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GEOCHEMISTRY, ORIGIN, AND U-PB ZIRCON AGES OF THE SIERRA CUCHILLO LACCOLITH, SIERRA COUNTY, NEW MEXICO

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Abstract—Eocene-Oligocene volcanism in New Mexico, Colorado, Arizona, and west Texas is commonly thought of as regional ash flow tuffs associated with Rio Grande rift calderas, although intermediate-composition volcanism also built stratovolcanos. The Sierra Cuchillo laccolith in Sierra County, New Mexico, represents a third, smaller type of Eocene-Oligocene magmatism. The laccolith is composed of a zoned porphyritic granodiorite to quartz monzonite that has undergone metasomatic alteration replacing hornblende, biotite and plagioclase with epidote and chlorite, creating three distinct mineralogical zones. U-Pb zircon dating of the laccolith yielded crystallization ages of 39.28 $\pm$ 0.78 and 38.0 $\pm$ 1.9 Ma (2σ error) as determined by LA-ICPMS. Other intrusions in the area that were dated include the Vindicator sill at 37.8 $\pm$ 0.34 Ma and the Willow Springs dome yielding an age of 28.0 $\pm$ 0.31 Ma. Two volcanic sequences present in the area, the dacite-rhyolite sequence and the latite-andesite sequence, yielded ages of 36.9 $\pm$ 0.5 Ma and 36.3 $\pm$ 0.4 Ma respectively. Trace element and geochronologic data are consistent with correlation of the Sierra Cuchillo laccolith to the Vindicator sill (38 Ma) 0.3 km to the north and to the latite-andesite volcanic sequence (36.3 Ma) of Jahns et al. (2006) located to both the east and west of the Sierra Cuchillo on the down-dropped hanging walls of the horst-bounding normal faults. The Willow Springs dome (28.0 Ma) and the dacite-rhyolite volcanic sequence (36.9 Ma) of Jahns et al., (2006), both have much lower Eu concentrations relative to other rare earth elements (measured as the Eu/Eu* ratio of 0.10 and 0.54, respectively), in contrast to the Sierra Cuchillo laccolith, which has much higher Eu/Eu* ratios, ranging from 0.97 to 1.04. The dacite-rhyolite sequence, while only slightly younger than the laccolith, is not directly related to the laccolith; the Willow Springs dome clearly represents a younger phase of magmatism. The zones of alteration present within the Sierra Cuchillo laccolith are interpreted as the result of circulation of internal magmatic fluids during cooling. This is evident by the lack of a hydrothermal contact aureole around the laccolith and by the increased alteration of plagioclase and hornblende in the interior zones. Whole-rock geochemical data suggest that the soluble major and trace elements are randomly distributed throughout the laccolith, indicating pervasive mobilization by late-stage magmatic fluids. Nb concentrations in the Sierra Cuchillo laccolith (5-9 ppm) are similar to concentrations of basaltic magmas from a subduction-modified lithospheric mantle source (ca. 8 ppm) but lower than basalts from ocean island basalt-modified lithospheric mantle (ca. 20 ppm) and asthenospheric mantle (ca. 32 ppm) sources as defined by McMillan (1998). Assimilation of continental crust is indicated by zircon cores with Precambrian ages (1.4 – 1.6 Ga). $^{87}Sr/^{86}Sr$ initial ratios of the Sierra Cuchillo laccolith (0.706461 - 0.706804) also reflect assimilation of continental crust. The parental mafic magma must have had low Nb and low $^{87}Sr/^{86}Sr$ ratio, and is interpreted as being derived from subduction-modified lithospheric mantle.

INTRODUCTION

Silicic volcanism and caldera formation are processes associated with the early development of the Rio Grande rift (Chapin et al., 2004). However, there are relatively few shallow silicic intrusions that are unrelated to caldera formation associated with the Rio Grande rift (Chapin et al., 2004). These intrusions represent a different style of magmatism from the large calderas and are the topic of this paper. Examples include: the Taylor Creek rhyolite (Wittke et al., 1996), the Cedar Hills vent zone (Seager and Clemons, 1975), the Ortiz porphyry belt (Maynard, 2005), and the Sierra Cuchillo laccolith (Fig. 1).

Timing of magmatism associated with the rift varies depending on location (McMillan et al., 2000; Parker and McMillan, 2007). The earliest eruptions are at ~45 Ma (K-Ar; Henry et al., 1989) around Big Bend National Park and with the most recent eruptions as late as 3 ka (^{3}He and ^{14}C ages) in the Zuni-Bandera volcanic field (Laughlin et al., 1994; McMillan, 1998; Parker and McMillan , 2007; Wolff et al., 1996; Baldridge, 2004). Sources of these magmas have been hypothesized by McMillan (1998) and McMillan et al. (2000) to have either come from depleted asthenospheric mantle, subduction-modified lithospheric mantle, or mantle plume-modified lithospheric mantle.

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The Sierra Cuchillo laccolith has a reported K-Ar age from hornblende of 48.8 $\pm$ 2.6 Ma (Dictator mine, 0.4 mi north of Cuchillo Mountain; Chapin et al., 1978), although the nearby Reilly Peak rhyolite was dated by K-Ar at 36.0 $\pm$ 1.4 Ma (Davis, 1986). These dates suggest that the Sierra Cuchillo laccolith intruded at a critical time in the transition from Laramide subduction to Rio Grande rift extension. The laccolith does not show evidence of Laramide shortening, but is bounded by normal faults from Rio Grande rifting (McMillan, 1979). Metasomatism has altered the laccolith, making it difficult to correlate with local volcanic sequences and other intrusive bodies within the area. This paper presents new U-Pb zircon ages for the laccolith and surrounding rocks, proposes correlations between the laccolith and nearby volcanic rocks, and presents models for the origin of the magma and the alteration of the pluton.

BACKGROUND GEOLOGY

Sierra Cuchillo Laccolith

The Sierra Cuchillo laccolith consists of porphyritic quartz monzonite to granodiorite that have been metasomatically altered. The intrusion lies to the northwest of Truth or Consequences, New Mexico near the town of Winston, NM, within the

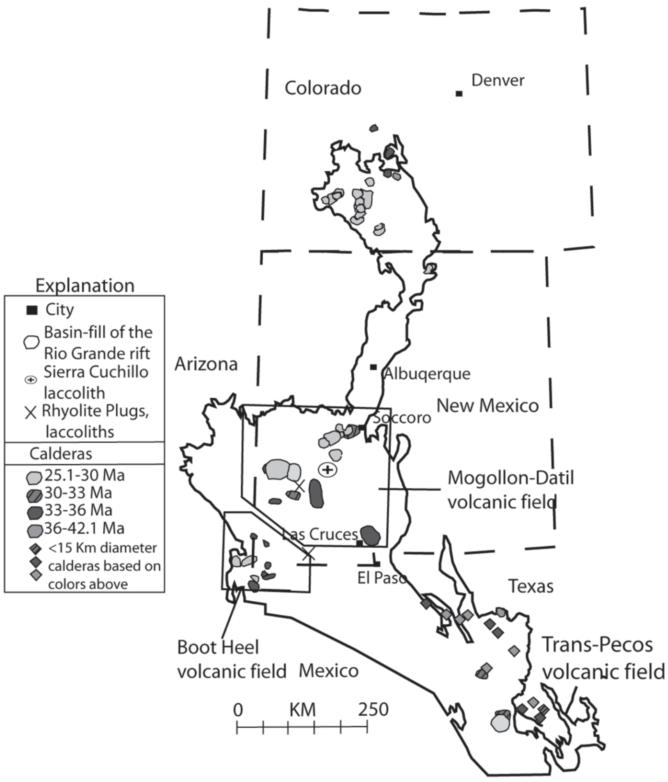

FIGURE 1. Generalized map showing calderas, flow-banded rhyolite flows and intrusions, and shallow laccolith intrusions within the Rio Grande rift. Modified from Chapin et al. (2004).

horst and graben structures of the Rio Grande Rift (Jahns, 1955; Chapin et al., 1978; Jahns et al., 1978). Uplift by normal faults to the east and west provide a cross sectional view of the intrusion (Fig. 2; Jahns, 1955; Jahns et al., 1978; 2006; McMillan, 1979; McMillan, 1986). The laccolith consists of three distinct mineralogic zones as seen by field observations based on the presence and alteration of hornblende, biotite, and plagioclase phenocrysts (McMillan, 1986). Petrographically, McMillan (1979) described the modal percentages of phenocrysts as 66% feldspar (combination of plagioclase and alkali feldspars), 23% mafic minerals, and 10% quartz in the exterior zone; 59% feldspar, 27% mafic minerals and 12% quartz in the intermediate zone; and 51% feldspar, 35% mafic minerals, and 12% quartz in the interior zone. Mafic minerals include hornblende, epidote, chlorite, hematite, and Fe-Ti oxides. Accessory minerals apatite and zircon are also present (McMillan, 1979). Intermediate composition plagioclase (andesine-oligoclase) is observed only in the exterior zone (McMillan, 1979); elsewhere the plagioclase has been replaced with albite. McMillan (1979) described replacement that is consistent with metasomatism by exsolved volatiles during cooling. Alteration is increasingly more intense towards the pluton interior; igneous minerals that are present in the exterior zones can be seen only as remnant pseudomorphs in the interior zone. Also seen in the transition zone are miarolitic cavities produced by trapped late stage fluids (McMillan, 1986). McMillan (1979) described three alteration processes that affected the laccolith: 1) albitization of plagioclase, in which An_{40-50} at the pluton margin is replaced by An_{10} in the core; 2) alteration of hornblende to epidote and chlorite, increasing towards the interior zone (epidote in the exterior zone is focused along fractures and in vugs); and 3) alteration of plagioclase to epidote. Epidotization of plagioclase is ubiquitous throughout the laccolith and could suggest a process unrelated to the first two alteration processes (McMillan, 1986).

Local Volcanic Rocks

Local volcanic rocks may be the eruptive equivalents of the Sierra Cuchillo laccolith. Two sequences were described by Jahns (1943; 1955), Maxwell and Heyl (1976) and Jahns et al. (1978; 2006). The latite-andesite sequence is composed of four volcanic units (Jahns, 1955; Jahns et al., 1978). The basal member of the sequence is a porphyritic latite-trachyandesite lava. It is the only member of the sequence with extensive outcrops in the study area (Jahns et al., 1978; 2006). Phenocrysts of plagioclase and hornblende show alteration to epidote-albite and epidote-chlorite, respectively. Pyroxene and rare biotite have also been observed as phenocrysts (Jahns et al., 2006). Quartz and K-feldspar are abundant in the groundmass only (Jahns et al., 1978). The overlying thick beds of the tuff and the tuff breccia members are poorly exposed (Jahns et al., 2006). These units commonly contain clasts of the basal member as well as Permian sandstones and conglomerates of the Abo and Yeso Formations (Jahns et al., 2006). The fine-grained groundmass is generally altered pyroclastic material. The uppermost member of the sequence is a water-lain tuff (Jahns et al., 1978). It contains fragments of the lower members as well as what has been interpreted as ash fall material (Jahns et al., 2006). This unit forms very few outcrops.

The dacite-rhyolite sequence consists of six members that outcrop extensively in the southern part of study area (Jahns et al., 2006). The basal member is a densely-welded tuff breccia with small geodes near the top (Jahns et al. 1978; 2006). Devitrified glass and pumice are present within the trachyandesite, andesite, and trachyandesitic tuff. Plagioclase and quartz phenocrysts are rare (Jahns, 1955; Jahns et al., 1978, 2006). The tan, red, white and variegated members are vitric-crystal tuffs containing devitrified glass; pumice is locally welded (Jahns, 1955; Jahns et al., 1978). These members form few outcrops compared to the basal member and the overlying Lavender member. Each contains broken crystals of plagioclase, quartz, and biotite, and clasts of dacite and trachyandesite (Jahns, 1955; Jahns et al., 2006). The lavender member is the uppermost and most abundant member of the sequence. It is a vitric-crystal tuff and tuff breccia that is medium- to very thick-bedded and is locally welded, densely at the base of the member (Jahns et al., 2006). Sanidine and quartz are abundant as phenocrysts and in the groundmass. Phenocrysts of plagioclase, devitrified glass and pumice fragments are also common (Jahns et al., 2006).

Satellite Intrusions

Numerous small satellite intrusions are located near the Sierra Cuchillo laccolith (Jahns et al., 2006). Previous workers postulated that these intrusions are related to the laccolith (Jahns,

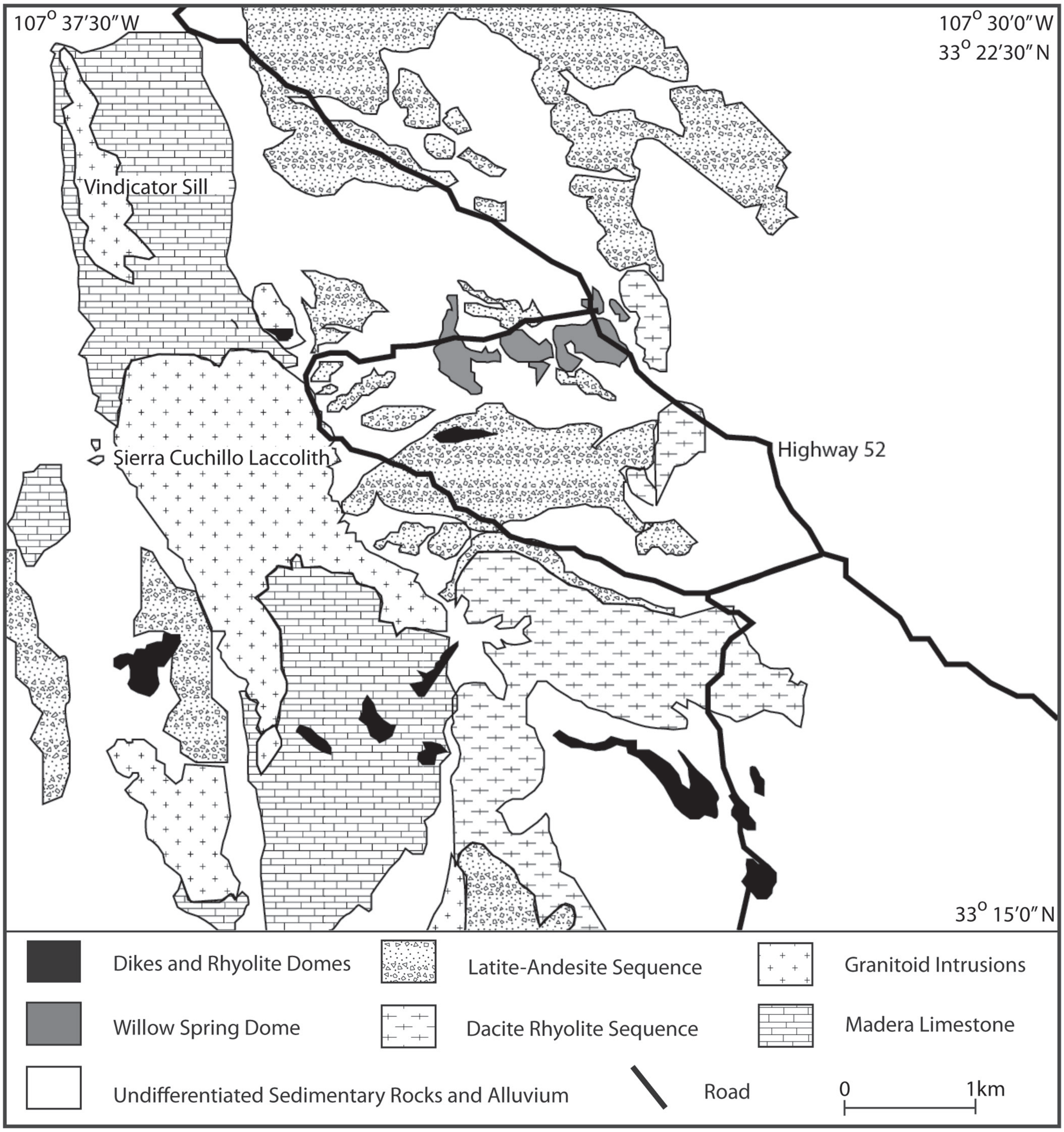

FIGURE 2. Geologic map of Chise quadrangle with sample locations and cross section lines. Modified from Jahns et al. (2006).

1955; Jahns et al., 1978; 2006; McMillan, 1979). Two of these intrusions, the Vindicator sill and the Willow Springs dome, were analyzed in this study to test the idea that they are part of a larger system that includes the Sierra Cuchillo laccolith. Little work has been done on these two intrusions since they have been interpreted to be part of the Sierra Cuchillo laccolith (Smyth, 1921; Harley, 1934; Jahns, 1943, 1955).

METHODS

Whole rock geochemistry and isotope analyses were performed at New Mexico State University. Major and trace element analysis was performed by wavelength dispersive Rigaku ZSX-100e XRF. Reference materials AGV-2 and STM-1 were analyzed multiple times to determine the precision and accuracy of major and trace element analyses. Nd and Sr isotopic analyses were acquired on a VG Sector 54 and analyzed by five Faraday collectors in dynamic mode. The $^{86}Sr/^{88}Sr$ ratio was analyzed at 3.0 V aiming intensity and normalized to 0.1194 using NBS 987 Standard (0.71029 8 $\pm$10) to ensure the precision of the analysis. Methods for sample preparation can be found in Ramos and Reid (2005). Trace elements, including the rare earth elements, were analyzed by a HP (now Agilent) 4500+ ICP-MS at Washington State University for eleven samples. Methods for trace element analysis can be found in Jarvis (1988). U-Pb zircon analysis was performed at the University of Arizona LaserChron Center using a MC-ICP-MS (GVI Isoprobe) coupled to a 193 nm Excimer laser ablation system. Beam diameter during analysis was 35 microns with an ablation depth of 15 microns. Between 25 and 50 zircons cores and rims were analyzed per sample. Methods for U-Pb zircon analysis can be found in Gehrels et al. (2008).

FIELD OBSERVATIONS AND PETROGRAPHY

Sierra Cuchillo Laccolith

The largest and most extensively outcropping zone of the Sierra Cuchillo laccolith is the exterior zone, where the intrusion has large hornblende and plagioclase phenocrysts with small phenocrysts of biotite, quartz, and alkali feldspar (sample locations and general descriptions are presented in Table 1). The groundmass consists of quartz and alkali feldspar. Zircon, apatite, titanite, and opaque minerals are present as accessory minerals. This zone contains the least alteration of hornblende and plagioclase to epidote. The outer edge of the zone is defined by a sharp contact with the country rock, with a chilled margin 1-5 m thick. The chilled margin is characterized by a fine-grained groundmass containing unaltered biotite, hornblende and plagioclase phenocrysts.

The next zone inwards is the transition zone, defined by large plagioclase phenocrysts with pseudomorphs of epidote after hornblende and biotite. The groundmass consists of alkali feldspar and quartz with a greater abundance of accessory minerals such as zircon, titanite, and apatite. Opaque minerals are the same as in the exterior zone. Thickness ranges from 5 to 25 m.

The interior zone contains the most highly altered phenocrysts. This zone is consistently ~10 m across. Weathering in the zone makes identification in the field difficult. Hornblende phenocrysts are pseudomorphed by groups of small epidote crystals; plagioclase phenocrysts have been replaced by Na-rich plagioclase (McMillan, 1979). The groundmass consists of quartz and alkali feldspars. The abundance of accessory minerals is similar to the transition zone.

Satellite Intrusions

The Vindicator sill lies directly north of Sierra Cuchillo. It is composed of a metasomatically altered porphyritic granodiorite to quartz monzonite, and intrudes both the Madera Limestone and the Abo Formation. Compositionally, it is very similar to the exte-

TABLE 1. Sample locations in UTM and sample description

Body	Zone	Sample	Easting	Northing	Description
Sierra Cuchillo	Exterior Zone	2408A	260000	369154	Quartz Monzonite
		2508A	260150	369120	Quartz Monzonite
		04B	259904	368977	Quartz Monzonite
	Transition Zone	07A	260028	3691135	Quartz Monzonite
		07F	259912	369042	Quartz Monzonite
		09E	260154	3690918	Quartz Monzonite
		10D	259421	3691104	Quartz Monzonite
	Interior Zone	10F	259311	3691056	Quartz Monzonite
		07E	259983	3690704	Quartz Monzonite
		07B	259918	3691105	Quartz Monzonite
		10B	259613	3691373	Quartz Monzonite
		10C	259551	3691247	Quartz Monzonite
		07D	260018	3690917	Quartz Monzonite
Rhyolite Dikes and Plugs		10A	259901	3692018	Rhyolite Plug
		SILL 1	259151	3690698	Apalite
Willow Springs Dome (WSD)		27A	252514	3692090	High Silica Rhyolite
Vindicator Sill		15A	257832	3694426	Quartz Monzonite
		17A	258049	3693499	Quartz Monzonite
Latite Andesite Sequence		29A	259835	3694709	Andesite Pyroclastic Flow
		28B	263756	3691120	Andesite Pyroclastic Flow
		L1C1	262478	3692288	Igneous Clast in Lahar Deposit
Dacite-Rhyolite Sequence (DRS)		28A	264202	3691206	RhyolitePyroclastic Flow

rior zone of the Sierra Cuchillo laccolith, containing phenocrysts of plagioclase, hornblende, and K-feldspar, mafic enclaves, and megacrysts. Metasomatism of the feldspars is limited to alteration from plagioclase to epidote; chloritization is only locally seen along joints and faults.

The Willow Springs dome lies approximately 2.4 km to the east of the Sierra Cuchillo (Fig. 2), had been dated by fission track at 27.8 $\pm$ 1.0 Ma (Heyl at el. 1983). It is only locally exposed in drainages off of State Highway 52. The dome is porphyritic with large phenocrysts of quartz in a groundmass of quartz and K-feldspar with little to no plagioclase. Hornblende, epidote, chlorite, and mafic enclaves are also absent. Poor exposure limits detailed analysis of the structure. Mapping suggests the east-west diameter to be about 2.2 km and 1.3 km in diameter from north to south. The dome shows no signs of flow banding or other flow structures suggesting that it may be either an intrusive dome or an upheaved plug as defined by Williams and McBirney (1979) though the intruded material is covered and any flexure of the country rock cannot be determined.

GEOCHRONOLOGY

^{238}U-^{206}Pb zircon dating was performed on samples from the Sierra Cuchillo laccolith, the Vindicator sill, the Willow Springs dome, the dacite-rhyolite sequence, and the latite-andesite sequence (Fig. 3; Appendix 1). These data demonstrate that the Sierra Cuchillo laccolith, surrounding intrusions and the local volcanic products are significantly younger than previously reported (Jahns et al., 1978). The Sierra Cuchillo laccolith yielded two ages. Thirty zircons from sample 04A yielded an average age of 39.28 $\pm$ 0.78 Ma with a MSWD of 8.3. In the second sample (22508A), 33 zircons were analyzed, but only four contained rims wide enough for LA-ICP-MS analysis. The rims of these zircons yielded an age of 38 $\pm$ 1.9 Ma with an MSWD of 3.6. Both samples contain two populations of zircons. One population contains cores (with or without rims) yielding ages of 1.455 to 1.7 Ga $\pm$ 15 Ma and rims (if present) of the ages presented above. The second population contains zircons with cores. These ages are slightly older than the age of the Vindicator sill, which yielded a crystallization age of 37.8 $\pm$ 0.34 Ma with a MSWD of 1.5 from 37 (20 rims) zircon analyses. The Vindicator sill also contains two populations of zircons similar to the Sierra Cuchillo laccolith with cores yielding ages from 1.455 to 1.7 Ga and the rims yielding the ages above. The latite- andesite sequence yielded a crystallization age of 36.27 $\pm$ 0.36 Ma with a MSWD of 1.7 from 29 zircons, and the dacite-rhyolite sequence yielded an age of 36.88 $\pm$ 0.51 Ma with an MSWD of 5.0 from 27 zircon rims. The dacite-rhyolite sequence contains cores within the zircons similar in age to the Sierra Cuchillo laccolith and the Vindicator sill ranging in age from 1.4-1.5 Ga. The Willow Springs dome yielded an age of 27.95 $\pm$0.31 Ma with a MSWD of 3.9 from 28 zircons. This age is similar to the age determined by Heyl et al. (1983) of 29.2 $\pm$ 1.1 Ma by fission tracks in zircons. The latite-andesite sequence and the Willow Springs dome both contained only one population of zircons with ages presented above. All errors are presented at 2σ standard deviation.

GEOCHEMISTRY

Whole rock major and trace element compositions were analyzed for 26 samples: 15 from Sierra Cuchillo and 11 from the satellite intrusions, volcanic material and localized sills (Fig. 4; Table 2). The Sierra Cuchillo laccolith shows very little geochemical variation (SiO_2 = 65-66 wt.%). CaO (2.8-5.4 wt%) and MgO (1.2-3.0 wt%) show the most variation in the major elements; variations in major element composition are not related to position in the laccolith. Mobile trace elements such as Sr (525-888 ppm), Cs (1.-7. ppm) and F (472-775 ppm) show large variation while less mobile trace elements such as Nb (6.3-6.7 ppm), and Zr (143-156 ppm) show very little variation (Fig. 5). F concentrations are much higher in the interior zone than in the transition or exterior zones. $^{143}Nd/^{144}Nd_i$ isotopes range from 0.512141 to 0.512335 (ε_{Nd}= -6.9 to -7.5) and $^{87}Sr/^{86}Sr_i$ ratios from 0.7064 to 0.7068 (Table 2; Fig. 6). Changes in composition do not appear to be spatially related.

The Vindicator sill ranges from 61-62 wt% SiO_2 and has a very narrow range of all major elements (Fig. 4). Nb (10 ppm), Sr (552-563 ppm), Rb (70-103 ppm) and Y (15.9-19 ppm) and F (531-558 ppm) show very little variation from the north to the south side of the sill in the two samples collected (Fig. 5). $^{143}Nd/^{144}Nd_i$ isotopes were measured at 0.512214 (ε_{Nd} = -7.3) and $^{87}Sr/^{86}Sr_i$ ratios at 0.7081 for one sample (Table 3; Fig. 6).

One sample of the Willow Springs dome was analyzed; it is geochemically distinct from the laccolith and the Vindicator sill (Figs. 4, 5). SiO_2 is high at 81.2 wt%. MgO (0.22 wt %), FeO* (total iron as FeO, 0.58 wt %), Na_2O (0.48 wt%), and CaO (0.15 wt%) are all below 1 wt% and K_2O was measured at 5.8 wt% (Fig. 4). Concentrations of Rb (280 ppm) Nb (49 ppm), and Y (85.3 ppm) are higher than the Sierra Cuchillo laccolith, while all other trace elements are lower, especially Sr (Fig. 5). $^{87}Sr/^{86}Sr_i$ ratio was measured at 0.7153 for one sample (Table 3; Fig. 6).

The volcanic rocks from the latite-andesite sequence and dacite-rhyolite sequence show more variation than the intrusive bodies (Fig. 4). These range in SiO_2 from 61-69 wt% and all other major elements show variation. The latite-andesite sequence ranges in TiO_2 from 0.6-1.0 wt%, FeO* from 4.2-6.6 wt%, MgO from 1.9-2.4 wt%, Na_2O from 3.9-4.5 wt% and P_2O_5 from 0.2-0.4 wt%. Rb and Sr show very large ranges (Sr: 79-1042 ppm; Rb: 65-300 ppm; Fig. 5). $^{87}Sr/^{86}Sr$ was measured at 0.7065 for one sample from the latite-andesite Sequence (Table 3; Fig. 6).

DISCUSSION

Alteration During Late-Stage Crystallization or Cooling as the Origin of Zones

Geochemically there is little variation between the three zones of the Sierra Cuchillo laccolith, except for mobile elements expected to be transported in hydrothermal fluids (Ca, Mg, Sr, F; Figs. 4, 5). This is in contrast to work suggesting that plutonic bodies with zones of differing mineralogies are pieced together over time (Morgan et al., 1998; Glazner et al., 2004). The zircon

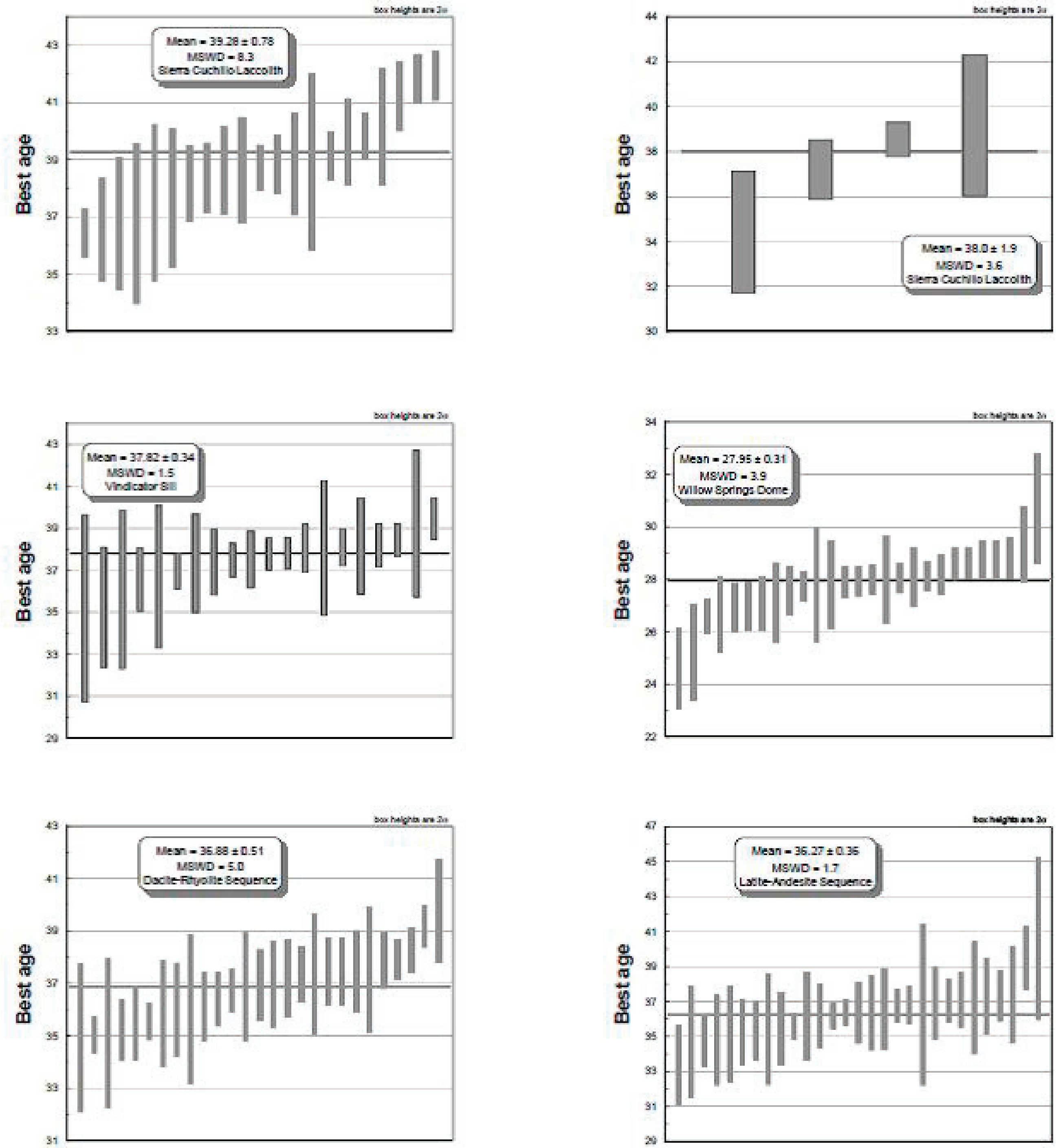

FIGURE 3. U-Pb zircon ages and 2σ errors for igneous rocks in Sierra Cuchillo.

age from the exterior zone (39.3 ± 0.78 Ma) is indistinguishable from the zircon age of the interior zone (38.0 ± 1.9 Ma). This suggests that the zones are caused by the alteration of plagioclase, biotite and hornblende during the late stages of crystallization or during cooling (Boles, 1982; Lee and Parsons, 1997; Ibrahim et al., 2000; Sirbescu and Nabelek, 2003 Perez and Boles, 2005). Albitization of plagioclase or alkali feldspars are normally associated with low-temperature, post-crystallization fluids (Lee and Parsons, 1997), reflecting secondary alteration of the body after crystallization. The porphyritic texture in the interior and transition zones and the presence of miarolitic cavities along the transition/ interior zone boundary (McMillan, 1979) are consistent with models for pegmatite creation (London, 2005). The higher degree of alteration of minerals in the interior zone compared to the exterior zone indicates that the altering fluid was internal. As crystallization of plagioclase, hornblende and quartz continued, the melt cooled, and remaining vapors and fluids would have started to react with the crystallized minerals replacing the higher temperature more unstable minerals (Ca-rich plagioclase and hornblende) with epidote, chlorite and a more Na-rich pla-

TABLE 2. Major and trace element analyses of Sierra Cuchillo laccolith and related igneous rocks.

	Sierra Cuchillo																				
	Exterior Zone		Transition Zone						Interior Zone					Rhyolite Dikes		WSD[1]	Vindicator		Latite Andesite			DRS[2]
	2408A	2508A	04B	07A	07F	09E	10D	10F	07E	07B	10B	10C	07D	10A	SILL 1	27A	15A	17A	29A	28B	L1C1	28A
SiO_2	64.30	65.21	63.92	63.01	62.53	62.74	63.37	64.27	65.72	62.44	63.53	65.48	63.91	84.08	56.97	79.78	61.59	61.81	63.45	61.13	56.72	69.21
TiO_2	0.57	0.57	0.54	0.54	0.61	0.55	0.54	0.60	0.53	0.53	0.58	0.57	0.57	0.10	0.87	0.14	0.61	0.53	0.57	0.95	0.81	0.42
Al_2O_3	15.96	16.00	16.17	16.10	15.49	15.37	15.73	15.71	15.47	15.72	15.74	16.10	15.88	7.78	17.62	11.11	16.99	16.19	15.74	16.84	16.73	14.38
FeO*	3.66	4.08	3.76	3.61	4.10	3.95	3.96	3.92	3.71	3.95	4.08	4.05	3.78	0.59	7.16	0.70	4.98	4.45	4.23	6.58	6.54	2.40
MnO	0.06	0.06	0.06	0.06	0.07	0.08	0.07	0.07	0.08	0.08	0.13	0.07	0.07	0.00	0.09	0.02	0.09	0.07	0.06	0.05	0.10	0.02
MgO	2.23	2.21	1.93	1.79	2.55	2.08	2.15	2.61	1.98	1.17	2.32	2.51	2.87	0.01	2.31	0.21	2.22	2.04	1.90	2.40	2.00	0.56
CaO	3.67	3.69	4.19	2.90	3.00	4.46	4.21	3.21	4.58	5.09	2.79	3.24	2.70	0.22	5.89	0.15	3.64	4.81	4.67	4.96	6.72	0.45
Na_2O	4.66	4.69	4.35	5.02	4.23	4.36	4.22	4.24	3.61	3.03	4.32	5.05	4.21	0.76	5.69	0.47	4.47	4.48	3.93	4.51	5.72	1.49
K_2O	2.97	2.96	2.86	2.99	3.44	3.11	2.90	3.41	3.09	3.32	3.01	3.01	3.68	5.76	2.47	5.67	3.06	2.04	3.15	3.33	2.18	7.15
P_2O_5	0.22	0.22	0.21	0.22	0.26	0.21	0.21	0.26	0.20	0.20	0.21	0.22	0.21	0.05	0.40	0.02	0.29	0.27	0.22	0.41	0.37	0.09
LOI	2.04	2.02	1.96	1.93	1.61	1.71	3.59	3.10	2.76	2.09	2.43	1.62	3.38	1.25	1.70	1.47	2.43	2.52	2.56	1.34	2.96	3.58
Total	100.34	101.70	99.94	98.18	97.87	98.62	100.96	101.41	101.73	97.63	99.13	101.90	101.27	100.60	101.18	99.74	100.36	99.22	100.49	102.50	100.85	99.76
La		28		32	29				27	25			29			40	33		26	50		67
Ce		54		55	55				51	55			54			102	65		52	98		138
Pr		6.48		7.03	6.57				6.11	5.88			6.75			10.53	7.70		6.18	11.87		16.27
Nd		25		27	25				23	22			26			36	29		24	45		59
Sm		4.69		5.04	4.68				4.24	4.09			4.76			9.27	5.32		4.56	7.97		11.33
Eu		1.34		1.50	1.34				1.26	1.16			1.38			0.32	1.65		1.34	2.20		1.84
Gd		3.76		4.14	3.60				3.31	3.31			3.77			9.80	4.19		3.69	5.59		9.71
Tb		0.54		0.62	0.52				0.48	0.46			0.53			2.24	0.62		0.54	0.78		1.66
Dy		3.04		3.50	2.96				2.68	2.75			3.02			16.26	3.55		3.20	4.19		10.31
Ho		0.61		0.70	0.57				0.54	0.54			0.59			3.62	0.69		0.62	0.79		2.14
Er		1.56		1.82	1.53				1.42	1.46			1.57			10.99	1.80		1.69	2.02		6.05
Tm		0.24		0.26	0.22				0.21	0.22			0.23			1.73	0.27		0.24	0.28		0.93
Yb		1.48		1.57	1.41				1.30	1.39			1.44			11.19	1.64		1.54	1.71		5.84
Lu		0.23		0.25	0.22				0.21	0.22			0.23			1.68	0.26		0.24	0.27		0.91
Ba		1300		1394	1344				1237	1461			1463			428	1018		1456	1535		1297
Nb		6.73		6.32	6.47				6.26	6.50			6.62			41	9		7	11		20
Y		15		21	14				15	13			16			98	18		16	21		57
Hf		4.27		3.89	4.09				3.86	3.98			3.99			7.30	4.66		4.02	5.97		10.61
Rb		64		80	71				117	127			125			292	105		63	69		321
Cs		1.32		1.15	1.72				7.38	1.94			3.08			7.14	1.23		2.25	2.80		7.70
Sr		950		788	997				593	788			558			40	590		1113	1182		107
Zr		156		147	150				143	148			151			163	178		152	242		370
F	734	484	580	553	493	672	647	775	736	611	713	472	781	413	884	698	558	531	420	695	390	1006

FeO* is total iron as FeO.

[1]WSD = Willow Springs Dacite

[2]DRS = Dacite-Rhyolite Series

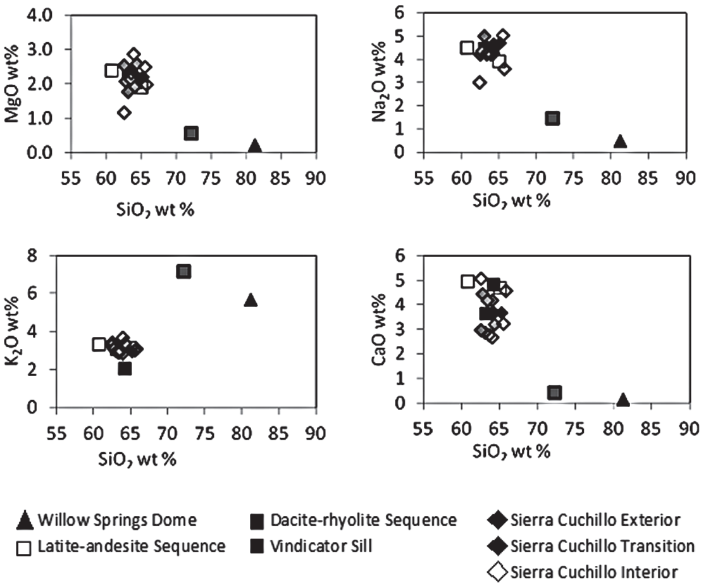

FIGURE 4. Major element variation diagrams. Fields are shown weight percent element versus weight percent silica. K_2O, CaO, Na_2O and MgO show variation within the Sierra Cuchillo laccolith. More variation is seen within the volcanic sequences. The Willow Springs dome plots with much higher silica than the other bodies.

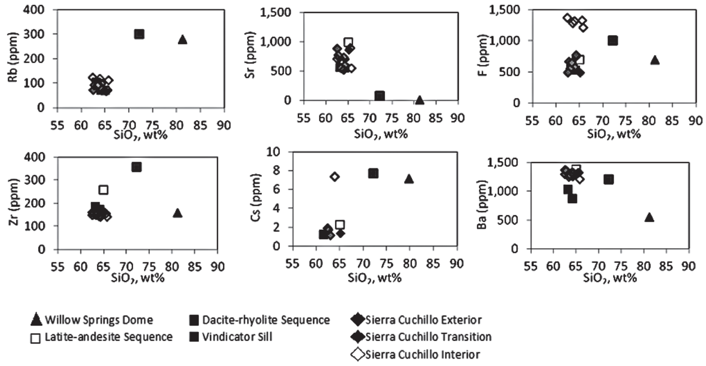

FIGURE 5. Trace element variation diagrams. Sierra Cuchillo interior samples contain higher fluorine compared to the transition and exterior zone. One interior sample contains much higher Cs than other Sierra Cuchillo samples. All other trace elements from the Vindicator sill and the Sierra Cuchillo laccolith show little variation between bodies and zones. The Willow Springs dome and the dacite-rhyolite sequence are distinct in all trace elements. Symbols are the same as in Figure 4.

gioclase (McMillan, 1979). When the concentrations of the trace elements in the interior, transition, and exterior zones are normalized to the composition of the least altered sample (as determined by having the lowest LOI), the rare earth elements and high field strength elements La through Zr show little variation, with ratios near 1, indicating that they were largely immobile during alteration (Fig. 7). In contrast, the mobile elements U, Rb, Cs and Sr, have large variations compared to the least altered sample, especially in the interior zone. This is consistent with petrographic evidence for more extensive alteration in the interior zone, and suggests that the altering fluid was generated by the pluton itself. If the fluid were derived from a source exterior to the pluton, it is likely that the exterior zone would be the most highly altered part of the pluton.

Chronology and Geochemical/Stratigraphic Relationships

U-Pb zircon age determinations suggest that the Sierra Cuchillo laccolith has a complex plumbing system that is linked to other bodies in the study area. The laccolith, the Vindicator sill and the latite-andesite sequence were all erupted or intruded from a common reservoir during approximately two million years. The laccolith and Vindicator sill have similar, but not overlapping, zircon crystallization ages (39.3 $\pm$ 0.78 Ma and 37.8 $\pm$ 0.34 Ma). Both samples from the Sierra Cuchillo laccolith and the sample from the Vindicator sill contain zircons with similar core ages of 1.4-1.6 Ga. The mineralogy of the sill is very similar, showing alteration of the plagioclase and hornblende to epidote and a more sodic plagioclase (McMillan, 1979; Jahns et al., 2006). The alteration is less extensive in the sill, suggesting that it may correlate with the exterior zone of the Sierra Cuchillo laccolith.

High ratios of Sr/Y and Eu/Eu* values near one suggest that the parental magma of both the Sierra Cuchillo laccolith and the Vindicator sill is a partial melt of plagioclase-free peridotite (Fig. 8) similar to arc front volcanism seen in the Central Andean Volcanic Zone (Michelfelder et al., 2011; Feeley, 1993). Subduction-related fluids from Laramide arc related material that crystallized in the subcontinental lithosphere from 80-50 Ma could have caused the arc-like trace element patterns observed (Fig. 9; Feeley, 1993; Feeley and Hacker, 1995; Feeley and Sharp, 1996). Further, the low La_N/Yb_N ratios suggest the mantle source was not garnet-bearing, i.e., was fairly shallow, and low Nb and Zr concentrations indicate that the source had low concentrations

TABLE 3. Isotopic analyses of Sierra Cuchillo laccolith and related igneous rocks.

Body	Zone (Sample)	$^{87}Sr/^{86}Sr$ (M)	$^{87}Sr/^{86}Sr$ (I)	$^{143}Nd/^{144}Nd$	ε^{Nd}
Sierra Cuchillo	Exterior (2408A)	0.706565	0.706461	0.512235	-7.5
	Transition (10D)	0.707067	0.706804		
	Interior (10C)	0.706700	0.706568	0.512231	-6.9
Willow Springs Dome	(27A)	0.715326	0.706924		
Vindicator Sill	(15A)	0.708457	0.708182	0.512241	-7.3
Latite-Andesite Sequence	(29A)	0.706597	0.706513		

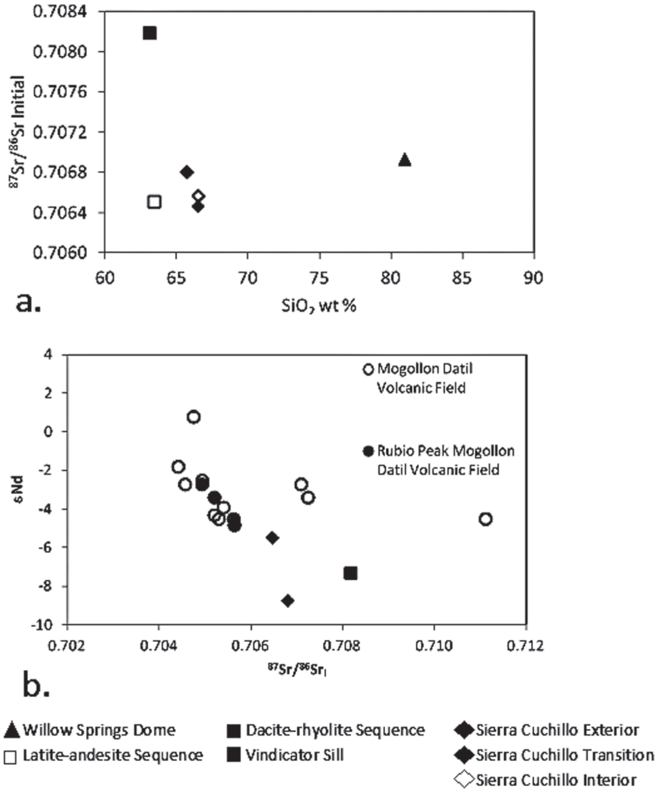

FIGURE 6. a. $^{87}Sr/^{86}Sr$ Initial ratios versus SiO_2. Little variation in $^{87}Sr/^{86}Sr$ Initial ratios is seen between the exterior and interior zones. The transition zone varies contains a higher initial ratio. The Willow Springs dome and the Vindicator sill have much higher initial ratios than the laccolith. Suggesting other processes was involved during emplacement. b. ε_{Nd} values for Sierra Cuchillo laccolith, the Vindicator Sill and the Willow Springs dome compared to other volcanic products near the study area. The Sierra Cuchillo laccolith and the Vindicator Sill are much more crustal than other volcanic products from the Mogollon-Datil Volcanic field. Mogollon-Datil Volcanic Field data from Davis and Hawkesworth (1994a) and McMillan et al (2000).

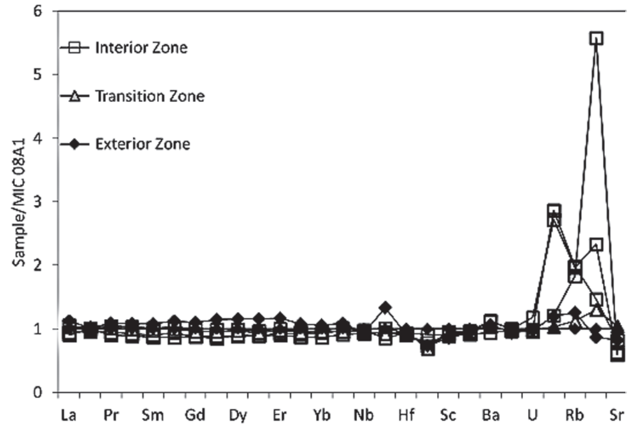

FIGURE 7. Spider diagram plotting samples from zones within the Sierra Cuchillo laccolith over the least altered sample in thin section (2408A). Diagram shows LIL elements Ba, Th, U, and Pb enriched in the transition and interior zones compared to the exterior zone. HFSE and REE elements show little variation across the laccolith. Data obtained by ICP-MS.

of high field strength elements typical of an arc source (Fig. 8; Feeley, 1993). These same relationships are seen in volcanic products throughout the Mogollon-Datil volcanic field for material erupted from 36 to 23 Ma (Duffield and Dalrymple, 1990; Davis and Hawkesworth, 1994a; 1994b; Chapin et al., 2004).

Isotopically, both the Sierra Cuchillo laccolith and the Vindicator sill have radiogenic signatures suggesting that their parental magmas assimilated continental crust (Fig. 6). Core zircon ages of 1.6 - 1.4 Ga inherited from Precambrian crust of Mazatzal-age (Karlstrom et al., 2004). The Vindicator sill has a higher $^{87}Sr/^{86}Sr$ ratio than the laccolith (Fig. 6a). Because of the geochemical, geochronological, and mineralogical similarities between the two intrusions, the high initial $^{87}Sr/^{86}Sr$ ratio of the Vindicator sill is interpreted to result from water-rock interaction between the sill and its Permian Madera Limestone host rock.

U-Pb zircons ages of the latite-andesite sequence suggest that the sequence may be part of the Sierra Cuchillo laccolith system, in contrast to the original interpretation of the latite-andesite sequence as being older than the Sierra Cuchillo laccolith (49 Ma; Jahns et al., 1978). U-Pb zircon dating of the sequence as part of this study yields an age of 36.3 Ma $\pm$ 0.36 Ma. Geochemically, this sequence is similar to the Sierra Cuchillo laccolith, and it should be considered as being derived from a common source. The volcanic samples have slightly higher Sr, P and REE concentrations and slightly lower SiO_2 concentrations; all other elements fall within the range of laccolith analyses. Plagioclase and hornblende are the dominant phenocrysts in both the latite-andesite sequence and the laccolith. These similarities in geochemistry and mineralogy suggest that the volcanic sequence may have erupted from the Sierra Cuchillo laccolith. However, the laccolith has fairly homogeneous geochemistry and mineralogy, suggesting that it was a single magmatic intrusion; it is also fairly small at its current erosional level to have produced a large packet of eruptive equivalents. The slightly younger age of the latite-andesite sequence also suggests that it was erupted after the crystallization of the Sierra Cuchillo laccolith and the Vindicator sill. Thus, it is possible that the latite-andesite sequence erupted from a nearby, now deeply eroded, volcano of similar composition and possibly related to the same plumbing system.

The dacite-rhyolite sequence, lacking plagioclase and hornblende, is mineralogically distinct from the Sierra Cuchillo system. The sample from the dacite-rhyolite sequence does contain zircon cores with ages of 1.4-1.6 Ga, indicating a similar source as the Sierra Cuchillo laccolith. Additionally, the rims of the zircons have an age of 36.9 $\pm$ 0.5 Ma and fall within the error of the Sierra Cuchillo laccolith age determinations. However, the dacite-rhyolite sequence is geochemically distinct from the laccolith (Figs. 4, 5 and 8). These volcanic products plot in the intraplate field as defined by Pearce et al. (1984), similar to the Willow Springs dome. Ba/Nb_N ratio (Fig. 8) suggests that it does contain an arc derived signature, but this is most likely inherited as the result of melting a Precambrian arc source (Menzies et al.

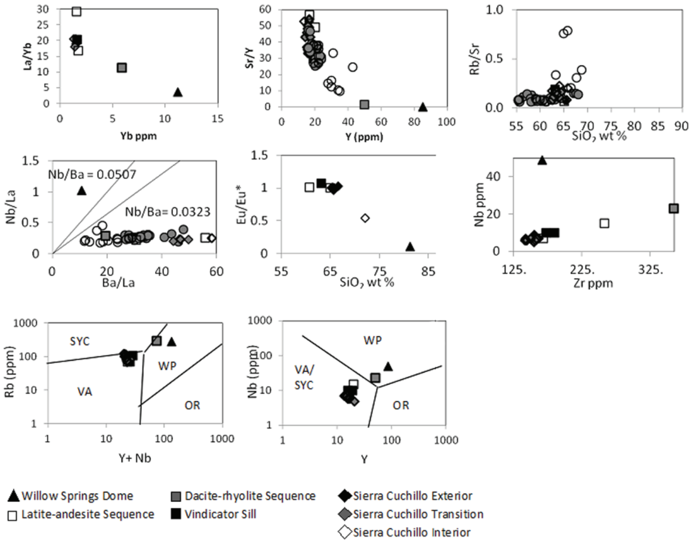

FIGURE 8. Trace Element Ratio diagrams. Mogollon-Datil Volcanic Field data from Davis and Hawkesworth (1994a) and McMillan et al. (2000). Nb/Ba = 0.0507 and Nb/Ba = 0.0323 are two ratios commonly used to distinguish between arc-related rocks (low Nb/Ba) and rift-related rocks (high Nb/Ba; Menzies et al., 1991). Fields defined by Pearce et al. (1983), VA is volcanic arc, SYC is syn-collision, WP is within plate, and OR is ocean ridge.

1991; Karlstrom et al., 2004). This sequence is interpreted to be part of a separate volcanic system within the area.

There is no correlation between the Sierra Cuchillo laccolith and the Willow Springs dome, which are geochronologically, mineralogically, and geochemically distinct. High Nb/Ba_N ratios (0.096) in the dome (Fig. 8) suggest that the dome contains a rift related source (Menzies et al., 1991). This is in contrast to the Sierra Cuchillo laccolith and Vindicator sill (0.004-0.008) which both contain ratios below 0.0323 (Fig. 8), indicating an arc-like source (Menzies et al., 1991). Lower ratios of Sr/Y, Eu/Eu* and La/Yb for the Willow Springs dome suggest a plagioclase-bearing source (Fig. 8 & 9). The high $^{87}Sr/^{86}Sr$ isotopic ratio suggests that old crystalline basement is a major source for the Willow Springs dome.

Tectonics

The Sierra Cuchillo laccolith is not an ideal intrusion for determining tectonic environment during emplacement. Source magmas assimilated crust contaminants or melted continental crust giving the magma a crustal trace element signature rather than a mantle signature. The alteration within the laccolith has distorted the soluble geochemical signature of the environment. The insoluble elements seem to have not been affected by the alteration and will be used to attempt to place the intrusion into a tectonic regime.

McMillan et al. (2000) suggested three periods of magmatism in southern New Mexico: 1) Laramide subduction- related magmatism; 2) arc-like neutral stress magmatism; 3) Rio Grande rift- related magmatism. Normal faults to the east and west of the Sierra Cuchillo laccolith cut the intrusion. This relationship indicates that the laccolith must have been emplaced prior to extension in the area. Mack (2004) and McMillan et al. (2000) suggest that block faulting in the southern Rio Grande rift began as early as the late Eocene (~36 Ma) and was complemented by silicic caldera formation and lithosphere-derived basaltic andesite and basalts. This suggests that the Sierra Cuchillo laccolith may have been emplaced in the early extensional history of the rift or arc-like neutral stress magmatism.

The rims and cores in the zircons from the Sierra Cuchillo laccolith provide evidence for a crustal source or assimilated component for the magma. The cores represent xenocrysts of the melted crust dating from 1.6-1.4 Ga. The age of these cores place the source as Mazatzal Province related basement (Karlstrom et al., 2004). The Precambrian cores also explain the $^{87}Sr/^{86}Sr$ ratios above 0.706.

McMillan (1998) suggests three sources for mafic magmas beneath the Rio Grande rift using geochemistry: asthenospheric mantle, subduction-modified lithospheric mantle and plume-modified lithospheric mantle. Even though there has been altera-

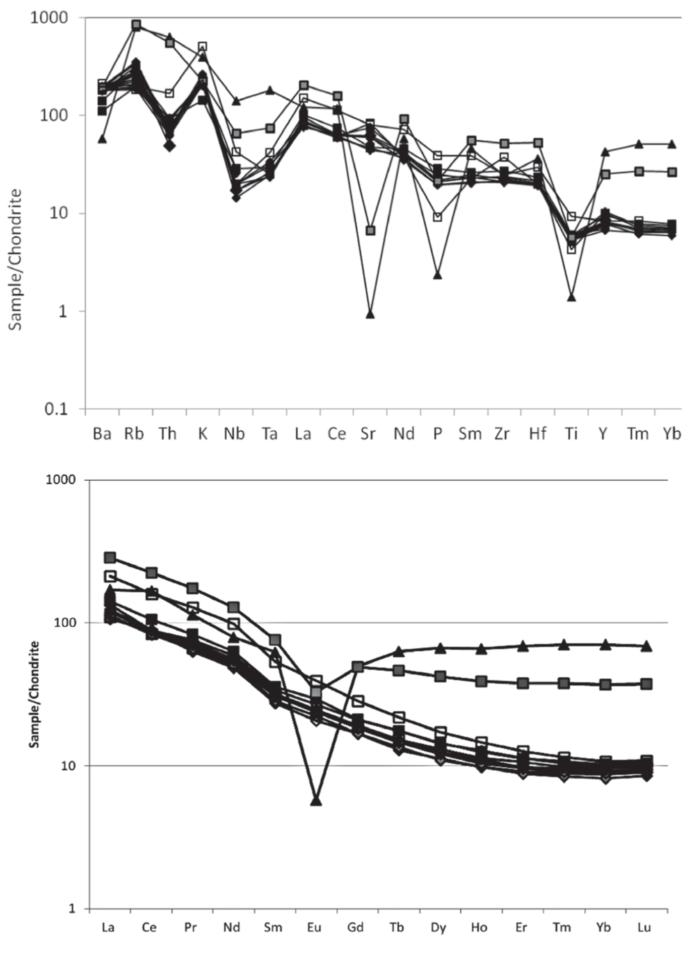

FIGURE 9. Spider diagram of trace elements normalized to chondrite. Note the troughs for the Willow Springs dome and dacite-rhyolite sequence in Sr, P, Ti, and Ba. Chondrite normalization values from Thompson (1982). Sierra Cuchillo laccolith samples are in red. Willow Springs dome samples are in black. Vindicator sill samples are in brown. Symbols are the same as Figure 4.

tion of the laccolith, the $^{87}Sr/^{86}Sr$ ratio can be generalized to be a moderate ratio (0.704-0.712) higher than the ratios of asthenospheric mantle and OIB-modified lithospheric mantle (<0.704). The Nb/Ba_N ratio of the Sierra Cuchillo laccolith Vindicator sill are considered low (Fig. 8), corresponding to troughs at Nb and Ta on a chondrite-normalized incompatible trace element diagram (Fig. 9) while the Rb/Nb_N (9.5-19.5)and Ba/Y_N (19.6-31.8) ratios are higher than those seen in Rio Grande rift volcanic rocks produced from the asthenospheric mantle or OIB-modified lithospheric mantle (Rb/Nb_N :1.25-5.38 and Ba/Y_N :9-20; McMillan et al., 2000). It is likely that the mantle source of the Sierra Cuchillo laccolith and Vindicator sill contained an arc-related component, with a moderate $^{87}Sr/^{86}Sr$ ratio, low Nb/Ba_N ratio, and high Rb/Nb_N and Ba/Y_N ratios. The Willow Springs dome is the only sample to plot in the non-arc related source region of the diagrams with an Nb/Ba_N ratio of 0.1 (Figs. 8).

The Sierra Cuchillo laccolith was emplaced in a critical time in southern New Mexico. The tectonic regime in which it was emplaced is difficult to determine due to an alteration event post-emplacement and the lack of mafic igneous rocks. The laccolith is older than most faulting associated with Rio Grande rift extension. It does not exhibit deformation resulting from Laramide subduction, but does contain an arc-derived geochemical signature. The emplacement took place near the end of the arc-like neutral stress magmatism period as suggested by McMillan et al. (2000), just before ignimbrite volcanism in the region. It is our interpretation that the laccolith is the result of initial melting of subduction-modified lithospheric mantle and assimilation or melting of mid-to lower-crustal arc-derived basement at the transition from arc-like magmatism to the initiation of rifting in southern New Mexico. Assimilation of continental crust resulted in the intermediate composition magmas of Sierra Cuchillo. Rifting in the region is not interpreted to be controlling magmatic sources in this area until the emplacement of the Willow Springs dome.

CONCLUSIONS

Petrographic zones seen in the field and described from thin sections are the result of an internal altering fluid. This fluid was most likely composed of late stage water and soluble elements reacting with phenocrysts of plagioclase and hornblende to form epidote and chlorite (Boles, 1982; Lee and Parsons, 1997; Ibrahim et al., 2000; Sirbescu and Nabelek, 2003; Perez and Boles, 2005). This alteration is seen geochemically in large variation in the concentrations of the soluble elements.

The Sierra Cuchillo laccolith is the result of contamination by lower to mid-crustal Precambrian crustal rocks (1.6-1.4 Ga) of a subduction-modified lithospheric mantle melt (McMillan, 2004). This is evident by the cored zircons and the low Nb/Ba_N and Ta/Ba_N ratios. Assimilation of Precambrian arc-related crust would not significantly change the Nb/Ba_N and Ta/Ba_N ratios. The Sierra Cuchillo laccolith is not directly related to Laramide subduction magmatism in southern New Mexico. There is no evidence that this magma was produced as a direct result of Rio Grande rifting as suggested by Parker and McMillan (2007), but crustal thinning at the transition from neutral stress arc magmatism to rifting is still a possible mechanism for melt production through adiabatic melting of the mantle wedge melting lower mafic crust.

The Vindicator sill is related to the intrusion of the Sierra Cuchillo laccolith. It contains similar amounts of alteration as the exterior zone of the laccolith and is geochemically very similar. Both intrusions were most likely emplaced as a partially crystalline mush which chilled against the host rock, causing internal circulation of exsolving fluids and alteration.

The latite-andesite sequence can be clearly correlated to the Sierra Cuchillo laccolith system. This volcanic sequence may not have been directly related to the laccolith as the volcanic center but the volcanic center and the laccolith at a minimum share a source, and were spatially close. The dacite-rhyolite sequence may be related to the system but the negative Eu anomaly suggests that this is from an eruption most likely related to a nearby caldera.

The Willow Springs dome is not related to the Sierra Cuchillo laccolith but does represent silicic magmatism at 28 Ma in southern New Mexico. It may be related to the rhyolitic domes located to the west of the Cuchillo Range. This intrusion should no longer be classified as a monzonite and should now be classified as a quartz-rich granite.

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