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New Mexico Geological Society Guidebook, 69th Field Conference, Las Cruces Country III, 2018, p. 173-179.

SR AND PB ISOTOPE VARIATIONS OF IGNEOUS FELDSPARS IN THE DOÑA ANA MOUNTAINS

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Abstract—Igneous rocks in the Doña Ana Mountains record a poorly studied portion of mid-Tertiary magmatism affecting southern New Mexico. Here, Sr and Pb isotopes of feldspars are used to evaluate the origins and potential magmatic relationships between compositionally variable igneous rocks. Overall, plagioclase, sanidine and orthoclase crystals from igneous rocks in the Doña Ana Mountains crystallized from magmas with very different Sr and Pb isotope characteristics. Plagioclase crystals from Early Eocene Palm Park Formation andesite and dacite have similar $^{87}Sr/^{86}Sr$ ratios but vary widely in $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$. These variations are consistent with the presence of variable magmatic sources that were not involved in Late-Eocene/Early Oligocene magmatism in the Doña Ana Mountains. Sanidine crystals from the Doña Ana Rhyolite and nearby Goat Mountain Rhyolite have similar $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios but variable $^{87}Sr/^{86}Sr$ ratios, which precludes a simple petrogenetic relationship between them and which also confirms the presence of multiple, highly-evolved magma compositions at ~36 Ma. Orthoclase crystals from syenite dikes that crosscut volcanic rocks in the Doña Ana Mountains, which were presumed to have been parental to the rhyolites, have different $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios that undermine any direct magmatic connections between the syenite and rhyolites in the Doña Ana Mountains.

INTRODUCTION

The Doña Ana Mountains, located north of Las Cruces, NM (Fig. 1), record several episodes of Early Eocene and Late Eocene-Early Oligocene volcanism, including andesitic volcanism associated with the Palm Park Formation and later caldera formation likely associated with the ignimbrite flair-up (e.g., Chapin et al., 2004). The range is composed of Pennsylvanian/Permian sedimentary rocks and Eocene to Oligocene volcanic and plutonic rocks (Seager et al., 1976) and is exposed as a result of Rio Grande rift block faulting. Tectonically, the Doña Ana Mountains are subdivided into three blocks (Seager and Mack, this volume) separated by faults or fracture zones. The northern block is composed of Pennsylvanian and Permian sediments that are intruded by the younger, 33.7 Ma Oligocene Summerford Mountain syenite sill (Seager et al., 1976). The central block is composed of Eocene andesitic and dacitic lavas of the Palm Park Formation. The southern block is composed mainly of Late Eocene/Early Oligocene rhyolitic ash flow tuffs related to caldera collapse, and rhyolite flows, domes, and dikes likely formed as a result of post-caldera activity (Haga, 1994). An additional volcanic plug, Goat Mountain, is composed of rhyolite that is exposed ~5 km south of the Doña Ana Mountains.

Volcanic rocks in the Doña Ana Mountains have variable ages and uncertain magmatic relationships. It is unclear which portion (i.e., upper, middle, or lower) of the Palm Park Formation is exposed in the Doña Ana Mountains and how it relates more broadly to other Palm Park exposures in nearby ranges (e.g., in the Organ Mountains). The Palm Park Formation ranges from ~39 to 46 Ma (Creitz and Hampton, this volume) regionally, but the highly heterogeneous and variably altered

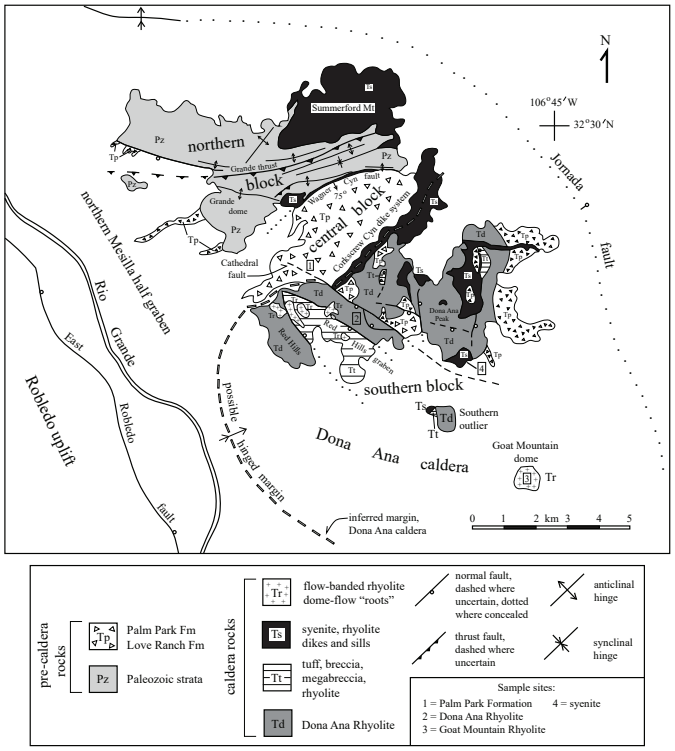


FIGURE 1. Map of the Doña Ana Mountains showing sample locations of whole rocks collected for this study. Palm Park Formation andesite and dacite are located in the central block of the Doña Ana Mountains. Doña Ana Rhyolite and Doña Ana syenite sample locations are in the southern block and Goat Mountain rhyolite is sampled from Goat Mountain at the southern edge of the map area. Map modified from Seager and Mack, this volume.

nature of Palm Park volcanic rocks largely prevents direct stratigraphic correlations linking regional exposures.

In addition to the Palm Park, two highly-evolved igneous rocks are present in the Doña Ana Mountains. The southern block is dominated by Doña Ana caldera fill rhyolite tuff, which is intruded by dikes of syenite that are pervasive throughout the area. Although a relationship between the syenite and Doña Ana Rhyolite (via fractional crystallization) was suggested by Haga (1994), it is uncertain how and if extrusive and intrusive rocks in the southern block are actually related or if they are associated with andesitic and rhyolitic magmatism of similar age in other nearby ranges such as the Organ Mountains (e.g., Zimmerer and McIntosh, 2013). In addition to volcanic rocks of the Doña Ana Mountains, a small rhyolite plug located to the south, called Goat Mountain, is also included in this study. Here, we analyze Sr and Pb isotopes of plagioclase, sanidine, and orthoclase crystals from both Eocene Palm Park volcanic rocks and Late Eocene/Early Oligocene volcanic and plutonic rocks in the Doña Ana Mountains to evaluate magmatic relationships in this region of southern New Mexico.

METHODS

Whole rocks were collected from selected locations in the Doña Ana Mountains that included Palm Park Formation andesite and dacite, Doña Ana Rhyolite tuff, and syenite dikes presumably related to the Summerford Mountain sill exposed in the northern block of the Doña Ana Mountains (Table 1). Additional samples were collected from Goat Mountain located to the south of the Doña Ana Mountains. Whole rocks were crushed and sieved. Whole rock gravels free of alteration and lithics were powdered and analyzed for major and trace elements using XRF and ICPMS at the Peter Hooper GeoAnalytical Laboratory at Washington State University. Strontium, neodymium, and lead isotopes of these rock powders were analyzed at NMSU using MC-ICP-MS and TIMS. Individual feldspars were also hand picked from sieve fractions. Feldspars, including sanidine from the Doña Ana and Goat Mountain Rhyolites, orthoclase from syenite dikes, and plagioclase from dacite and andesite of the Palm Park Formation were etched in 10% hydrofluoric acid for 5–20 minute intervals. Crystals were then rinsed in distilled water and sonicated to obtain crystals free of adhering materials. Feldspars chosen for single crystal analyses ranged from 0.3 to 15 mg.

Individual clean sanidine, orthoclase, and plagioclase crystals were dissolved using hydrofluoric, nitric, and hydrochloric acids. Strontium was purified using cation exchange chromatography and 2.5N hydrochloric acid. Lead was purified using 1N hydrobromic acid and anion exchange chromatography. Lead was analyzed using multi-collector inductively coupled plasma mass spectrometry with Pb isotopes normalized to NBS997 $^{205}Tl/^{203}Tl$=0.41892 and Sr was analyzed using thermal ionization mass spectrometry with Sr normalized to $^{86}Sr/^{88}Sr$=0.1194 at the Johnson Mass Spectrometry Laboratory at NMSU.

RESULTS

Thirty-one feldspars, one biotite, and five whole rocks were analyzed for Sr and Pb isotopes (Tables 2 and 3). This manuscript focuses on Sr and Pb isotopes of feldspars but for completeness, whole rock major and trace element concentrations and Sr, Nd, and Pb isotope ratios are included in Table 2 but not discussed other than to define volcanic rock types.

Three plagioclases and one biotite (Table 3) were analyzed from an andesitic Palm Park lava flow from Cleofas Canyon that yielded a $^{40}Ar/^{39}Ar$ plagioclase age of 43.05±0.28 Ma (Ramos and Heizler, this volume). Five plagioclase crystals were also analyzed from a Palm Park dacitic lava flow in Cleofas Canyon west of the andesite. Andesitic and dacitic plagioclases have different Rb (<1 ppm vs. 17–23 ppm) and Sr (~450 ppm vs. 1000 to 2200 ppm) concentrations but both retain low $^{87}Rb/^{86}Sr$ ratios minimizing $^{87}Sr/^{86}Sr$ variations resulting from variable aging, which may be as different as ~7 My (Creitz and Hampton, this volume). Age-corrected $^{87}Sr/^{86}Sr$ ratios of both the andesitic and dacitic plagioclases are generally similar (~0.7046–0.7049) but one plagioclase in the andesite is strikingly unradiogenic (~0.7034; Fig. 2). In contrast to Sr isotopes, age-corrected Pb isotope ratios are dramatically different (Table 3) with Palm Park andesitic plagioclases being highly radiogenic compared to plagioclases in the dacite (Figs. 2, 3, and 4). Age-corrected Pb isotopes of a single biotite from this andesite are similar to the accompanying plagioclase crystals, but the $^{87}Sr/^{86}Sr$ ratio of this biotite is more radiogenic (0.7060 vs. 0.7048) likely indicating variable phenocrystic origins for these minerals.

Six sanidine crystals were analyzed from the Doña Ana Rhyolite collected from the Red Hills area that yielded a 36.04±0.01 Ma $^{40}Ar/^{39}Ar$ age (Ramos and Heizler, this volume). These sanidines have high Rb (75–95 ppm) and low Sr (5–17 ppm) concentrations that result in elevated $^{87}Rb/^{86}Sr$ ratios that reflect significant radiogenic ingrowth since the late

TABLE 1. Table showing sample identifiers, formations, ages, compositions, and locations of Doña Ana Mountains whole rocks.

Sample ID	DAA	DAD	DAR	DAMP	DAG
Formation	Palm Park	Palm Park	Dona Ana Rhyolite	Dona Ana Syenite	Goat Mountain
Age	43.05±0.28 Ma		36.04±0.01 Ma	33.2±0.2 Ma	35.98±0.02
Composition	andesite	dacite	rhyolite	syenite	rhyolite
Latitude	32.462	32.457	32.438	32.439	32.405
Longitude	-106.839	-106.853	-106.838	-106.784	-106.761

TABLE 2. Major oxides, trace elements, and Sr, Nd, Pb isotopes of Doña Ana Mountains whole rocks.

Sample ID	DAA	DAD	DAR	DAMP	DAG
XRF major element oxides normalized to 100%					
SiO_2	61.45	63.26	77.19	66.35	70.22
TiO_2	0.81	0.72	0.10	0.61	0.35
Al_2O_3	16.70	16.03	12.16	17.20	15.55
FeO*	5.35	5.53	1.71	2.48	2.19
MnO	0.06	0.05	0.03	0.08	0.08
MgO	2.31	1.15	0.08	0.50	0.24
CaO	5.99	5.02	0.20	1.33	0.93
Na_2O	4.64	4.57	3.83	5.29	4.81
K_2O	2.41	3.38	4.67	6.01	5.56
P_2O_5	0.28	0.30	0.03	0.14	0.07
Total	100	100	100.0	100.0	100
XRF trace elements (ppm)					
Ni	66	13	4	14	8
Cr	143	27	3	3	2
Sc	11	9	2	6	5
V	138	95	5	24	5
Ba	1054	1191	95	960	832
Rb	41	86	224	94	126
Sr	1015	836	39	182	123
Zr	126	172	278	633	556
Y	11	18	68	26	45
Nb	6	9.5	73	27.4	41
Ga	22	17	25	20	23
Cu	10	18	4	2	1
Zn	68	68	94	53	74
Pb	10	12	30	19	22
La	24	35	55	66	102
Ce	49	67	124	119	209
Th	6	10	25	11	19
Nd	24	28	47	43	78
U	2	3	4	2	3
Sr Isotopes					
Whole rock	0.704410±0.000005	0.704739±0.000004	0.706924±0.000023	0.706353±0.000011	0.706594±0.000006
Nd Isotopes					
Whole rock	0.512529±0.000004	0.512439±0.000004	0.512471±0.000003	0.512501±0.000004	0.512433±0.000005
Pb Isotopes					
Whole rock					
$^{206}Pb/^{204}Pb$	17.258±0.001	17.210±0.001	17.551±0.001	17.862±0.001	17.497±0.001
$^{207}Pb/^{204}Pb$	15.433±0.001	15.420±0.001	15.457±0.001	15.487±0.001	15.451±0.001
$^{208}Pb/^{204}Pb$	37.318±0.001	37.484±0.001	37.951±0.001	38.166±0.004	37.851±0.002

All samples were whole rocks generated from hand-picked gravels. Isotope ratios are age corrected to ages from Ramos and Heizler, this volume. Iron was measured as total Fe (FeO*). Strontium isotopes were analyzed using TIMS and Nd and Pb were analyzed using MC-ICP-MS at NMSU. NBS987 Sr standard results were 0.710293 (n=37) with 0.000033 SD, JNdi-1 results were 0.512093 (n=44) with 0.000008 SD; and NBS981 results were $^{206}Pb/^{204}Pb$=16.929 (n=59) with a 0.003 SD, $^{207}Pb/^{204}Pb$=15.482 (n=59) with a 0.003 SD, $^{208}Pb/^{204}Pb$=36.668 (n=59) with a 0.010 SD for the six months surrounding the actual period of analyses. NBS987 analyzed with the samples was $^{87}Sr/^{86}Sr$= 0.710281, n=2. Similarly, JNdi-1 Nd standard was $^{143}Nd/^{144}Nd$: 0.512093, n=2 and $^{145}Nd/^{144}Nd$: 0.348406, n=2. NBS981 Pb standard ratios were $^{206}Pb/^{204}Pb$: 16.931, n=2; $^{207}Pb/^{204}Pb$: 15.485, n=2, and $^{208}Pb/^{204}Pb$: 36.677, n=2.

TABLE 3. Table showing selected trace element and isotope ratios of Doña Ana Mountains plagioclase, sanidine, and orthoclase crystals. Note that Sr and Pb isotope ratios are corrected for 43 My, 36 My, and 33 My of decay.

Sample	*Rock Name* Mineral	Age (Ma)	Crystal Weight (grams)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)I$	Error (2σ)	U/Pb	$(^{206}Pb/^{204}Pb)i$	Error (2σ)	$(^{207}Pb/^{204}Pb)i$	Error (2σ)	$(^{208}Pb/^{204}Pb)i$	Error (2σ)
	Palm Park Andesite															
DAA Pl#1	Plag	43.1	0.015	0.17	448.7	0.002	0.704963	0.704962	*0.000010*	0.02	18.728	*0.002*	15.624	*0.002*	38.300	*0.006*
DAA Pl#2	Plag	43.1	0.001			0.002	0.703360	0.703359	*0.000010*	0.02	19.031	*0.004*	15.648	*0.004*	38.466	*0.010*
DAA Pl#3	Plag	43.1	0.001	0.15	448.7	0.002	0.704836	0.704836	*0.000011*	0.02	19.059	*0.001*	15.669	*0.001*	38.527	*0.003*
DAA Bio#1	Biot	43.1		0.05	2.5	0.098	0.706042	0.706004	*0.000055*	0.02	18.824	*0.004*	15.643	*0.003*	38.375	*0.007*
	Palm Park Dacite															
DAD #4	Plag	43.1	0.002							0.02	17.313	*0.008*	15.425	*0.008*	37.596	*0.022*
DAD #5	Plag	43.1	0.000	16.8	1390.2	0.05	0.704678	0.704657	*0.000010*	0.02	17.333	*0.001*	15.437	*0.001*	37.388	*0.001*
DAD #7	Plag	43.1	0.004	18.9	2151.3	0.04	0.704843	0.704828	*0.000013*	0.02	17.232	*0.001*	15.413	*0.001*	37.436	*0.003*
DAD #8	Plag	43.1	0.000	22.8	1746.9	0.06	0.704727	0.704704	*0.000014*	0.02	17.260	*0.003*	15.416	*0.002*	37.464	*0.006*
DAD #9	Plag	43.1	0.002	19.3	1046.3	0.08	0.704803	0.704770	*0.000013*	0.02	17.243	*0.002*	15.413	*0.002*	37.463	*0.005*
	Doña Ana Rhyolite															
DAR #1	San	36.0	0.000	81.1	16.6	21.9	0.730171	0.722910	*0.000100*	0.02	17.553	*0.004*	15.449	*0.003*	37.946	*0.010*
DAR #2	San	36.0	0.000	94.6	6.4	66.5	0.756287	0.734190	*0.000050*							
DAR #3	San	36.0	0.001	95.4	5.5	77.3	0.758205	0.732517	*0.000010*	0.02	17.536	*0.003*	15.447	*0.003*	37.919	*0.008*
DAR #4	San	36.0	0.000	75.2	5.3	63.3	0.750901	0.729877	*0.000112*	0.02	17.555	*0.007*	15.459	*0.006*	37.954	*0.016*
DAR #5	San	36.0	0.001	78.0	8.9	39.5	0.745035	0.731923	*0.000280*	0.02	17.524	*0.003*	15.440	*0.003*	37.893	*0.007*
DAR #6	San	36.0	0.000							0.02	17.545	*0.006*	15.449	*0.005*	37.926	*0.012*
	Doña Ana Syenite															
DAMP #1	San	33.2	0.001	70.2	93.3	3.4	0.707469	0.706442	*0.000030*	0.02	17.893	*0.002*	15.484	*0.003*	38.168	*0.004*
DAMP #3	San	33.2	0.000	850.4	1041.9	3.7	0.707537	0.706423	*0.000014*	0.02	17.879	*0.003*	15.474	*0.003*	38.128	*0.007*
DAMP #4	San	33.2	0.005	44.8	121.8	1.7	0.707084	0.706581	*0.000019*	0.02	17.857	*0.001*	15.478	*0.001*	38.148	*0.003*
DAMP #5	San	33.2	0.000	196.9	771.5	1.1	0.707061	0.706713	*0.000019*	0.02	17.875	*0.003*	15.484	*0.003*	38.147	*0.008*
DAMP #6	San	33.2	0.001	154.5	82.5	8.4	0.708566	0.706011	*0.000016*	0.02	17.862	*0.001*	15.480	*0.001*	38.147	*0.004*
	Goat Mountain Rhyolite															
DAG 1	San	36.0	0.001	59.0	14.5	18.2	0.748224	0.742179	*0.000480*	0.02	17.579	*0.003*	15.472	*0.003*	37.988	*0.008*
DAG 2	San	36.0	0.001	59.5	15.6	17.1	0.748442	0.742771	*0.000332*	0.02	17.529	*0.002*	15.447	*0.002*	37.916	*0.004*
DAG 5	San	36.0	0.001	57.5	12.7	20.3	0.747638	0.740907	*0.000025*	0.02	17.546	*0.004*	15.459	*0.004*	37.960	*0.010*
DAG 6	San	36.0	0.001	56.2	16.5	15.3	0.748261	0.743185	*0.000013*	0.02	17.558	*0.006*	15.471	*0.006*	37.987	*0.004*
DAG 8	San	36.0	0.001	64.1	15.0	19.2	0.736508	0.730142	*0.000034*	0.02	17.576	*0.004*	15.471	*0.004*	37.984	*0.008*
DAG 9	San	36.0	0.001	57.6	15.8	16.4	0.748167	0.742735	*0.000472*	0.02	17.531	*0.003*	15.453	*0.003*	37.937	*0.007*
DAG 10	San	36.0	0.001	49.2	17.5	12.6	0.745909	0.741716	*0.000363*	0.02						
DAG 14	San	36.0	0.002	68.8	9.8	31.5	0.752907	0.742445	*0.000286*	0.02	17.538	*0.002*	15.457	*0.002*	37.953	*0.005*
DAG 15	San	36.0	0.001	58.7	15.5	17.0	0.749008	0.743357	*0.000340*	0.02	17.545	*0.004*	15.461	*0.003*	37.961	*0.009*
DAG 17	San	36.0	0.002	60.8	13.6	20.1	0.750972	0.744308	*0.000269*	0.02	17.538	*0.002*	15.454	*0.001*	37.952	*0.004*
DAG 19*	San	36.0	0.001	48.9	17.8	12.3	0.747713	0.743621	*0.000013*	0.02	17.561	*0.006*	15.472	*0.005*	54.838	*0.017*
DAG 21*	San	36.0	0.001	57.3	13.5	19.1	0.748703	0.742375	*0.000020*	0.02	17.558	*0.005*	15.640	*0.003*	71.376	*0.022*

Standards analyzed with unknowns included NBS987 (n=5) with an $^{87}Sr/^{86}Sr$ of 0.710285 and NBS981 (n=19) $^{206}Pb/^{204}Pb$=16.925 (SD=0.005), $^{207}Pb/^{204}Pb$=15.475 (SD=0.005), $^{208}Pb/^{204}Pb$=36.648 (SD=0.014) for standards with Pb concentrations similar to unknowns. Pb blanks were <19 pg.

"*" indicates spiked samples with sanidine Pb concentrations of ~4 ppm. Plagioclase Pb concentrations were not determined.

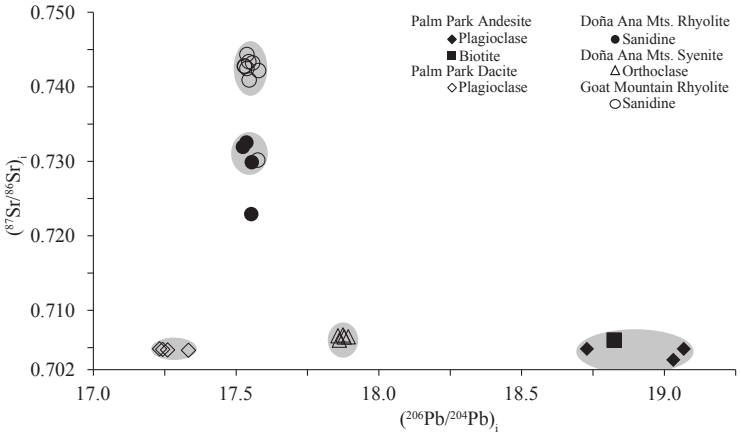


FIGURE 2. Age-corrected $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ diagram illustrating individual plagioclase crystals from Palm Park Formation andesite and dacite, sanidine crystals from the Doña Ana Mountains Rhyolite and Goat Mountain Rhyolite, and orthoclase crystals from the Doña Ana Mountains syenite. Note, feldspars from individual volcanic rocks define separate fields reflecting their uniqueness compared to other volcanic rocks in the Doña Ana Mountains. Only two individual sanidine crystals, one each from the Doña Ana Rhyolite and Goat Mountain Rhyolite have intermediate Sr and Pb isotope signatures.

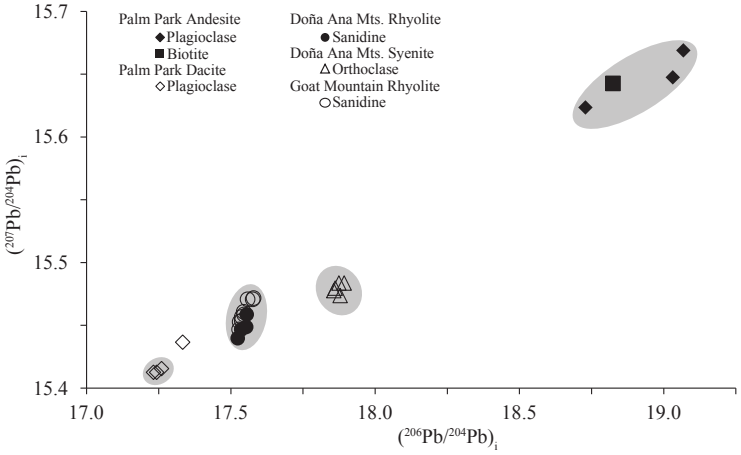
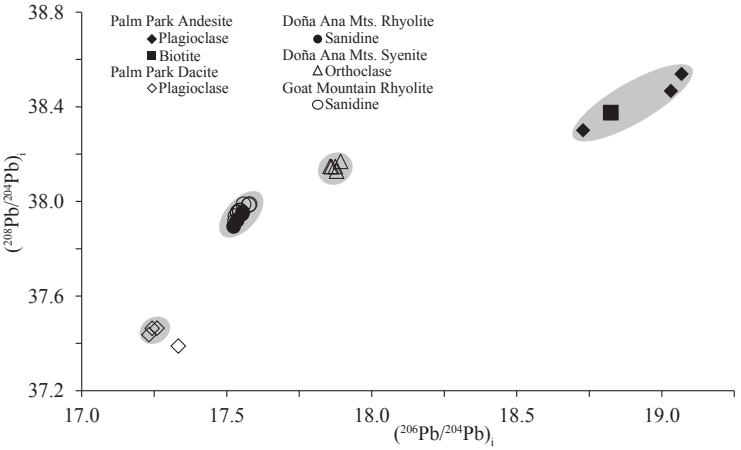


FIGURE 3. Age-corrected $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ diagram illustrating individual plagioclase crystals from Palm Park Formation andesite and dacite, sanidine crystals from the Doña Ana Mountains Rhyolite and Goat Mountain Rhyolite, and orthoclase crystals from the Doña Ana Mountains syenite. In general, feldspars from the Doña Ana Mountains define linear trends where only the Doña Ana Mountains Rhyolite and Goat Mountain Rhyolite have similar signatures.



Eocene. Age-corrected $^{87}Sr/^{86}Sr$ ratios of Doña Ana Rhyolite range from 0.723–0.734 (Fig. 2). Additionally, the range of age-corrected Pb isotope ratios is relatively limited and dissimilar to those of both Palm Park dacite and andesite (Figs. 3 and 4).

Twelve sanidine crystals were analyzed from Goat Mountain Rhyolite that yielded a $^{40}Ar/^{39}Ar$ age of 35.98±0.02 Ma (Ramos and Heizler, this volume). Sanidines from Goat Mountain Rhyolite are highly radiogenic with intermediate Rb (49–69 ppm) and Sr (10–18 ppm) concentrations. These Rb and Sr characteristics result in $^{87}Rb/^{86}Sr$ ratios between 8 and 20 and generate age-corrected $^{87}Sr/^{86}Sr$ ratios of 0.7409 to 0.7443 with one sanidine crystal having a distinctly less radiogenic ratio of 0.7301 (Fig. 2). In addition to highly radiogenic Sr isotope ratios, these sanidines have intermediate Pb isotope ratios that are similar to sanidines from the Doña Ana Rhyolite and are very different than either the Palm Park andesite or dacite (Figs. 3 and 4).

Lastly, five orthoclase crystals were analyzed from a syenite dike that crosscut the Doña Ana Rhyolite. These orthoclases have highly variable Rb (45–850 ppm) and Sr (82–1042 ppm) concentrations. Orthoclase crystals from this dike yield a 33.2±0.2 Ma age (Ramos and Heizler, this volume). Age-corrected $^{87}Sr/^{86}Sr$ range from 0.7060 to 0.7067 and are unlike both rhyolites (Fig. 2). $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios of syenitic orthoclases are greater than both rhyolites and different than Palm Park andesite and dacite plagioclases (Figs. 3 and 4).

Overall, feldspar rubidium, strontium, $^{87}Sr/^{86}Sr$, and $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios vary widely amongst all investigated units. Plagioclase crystals from Palm Park andesite and dacite generally have low Rb and high Sr concentrations resulting in low $^{87}Rb/^{86}Sr$ ratios but Pb isotopes ratios that vary widely. In contrast, sanidines from the Doña Ana and Goat Mountain Rhyolites have high Rb and low Sr concentrations resulting in high $^{87}Rb/^{86}Sr$ ratios. $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios of Doña Ana and Goat Mountain Rhyolite sanidines are similar but different than those of Palm Park plagioclases. Sanidines from the Doña Ana Rhyolite also have far higher $^{87}Rb/^{86}Sr$ ratios than any other volcanic rocks in the Doña Ana Mountains. In addition, orthoclase crystals from Doña Ana syenite dikes have intermediate Rb and Sr concentrations and lower $^{87}Sr/^{86}Sr$ ratios than sanidines from the Doña Ana and Goat Mountain Rhyolites. They also have more radiogenic $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios.

FIGURE 4. Age-corrected $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ diagram illustrating individual plagioclase crystals from Palm Park Formation andesite and dacite, sanidine crystals from the Doña Ana Mountains Rhyolite and Goat Mountain Rhyolite, and orthoclase crystals from the Doña Ana Mountains syenite. In general, feldspars from the Doña Ana Mountains define linear trends where only the Doña Ana Mountains Rhyolite and Goat Mountain Rhyolite have similar signatures.

Age corrections for Sr and Pb isotopes use measured $^{87}Rb/^{86}Sr$ ratios and assumed U/Pb and Th/Pb ratios. Age corrections for Pb isotopes assume U/Pb and Th/Pb ratios for feldspar of 0.02 and 0.08, respectively (Wolff and Ramos, 2003). Actual U/Pb and Th/Pb ratios were not measured but age corrections generate only minor variations in ratios compared to overall Pb isotope variations and do not substantially impact interpretations regarding feldspar origins.

DISCUSSION

Palm Park Formation feldspars

Strontium and lead isotope ratios of Palm Park andesite and dacite plagioclase crystals contrast dramatically. Andesitic and dacitic plagioclases have different Rb and Sr concentrations but similar age-corrected $^{87}Sr/^{86}Sr$ between the two different compositions, consistent with their origin from similar sources. The amount of differentiation (e.g., crystal fractionation) however, impacting the two compositions were quite different, which likely led to more evolved compositions, higher incompatible element concentrations (Table 2), and higher Rb and Sr concentrations in the dacite. In contrast, Pb isotope ratios are dramatically different (Figs. 2, 3 and 4) with Palm Park andesite plagioclases being much more radiogenic compared to plagioclases in the dacite, which likely precludes an origin from similar sources. Such unradiogenic signatures require the dacite to have undergone extensive assimilation of unradiogenic crustal materials or may even reflect wholesale remelting of pre-existing unradiogenic crust. In any case, Sr and Pb isotope variations of plagioclases confirm the involvement of highly variable magmatic sources and compositions associated with Palm Park volcanism.

Doña Ana Rhyolite feldspars

Sanidines from the Doña Ana Rhyolite have high Rb and low Sr concentrations likely resulting from extensive feldspar fractionation common to rhyolitic magma compositions (e.g., Wolff and Ramos, 2013). Age-corrected $^{87}Sr/^{86}Sr$ ratios range from 0.723-0.734 and are significantly more radiogenic than plagioclases from Palm Park andesite and dacite. Additionally, Doña Ana Rhyolite sanidines define a limited range in age-corrected Pb isotope ratios that are also dissimilar to those of both Palm Park andesite and dacite (Figs. 2, 3, and 4). Overall, both Sr and Pb isotope variations confirm the different nature of the Doña Ana Rhyolite compared to Eocene Palm Park volcanics, consistent with the conclusions of Haga (1994), and likely preclude the possibility that Palm Park volcanic rocks could have been melted and remobilized to generate the Doña Ana Rhyolite.

Goat Mountain Rhyolite Feldspars

Sanidines from the Goat Mountain Rhyolite are highly radiogenic with intermediate Rb and Sr concentrations. Age-corrected $^{87}Sr/^{86}Sr$ ratios range from 0.7409 to 0.7443, which are substantially more radiogenic than either plagioclases from Palm Park volcanic rocks or sanidines from the Doña Ana Rhyolite. Such highly radiogenic $^{87}Sr/^{86}Sr$ ratios require involvement of a more highly radiogenic source than any other Doña Ana volcanic rocks. In addition, the similar ages of the Doña Ana Rhyolite and Goat Mountain Rhyolite require that both magmas existed simultaneously, confirming the presence of a complex magma system that fed the Doña Ana Mountains. The additional presence of a single sanidine crystal in the Goat Mountain Rhyolite feldspar suite, which has $^{87}Sr/^{86}Sr$ and Pb isotope ratios similar to those of the Doña Ana Rhyolite sanidines (Fig. 2), supports the possibility that the rhyolites mixed prior to eruption or emplacement. In addition to $^{87}Sr/^{86}Sr$, Pb isotope ratios of sanidines from Goat Mountain Rhyolite are different than Palm Park plagioclases but similar to sanidines from the Doña Ana Rhyolite. Such similarities suggest that both the Goat Mountain Rhyolite and the Doña Ana Rhyolite resulted from either extensive crustal assimilation or crustal melting, a common feature of volcanic rocks associated with the ignimbrite flare-up (Chapin et al., 2004).

Syenite Dike feldspars

Syenite dikes in the southern Doña Ana Mountains caldera block are generally thought to be related to the Summerford Mountain syenite sill located in the northern block of the Doña Ana Mountains. Previous assessments determined that the syenite was likely parental to the Doña Ana Rhyolite (Haga, 1994). Orthoclase crystals in the Doña Ana syenite have intermediate Rb and Sr concentrations and age-corrected $^{87}Sr/^{86}Sr$ ratios that are relatively unradiogenic compared to both the Doña Ana and Goat Mountain Rhyolites. These ratios are also generally more radiogenic than dacitic and andesitic Palm Park plagioclases. In addition to Sr isotopes, Pb isotope ratios of orthoclase crystals from the syenite are different than feldspars from both Palm Park volcanics and the Doña Ana and Goat Mountain rhyolites. These combinations of ratios likely preclude the possibility that the syenite was related to any previously erupted volcanic rocks in the Doña Ana Mountains, including the Doña Ana Rhyolite (Haga, 1994). This observation is also consistent with its younger 33.2 Ma age (Ramos and Heizler, this volume), which is far younger than all other volcanic rocks in the Doña Ana Mountains.

Overall, feldspars from volcanic rocks in the Doña Ana Mountains originate from a wide range of magma compositions. Volcanic rocks from the ~43.1 Ma Doña Ana Mountains section of the Palm Park Formation (i.e., the section present in the Doña Ana Mountains) clearly tap magmas generated from variable sources with similar $^{87}Sr/^{86}Sr$ ratios but vastly different $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios. This must result from either a complex magmatic system or the involvement of multiple magmas that ultimately generated the 46-39 Ma Palm Park Formation.

Late Eocene-Early Oligocene magmatism also appears to involve a complex magmatic system characterized by the simultaneous presence of variable composition magmas. The Doña Ana and Goat Mountain Rhyolites retain sanidines with similar $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios but very

different $^{87}Sr/^{86}Sr$ ratios that must have been imparted to their host magmas from variable sources, which likely involved crust. These sanidines have different isotope characteristics compared to orthoclase crystals in the 33.2 Ma syenite dikes (Haga, 1994), their previously presumed parental magma, and thus must have originated from different magmatic sources.

Compared to the nearby Organ Mountains, volcanic activity in the Doña Ana Mountains only overlaps the age of the youngest Squaw Mountain Tuff (36.03 Ma; Zimmerer and McIntosh, 2013), while syenite dike emplacement overlaps the age of Organ Mountains plutonic activity (~36 Ma to at least ~30 Ma, Zimmerer and McIntosh, 2013). In general, volcanic feldspars from the Doña Ana and Goat Mountain Rhyolites have more radiogenic signatures (>0.715, Table 3) than plutonic rocks in the Organ Mountains (e.g., <0.715, Organ Needles Pluton) but $^{87}Sr/^{86}Sr$ ratios of Doña Ana Mountain syenite dikes are similar to those of syenites in the Organ Mountains, potentially allowing for a more regional correlation (Verplanck et al., 1995, 1999). Sr isotope ratios of Precambrian rocks in the Organ Mountains have highly radiogenic isotope $^{87}Sr/^{86}Sr$ ratios (Verplanck et al., 1999), which may allow the Doña Ana and Goat Mountain Rhyolites to result from direct crustal melting or crustal assimilation of Precambrian basement. And in contrast to $^{87}Sr/^{86}Sr$, Organ Mountains rocks have not been targeted for Pb isotopes studies, thus further comparisons are limited.

CONCLUSIONS

Strontium and lead isotope ratios of feldspars from volcanic rocks in the Doña Ana Mountains confirm the presence of a range of magma compositions that must have originated from variable magmatic sources. Dacitic and andesitic plagioclase crystals from the Palm Park Formation retain similar $^{87}Sr/^{86}Sr$ but widely different $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios confirming the presence of different composition volcanic rocks in the Doña Ana Mountains section of the Eocene Palm Park Formation. Late Eocene to Early Oligocene volcanic rocks in the Doña Ana Mountains tapped highly radiogenic, $^{87}Sr/^{86}Sr$ sources that likely resulted from extensive crustal contamination or remelting of older, pre-existing Precambrian basement. In contrast to earlier assessments (e.g., Haga, 1994), volcanic rocks in the Doña Ana Mountains are different from one another and the Sr and Pb isotope signatures of their feldspars preclude a simple petrogenetic relationship between them. Rather, Late Eocene rhyolites and Early Oligocene syenites reflect the highly variable nature of mid-Tertiary magmatism in the Doña Ana Mountains.

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Mums growing in the Masson Farm's Geothermal Greenhouses. Photograph by Peter A. Scholle.