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PROTEROZOIC MAGMATISM AND REGIONAL CONTACT METAMORPHISM IN THE SANDIA-MANZANO MOUNTAINS, NEW MEXICO, USA

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ABSTRACT—The Sandia-Manzano and adjacent Los Piños mountains, the eastern uplift of the Rio Grande rift along the Albuquerque basin, expose a series of Paleoproterozoic and Mesoproterozoic plutons that intrude the 1.70-1.60 Ga Manzano Group within the Manzano thrust belt. This paper summarizes the age and tectonic setting of two distinct pulses of magmatism: one at 1.67-1.64 Ga and one at 1.46-1.45 Ga. The 1.67-1.64 Ga granite plutons are as follows, from north to south, the 1669±13 Ma Monte Largo Hills, 1653±16 Ma Cibola, 1655±14 Ma Manzanita, 1659±5 Ma Ojito, and 1655±1 Ma Los Piños/Sepultura granites. Circa 1.45 Ga magmatism is recorded in the 1453±12 Ma Sandia Pluton, and the 1456±13 Ma Priest Pluton. The plutons range from monzogranite to granodiorite. The older plutonic suite is closely associated with a period of voluminous bimodal rhyolite-basalt volcanism. The temporal, spatial, and chemical proximity of these volcanics to the 1.65 Ga plutons suggests a tectonic relationship between intrusive and extrusive products of the same magmatic system. This relationship is explained in terms of rhyolitic, caldera-style eruptions that were intruded by plutons of similar age. Metamorphic assemblages and fabrics in aureoles of both the 1.65 Ga and 1.46 Ga plutons indicate syntectonic (syncontractional) emplacement at middle crustal depths of 3-4 km. Contact aureoles of 1.65 plutons have andalusite-sillimanite assemblages, and those of 1.46 plutons have triple point aluminosilicate assemblages (550°C, 3.5 kbars). The 1.45-1.46 Ga suite has no known proximal extrusive activity and is associated with late-stage aplite and pegmatite dikes, which frequently crosscut the outer margins of the plutons. Extrusive equivalents may be present east of the Rocky Mountain front in the western Granite-Rhyolite provinces. The plutons and their aureoles record two episodes of deformation and metamorphism: the 1.65 Ga Mazatzal orogeny, and the 1.45 Ga Picuris orogeny. Collectively, these two events produced the observed polyphase strain fabric in the Manzano Group rocks of the Manzano Mountains.

INTRODUCTION

The timing and tectonic setting of Precambrian magmatism in central New Mexico has been the focus of numerous studies since the basement was first mapped in detail during the first half of the 20th century (Reiche, 1949). After the advent of radiometric dating and the development of the theory of plate tectonics, the 93-km Sandia-Manzano uplift and neighboring 16-km Los Pinos Mountains, which collectively form the Sandia-Manzano-Los Piños (SMP) block (Condie and Budding, 1979), have been the focus of study and debate surrounding the nature of Proterozoic orogeny and lithospheric evolution of the southwestern United States (Karlstrom et al., 2004). Central to these debates have been the nine granitic bodies and their aureoles that comprise about half of the exposed basement (Fig. 1; Color Plate 4). These plutons record two major episodes of regional magmatism, the first pulse at ca. 1.65 Ga and the second at ca. 1.45 Ga (Karlstrom et al., 2004). Illuminating the connections between these intrusions and any associated volcanic rocks is essential to assessing the current proposals for depth of emplacement, tectonic regime, and tectonic evolution along the southern margin of the Laurentian continent during the Proterozoic (Whitmeyer and Karlstrom, 2007).

The goal of this paper is to synthesize and interpret published data on the plutons, associated volcanic rocks, and character of pluton aureoles. We also discuss the plutons in terms of ongoing controversies regarding the relative importance of the ca. 1.65 Ga Mazatzal and ca.1.45 Ga Picuris orogenies in creating the observed deformational fabrics observed in these rocks.

1.70-1.60 GA MAGMATISM: GREENSTONE BELTS, RHYOLITIC CALDERAS AND CONTINENTAL ARC PLUTONS

The oldest magmatic rocks of the Sandia-Manzano uplift are supracrustal rocks of the lower Manzano Group. Karlstrom et al. (2004) correlated several volcanic successions as part of a bimodal mafic-felsic volcanic package that forms the base of the Manzano Group. Mafic volcanics include pillow basalt of likely submarine origin and the Sevilleta rhyolites include metamorphosed high silica ash flow tuffs of probable caldera origin (Parchman, 1980). The two lithologies are interlayered: basalts dominate in lower parts of the succession and rhyolites in upper parts. U-Pb dates on the Sevilleta rhyolites range from 1700±20 Ma to 1662±1 Ma with the more precise 1662 Ma age considered more representative of the timing of major volcanism (Holland et al., this volume). An additional U-Pb titanite age of 1660±2 Ma was obtained on the mafic rocks (Shastri, 1993), which agrees well with other dates. The volcanics are overlain by a several kilometer thick succession of metasedimentary rocks (schists and quartzites), and the Manzano Group is capped by a younger rhyolite succession dated as 1.6 Ga (Luther, 2006).

The Sevilleta metarhyolite and associated metavolcanics

The most voluminous of metavolcanics suites in the SMP block is the Sevilleta metarhyolite (Stark and Dapples, 1946). Stark and Dapples (1946) described the unit as a thick succession of interbedded metarhyolites, pelitic schists, and amphib-
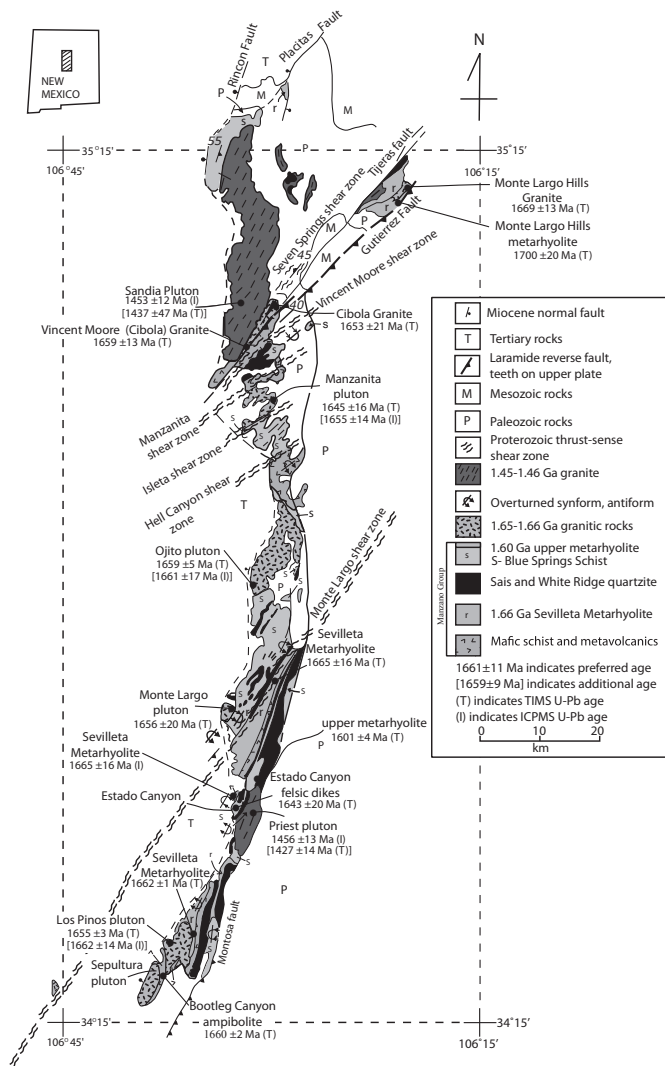
FIGURE 1. General geologic map of the Sandia-Manzano-Los Pinos (SMP) uplift with preferred ages for igneous units and current accepted ages in brackets. Letters in parenthesis indicate U-Pb zircon age from TIMS (T) or ICPMS (I) analysis. See also Color Plate 4.

olites. They described the majority of the unit as a glassy, tan to dark red, fine-grained metarhyolite with abundant potassium feldspar phenocrysts. Condie and Budding (1979) reported an average modal mineralogy of 25% quartz, 30% plagioclase, 40% potassium feldspar, 1% muscovite, 1% biotite, 1% epidote, 1% oxides, and 1% accessory minerals. They described common accessory minerals as actinolite, chlorite, epidote, carbonate minerals, and zircon.

Several samples of the Sevilleta metarhyolite have been analyzed for geochronology since the 1970s. These ages range from 1658 Ma to 1670 Ma (Bauer and Pollock, 1993). The current consensus age is 1662±1 Ma from TIMS analysis reported by Shastri (1993), which is very similar to the ICPMS age of 1665±16 Ma reported by Holland et al. (this volume) (Fig. 1).

Similar units have been described in the Hell Canyon area (Parchman, 1980), in the northern Manzanita Mountains (the North Canyon and Coyote Canyon metavolcanics sequences described by Reiche, 1949), and in the Monte Largo Hills (Timmons et al., 1995). Brown (1999) correlated these units using

physical and geochemical descriptions provided by Condie and Budding (1979), Parchman (1980), Timmons et al. (1995), and by her own examinations of the exposures in the Manzanita Mountains. The Monte Largo Hills metarhyolite has been dated to 1700 Ma with no reported error (Karlstrom et al., 2004). Hell Canyon volcanics have a minimum age 165±42 Ma based on $^{40}Ar/^{39}Ar$ ages of biotite in amphibolite (Brown, 1999). Intrusive relationships with the 1653 Ma Cibola granite provide a minimum age of the North Canyon and Coyote Canyon sequences, but recent monazite work suggests that portions of the Hell Canyon complex may be significantly older (Karlstrom et al., 2000; Karlstrom et al., this volume).

1.65 Ga Plutonism: Syntectonic magmatism in an evolving continental margin

The 1.66-1.64 Ga plutons intrude the Manzano Group and may overlap in age with the volcanics. These plutons locally contain large enclaves of thermally altered metarhyolites and metadacites (Brown, 1999; Parchman, 1980, and others). The characteristics of the 1.65 plutons are summarized below, from north to south.

Monte Largo Hills pluton

Condie and Budding (1979) studied the granitic rocks of the Monte Largo Hills and defined a granitic body in the central Monte Largo Hills area as the Monte Largo Hills pluton. They give approximate modal mineral abundances for this body as follows: 35% potassium feldspar, 34% plagioclase feldspar, 25% quartz, 1% biotite, 3% muscovite, 1% opaques, and 1% trace minerals. Ferguson et al. (1996) described the unit without name as a "Sheared, coarse-grained biotite granite" that underwent post-emplacement deformation at temperatures possibly greater that 500°C as indicated by recrystallized feldspar porphyroclasts. Timmons et al. (1995) mapped most of the area as rhyolite and considered the coarse grained granites as possibly coeval with the Sandia granite. However, Karlstrom et al. (2004) reported a zircon U-Pb age of 1669±13 Ma for the coarse grained granite and 1700±20 Ma for the rhyolite (Fig. 1). Timmons et al. (1995) found the aureole of this pluton to represent upper greenschist grade conditions with sillimanite replacing andalusite near the pluton. Timmons et al. (1995) interpreted this to represent temperatures of 500-600°C and pressures of 2-3.5 kbar.

Cibola granite

The Cibola Granite lies in the southern section of the Sandia Mountains, flanked on the northwest by the Sandia Granite and by the Seven Springs shear zone and the Tijeras fault zone in the south, with several minor outcrops occurring on the south side of the Tijeras fault zone and in the Monte Largo Hills (Timmons et al., 1995; Karlstrom et al., 2000). This unit has been interpreted as including several different bodies ranging from a cohesive gneissic metamorphic suite containing orthogneiss, aluminosilicate-bearing quartzite, and amphibolites (Kelley and Northrop, 1975) to a sheared compositionally variant section of the Sandia Granite (Kirby et al., 1995a). The

explanation on the Tijeras Quadrangle map reports three compositionally distinct phases within the Cibola granite: a fine-grained, peraluminous, two-mica bearing leucogranite with a reported age of 1632±45 Ma, a medium-grained equigranular monzogranite with a reported age of 1659±13 Ma from an outcrop on the south side of the Tijeras fault zone, and a generally coarse-grained monzogranite with no reported age (Karlstrom et al., 2000) (Fig. 1). The Cibola granite is locally mylonitic and has a strong gneissic metamorphic fabric defined by alignment of micas (Kirby et al., 1995a; Timmons et al., 1995) such that some workers referred to it as the Cibola gneiss (Kelley and Northrop, 1975; Condie and Budding, 1979; Timmons et al., 1995).

Condie and Budding (1979) give the approximate modal mineralogy of the Cibola granite (listed as the Cibola gneiss) as: 35% quartz, 30% plagioclase, 20% potassium feldspar. This percentage is noted to increase at the expense of plagioclase with proximity to the Sandia granite, 7% muscovite, 6% biotite, 1% opaques, and 1% trace minerals. The trace minerals observed by Condie and Budding (1979) are actinolite, chlorite, epidote, andalusite, sphene, zircon, rutile, aparite, tourmaline, and limonite. Textures of interest include perthitic texture in potassium feldspar and the coexistence of sillimanite and potassium feldspar only in the area surrounding the contact with the Sandia granite (Condie and Budding, 1979; Kirby et al., 1995a). Additionally, Karlstrom et al. (2000) recognized xenoliths of quartzite, lithic arenite, amphibolite, and phylitic schist within the main body on the north side of the Tijeras fault zone.

These bodies commonly contain andalusite, kyanite, sillimanite, fibrolite, and retrograde chlorite (Kirby et al., 1995a; Karlstrom et al., 2000). It is difficult to interpret whether these assemblages could be considered representative of country rock conditions at the time of emplacement due to lack of in-situ country rock presence, but it is notable that these conditions are similar to those found in the aureole of the laterally adjacent Manzanita pluton (Brown, 1999).

Manzanita granite

The Manzanita granite was described by Condie and Budding (1979) as an intrusive unit, whereas Reiche (1949), Stark (1956), and others had mapped the unit as a metarhyolite. The Manzanita granite is a pink to tan, fine-to-medium grained gneissic leucogranite that has local compositional variations closer in composition to monzonite. This unit is commonly crosscut by aplite and pegmatite dikes (Brown, 1999). Brown (1999) mapped the main body of relatively homogenous granitic gneiss as the Manzanita granite with a penetrative northeast trending foliation that is increasingly mylonitic near the Manzanita shear zone in the north and the Isleta shear zone in the south. Unrue (in Karlstrom et al., 2004) reported a U-Pb zircon TIMS age of 1645±16. Holland et al. (this volume) reported a similar U-Pb zircon ICPMS age of 1655±14 Ma for the Manzanita granite (Fig. 1). Brown (1999) interpreted the shearing to be synmagmatic based on parallelism of magmatic and solid state foliations and the high temperature (>500°C) inferred for the shearing based on ductility of feldspar porphyroclasts.

The granite contains 40% potassium feldspar, 30% plagioclase feldspar, 20% quartz, 5% muscovite, 4% biotite, and 2% trace minerals (sphene, epidote, chlorite, white mica, and rare carbonates), and opaques (Condie and Budding, 1979). Similar to the Cibola granite, the Manzanita granite intrudes lithic arenite, pelitic schist, amphibolites, and aluminosilicate-bearing quartzite of the Manzano Group and contains abundant xenoliths of these units. The contact aureole is well defined on the southern margin with a typical assemblage near the pluton margin of sillimanite + andalusite + garnet + plagioclase + quartz + tourmaline with minor actinolite, albite, epidote, and hornblende. Farther from the margin, greenschist grade assemblages are present, including white mica + chlorite + biotite + quartz in pelitic units, and chloritoid + margarite + chlorite + white mica + quartz in the amphibolites (Brown et al., 1999). Brown (1999) interpreted this assemblage to record emplacement at 2-3 kbar and 600-620°C, with higher temperatures found immediately adjacent to the pluton. The maximum width of the exposed aureole is about 1.5-2 km wide (Brown, 1999).

Ojito pluton

The Ojito pluton lies near the center of the Manzano Mountains, and is the most voluminous granitic outcrop in that mountain range (Condie and Budding, 1979). It is bound by the Laramide Montosa fault to the east, and has visible intrusive contacts with the Hell Canyon greenschist complex as described by Parchman (1980) in the north, and with an andalusite-bearing lithic arenite in the south (Karlstrom et al., 1999a). Karlstrom et al. (1999a) described the contact as gradational from fibrolite and sillimanite bearing at the contact with the granite to andalusite bearing within one kilometer of the contact. This description is similar to that of the Manzanita aureole as described by Brown (1999), recording similar emplacement conditions to that of the Manzanita at 2-3 kbar and 600-620°C (Parchman, 1980). However, in contrast to the synmagmatic penetrative foliation of the Manzanita granite, the Ojito pluton is weakly foliated to unfoliated and is interpreted to have been emplaced as a sheet-like intrusion. This hypothesis is supported by roof pendants of schist and volcanics preserved along the southern margin of the Ojito granite that suggest low angles of emplacement (Karlstrom et al., 1999a). Compositionally, the Ojito pluton is more mafic than most other 1.65 Ga plutons—except the Monte Largo pluton—and is granodiorite, bordering on quartz monzonite, with $Na_2O+K_2O=6.98$ and $SiO_2=65.9$, and high Al_2O_3 (Condie and Budding, 1979). It shows increasingly mafic compositional zonations toward the southwestern contact with the country rock. Condie and Budding (1979) described a minor body of quartz gabbro toward the southwestern section of the pluton. Average modal mineralogy is: 27% quartz, 44% plagioclase (~Ab_{88}), 16% potassium feldspar, 4% biotite, 6% epidote (described as psudomorphic after hornblende and feldspar), and 3% accessory minerals (Reiche, 1949; Condie and Budding, 1979). Condie and Budding (1979) described common accessory minerals for the Ojito pluton as hornblende, sphene, apatite, magnetite, and zircon. Textures of interest include euhedral albite commonly rimmed with orthoclase (Condie and Budding, 1979) and perthitic texture in potassium

feldspar that is interpreted by Reiche (1949) to be microcline and oligoclase. These factors indicate partitioning of Ca toward the later stages of crystallization (Johannes and Holtz, 1996). Holland et al. (this volume) reported an updated U-Pb crystallization age for the Ojito pluton of 1661±17 Ma, similar to the previously reported U-Pb zircon TIMS age of 1659±5 (Karlstrom et al., 2004) (Fig. 1). Karlstrom et al. (1999) reported that the Ojito contains a northeast-striking foliation defined by aligned chlorite and biotite that is consistent with the regional S_1 fabric, and Reiche (1949) presented evidence for a magmatic fabric defined by alignment of mafic enclaves and xenoliths.

Monte Largo pluton

The Monte Largo pluton is a small (~3 km^2) outcrop of granodiorite that is roughly coeval and nearly compositionally identical to the Ojito pluton. This led Condie and Budding (1979) to suggest that it is an apophysis of the Ojito, perhaps repeated across a large fold (Karlstrom et al., 2000; Rogers, 2002). A U-Pb zircon age for the Monte Largo Pluton is 1656 ±10 Ma (Karlstrom et al., 2000) (Fig. 1). Internally, the pluton contains at least two penetrative foliations and a third fabric that forms a zone of fine-grained shearing that defines its contact. The aureole of the Monte Largo pluton contains the minerals kyanite, andalusite, garnet, chlorite, staurolite, and biotite with fibrolite replacing andalusite near the pluton, which is similar to that found in the Ojito pluton, further supporting relationship between the two bodies (Parchman, 1980, Northrup, 1991; Rogers, 2002).

Los Piños pluton

The Los Piños pluton is bounded along the northern exposure by the Sevilleta metarhyolite and is described as concordant along the eastern contact by Condie and Budding (1979). However, no mention of a metamorphic aureole is made regarding this contact, and Beers (1976) described it as severely weathered and difficult to interpret due to the poor quality of the exposure. Beers (1976) interpreted the country rocks near to the pluton as amphibolite grade with fibrolite and kyanite present, further supporting regional P-T conditions in the neighborhood of 2-3 kbar and ~600°C. Condie and Budding (1979) described the Los Piños pluton as a pink to orange, fine- to medium-grained granite with a variably developed northeast-trending foliation defined by biotite and containing deformed plagioclase grains. IUGS classification, based on descriptions by Condie and Budding (1979), indicates that the Los Piños pluton is a monzogranite. Beers (1976) described rapakivi texture in potassium feldspar throughout the Los Piños granite, as well as the presence of rare myrmekitic intergrowth of quartz and plagioclase. He also described an increasing abundance of muscovite toward the southern margin of the pluton, near its contact with the Bootleg Canyon sequence. Condie and Budding (1979) gave approximate modal mineralogy as follows: 39% potassium feldspar, 13% plagioclase feldspar (An$_{34}$), 40% quartz, 5% biotite, 2% trace minerals, and 1% muscovite. Common trace minerals include chlorite, titanite and magnetite (Beers, 1976). Shastri (1993) described northeast-trending magmatic foliation in the pluton that is parallel to (and seemingly continuous along the north margin) foliation in

the adjacent Sevilleta Formation and mafic volcanics. Shastri (1993) interpreted the foliation to have developed synmagmatically with emplacement of the pluton at 1655 Ma. U-Pb ages for this pluton and its adjacent supracrustal rocks are: 1662±1 Ma for the Sevilleta metarhyolite, 1660±2 Ma for titanite in the mafic volcanics, and 1655±3 Ma for the Los Pinos pluton (Fig. 1). The temporal proximity of these ages suggests that the pluton intruded it own volcanic carapace during regional tectonism.

Sepultura pluton

Beers (1976) described the Sepultura granite as a pink to tan, medium-to-fine grained two-mica leucogranite with an abundance of twinned and perthitic microcline phenocrysts. Beers (1976) gave an average modal mineralogy of 37% potassium feldspar, 18% plagioclase (An$_{32}$), 36% quartz, 4% biotite, 4% muscovite, and 1% accessory minerals. Shastri (1993) suggested it was part of the same pluton as the Los Piños granite even though it is compositionally distinct. Bauer and Pollock (1993) reported a U-Pb age of 1630 to 1653 Ma from zircon initially obtained by Shastri (1993). Brookins (1982a) reported a whole-rock Rb-Sr age for the Sepultura granite of 1350 ±106 Ma. However, based on the relationships reported by and age obtained by Shastri (1993), this age is interpreted as a metamorphic age. The Sepultura pluton contains a northeast-southwest foliation defined by micas (Shastri, 1993). As with the Los Piños pluton to the north, contact relationships between the Sepultura pluton and adjacent country rock are not well defined due to weathering and limited exposure of the aureole (Beers, 1976).

1450 Ma Plutonism: Ferroan magmatism and intracontinental deformation

Debate surrounding the relative importance of 1.65 versus 1.45 tectonism has been ongoing since the mid-1980s. Initially, 1.45 Ga magmatism in New Mexico was considered to be anorogenic, with mantle processes driving thermally controlled melting of continental crust and only diffuse deformation recognized immediately surrounding the plutons (Anderson and Bender, 1989). However, with more detailed mapping and structural analysis of the Sandia granite and the Priest pluton, and compilation of $^{40}Ar/^{39}Ar$ thermochronologic data from amphiboles and micas in the mid-to-late 1990s (Karlstrom et al., 1997), it became clear that the "anorogenic" label for this event was no longer appropriate (Kirby et al., 1995a, b; Timmons et al., 1995; Thompson et al., 1996; Brown et al., 1999; Shaw et al., 2005). This suggested the need to reconcile the "A-type" composition of the 1.4 Ga plutons, previously interpreted as solely occurring in anorogenic or extensional terranes (Anderson and Bender, 1989; Frost and Frost, 2011), with better understandings of the nature of the proposed 1.4 Ga tectonism (Kirby et al., 1995a, b; Thompson et al., 1996; Karlstrom et al., 2004).

Sandia granite

The Sandia granite is the most prominently exposed pluton in the SMP block, with almost 1.5 km of vertically exposed

granite along the eastern flank of the Rio Grande rift (Karlstrom et al., 1999b). Part of the contact aureole of the pluton is preserved at the northern end and another part is exposed at the southern end (Vernon, 1987; Timmons et al., 1995). Brookins (1982a) reported a Rb-Sr whole rock age of 1440±40 Ma, Kirby et al. (1995b) recalculated older U-Pb zircon analyses as 1437±37 Ma (Karlstrom et al., 2004), and a new ICPMS U-Pb age of 1453±12 Ma is reported by Holland et al. (this volume) (Fig. 1). Brookins (1982b) mapped the Sandia granite as two synchronous plutons, the north and south Sandia pluton, but this was not confirmed by later studies that considered it as a single, contiguous body that is chemically and petrologically heterogeneous (Kirby et al., 1995a).

Compositionally, the Sandia granite has several distinct phases. The primary phase is monzogranite, with a secondary phase of granodiorite (Kirby et al., 1995b). In addition to these two more significant phases, Kelley and Northrop (1975) discuss several outcrops of orbicular granite near the northwest margin of the pluton, while Affholter and Lambert (1982) describe occurrences of this rock type in isolated sections throughout the western and southern margins of the granite. Affholter and Lambert (1982) suggested that this texture was the result of fractionation of H_2O-vapor rich phases of the magma, likely during later phases of crystallization. Both the primary and secondary phases contain abundant enclaves of diorite that are thought to be co-mingled melts. Condie and Budding (1979) described the average exposure of the Sandia granite as pink to gray, medium-to-coarse grained, monzogranite with common aplite and pegmatite dikes that are crosscut by quartz veins. The average modal mineralogy is as follows: 28% quartz, 25% potassium feldspar, 38% plagioclase, 8% biotite (local abundances of biotite are as high 20%), and 1% accessory minerals (Affholter and Lambert, 1982). Common accessory minerals are magnetite, titanite, zircon, hornblende, apatite, and muscovite. Reaction textures of note are perthitic potassium feldspar megacrysts of up to 6 cm in length (Affholter and Lambert, 1982).

Kirby et al. (1995a) indicated that there were at least three generations of deformation preserved in the contact aureole that are consistent regionally and indicate deformation on a larger scale than would be required for accommodation of the pluton. Additionally, Kirby et al. (1995a) presented $^{40}Ar/^{39}Ar$ data that indicate a regional heat flow that resulted in resetting of the whole? rock Ar system at approximately 1450 Ma. A second paper by Kirby et al. (1995b) presented structural relationships from throughout the pluton, its aureole, and the Seven Springs shear zone south of the pluton contained a persistent microstructural features and both magmatic and metamorphic foliations that indicated east-west compressional stresses and north-south extensional stresses during and shortly after pluton emplacement.

The contact aureole of the Sandia pluton is well exposed in the northern Sandia Mountains. Andronicos (1995) noted that early (possibly Paleoproterozoic) fabrics include lineated kyanite, deformed chloritoid, and these fabrics were crosscut by the pluton. Notably absent from the aureole assemblage is staurolite, which is present in the aureole of the Priest pluton

to the south and suggests a shallower level of emplacement for the Sandia pluton. Heat from pluton emplacement is interpreted to have caused growth of andalusite and sillimanite with increase in temperature toward the pluton and anatectic migmatites within tens of meters of the contact. Mineral assemblages suggest a P-T path during pluton emplacement involving heating to ~650°C at pressures of 2-3 kbars (7-10 km depth). Aureole rocks record intense fabric development suggestive of transpressive deformation but pluton interiors are undeformed suggesting that ~1.45 Ga solid state deformation in the aureole was accompanied by magmatic flow in the pluton.

The Priest pluton

The Priest pluton lies in the southern Manzano Mountains, with its northern contact aureole exposed on the west (Estadio Canyon), north, and south, near Abo Pass (Bauer, 1982). Bauer et al. (1993) reported a U-Pb age of 1427±10 Ma for the Priest pluton. Holland et al. (this volume) report a newer U-Pb LA-ICPMS age of 1455±13 Ma (Fig. 1). This new age is preferred because it agrees with coarse muscovite $^{40}Ar/^{39}Ar$ ages from Gaston (2014). This implies that the Sandia Granite and Priest Pluton are both very similar in age at ~1.46-1.45 Ga.

The composition of the pluton is described as a light pink to gray, coarse-grained to megacrystic, peraluminous, two-mica bearing, porphyritic quartz monzonite with isolated zones closer to granodiorite in composition (Condie and Budding, 1979; Thompson and Barnes, 1999). Average modal mineralogy for the Priest is described as follows: 38% potassium feldspar, 23% plagioclase (Ab_{92}), 30% quartz, 3% muscovite, 4% biotite, and 1% accessory minerals (Stark, 1956; Condie and Budding, 1979; Thompson et al., 1999). Common accessory minerals are magnetite, apatite, and zircon. Textures of interest include poikilitic quartz and biotite, and frequent microcline megacrysts (Condie and Budding, 1979). The unit is described as having two well-defined foliations, a primary NE-dipping fabric defined by magmatic alignment of feldspar phenocrysts, and a weaker solid-state foliation defined by alignment of biotite and quartz (Thompson et al., 1999).

Contact relationships indicate that the Priest pluton intruded into the Blue Springs and Sevilleta Formations at temperatures locally greater than 700°C and pressures near 3-5 kbars (Thompson et al., 1996). These conditions are consistent with country rock assemblage conditions in these formations outside of the aureole, which are reported to be between 400°C and 540°C at pressures nearing 4 kbars (Thompson et al., 1996). These conditions appear to reflect a higher temperature and pressure than conditions found in the aureoles of the 1.65 Ga plutons. The higher pressure and temperature recorded in the 1450 Ma suite are interpreted to result from emplacement in an orogenic thrust belt associated with the 1.45 Ga Picuris orogeny.

DISCUSSION

Plutons of the SMP block reveal episodes of syntectonic middle crustal plutonism at 1.66-1.65 Ga and again at 1.46-1.45 Ga during regional Mazatzal and Picuris contractional orogenic events. The earlier 1.65 Ga plutonism involved mainly calc-al-

kaline granodiorites and granites, and we envision this as a single 1.66-1.65 Ga magmatic-plutonic complex. This episode was temporally associated with and is perhaps cogenetic with bimodal 1.66 Ga mafic and rhyolitic volcanic tuffs and flows. The plutons intrude both the lower volcanic rocks of the Manzano Group and also the quartzites suggesting shallow volcanic and basinal rocks were buried by thrusting before and during 1.66- 1.65 Ga pluton emplacement. Because the best dated metasedimentary rocks are <5 Ma older than the plutons that intrude them (Shastri, 1993), this requires relatively rapid burial of these successions to depths approaching 5-10 km. The 1.66-1.65 Ga plutons contain the regional penetrative S2 foliation (Condie and Budding, 1979; Kirby et al., 1995a; Timmons et al., 1995; Brown et al, 1999; Ferguson et al., 1999), and syntectonic aureoles suggest present exposures formed at 2-3 kbars (7-10 km depths) accompanied by regional resetting of the $^{40}Ar/^{39}Ar$ system at 1.45 Ga. These rocks are consistent with the geochemical constraints implied by Condie (1978), who argued that the high-Ca nature of these rocks is consistent with partial melting of siliceous granulite facies country rock with limited components of amphibole and no presence of garnet. The exception to this is the Ojito pluton, which contains a zone of quartz gabbro that suggests parentage from a more mafic source than that of the other, two-mica bearing plutons from the 1.65 Ga suite (Condie and Budding, 1979).

While Condie (1978) interpreted the granitic rocks of the SMP block to fall into the same high-Ca group of similar origin, the 1.46-1.45 Ga plutons are distinctly different in composition from the 1.65 plutons and belong to a class of A-type or ferroan granites that are widespread across the Southwest at this time. These rocks have Fe, K, and Al enrichment, interpreted to be due to syntectonic assimilation of continental crust by anhydrous partial melting of thickened continental lithosphere and incorporation of melt from the upper-most mantle (Frost and Frost, 2011) rather than hydrous melting in a subduction setting. The presence of mafic enclaves in these plutons and the peraluminous nature of the Priest pluton (Thompson and Barnes, 1999) is compatible with petrogenetic models involving mafic underplating of the crust by mantle partial melt and resulting crustal melting and differentiation that is interpreted as a means of generating "A-type" plutons in subduction-related orogenic settings (Frost and Frost, 2011).

The extent of regional penetrative deformation, varying grades of metamorphism, and resetting of $^{40}Ar/^{39}Ar$ ages around 1.45 Ga indicate that the 1.45 Ga plutons were emplaced during regional metamorphism and deformation associated with the Picuris orogeny. Both the Sandia Pluton (Vernon, 1986; Kirby et al., 1995a; Andronicos, 1995) and Priest Pluton (Thompson and Barnes, 1999) are considered to be syntectonic plutons emplaced at 2-4 kbars corresponding to depths of 7-12 km. Our interpretation is that these plutons perforated the already assembled crust of the Mazatzal province (Magnani et al., 2004), which is supported by a lack of detritus or volcanics of similar age preserved in the region (Karlstrom et al., 2004).

The contrast between the 1.65 Ga and 1.45 Ga plutonic suites has significant implications for timing and assembly of the North American continent during the Proterozoic. One pri-

mary observation is that each event records emplacement of plutons in varying P-T space, with the 1.65 Ga event occurring at shallower pressures and temperatures that the 1.45 Ga event (2-3 kbar and ~600°C for the 1.65 Ga plutons versus 3-5 kbar and 650-700°C for the 1.45 Ga event) (Andronicos, 1995; Thompson et al., 1996; Brown, 1999; Thompson and Barnes, 1999). This supports regional crustal thickening and prolonged residence at middle-crustal depths between 1.65 and 1.45 Ga with exhumation of these units occurring later than the 1.45 Ga magmatic event (Williams and Karlstrom, 1996) and is consistent with the models suggesting juvenile terrane accretion across southwest Laurentia through 1.6 Ga (Karlstrom et al., 2004; Grambling et al., 2015; Karlstrom et al., this volume).

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Chevron folds from Estadio Canyon.
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