramide Regional Extension: Latest Eocene mountain building followed by stratovolcano eruptions that produced the 32-30 Ma San Juan Formation. This was followed by incipient extension starting at ~28 Ma with production of alkaline mafic magmas (Navajo volcanic field, Dulce dike swarm, and other dikes) and start of caldera eruptions (28-26 Ma). Bimodal magmatism after 20 Ma produced plutons with a low proportions of inherited zircons.

FIGURE 2. A comparison of the age distribution of latest Mesozoic to Cenozoic plutonic rocks in southwestern Colorado in the context of regional tectonic-magmatic events.

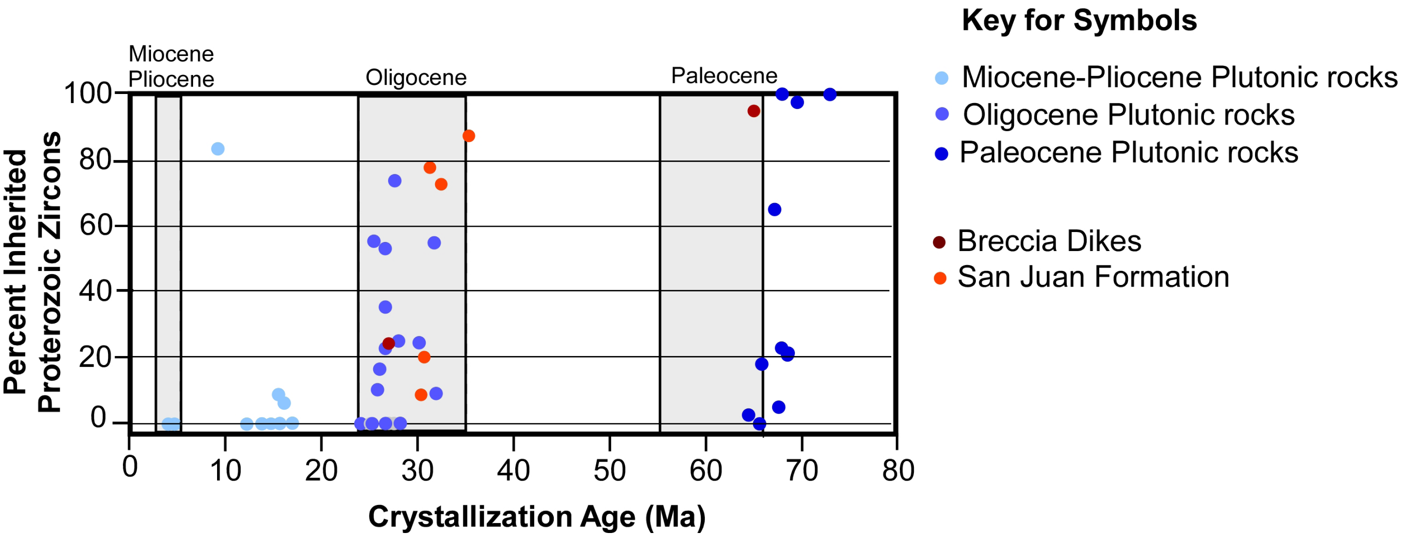


FIGURE 3. Plot of ages of latest Mesozoic to Cenozoic plutonic rocks, breccia dikes, and San Juan Formation against the proportions of inherited zircons analyzed in the samples. Note that 75–26 Ma rocks have a variable but overall high proportion of Proterozoic to Archean zircons, whereas post–20 Ma rocks and some 26–25 Ma intrusive rocks have significantly lower proportions of inherited zircons.

TABLE 1. Summary of U-Pb zircon age data for the San Juan Formation, breccia dikes, and latest Mesozoic to Cenozoic plutonic rocks of the western San Juan Mountains. Analytical data for each sample are reported in Appendix 1.

Geologic Unit, Location, Rock Type	#	Latitude	Longitude	Crystallization Age in Ma (±2σ)	Zircon Age Populations (Ma)									% Inherited Pre-541 Ma Zircons
					>2500	2500–1850	1850–1600	1600–1390	1390–1000	1000–541	541–252	252–75	<75	
San Juan Formation (36–30 Ma)														
[6]Coxcomb Peak, dacite lava flow	1	38.08004	-107.54295	30.5±0.3 (n = 28)			3						32	8.6
[1]Weehawken Creek, andesitic tuff breccia	2	38.00703	-107.73565	30.9±0.34 (n =10) 30.9±0.35 (n =12)			3	3					23	20.7
[6]Bear Creek, andesitic tuff breccia	3	38.003353	-107.65512	31.4±0.4 (n = 6)		1	2	16	2				6	77.8
[1]Silver Jack Basin, dacitic flow breccia	4	38.228733	-107.52556	32.5±0.4 (n = 9)			16	12	1				11	72.5
[6]Portland mine, andesitic tuff breccia	5	38.018918	-107.64167	35.5±5.9 (n = 3)		1	7	13					3	87.5
[1]Mears Basin, dacitic tuff breccia	6	38.018631	-107.87849	ND	4		2	20	19	14	14	4		76.6
Breccia dikes (65 and 27 Ma)														
[5]Ouray (TKic)	7	38.042852	-107.67946	65.2±1.0 (n = 10)	2	2	37	230	16	4	1	7	8	94.8
[5]Placerville (cl)	8	38.008309	-108.04539	ND			27	66	1		9			93.2
[5]Stony Mountain	9	37.98141	-107.76585	27.2±0.1 (n = 157)	1	1	10	24	31	17	18	9	185	24.4
Miocene-Pliocene intrusive rocks (23–2.58 Ma)														
[4]Priest Creek, quartz monzonite (Tcl)	10	37.66902	-108.11697	4.1±0.08 (n = 25)									29	0
[4]Calico Peak, quartz monzonite (Tca)	11	37.72443	-108.07922	4.7±0.08 (n = 31)									33	0
[1]Yankee Boy Basin, granite porphyry (rh)	12	37.98891	-107.77137	12.1±0.1 (n = 32)									34	0
[2]Chicago Basin, granite porphyry (Ti)	13	37.602500	-107.60830	ND			1	4			1			83.3
[2]Chicago Basin, granite porphyry (Ti) (2 phases)	14	37.602500	-107.60833	9.1±0.44 (n = 7) 28.2±0.47 (n = 15)									7	0

[1]Telluride, granite porphyry (rp)	15	37.939706	-107.856544	13.9±0.2 (n =31)									34	0
[2]Rolling Mountain, monzonite (Tig)	16	37.780072	-107.814300	14.6±0.2 (n = 23)									23	0
[1]Archuleta Mesa #1, granodiorite (Tis)	17a	37.009409	-107.008130	NA				1					2	
[2]Archuleta Mesa #2, granodiorite (Ti)	17b	37.009409	-107.008130	15.7±0.3 (n = 18)			1	1					20	9.1
[2]Lime Creek, granite porphyry (Ti)	18	37.728343	-107.743889	15.6±1.4 (n = 29)									29	0
[2]Engineer Mtn, granite porphyry (Ti)	19	37.700833	-107.802500	16.0±0.7										
[2]Flattop Mountain, monzonite porphyry (Trl)	20	37.751935	-107.975476	16.0±1.0 (n = 30)			2						30	6.3
[2]Barlow Creek, granite porphyry (Tbr)	21	37.719444	-107.918606	16.9±0.9 (n = 13)									13	0
[1]Disappointment Valley, granodiorite (Tg)	22	37.949436	-108.653425	16.9±4.5 (n = 1)									1	0
[1]Buckles Lake, gabbro (Ti)	23	37.136687	-106.795414	ND				1			1	1		33.3
Oligocene intrusive rocks (34–23 Ma)														
[3]Red Mountain, monzonite porphyry (ql)	24	37.913828	-107.696661	24.03±0.1 (n = 33)									35	0
[2]Jackson Mountain #1, monzonite porphyry (Ti)	25	37.338861	-106.941722	25.1±0.4 (n = 24)									24	0
[2]Jackson Mtn #2, monzonite porphyry (Ti)	26	37.357386	-106.958747	25.1±0.4 (n = 24)									30	0
[1]San Miguel Mts, quartz monzonite (Tpa)	27	37.848306	-107.994944	25.3±0.11 (n = 22)									35	0
[1]San Miguel Mts, granodiorite porphyry (Trl)	28	37.807778	-108.038889	25.5±0.29 (n = 5)	1		2	7		1	3		5	55.6
[1]San Miguel Mts, granodiorite porphyry (Tgd)	29	37.856443	-107.989307	25.3±0.14 (n = 22)				1	1				35	5.5

[1]San Miguel Mts, quartz monzonite (Tap)	30	37.849165	-108.029438	25.9±0.17 (n = 17)			1				1		17	10.5
[2]Black Face, granodiorite porphyry (Tgdp)	31	37.834444	-107.892500	26.0±0.8 (n = 25)			4	1					25	16.7
[2]Ophir #1, granodiorite porphyry (Tgg)	32	37.848639	-107.878917	26.7±1.5 (n = 11)			2	4					11	35.3
[2]Ophir #2, diorite-gabbro (Tgg)	33	37.858610	-107.882223	ND			10							100
[1]Mears Basin, graniodiorite (Ti)	34	38. 01861	107.87805	26.7±0.2 (n = 17)			3	2					17	22.7
[2]San Bernardo Mtn, granodiorite (Tgdp)	35	37.853111	-107.894167	26.7±0.6 (n = 15)			10	7					15	53.1
[2]Sultan Mountain, granodiorite porphyry (Tim)	36	37.789722	-107.672778	26.6±0.6 (n = 28)									28	0
[2]Mt. Sneffels, diorite-granodiorite (Ti)	37	38.000366	-107.792972	27.05±0.9 (n = 26)									26	0
[1]Silver Gulch, breccia dike (cl)	38	37.981294	-107.658325	27.2±3.3 (n = 5)		4	13	11					10	73.7
[1]Henderson Gulch, granite porphyry (rh)	39	37.98891	-107.77137	27.5±0.15 (n = 25)									25	0
[1]Gray Head, granodiorite (Tgd)	40	37.99076	-107.97319	27.5±0.3 (n = 21)			2	6			1	1	22	25.0
[1]Abajo Mountains, granodiorite porphyry	41	37.89594	109.51429	27.9±0.2 (n = 30)			3	7					31	24.4
[1]Silver Gulch, diorite dike (an)	42	37.983108	-107.652753	28.0±0.31 (n = 4)	1		8	1		2	2	2	5	55.0
[5]Calliope Dike, monzonite (Tiq, ql)	43	38.06387	107.65514	30.2±0.9 (n = 4)				2					20	9.0
[1]Silver Gulch, Cu-Fe breccia pipe	44	37.981569	-107.659094	31.8±0.4 (n = 1)	1	2	6	3	5	2	2		1	85.7
[2]Square Top Mountain, diorite porphyry (Ti)	45	37.255608	-106.807475	31.9±7.8 (n = 1)	2								1	67
[1]Little Cone. monzonite porphyry (Tgg)	46	37.89043	108.09771	Ar/Ar age ~27 Ma			8		2		3	2		66.7

Late Cretaceous to Paleocene intrusive rocks (75–60 Ma)														
[2]Oak Creek Canyon, diorite porphyry (gp)	47	38.021869	-107.690691	64.6±1.0 (n = 35)				1					35	2.8
[2]The Blowout, diorite porphyry (gp)	48	38.038693	-107.671057	65.9±1.2 (n = 27)			1	5					27	18.2
[1]Black Lake, altered monzonite (pa)	49	38.072479	-107.700285	65.8±0.5 (n = 8)	2						3		8	0
[2]Coal Bank Pass, granite porphyry (Ti)	50	37.688889	-107.787222	67.3±2.2 (n = 7)			**8**	**5**					7	65
[1]San Miguel Mts, monzonite porphyry (Tla)	51	37.776111	-108.072694	67.65±0.37 (n = 19)			1						19	5.0
[2]Hermosa Peak, diorite porphyry (Thl)	52	37.713323	-107.925019	68.1±0.7 (n = 27)			2	1						100
[4]Scotch Creek, diorite porphyry (Thl)	53	37.65259	-108.04023	68.1±0.69 (n = 23)			1	3				1	23	23
[4]Expectation Peak, monzonite porphyry (Tm)	54	37.69728	-108.06119	68.6±0.74 (n = 22)				4	1			1	22	22
[4]Elliott Peak, diorite porphyry (Thl)	55	37.73158	-108.05997	68.7±0.93 (n = 21)			5	6				1	20	21
[2]La Plata Mts ("The Notch"), diorite porphyry	56	37.440801	-108.007617	69.6±5.8 (n = 1)			35	5					1	97.6
[2]La Plata Mts (Helmet Peak), diorite porphyry	57	37.411293	-108.135271	ND			24							100
[2]McElmo Canyon, diorite porphyry (Tkd)	58	37.329392	-108.770594	72.9±5.4 (n = 1)			13	4		2			1	95.0
[1]Lone Cone, diorite porphyry (Ti)	59	37.885953	-108.256850	ND			3	31						100

[1]New inherited zircon ages reported in this paper
[2]Gonzales (2015)
[3]Gonzales and Larson (2017)
[4]Gonzales (2017)
[5]Gonzales (2019)
[6]Gonzales et al. (2021)
[7]Crystallization age not constrained
Zircon crystals were extracted at the University of Arizona LaserChron Center by traditional separation methods. An in-depth discussion of these methods is available at the Arizona LaserChron Center webpage.

Oligocene (35–23 Ma) magmatic "flare up" (e.g., Lipman et al., 1973; Steven and Lipman, 1976; Lipman, 1989; Bove et al., 2001; Lipman, 2007; Lipman and Bachmann, 2015; Gonzales and Lake, 2017; Gonzales et al., 2021). The calderas formed in the initial stages of incipient rifting in southwestern Colorado.

Numerous radial and concentric fractures on the margins of the San Juan-Silverton caldera complex (Fig. 1) provided avenues for emplacement of shallow intermediate to felsic plutons, as well as hydrothermal fluids related to breccia pipes and veins (e.g., Gonzales and Larson, 2017; Gonzales, 2019). The plutons are linked to a larger batholith complex at depth that is revealed by geophysical data (Drenth et al., 2012). Breccia dikes formed by release of gas-charged eruptions associated with coeval plutons (e.g., Ransome, 1901; Irving, 1905; Kelly and Silver, 1946; Gonzales, 2019) are intimately affiliated with mineral deposits in some locations.

In the western San Juan Mountains, the alliance of mafic magmas with shallow felsic plutons continued to ~4 Ma (e.g., Naeser et al., 1980; Gonzales, 2015, 2017; Zhang and Audetat, 2017). Several of the post-5 Ma plutons are associated with molybdenum mineralization near Rico (Cameron et al., 1986; Zhang and Audetat, 2017).

METHODS

Summary of Samples

Crystallization ages of post–80 Ma igneous rocks as well as the age populations and proportions of inherited zircons are presented in Table 1 and Appendix 1. These compilations include published data (Gonzales, 2015, 2017, 2019; Gonzales and Larson, 2017; Gonzales et al., 2021) and the author's previously unpublished U-Pb zircon analyses. All of the plutonic and breccia dike samples, even those reported with 100% Proterozoic zircon populations, were accurately mapped in previous studies as latest Mesozoic to Cenozoic. The data presented herein are representative of all major plutonic events, the San Juan Formation, and breccia pipes and dikes.

U-Pb Zircon Analyses

Zircon separates (Table 1) were obtained from 10–20 lbs of sample at the University of Arizona LaserChron Center by standard separation methods. Up to ~300 zircons were mounted on a 1-in.-diameter epoxy puck with fragments or loose grains of Sri Lanka, FC-1, and R33 zircon standards. The surface of the epoxy mounts was sanded down to a depth of ~20 µm, polished, imaged using a Gatan Chroma cathodoluminescence (CL) detector coupled to a Hitachi S2400 scanning electron microscope, and cleaned in 1% HNO_3 and 1% HCl prior to isotopic analyses. The CL images revealed zonation in crystals, potential inherited xenocrysts and antecrysts, and mineral inclusions.

U-Pb analyses of zircons were conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (e.g., Gehrels et al., 2006, 2008; Gehrels and Pecha, 2014). Ablation was achieved with a Photon Machines Analyte G2 excimer laser equipped with a HelEx ablation cell using a spot diameter of 20 µm at selected points. Data were used to define weighted mean crystallization ages using Isoplot (Ludwig, 2008). Inheritance in zircons was assessed in each population by comparing the ages of cores and rims of crystals.

More detailed descriptions of the methods used for previously published results are provided in Gonzales (2015, 2017, 2019). In-depth descriptions of the methods are available at the Arizona LaserChron Center website (https://sites.google.com/laserchron.org/arizonalaserchroncenter/home).

RESULTS

The age divisions for the zircon populations in Table 1 mostly follow those of Walker et al. (2018). Exceptions are the 1850–1600 Ma and 1600–1390 Ma ranges that represent the dominant ages of Proterozoic to Mesoproterozoic basement rocks in southwestern Colorado (Gonzales and Van Schmus, 2007). The <75 Ma division is used for the youngest population, which includes all of the latest Mesozoic to Cenozoic igneous rocks (Gonzales, 2015, 2017).

The different total number of zircons analyzed for a given sample (Table 1) makes it challenging for direct comparison of inherited populations. The data do reveal (Figs. 3 and 4; Table 1), however, that many 75–4 Ma plutonic and volcanic rocks contain >5% inherited Proterozoic zircons regardless of age or composition. The capture of Precambrian zircons via melting ± crustal assimilation is also noted in Paleozoic to Cenozoic igneous rocks in other settings (e.g., Ducea et al., 2004; Miller et al., 2007; Smyth et al., 2007; Bryan et al., 2008; Stern et al., 2010; Zhang et al., 2015; Zhang et al., 2016).

Inherited 2800–2500 Ma zircons are uncommon in the zircon populations that were analyzed. The 1850–1390 Ma zircon populations dominate in most samples with high proportions (24–95%) in the 32–30 Ma San Juan Formation and Cenozoic breccia dikes and pipes and the 75–26 Ma plutonic rocks (18–100%) (Figs. 3 and 4; Table 1). In contrast, the proportions of inherited Proterozoic zircons in some ~25 Ma and most–23 Ma intrusive rocks are less than 10%. Inherited zircons with ages from 1390–541 Ma and 541–75 Ma were mostly found in breccia dikes and pipes, and the San Juan Formation at Mears Basin. Twelve samples of plutonic rock also contain 1390–75 Ma inherited zircons with only two samples containing 6-7 total zircons of this heritage and the rest yielding less than 4 zircons.

DISCUSSION

Inherited Proterozoic zircons in latest Mesozoic to Cenozoic igneous rocks in the western San Juan Mountains offer a glimpse into provenance of magmas. These data (Figs. 3 and 4; Table 1; Appendix 1) along with geochemical and isotopic signatures of plutonic rocks reveal the involvement of 1850–1390 Ma metamorphic and plutonic crust with a volcanic-arc heritage (e.g., Gonzales and Lake, 2017; Lang and Gonzales, 2019) over the past 75 Ma regardless of magma composition or tectonic regime.

Provenance of Inherited Zircons

San Juan Formation and breccia dikes-pipes

Volcanic breccias of the San Juan Formation and breccia dikes and pipes are distinguished by higher proportions and greater age range of inherited Proterozoic zircons (Fig. 3; Table 1). Most of the zircons range from 1850 to 1390 Ma, akin to Proterozoic metamorphic and plutonic rocks exposed in the region (Fig. 1; Gonzales and Van Schmus, 2007; Karlstrom et al., 2017; Hillebrand et al., 2023). This vintage of zircons could be direct contributions from melting and assimilation of 1800–1390 Ma basement or from recycled Paleozoic to Mesozoic strata containing detrital Proterozoic zircons (e.g., Malone et al., 2014; Nair et al., 2018; McGuire et al., 2019). The volcanic and magmatic-hydrothermal breccias often contain pieces of Proterozoic basement and Paleozoic to Cenozoic strata, indicating a high degree of interaction of gas-charged magmas with country rocks (e.g., Gonzales, 2019). Only the dacitic lava flow from Coxcomb Peak in the San Juan Formation contains <20% inherited zircons.

Inherited zircons with ages of >2500 Ma, 1390–541 Ma, and 541–75 Ma are most abundant in the breccia dikes and pipes and the San Juan Formation at Mears Basin (Fig. 3; Table 1). The >2500 Ma and 1390–541 Ma zircons are not representative of any exposed rocks in southwestern Colorado. Archean zircons might be xenocrysts from Proterozoic basement or detrital crystals from Paleozoic to Mesozoic sedimentary rocks (e.g., Gonzales, 2019). The 1390–541 Ma and 541–75 Ma zircons likely (Gonzales, 2019) likely originated from interaction of gas-charged magmas with Paleozoic to Mesozoic strata containing detrital zircons from various sources (e.g., Grenville basement rocks, Pikes Peak Batholith; Van Schmus and Bickford, 1993; Becker et al., 2005; Moecher and Samson, 2006; Gleason et al., 2007; Evans and Soreghan, 2015; Guitreau et al., 2016; Alsalem et al., 2017). Alternatively, some of the 1390–1000 Ma zircons could represent discordant ages of Mesoproterozoic to Paleoproterozoic zircons that underwent Pb loss.

Laramide zircons (Table 1) in some breccia dikes were entrained from 75 to 60 Ma igneous rocks (Gonzales, 2019). The 36–25 Ma zircons in the breccia dike at Stony Mountain were sourced from Oligocene intrusive and volcanic country rocks, predominantly from the ~27 Ma Stony Mountain stock (Gonzales, 2019).

Latest Cretaceous to Cenozoic plutonic rocks

The ages of inherited Proterozoic zircons in most (24 of 28) of the 75–60 Ma (18–100%) and 32–26 Ma intrusive rocks (9–86%) fall within the 1800–1390 Ma range (Figs. 1, 3 and 4; Table 1; Appendix 1) of metamorphic and plutonic rocks in the Needle Mountains complex (Gonzales and Van Schmus, 2007; Karlstrom et al., 2017; Hillebrand et al., 2023). The high proportions of Proterozoic xenoliths in some 75–26 Ma plutonic rocks (i.e., La Plata Mountains and Rico Mountains) offer supporting evidence for partial melting of Proterozoic basement rocks ± crustal contamination. The data cannot, however, resolve the relative proportions of 1850–1390 Ma zircons captured by direct melting versus assimilation. The minor amounts of post–1300 Ma zircons were likely from assimilation of Paleozoic to Mesozoic strata (Fig. 4; Table 1), though evidence (e.g., xenoliths) for this interpretation is lacking. Inherited Laramide zircons were also found in some post–32 Ma plutonic rocks (i.e., Calliope dike; Figs. 3 and 4; Table 1).

Most post–16 Ma plutonic rocks did not yield any inherited zircons of any age; the most notable exception is the ~9 Ma granite stock in Chicago Basin, which was emplaced within ~1400 Ma granite (Fig. 1). Several 26–25 Ma samples also did not yield inherited zircons (Figs. 3 and 4; Table 1).

The Role of Proterozoic Lithosphere in Magma Genesis

Many researchers attribute the latest Mesozoic to Cenozoic magmatic record in the region to shallow subduction of the Farallon plate during the Laramide orogeny, followed by slab rollback during regional extension (e.g., Coney and Reynolds, 1977; Humphreys, 1995; Humphreys et al., 2003; Chapin et al., 2004; Chapin, 2012; Ricketts et al., 2016). In a review of latest Mesozoic to Cenozoic magmatic patterns across the western United States, Glazner (2022) stated, "Indeed, it is time to renew investigations into just how magmas are generated in arc settings and how arc-like magmas are generated in non-arc settings, such as the magmatism that followed in the wake of the Mendocino triple junction" (p. 105). The magmatic record in the western San Juan Mountains involving Proterozoic rocks with typical arc geochemical and isotopic signatures shed light on this conversation, especially for post–23 Ma plutonic rocks that formed during regional extension.

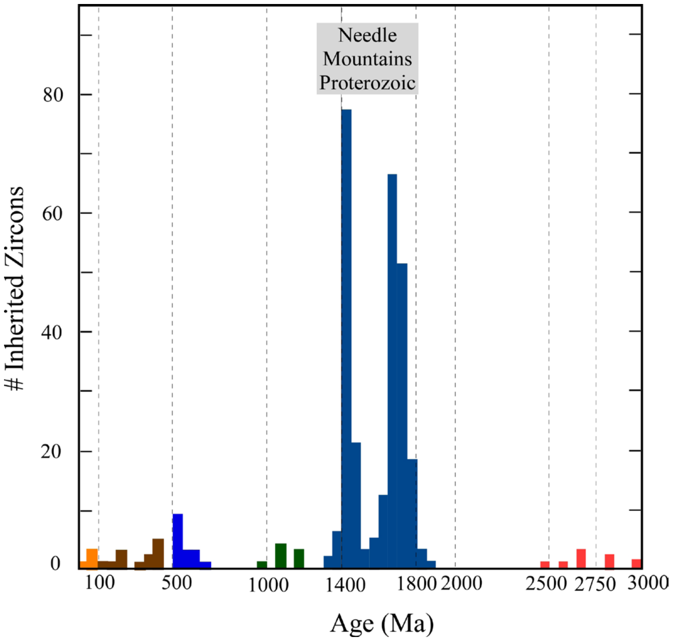


FIGURE 4. Histogram of inherited zircons in 75–4 Ma plutonic rocks in the western San Juan Mountains. Note that the majority of zircons fall within the 1800–1390 Ma ages of metamorphic and plutonic rock in the Needle Mountains complex.

Most of the 75–4 Ma intermediate to felsic plutonic rocks in southwestern Colorado share trace element and rare earth element signatures indicative of typical magmatic arcs such as enrichment in large-ion lithophile elements (e.g., Rb, Ba, Pb) and depletion in high-field-strength elements (e.g., Ta, Nb; Fig. 5; Wegert and Parker, 2011; Gonzales, 2015). Similar arc affinities are documented in 28–18 Ma and 10–4 Ma alkaline mafic rocks formed by melting of lithospheric mantle and lower crust (e.g., Gonzales et al., 2010; Gonzales and Lake, 2017; Lang and Gonzales, 2019; Lipman and Zimmerer, 2019; McCormick and Gonzales, 2023).

Bulk-rock Sr and Nd isotopic data for 28–4 Ma alkaline mafic rocks (e.g., Gonzales et al., 2010; Gonzales and Lake, 2017; Lipman and Zimmerer, 2019; McCormick and Gonzales, 2023), and 68–4 Ma intermediate to felsic rocks near Rico (e.g., Gonzales and Lake, 2017; Lang and Gonzales, 2019) lend evidence for partial melting of 1.8–1.3 Ga lithosphere (mantle or crust) during magma production.

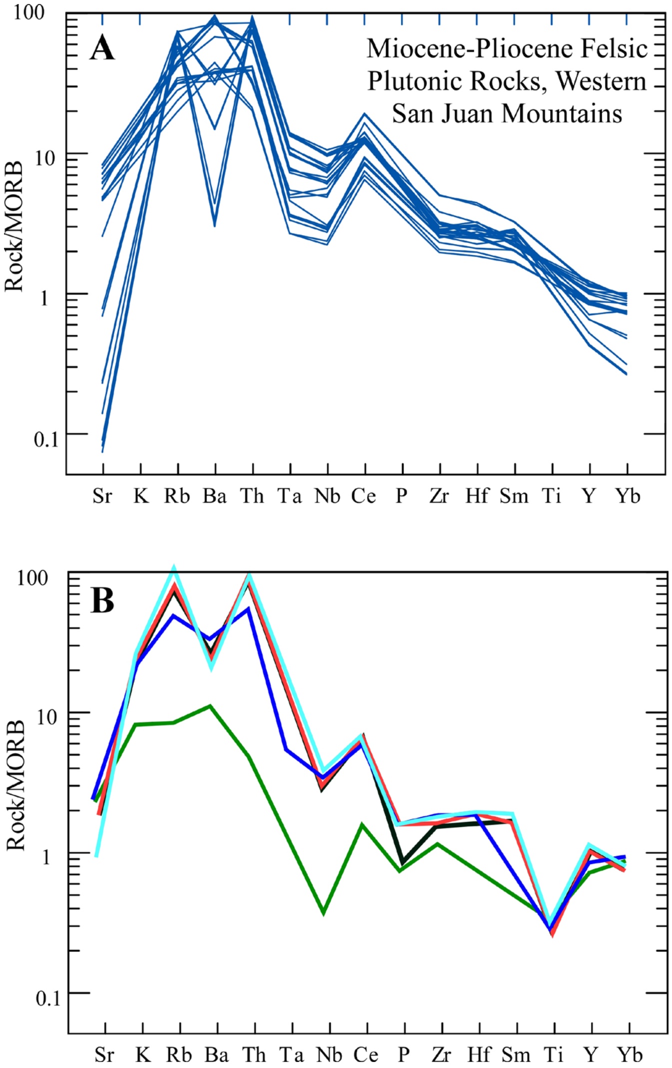


FIGURE 5. (A) MORB-normalized element abundances for intermediate to felsic post–25 Ma plutonic rocks from the western San Juan Mountains. These patterns are consistent with rocks formed in magmatic arc systems (e.g., Winter, 2010) despite forming after the Laramide; they are similar to patterns found in 28–4 Ma mafic rocks in the region (Gonzales and Lake, 2017). (B) Average MORB-normalized patterns for granitic rocks in magmatic arc systems from Winter (2010). Green lines are M type (n = 17), light blue lines are S type (n = 704), dark blue lines are I and M type (n = 250), and red lines are I type (n = 1074). Normalizing element concentrations are from Pearce (1983).

The geochemical and isotopic signatures along with the zircon inheritance of 74–4 Ma plutonic rocks (Figs. 3 and 4; Table 1) are evidence for the involvement of 1850–1390 Ma arc lithosphere in magma production. This affiliation is apparent over the entire 75 Ma magmatic record and regardless of rock composition (Fig. 2).

The geochemical signatures of 75–60 Ma plutons are consistent with melting of a subducted slab during the Laramide, but zircon populations and isotopic data show that melting of Proterozoic arc basement was involved. The arc signatures of Laramide plutonic rocks could come from either source, but the isotopic data support a Proterozoic provenance.

Gonzales and Lake (2017) argued that from 30 to 4 Ma, asthenospheric melts underplated and invaded lithospheric mantle with Proterozoic heritage, generating alkaline mafic rocks. Ascent of these magmas into higher crustal levels was involved in the production of small-volume intermediate to felsic magmas (Zhang and Audetat, 2017; Lang and Gonzales, 2019). The more “evolved” Proterozoic upper crustal source for the post–16 Ma magmas is supported by isotopic data (Nd, Sr, Hf) from ~4 Ma intrusive rocks in the Rico Mountains (Lang and Gonzales, 2019).

Changes in Zircon Inheritance

The data (Table 1; Appendix 1) support the hypothesis that inherited Proterozoic zircons in 74–4 Ma plutonic rocks mostly originated by partial melting ± wall-rock assimilation of 1800–1390 Ma basement rocks. There is no supporting evidence that the reduction in inherited zircons in plutonic rocks starting ~26 Ma is related to distinct melt sources (e.g., Lang and Gonzales, 2019). The lower preservation of inheritance is more likely related to changes in the conditions of magmatism, but only limited data are available to evaluate this idea. The mechanisms involved are therefore uncertain, but possibilities are: (1) partial melting of a crustal source depleted in inherited zircons due to multiple episodes of prior melting, and (2) a shift in the thermal regime of melting that reset the isotopic systems in older zircons.

The post-23 Ma intrusive rocks with low zircon inheritance (Table 1) are porphyritic-aphanitic granite and monzonite (e.g., Gonzales, 2015) whose genesis involved melting of Proterozoic upper crust (Lang and Gonzales, 2019). Repeated melting of a given source over time would cause depletion in certain constituents (e.g., Si, Sr, K, Rb, and Ba) which is not consistent with the geochemical signatures of these rocks.

Drenth et al. (2012) proposed that the San Juan-Silverton caldera complex is underlain by a subvolcanic Oligocene batholith complex whose western margins extend into the Rico-Telluride area. Partial melting of this plutonic complex might be a potential source of felsic melts with lower inherited zircons, but evidence to support this premise is lacking.

The other possible hypothesis is that the thermal regime during magma production after 23 Ma was elevated and reset the U-Pb systems in inherited zircons. This would require temperatures in excess of 900°C (e.g., Lee et al., 1997; Cherniak and Watson, 2000; Hermann et al., 2021) to invoke solid-state diffusional Pb loss with a partial to complete reset. Melt temperatures lower than 900°C would favor preservation of inherited Proterozoic zircons. Many factors influence Pb diffusion in zircons (e.g., crystal size, radiation damage, alteration by fluids, rapid emplacement; Watson, 1996; Cherniak and Watson, 2000; Miller et al., 2003; Bea et al., 2007; Miller et al., 2003). Lee et al. (1997) concluded that ages of inherited zircons can reset during partial melting, but the required temperature (~900°C) is higher than those for the production of most felsic magmas (i.e., <750–850°C).

Starting at ~28 Ma in the western San Juan Mountains, swarms of mafic dikes invaded the upper crust along zones of incipient extension (e.g., Gonzales, 2015; Gonzales and Lake, 2017; McCormick and Gonzales, 2023). This elevated the thermal gradients in the lithosphere and produced small volumes of felsic magmas from 23 to 4 Ma (e.g., Rico to Ouray; Fig. 1; Gonzales, 2015; Zhang and Audetat, 2017; Lang and Gonzales, 2019). Zhang and Audetat (2017) provided evidence that granitic rocks in the ~4 Ma Silver Creek pluton near Rico crystallized at 780–800°C and 2–5 kbars and that magma production involved mafic melts. The temperature to generate the magma could realistically have exceeded 900°C. A shift in the thermal conditions of the lithosphere from the Laramide into the middle to late Cenozoic during regional extension is therefore a viable option for lower proportions of inherited zircons in rocks that formed after 23 Ma.

Xenoliths in Oligocene volcanic rocks on the Colorado Plateau record metasomatism and recrystallization of lithospheric mantle ± slab during subduction of the Farallon plate from 80 to 30 Ma (e.g., Broadhurst, 1986; Wendlandt et al., 1993, 1996; Smith 1979, 1995; Roden et al., 1990; Usui et al., 2002, 2003; Smith et al., 2004). Dehydration and release of fluids from the subducted slab "cooled" the lithosphere (e.g., Usui et al., 2002, 2003; Smith et al., 2004), favoring melting at <800°C with greater preservation of inherited Proterozoic zircons in 75 to 25 Ma plutonic rocks.

In deciphering the magmatic history of a region, it is critical to understand the melt provenance and its influence on the genesis and traits of different generations of rocks. Insight into the post–75 Ma records in the Southern Rocky Mountains must consider the contributions of Proterozoic lithosphere in magma production during shifting tectonic regimes.

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