Polyphase Proterozoic deformation in the Four Peaks area, central Arizona, and relevance for the Mazatzal orogeny

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ABSTRACT

For more than 25 yr, the Mazatzal orogeny has been a central component of virtually all tectonic models involving the Proterozoic rocks of the southwestern United States. Recent recognition that some sedimentary sequences and some major structures are Mesoproterozoic rather than Paleoproterozoic has led to new questions about the nature, even the existence, of the Mazatzal orogeny. This study aims to clarify the relationship between Mazatzal (ca. 1.65 Ga) and Picuris (ca. 1.45 Ga) orogenic activity. New U-Pb geochronology of variably deformed igneous and metasedimentary rocks constrains several periods of deformation at ca. 1.68 Ga, 1.66 Ga, and 1.49–1.45 Ga in the Four Peaks area of central Arizona. Detrital zircon analyses and field relationships indicate the deposition of a rhyolite-sandstone-shale assemblage at ca. 1.660 Ga with renewed deposition at 1.502–1.490 Ga and a significant disconformity, but no recognized angular unconformity, between these episodes. Three populations of monazite growth at 1.484 ± 0.003 Ga, 1.467 ± 0.004 Ga, and 1.457 ± 0.006 Ga indicate prolonged Mesoproterozoic metamorphism. The ca. 1.485 Ga population is associated with the formation of the Four Peaks syncline during Mesoproterozoic orogenesis and subsequent amphibolite-facies contact metamorphism. Rocks in the Four Peaks area record polyphase deformation, sedimentation, and plutonism from the Paleoproterozoic to Mesoproterozoic. Hf-isotopic data suggest the involvement of older, nonjuvenile crust. In this area, effects of the Mazatzal (ca. 1.65 Ga) and Picuris orogenies (ca. 1.49–1.45 Ga) are entwined and involved sedimentation, deformation, pluton emplacement, and pluton-enhanced metamorphism.

INTRODUCTION

Proterozoic orogenic belts (1.8–1.0 Ga) define a 1000-km-wide swath across southern North America and underlie much of the lower 48 United States. For more than 25 yr, the southward growth of the Laurentian continent has been interpreted in terms of successive accretionary orogenic events, incrementally adding juvenile (and some continental) material to the long-lived plate margin (Fig. 1; Karlstrom and Bowring, 1988; Karlstrom et al., 2001; Whitmeyer and Karlstrom, 2007). Three main crustal age provinces account for much of the growth. They are defined by crystallization age of exposed rocks, and the Nd and Hf isotopic character of plutons, which provides an indication of the bulk crustal age. These provinces include the 1.80–1.70 Ga Yavapai Province, the 1.70–1.60 Ga Mazatzal Province, and the 1.50–1.35 Ga Granite-Rhyolite Province. The assembly of each crustal age province is thought to correspond to distinct orogenic episodes, referred to as the Yavapai (1.71–1.68 Ga), Mazatzal (1.66–1.60 Ga), and Picuris orogenies (1.49–1.45 Ga), respectively. The combined provinces have been interpreted to document punctuated episodes within a long-lived convergent plate margin along southern Laurentia (Karlstrom et al., 2001) that culminated with the ca. 1.2–1.0 Ga Grenville orogeny and the final assembly of the supercontinent Rodinia.

Several new data sets provide major challenges to elements of this model for sequential southward continental growth, particularly, the timing of accretion and major orogenic events. New U-Pb-zircon ages (detrital and ash layers) from New Mexico (Jones et al., 2011; Daniel et al., 2013) and Arizona (Doe et al., 2012a, 2012b, 2013; Bristol et al., 2014) have identified younger (1.502–1.45 Ga) depositional successions within the Mazatzal and southern Yavapai Provinces. These rocks form the upper parts of sequences previously thought to be entirely Paleoproterozoic (i.e., the Hess Canyon Group of Arizona and Hondo Group of New Mexico) and part of the cover sequence interpreted to separate the Yavapai and Mazatzal orogenies (i.e., the Hondo Group of New Mexico). Thus, the upper parts of at least some “Mazatzal-age” sedimentary successions are actually Mesoproterozoic (1.50–1.48 Ga) in age. Importantly, no angular unconformities have yet been recognized, and some regional structures involve both the lower (Paleoproterozoic) and upper (Mesoproterozoic) parts of the sections. This has been interpreted to suggest that some, and perhaps much, of the deformation and metamorphism previously attributed to the Mazatzal orogeny is Mesoproterozoic in age and may correspond with the newly named Picuris orogeny (Daniel et al., 2012a, 2012b, 2013). These recent data raise questions about the extent of 1.7–1.6 Ga juvenile crust (Mazatzal crustal province), 1.70–1.60 Ga sedimentary sequences (Mazatzal basins), and the nature of the ca. 1.68–1.60 Ga Mazatzal deformation and metamorphism (Mazatzal orogeny) and the way in which Mesoproterozoic orogenesis overprints these.

Models for the growth of Laurentia and paleogeographic reconstructions critically depend on a clarified understanding of the relative importance of
the Mesoproterozoic and Paleoproterozoic tectonism (Picuris, Mazatzal, and Yavapai orogenies). Proterozoic crustal age provinces have been correlated across Laurentia (Holm et al., 1998, 2005; Whitmeyer and Karlstrom, 2007; Jones et al., 2013) and are used as pinning points for supercontinent reconstructions (Karlstrom et al., 1999, 2001; Burrett and Berry, 2000; Betts et al., 2008; Li et al., 2008; Betts et al., 2011). The spatial and temporal transitions among the Yavapai, Mazatzal, and Picuris orogenies are particularly important (Shaw and Karlstrom, 1999), as are the extent and significance of older crustal components within what have been considered to be dominantly juvenile crustal provinces (Bickford and Hill, 2007; Karlstrom et al., 2007).

The purpose of this paper is to summarize relationships and constraints from one of the classic, but now questionable, exposures of Mazatzal stratigraphy and Mazatzal tectonism. The Four Peaks area (Fig. 2) is south of the proposed boundary of the Yavapai and Mazatzal crustal provinces, the Slate Creek shear zone (Labrenze and Karlstrom, 1991), in central Arizona. Our new data show that, at Four Peaks, an ~1.5-km-thick section of Proterozoic metasediments includes a lower Paleoproterozoic and an upper Mesoproterozoic component. The metasedimentary section is folded into a kilometer-scale, overturned, north-verging syncline (Estrada, 1987; Fig. 3) similar to other folds and thrusts of the Mazatzal Group and related successions (Wilson, 1939). The metasedimentary and metavolcanic rocks are presently surrounded by a sea of variably deformed plutonic rocks, which we use to place constraints on the age of sedimentation and tectonism. New detrital and igneous zircon geochronologic data, coupled with field relationships, show components of both Mesoproterozoic and Paleoproterozoic age in the Four Peaks area (Fig. 2) is south of the proposed boundary of the Yavapai and Mazatzal crustal provinces, the Slate Creek shear zone (Labrenze and Karlstrom, 1991), in central Arizona. Our new data show that, at Four Peaks, an ~1.5-km-thick section of Proterozoic metasediments includes a lower Paleoproterozoic and an upper Mesoproterozoic component. The metasedimentary section is folded into a kilometer-scale, overturned, north-verging syncline (Estrada, 1987; Fig. 3) similar to other folds and thrusts of the Mazatzal Group and related successions (Wilson, 1939). The metasedimentary and metavolcanic rocks are presently surrounded by a sea of variably deformed plutonic rocks, which we use to place constraints on the age of sedimentation and tectonism. New detrital and igneous zircon geochronologic data, coupled with field relationships, show components of both Mesoproterozoic and Paleoproterozoic age.
proterozoic and Paleoproterozoic tectonism. In addition, new Hf isotopic data from Mazatzal-age (1.70–1.60 Ga) plutons from this area suggest the granites were derived from an underlying pre-Mazatzal-age (pre–1.7 Ga) crust. Our ultimate goal is to build a new model for Proterozoic accretionary orogenesis in Arizona that accommodates both the new and the long-standing constraints and, thus, can serve as a template for a refined understanding of North American continental growth.

**BACKGROUND**

Paleoproterozoic and Mesoproterozoic tectonism has been documented across the North American continent. Beginning at ca. 1.8 Ga, the Laurentian craton rapidly grew southward by the addition of juvenile crust and older crustal components in a series of orogenic events. The rocks that record this growth are divided into several provinces on the basis of age and isotopic characteris-
tics (Fig. 1; Condie, 1986; Reed et al., 1987; Karlstrom et al., 1987; Bennett and DePaolo, 1987; Hoffman, 1989). The Penokean Province represents terrane accretion from 1.875 to 1.835 Ga and is exposed in the midcontinent, Great Lakes region (Van Schmus, 1976; Holm et al. 2005, 2007). The 1.80–1.70 Ga Yavapai Province formed by the accretion of largely juvenile materials, although the presence of some older crust in the subsurface is suggested by isotopic studies (Bennett and DePaolo, 1987) and inherited zircon (Hill and Bickford, 2001). The associated Yavapai orogeny peaked at 1.71–1.68 Ga (Whitmeyer and Karlstrom, 2007). The 1.7–1.6 Ga Mazatzal Province includes granitic plutons as well as supracrustal successions and is also considered to be dominantly juvenile (Bennett and DePaolo, 1987; Wooden and DeWitt, 1991). Thick rhyolite and quartzite sequences are characteristic (Whitmeyer and Karlstrom, 2007) and are interpreted as fill basins built on existing accreted crust via mechanisms of upper-plate extension due to slab roll back (Jones et al., 2009). The Mazatzal crustal province is correlated with crust of similar age in northeastern Canada, known as the Labradorian Province (Fig. 1; Gower et al., 1997; Whitmeyer and Karlstrom, 2007; Hynes and Rivers, 2010). The ca. 1.5–1.35 Ga Granite-Rhyolite Province includes potentially large domains of juvenile crust south of the Missouri Line (Van Schmus et al., 1993, 1996; Slagstad et al., 2009; Whitmeyer and Karlstrom, 2007; Bickford et al., 2015). Evidence for ca. 1.45 Ga crust formation and tectonism also exists in the Grenville Province of Ontario and is there termed the Pinwarian orogeny (1.5–1.45 Ga; Wasteneys et al., 1997). A voluminous suite of ferroan granites intruded across the older Laurentian provinces at 1.48–1.35 Ga (Anderson and Morrison, 2005; Goode and Vervoort, 2006; Bickford et al., 2015) and was associated with regional metamorphism and localized deformation in the southwestern United States (Grambling et al., 1989; Grambling and Dalmeyer, 1993; Nyman et al., 1994; Kirby et al., 1995; Williams and Karlstrom, 1996; Shaw et al., 2005).

The Mazatzal orogeny is thought to represent the 1.66–1.60 Ga amalgamation and deformation of the Mazatzal Province. It was originally proposed by Silver (1965) after Wilson’s (1939) “Mazatzal revolution,” which ascribed all of the penetrative deformation of Proterozoic rocks, including older greenstone successions, to a single event (Karlstrom and Bowring, 1988). This orogeny is characterized by fold-and-thrust–style deformation, penetrative shortening, and low- to medium-grade metamorphism (Wilson, 1939; Puls, 1986; Doe and Karlstrom, 1991; Williams, 1991a, 1991b; Williams and Karlstrom, 1996; Williams et al., 1999). The timing of deformation has been constrained to 1.660–1.600 Ga based on data from across Arizona and New Mexico (Silver, 1978; Labrenze and Karlstrom, 1991; Bauer and Williams, 1994; Brown et al., 1999; Shaw et al., 2001; Eisele and Isachsen, 2001; Amato et al., 2008), with some variation therein. These constraints are based primarily on dated 1.66–1.60 Ga intrusions cross-cutting deformation structures and fabrics. Deformation and magmatism far-
The current model for the timing and nature of the Mazatzal orogeny has been complicated by the recognition of younger sedimentary sequences within the Mazatzal Province of Arizona and New Mexico (Jones et al., 2011; Doe et al., 2012a; Daniel et al., 2013; Doe, 2014). For example, metatuffs interlayered with siliciclastics from the lower Yankee Joe Group of the upper Salt River Canyon, Arizona, are dated at 1.502–1.479 Ga (Bristol et al., 2014). Deposition and deformation of the Yankee Joe Group were previously interpreted as Paleoproterozoic (Trevena, 1979). In the northern Mazatzal Mountains, the Hopi Springs Shale is deposited on the Mazatzal Peak Quartzite (Doe, 1991; for alternative interpretation, see Puls, 1986; Cox et al., 2002). New detrital zircon data collected from lower Hopi Springs Shale suggest a maximum depositional age of ca. 1.571 Ga (Doe, 2014). The Hopi Springs Shale appears to be folded and thrust beneath Mazatzal Peak Quartzite, and this is interpreted to be Mazatzal deformation. In north-central New Mexico, metatuff layers from the Pilar Formation in the Picuris Mountains yielded similar, near-concordant U-Pb zircon ages ranging from 1.504 to 1.479 Ga (Daniel et al., 2013).

Tectonism at ca. 1.45 Ga has largely been thought to consist of widespread metamorphism (Karlstrom et al., 1997) and deformation localized around plutons (Nyman and Karlstrom, 1997; Karlstrom and Humphreys, 1998). Although ca. 1.4 Ga plutons were initially considered anorogenic (Anderson and Bender, 1989), it was later shown that regionally significant deformation occurred during the Mesoproterozoic (Grambling and Dallmeyer, 1993; Nyman et al., 1994; Kirby et al., 1995; Karlstrom and Humphreys, 1998; Daniel and Pyle, 2006). Additionally, Daniel and Pyle (2006) found no evidence of ca. 1.65 Ga deformation in the Picuris Mountains. The recognition of large-scale structures in Mesoproterozoic metasedimentary rocks, but not in 1.45 Ga plutons, constrains Picuris orogenesis to 1.49–1.45 Ga (Daniel et al., 2013). Some models proposed the Picuris orogeny to represent significant ca. 1.45 Ga intracratonic metamorphism (Shaw et al., 2005) and deformation (Whitmeyer and Karlstrom, 2007) well inboard from a 1.5–1.4 Ga accretionary boundary. Others (Daniel et al., 2013, their fig. 10C) suggested that the 1.49–1.46 Ga Mesoproterozoic strata were deposited above undeformed Paleoproterozoic sediments, and then both were deformed at 1.46–1.40 Ga during final suturing of Mazatzal Province crust to the southern margin of Laurentia. In the former model, the Mazatzal crustal province was already part of Laurentia by 1.6 Ga; in the latter model, the Mazatzal crustal province (Fig. 1) could have been exotic to North America until 1.46 Ga.

The Tonto Basin area of central Arizona, where the Four Peaks Wilderness of the southern Mazatzal Mountains is located, is an important location for studying the Proterozoic tectonism of southern Laurentia. The nearby northern Mazatzal Mountains expose a fold-and-thrust system that is interpreted as the foreland system of the Mazatzal orogeny (Doe and Karlstrom, 1991). The Slate Creek shear zone, exposed in this area, has been proposed as a major crustal boundary, juxtaposing younger (1.66–1.63 Ga), higher-grade crust in the SE against older (pre–1.7 Ga), lower-grade crust to the NW. Significant work has been done on the stratigraphy, sedimentology, and structural geology of the Proterozoic metasedimentary rocks of the Tonto Basin from 1.729 Ga Payson Ophiolite through the ca. 1.330 Ga Apache Group (Darton, 1925; Wilson, 1939; Gastil, 1958; Ludwig, 1974; Cuffney, 1977; Trevena, 1979; Anderson and Wirth, 1981; Hall-Burr, 1981; Vance, 1983; Alvis, 1984; Puls, 1986; Sherlock, 1986; Roller, 1987; Wrucke and Conway, 1987; Brady, 1987; Bayne and Middleton, 1987; Conway and Silver, 1988; Doe and Karlstrom, 1991; Doe, 1991, 2014; Labrenze and Karlstrom, 1991; Labrenze, 1990; Sherlock and Karlstrom, 1991; Wessels and Karlstrom, 1991; Dann, 1991, 1997, 2004; Stewart et al., 2001; Cox et al., 2002; Doe et al., 2012a, 2012b, 2013). The Mazatzal quartzite of the upper Tonto Basin Supergroup is broadly correlated with the Ortega Quartzite of northern New Mexico and the Uncompahgre Quartzite of Colorado. Most recently, significant sequences of deformed Mesoproterozoic sediments have been recognized within folded bedding beneath thrust sheets in the northern Mazatzal Mountains and folded beds along the Salt River Canyon, ~50 km east of the Four Peaks (Doe et al., 2012a, 2012b; Doe, 2014), raising questions about the timing of regional deformations.

The geology of the Four Peaks area (Fig. 2) consists of a kilometer-scale, doubly inward-plunging syncline of Proterozoic metasedimentary rocks (Fig. 3) that are interpreted as members of the Mazatzal Group (Estrada, 1987; Powicki, 1996). The syncline is interpreted as a roof pendant in a large volume of granitic rocks (Wilson, 1939; Estrada, 1987). A major, 12-km-wide, thrust-sense shear zone was proposed adjacent to the southern limb of the syncline (Powicki, 1996), although subsequent work (Skotnicki, 2000) has questioned the regional significance of the shear zone. Previous workers have attributed the major structures present in the Four Peaks area to Mazatzal-age deformation (Estrada, 1987; Powicki, 1996).

METHODS

Previous geologic mapping and stratigraphic analysis of rocks in the Four Peaks area were carried out by Estrada (1987), Powicki (1996), and Skotnicki (2000). Our new field research focused on key contact relationships between supracrustal and intrusive rock units, and on structural analysis.

U-Pb dating of detrital and igneous zircon was carried out at the University of Arizona LaserChron Center using a laser ablation–inductively coupled plasma–multicollector mass spectrometer (LA-ICP-MS). Analytical methods followed that of Gehrels et al. (2008). U-Th-Pb isotopic data were manually filtered based on U concentration, U/Th ratio, and concordance using the Age-Pick program (Gehrels, 2009). Only zircon grains that were 80%–105% concordant were included in final age calculations. Crystallization ages for igneous samples were interpreted from a weighted mean of ages determined to be cognetic based on these parameters. All uncertainties are given at 2σ and include all internal and external errors (the ages in Supplemental Table 1 are reported at 1σ). Detrital zircon age peaks were also determined with the Age-
Hf isotopic analysis of selected zircon grains was also carried out at the University of Arizona LaserChron Center, following the methods detailed in Gehrels and Pecha (2014). Grains were selected for Hf isotopic analysis on the basis of concordance and uncertainty in their U-Pb ages. The \( t_{ew} \) values were determined using the \(^{176}\text{Lu} \) decay constant of Scherer et al. (2001), the depleted mantle array of Vervoort and Blischot-Toft (1999), and the bulk silicate earth composition of Bouvier et al. (2008). All Hf isotope data are in Supplemental Table 2.3

Monazite was analyzed at the University of Massachusetts by electron probe microanalysis (EPMA). Monazite was identified from full thin section wavelength-dispersive spectrometry (WDS) compositional maps of Ce-La X-ray intensity on a Cameca SX-50 electron microprobe. Individual monazite grains were then mapped at high resolution for U, Th, Y, Ca, and Nd to identify compositional domains that might relate to generations of monazite growth. Selected monazite domains were analyzed on the Ultrachron electron microprobe using the methods of Williams et al. (2006) and Dumond et al. (2008). Monazite ages reported herein do not include systematic uncertainties from the electron probe microanalysis.

### RESULTS

#### Stratigraphic Relationships

Supracrustal rocks in the Four Peaks area include a basal rhyolite overlain by four metasedimentary units (Fig. 4; Powicki, 1996; Skotnicki, 2000). The rhyolite is exposed in two large bodies southwest and southeast of the Four Peaks syncline (Fig. 2). Smaller bodies of the rhyolite are consistently found below the lowermost sedimentary unit (lower quartzite), particularly on the northern limb of the syncline (smaller than map scale). The rhyolite consists of fine-grained quartz, muscovite, and plagioclase with minor oxides. Quartz “eyes” and, more rarely, plagioclase phenocrysts occur as porphyroclasts. It is strongly foliated in most localities, but unfoliated, low-strain exposures, are also present. The stratigraphically higher units are interpreted to be deposited on top of the rhyolite based on the consistent presence of rhyolite below the lower quartzite (Powicki, 1996; Skotnicki, 2000).

The lowermost metasedimentary unit is a thin (0–60 m), extremely pure (up to 99% quartz), basal quartzite (Powicki, 1996), referred to as the lower quartzite. Overlying the lower quartzite, there is a pelitic to psammitic unit, ~450 m thick, (Estrada, 1987; Powicki, 1996), referred to as the lower pelite. On the northern limb of the syncline (smaller than map scale), the rhyolite consists of fine-grained quartz, muscovite, and plagioclase with minor oxides. Quartz “eyes” and, more rarely, plagioclase phenocrysts occur as porphyroclasts. It is strongly foliated in most localities, but unfoliated, low-strain exposures, are also present. The stratigraphically higher units are interpreted to be deposited on top of the rhyolite based on the consistent presence of rhyolite below the lower quartzite (Powicki, 1996; Skotnicki, 2000).

#### Table 1. Detrital and igneous zircon geochronology of the Four Peaks area

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Unit name</th>
<th>UTM NAD 83 coordinates</th>
<th>( N_{\text{total}} )</th>
<th>Min (Ga) ±2σ</th>
<th>Max (Ga) ±2σ</th>
<th>Peak age(s) (Ga)</th>
<th>( N_{\text{peak}} ) ±2σ</th>
<th>Max. depositional age (Ga)</th>
<th>MSWD</th>
</tr>
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<tbody>
<tr>
<td>C13-029a</td>
<td>Four Peaks Quartzite</td>
<td>0469674 E, 3724354 N</td>
<td>91</td>
<td>1.635 ± .075</td>
<td>3.498 ± .008</td>
<td>1.685</td>
<td>7</td>
<td>1.684 ± 0.016</td>
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<tr>
<td>20130916-1</td>
<td>Upper pelite</td>
<td>0470789 E, 3726723 N</td>
<td>94</td>
<td>1.553 ± .017</td>
<td>3.288 ± .019</td>
<td>1.579</td>
<td>8</td>
<td>1.566 ± 0.014</td>
<td>7</td>
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<tr>
<td>K13-4PKS-4</td>
<td>Buckhorn granodiorite</td>
<td>0472773E, 3727262N</td>
<td>30</td>
<td>1.677 ± .014</td>
<td>1.766 ± .014</td>
<td>1.677 ± 0.014</td>
<td>0.39</td>
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<td>K13-4PKS-3</td>
<td>Post-tectonic rhyolite dike</td>
<td>0472773E, 3727262N</td>
<td>16</td>
<td>1.675 ± 0.015</td>
<td>1.766 ± 0.014</td>
<td>1.675 ± 0.015</td>
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<tr>
<td>K13-067b</td>
<td>Young granite</td>
<td>0501728E, 3779024N</td>
<td>18</td>
<td>1.579 ± 0.017</td>
<td>3.263 ± 0.019</td>
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<td>K13-FPKS-14</td>
<td>Granite at Soldier Camp</td>
<td>0468118E, 3729121N</td>
<td>30</td>
<td>15 m below</td>
<td>1.568 ± 0.015</td>
<td>1.568 ± 0.015</td>
<td>0.45</td>
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<tr>
<td>C13-082b</td>
<td>Basal rhyolite</td>
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<td>1.652 ± 0.014</td>
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<td>K13-4PKS-5</td>
<td>Megacrystic granite–Chillcut Tr.</td>
<td>0472760E, 3727509N</td>
<td>22</td>
<td>1.449 ± 0.013</td>
<td>1.562 ± 0.014</td>
<td>1.449 ± 0.013</td>
<td>0.71</td>
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<tr>
<td>C13-073</td>
<td>El Oso granite</td>
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<td>1.766 ± 0.014</td>
<td>1.651 ± 0.021</td>
<td>1.8</td>
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</table>

*Note: MSWD—mean square of weighted deviates; UTM NAD 83—Universal Transverse Mercator North American datum 1983.*
The north side of the Four Peaks syncline, a large area of this unit experienced intense contact metamorphism from the adjacent El Oso Granite and is now a gneissic, and commonly migmatitic, rock. The (200–400-m-thick) Four Peaks Quartzite occurs conformably above the lower pelite. It makes up the resistant ridge and topography of the Four Peaks. The quartzite is an extremely mature, gray to purple, fine-grained and finely cross-bedded quartzite with rare layers of pelitic phyllite to schist (Wilson, 1939; Estrada, 1987; Powicki, 1996). The syncline is cored by an upper pelitic to argillaceous unit, referred to as the upper pelite. The syncline is interpreted to be sharp because it occurs over a narrow interval (as little as 1 m), and no evidence for a gradational contact was seen either above or below the contact region.

Intrusive Rocks

Three intrusive igneous units were distinguished by Powicki (1996) and Skotnicki (2000). The Buckhorn granodiorite (Fig. 5A) is exposed southeast of the Four Peaks syncline (Fig. 2). The granodiorite has two unpublished ages of 1.685 ± 0.004 Ga (Skotnicki, 2000; Isachsen, unpublished data) and 1.669 ± 0.007 Ga (Powicki, 1996). Spencer and Richard (1999) reported that the Buckhorn granodiorite is gradational with other granitic rocks, which are included in the more regionally extensive Buckhorn Creek complex. The contact between Buckhorn granodiorite and the lower quartzite was not observed directly during this study. However, the supracrustal package is interpreted to be deposited on top of the Buckhorn granodiorite because the metasedimentary rocks were deposited on top of the rhyolite, which is younger than the granodiorite (see later herein).

Skotnicki (2000) interpreted the granites exposed west of Four Peaks (his units Xg and Xgm) to be equivalent to the Beeline Granite (1.632 ± 0.003 Ga; Isachsen et al., 1999) of the southwest Mazatzal Mountains (Fig. 5B). However, new data, presented here, suggest that the granite at Four Peaks has an age of ca. 1.660 Ga and thus is probably older than the Beeline Granite. This granite intrudes the lowermost sedimentary units in several places (for example, near Universal Transverse Mercator (UTM NAD 83, zone 12S) 0468165E, 3729082N; see also Skotnicki, 2000). Further, a large block of what appears to be lower quartzite is included in the granite (Mako, 2014). Various granitic rocks occur west and northeast of Four Peaks, probably a greater variety than described in the previous works or this study. For this study, these granites are collectively termed the granites of Soldier Camp. It is possible that the Beeline Granite is represented in the Four Peaks area; however, this remains unsubstantiated by our dating efforts.

The youngest major igneous unit is the El Oso Granite, which is also exposed over a large area of the southern Mazatzal Mountains and is similar to the ca. 1.4 Ga suite of ferroan granites that extend across North America (Fig. 5C; Whitmeyer and Karlstrom, 2007). The granite is distinguishable by the pervasive occurrence of 2–3 cm potassium feldspar megacrysts, a general lack of penetrative foliation, and its crumblily weathered appearance. There is a fine-grained phase of this granite that occurs as dikes and small isolated bodies across the study area. This generation of granite crosscuts all of the other rocks in the Four Peaks area (Skotnicki, 2000; Powicki, 1996). The El Oso Granite exhibits local, meter-scale shear zones, but it is largely undeformed.

Figure 4. Stratigraphic section of the Four Peaks metasedimentary package, modified after Estrada (1987), Powicki (1996), and Skotnicki (2000). Interpreted timing of deposition for each unit is shown on the right. See text for discussion. Lw. Qtzt—lower quartzite.
Figure 5. Relevant field photographs. (A) Typical appearance of foliation in the Buckhorn granodiorite (S1). (B) Typical appearance of foliation in the granites of Soldier Camp (S2) defined by the alignment of biotite. The tip of the pen (bottom center) is aligned with the foliation. (C) The typical texture and appearance of the El Oso Granite. (D) Rhyolitic dikes cutting across foliations in the Buckhorn granodiorite with pen parallel to foliation trace. (E) Isoclinal, intrafolial folds common in the metasedimentary rocks close to the granites of Soldier Camp. These features are suggestive of a bedding-parallel foliation (S3). (F) Folded migmatitic leucosomes. These might indicate that migmatization occurred prior to D4, and during crustal thickening, or that minor folding postdated granite emplacement.
Structural Geology

The Four Peaks area is dominated by a kilometer-scale syncline, the Four Peaks syncline (Fig. 3). It is a tight, doubly plunging (sheath-like) fold verging to the northwest. The stratigraphy on the southern limb is locally overturned and thin relative to the northern limb (Fig. 2; Estrada, 1987; Powicki, 1996). The fold has an axial surface striking 050° and dipping 60°–70°S (Estrada, 1987; Powicki, 1996). The fold is distinctly doubly plunging; the axis plunges to the southwest (55° → 210°) in the northeast and plunges to the northeast (47° → 030°) in the southwestern parts of the area. Axial plane cleavage is generally not present in the quartzite units, but it is present in the more pelitic units. Slatey axial plane cleavage dominates the upper pelite. The orientations of bedding, foliation, and minor structures are similar from the lowest to the youngest sedimentary units, although the minor folds axes in the upper pelite have a shallower plunge and a more northeasterly trend (14° → 057°, n = 4; Fig. 6A) than that of the Four Peaks Quartzite (22° → 074°, n = 9; Fig. 6B; Mako, 2014). The orientation of minor folds and beta axes of bedding from the upper pelite and Four Peaks Quartzite are all similar and lie nearly within the axial planar foliation of the Four Peaks syncline (Fig. 6C). This is relevant to the nature of an unconformity between these units (see later herein).

Mylonitic and locally ultramylonitic fabric is present in a 100–200-m-wide zone along the southern limb of the Four Peaks syncline (see also Powicki, 1996). Lineations in the mylonites plunge moderately east to southeast. Kinematic indicators (mainly sigma porphyroclasts and locally S-C-C′′ zone along the southern limb of the Four Peaks syncline (see also Powicki, 1996; Skotnicki, 2000) found little evidence for shearing and questioned the significance of shear zone associated with the Four Peaks syncline. In contrast, Skotnicki (2000) interpreted the mylonitic fabric along with localized fabrics in the Buckhorn granodiorite as a regionally significant shear zone associated with the Four Peaks syncline. In contrast, Skotnicki (2000) found little evidence for shearing and questioned the significance of shearing or thrusting. Field observations during this study suggest that there is indeed a zone of more intense, thrust-sense, shearing heterogeneously exposed along the southeast margin of the syncline. The presence of both rhyolite and Buckhorn granodiorite on either side of the shear zone suggests that the offset may be relatively small.

Metamorphism

Williams (1991b) concluded that regional metamorphism in the Sunflower tectonic block, including the Four Peaks area, ranged from greenschist to amphibolite facies and that metamorphism occurred at 1.66–1.60 Ga (during the Mazatzal orogeny). As discussed later herein, the metamorphic signature of the Four Peaks area is dominated by a Mesoproterozoic field gradient increasing northward toward the El Oso Granite (Powicki, 1996; Skotnicki, 2000; Mako, 2014). Pelitic rocks in the southern parts of the area have assemblages with quartz, muscovite, biotite, chlorite, and cordierite. Andalusite and cordierite are rarely preserved; typically, the rocks contain muscovite-rich or chlorite-rich pseudomorphs, respectively. Near the El Oso Granite, assemblages include quartz, biotite, and sillimanite, with migmatitic leucosomes locally present in rocks nearest the granite. The zone of migmatitic, sillimanite-grade rocks extends consistently ~1 km away from the El Oso Granite (see map by Skotnicki, 2000). Calculated isothermal phase diagrams for two rocks across the gradient indicate that temperatures ranged from <500 °C to >700 °C, at pressures of 0.3–0.4 GPa, equivalent to 11–15 km depth (Mako, 2014).

It is difficult to constrain the Paleoproterozoic metamorphic character of the Four Peaks area. No contact metamorphic effects associated with the Paleoproterozoic granites of Soldier Camp have been recognized. In places where a direct contact between the granites of Soldier Camp and the metasediments was observed (further from the El Oso Granite), contact metamorphic porphyroblasts are notably absent (see also map in Skotnicki, 2000). The lack of significant contact metamorphism may suggest that the Paleoproterozoic granites were emplaced at relatively shallow depth at cooler ambient temperatures. Rocks in the southernmost parts of the area, farthest from the El Oso Granite, may preserve Paleoproterozoic greenschist-facies conditions, consistent with regional conditions (Williams, 1991b). There is no evidence against Paleoproterozoic metamorphism, but contact metamorphism from the El Oso Granite generally obscures any earlier metamorphism.

Zircon Geochronology and Hf Isotopic Data

New U-Pb and Hf zircon data were obtained from eight samples from the Four Peaks area and one from near Young, Arizona. Seven key igneous rocks that constrain stages of the deformation history were dated. Detrital zircon data from two samples are also reported to constrain the timing of sedimentation (see also Doe, 2014). Samples and results are summarized next and in Table 1. Hf isotopic data from five igneous samples provide insight into the age and isotopic character of the lower-crust melt-source regions for the Paleoproterozoic and Mesoproterozoic intrusions in the Four Peaks region. Results for each analysis are shown in Figure 7 and are given in Supplemental Table 2. Descriptions of each analyzed sample are given next. It should be noted that the apparently short time spans between uplift, sedimentation, and emplacement of the various units are not well resolved given the uncertainties in our geochronology techniques (usually ~15 m.y.).

Isotopic Results

K13-4PKS-4 is a sample of the Buckhorn granodiorite, crosscut by post-tectonic rhyolitic dikes (Fig. 5D; Powicki, 1996). (Samples K13-4PKS-3, 4, and 5 were collected along the Chilicoot Trail.) This sample is composed of plagioclase, quartz, hornblende, and biotite and is pervasively deformed. Thirty zircon grains yield an age of 1.677 ± 0.014 Ga (mean square of weighted deviates [MSWD] = 0.4). This is within the error of both unpublished dates of this granodiorite, 1.685 ± 0.004 Ga and 1.689 ± 0.006 Ga (Skotnicki, 2000; Powicki, 1996, respectively). Hf isotopic analysis of 15 zircon grains yielded εHf(t) values ranging from +10.4 to +4.8. All εHf(t) values overlap with each other within 2σ
uncertainty. One grain yielded a value of +10.4. Others grains are 2–5.5 epsilon units more negative than the depleted mantle array value of +10.3 at 1.677 Ga.

Sample K13-4PKS-3 is from a post-tectonic, rhyolitic dike that cuts foliations (S1) in the Buckhorn granodiorite (Fig. 5D). Dikes at this locality are also deformed by small shear zones but clearly cut the S1 fabric in the host granodiorite. Sixteen zircon grains yielded a weighted mean crystallization age of 1.675 ± 0.015 Ga (MSWD = 1.9). If four of the oldest grains are excluded, the weighted mean is 1.670 ± 0.014 Ga (MSWD = 0.6). It is possible that some of these grains were assimilated from the Buckhorn granodiorite; however, because the grains are not distinct in size, internal texture, morphology, U concentration, or U/Th ratios, and both age determinations are within 2σ uncertainty of each other, the final age calculation includes all of the analyzed grains. Powicki (1996) reported an age of 1.660 Ga for this dike. Hf isotopic analysis of 10 zircon grains yielded $\varepsilon_{Hf}^{(t)}$ values ranging from +9.8 to +3.3. The oldest grains mentioned here did not yield distinct $\varepsilon_{Hf}^{(t)}$ values; five grains ranging in age from 1.695 to 1.668 Ga yielded a tight cluster of $\varepsilon_{Hf}^{(t)}$ values ranging
from +6.9 to +6.1. The $\varepsilon_{Hf}(t)$ values of all grains overlap with each other at the 2σ confidence level, with the exception of the grains K13-4PKS-3-10 and K13-4PKS-3-11, which yielded $\varepsilon_{Hf}(t)$ values of +3.3 and +9.6, respectively. Two of the grains plot within error of the depleted mantle array at 1.670 Ga (+10.3), but the rest of the zircons, with the exception of K13-4PKS-10, yielded $\varepsilon_{Hf}(t)$ values that are 2–4.1 epsilon units less positive than the +10.3 $\varepsilon_{Hf}(t)$ value of the depleted mantle at 1.67 Ga.

C13-082b is a sample of the rhyolite that is interpreted to be the base of the stratigraphic section in the Four Peaks area. The sample exhibits mylonitic to ultramylonitic, northeast-striking fabrics and steeply plunging lineations. Zircon grains were 100–200 µm and tabular to irregular in shape. Twenty-seven zircon grains yielded a crystallization age of 1.657 ± 0.014 Ga (MSWD = 0.4). No Hf isotopic data were collected for this sample.

C13-067B is a sample from the Young granite from near Young, Arizona. This granite is from within the Slate Creek shear zone and was interpreted to be syn- to post-tectonic because it crosscuts strongly foliated metasedimentary rocks (Labrenze and Karlstrom, 1991). No foliation or deformation structures were observed in this particular sample or in the immediate area from which it was taken. A weighted mean of 18 zircon ages yields an age of 1.664 ± 0.017 Ga (MSWD = 0.3). Hf isotopic analysis of 10 zircon grains yielded $\varepsilon_{Hf}(t)$ values ranging from +6.9 to +3.7. All $\varepsilon_{Hf}(t)$ values overlap with each other at 2σ, and they are between 3 and 7 epsilon units below the depleted mantle array value of +10.3 at 1.667 Ga.

C13-029a is a sample of the Four Peaks Quartzite. This sample was collected from the base of the Four Peaks Quartzite, several meters above the contact with the lower pelite. The quartzite consists of ~95% quartz with accessory sericite, oxides, monazite, and zircon. Zircon grains in this sample were small (50–150 µm long) and commonly fragmental. In cathodoluminescence (CL) images, oscillatory zoning and dark cores were very common. Ninety-one detrital zircon ages were obtained. The distribution is dominantly unimodal with peaks at 1.742 and 1.766 Ga (Table 1), and with subsidiary peaks at 1.685 and 1.855 Ga, and ~13 grains in the range 2.5–2.8 Ga. According to Dickinson and Gehrels (2009), the most robust maximum depositional age that can be determined from detrital zircon age data is determined by the weighted mean of at least the three youngest ages that overlap at 2σ. The weighted mean of the three youngest grains in the population is 1.684 ± 0.016 Ga (MSWD = 1.3); however, not all of these grains overlap at 2σ. The weighted mean of the two youngest grains that overlap at 2σ is 1.659 ± 0.039 Ga (MSWD = 0.6), which is more consistent with depositional constraints from the underlying rhyolite (see following). Neither of these maximum depositional ages meet the criterion of Dickinson and Gehrels (2009) exactly, but given that the former estimate includes more grains, the methodologically best maximum depositional age estimate is taken to be 1.684 ± 0.016 Ga. The Four Peaks Quartzite unimodal age spectra are typical of many Proterozoic quartzites in the southwest, including the Ortega Quartzite (New Mexico), and White Ledges Formation and Mazatzal Peak Quartzite (Arizona; Jones et al., 2009; Doe, 2014).

Sample K13-FPKS-14 is from the granites of Soldier Camp (Fig. 2). This sample was from a foliated (S2), biotite-bearing granite. It was mapped close to a contact between the lower quartzite and granites of Soldier Camp by Skotnicki (2000) and was correlated with the 1.632 ± 0.003 Ga (Isachsen et al., 1999)
Beeline Granite. Zircon from this sample yielded an age of 1.667 ± 0.016 Ga (32 grains, MSWD = 2.1). Two grains yielded older ages of 1.715 ± 0.014 Ga and 1.788 ± 0.034 Ga, outside the 2σ error of the population, which we interpret as inherited. If these grains are eliminated, a weighted mean age of 1.658 ± 0.015 Ga (30 grains) is calculated (MSWD = 0.5). Based on these data, this sample of the granites of Soldier Camp, in the Four Peaks area, is distinctly older than the Beeline Granite. HF isotopic analysis of 19 zircon grains yielded ε(t) values ranging from +10.3 to +2.4. This sample yields the greatest spread of ε(t) values of the Paleoproterozoic igneous samples. A cluster of four grains yield ε(t) values between +4.3 and +3.8 at ca. 1.66 Ga, as many as 8.0 epsilon units below the depleted mantle array of +10.4. Zircon K13-FPKS-14-7, with an age of 1.715 ± 0.014 Ma, yielded an ε(t) value of 6.3. Notably, this grain and K13-4PKS-5-1 (see following) yielded U-Pb ages and ε(t) values that overlap at 2σ. It should be noted that this sample was taken close to the metasedimentary rocks, so it is possible that the final age is dominated by assimilated grains, making the granites appear older. However, most zircon from this sample appears euhedral and igneous, not rounded.

K13-4PKS-5 is a sample of megacrystic granite from the Chillcut trail, east of the Four Peaks syncline. This granite is very similar in appearance to the Mesoproterozoic El Oso Granite and is weakly foliated. It was interpreted by Powicki (1996) to be Paleoproterozoic in age, while Skotnicki (2000) considered it Mesoproterozoic. Twenty-two zircon grains yielded an age of 1.655 ± 0.0015 Ga (MSWD = 2.0). One grain (K13-4PKS-5-1) yielded an age of 1.727 ± 0.024 Ga, well outside of the 2σ range of the rest of the population and probably inherited from an older source. If this grain is removed, a final age of 1.652 ± 0.014 Ga (MSWD = 0.4) is calculated. The older grain has a distinct CL-dark overgrowth, which was too small to be analyzed by a 30 μm beam. As shown by Powicki (1996), there are two bodies of Paleoproterozoic granite on either side of the Four Peaks syncline, cut by the large, Mesoproterozoic, El Oso pluton. HF isotopic analysis of 11 zircon grains yielded ε(t) values ranging from +10.4 to +6.2. Two grains gave values of +8.7 and +10.4 and are within error of the depleted mantle array at 1.655 Ga (+10.4). Nine grains plotted in a tight cluster with values of +7.5 to +6.2 and hence are 3–4 epsilon units below the depleted mantle array. K13-4PKS-5 and K13-FPKS-14 are petrologically, iso-topically, and chronologically similar, so they are both regarded as members of the granites of Soldier Camp.

Sample 20130916-1 is a sample of the upper pelite collected by coauthor Doe and was analyzed at the Arizona LaserChron Center (Doe, 2014). The sample was taken from the stratigraphically highest point available in the Four Peaks area in the upper pelite. A probability density plot of detrital zircon ages (94 grains) shows peaks at 1.580 and 1.785 Ga. Minor peaks occur at 1.730 Ga and 1.830 Ga, and several grains yielded Archean ages. The maximum depositional age of the upper pelite, based on the seven youngest zircon grains in the analyzed population, is 1.566 ± 0.014 Ga (Doe, 2014).

C13-073 is a sample of the El Oso Granite. This sample contains large 1–3 cm feldspar phenocrysts, along with quartz and biotite. Zircon grains were 200–300 μm and elongate, with some fractured cores (not analyzed).

Fabric Relationships

Four distinct structural fabrics were identified in the Four Peaks area based on their orientation and probable age, although overprinting relationships among some of the fabrics are not evident. The oldest structural fabric (S1) occurs in the Buckhorn granodiorite, the oldest unit in the study area (ca. 1.680 Ga). It is a heterogeneous, moderate to strongly developed foliation that generally strikes northeast and dips 85–90°SE with a steeply plunging lineation (Fig. 6D; Powicki, 1996; Skotnicki, 2000). The foliation is defined by ribbons of dynamically recrystallized feldspar, aligned biotite, and elongate quartz grains, indicating deformation temperatures of greater than 500 °C (Fig. 5A). Localized protomylonitic to mylonitic shear zones, generally parallel to the S1 foliation, exist throughout the granodiorite, alternating with areas of less intense fabric. S1 foliation formation preceded the intrusion of crosscutting rhythmic dikes (Fig. 5D; 1.675 ± 0.015 Ga).

The granites of Soldier Camp (1.680–1.655 Ga) contain a relatively weak to moderately strong fabric, here termed S2. Most commonly, S2 is defined by the alignment of biotite with a lesser component of aligned quartz and feldspar porphyroclasts. The presence of dynamically recrystallized quartz, observed in thin section, suggests that the fabric is a solid-state rather than symmagmatic fabric. As noted already, several different granite bodies are present in the Sol-
Monazite Geochronology

Monazite was identified in many of the metasedimentary rocks of the Four Peaks area. Much of the monazite was heavily altered, very small, and unsuitable for dating. Monazite was successfully mapped and dated in five samples: three samples of migmatic lower pelite (C13-011-1, C13-012, and C13-013a-1), one sample of Four Peaks Quartzite (C13-036-1), and one sample of the migmatic lower quartzite (C13-056a-1). All of these samples are very close to the contact with the El Oso Granite (<1 km) except for the sample of Four Peaks Quartzite, which was collected ~2 km from the granite. Dated monazite grains range in age from ca. 1.380 to ca. 1.78 Ga, but most dates are 1.49–1.45 Ga (Table 2).

Three different monazite populations can be distinguished within migmatic lower pelite and lower quartzite based on composition and texture. Many grains display high-Th and high-Y cores (population 1) with lower-Th and slightly lower-Y rims (population 2). A third population of grains is characterized by consistently low Th and low Y. Nine dated population 1 domains give...
are stratigraphically continuous with the Four Peaks Quartzite. Thus, the three units (lower quartzite and lower pelite) are intruded by and included within the Soldier Camp granites (1.658 ± 0.015 Ga and 1.652 ± 0.014 Ga). Therefore, the lower sediments were deposited immediately after the rhyolite. The Four Peaks Quartzite has a maximum depositional age of 1.657 ± 0.014 Ga (MSWD = 0.30). Four population 3 domains give a weighted mean age of 1.457 ± 0.005 Ga (4 domains, MSWD = 0.10). These results are summarized in Figure 8.}

Dates from population 1 domains are significantly older than the age of the El Oso Granite (1.449 ± 0.013 Ga), while population 2 just overlaps the granite at 95% confidence. We interpret grains in populations 1 and 2 to have grown during prograde metamorphism before the intrusion of the El Oso Granite. The drop in Th and Y in rocks with little or no garnet may suggest an early phase of partial melting prior to granite intrusion. Population 3 grains overlap in age with the El Oso Granite. We interpret these grains to be the result of crystallization of injected granite melt or fluids related to the El Oso Granite.

As noted already, most of the monazite-bearing samples are very close to the El Oso Granite contact. Monazite grains further away from the granite tend to be heavily altered, have patchy complex compositional zonation, and give inconsistent dates. It is possible that monazite was preserved in higher-temperature rocks near the El Oso Granite but was more extensively altered by late-stage fluids in cooler rocks more distant from the granite (Harlow et al., 2011; Williams et al., 2011).

Two monazite grains from the Four Peaks Quartzite (sample C13-036-1) give Paleoproterozoic ages (1.736 Ga and 1.781 Ga). The rocks also yielded grains and rims in the younger populations (see above). These older domains are interpreted to be detrital monazite cores present within the original quartz sandstone. These are consistent with detrital zircon ages from the same rocks. More extensive detrital monazite analyses from these sediments may provide additional insight into the depositional age and provenance of the sediments and also into possible Paleoproterozoic metamorphism.

### DISCUSSION

#### Timing of Deposition

Our new data provide improved constraints on the age of supracrustal rocks in the Four Peaks area with implications for the timing of tectonism. The whole stratigraphic package, including a basal rhyolite, was deposited on top of the older Buckhorn granodiorite (ca. 1.680 Ga). The rhyolite (1.657 ± 0.014 Ga) represents the base of the stratigraphic section, bracketing the onset of deposition to younger than 1.657 ± 0.014 Ga. The lower two sedimentary units (lower quartzite and lower pelite) are intruded by and included within the granites of Soldier Camp (1.658 ± 0.015 Ga and 1.652 ± 0.014 Ga). Therefore, the lower sediments were deposited immediately after the rhyolite. The Four Peaks Quartzite has a maximum depositional age of 1.659 ± 0.039 Ga or 1.684 ± 0.016 Ga based on detrital zircon data, and the lower quartzite and lower pelite are stratigraphically continuous with the Four Peaks Quartzite. Thus, the three lower sedimentary units were conformably deposited relatively soon after rhyolite deposition at ca. 1.660–1.655 Ga. This is broadly compatible with regional constraints on the timing of Mazatzal Group sedimentation (Doe, 2014). Early workers (Conway and Silver, 1989) interpreted the deposition of the entire Tonto Basin Supergroup to have been 1.710–1.675 Ga. Cox et al. (2002) constrained the age of the Lower Deadman Quartzite (a.k.a. Pine Creek Conglomerate) to ca. 1.70 Ga by dating an overlying rhyolite. Many of the rocks in the Tonto Basin now appear much younger.

The youngest unit in the stratigraphic section (upper pelite) has a maximum depositional age of 1.566 ± 0.014 Ga, based on detrital zircon ages (Doe, 2014). If only data from Four Peaks are considered, the sediments must have been deposited 1.566–1.449 Ga, with the younger constraint being the intrusion of the El Oso Granite (1.449 Ga), but based on regional correlations (see following), the upper limit may be closer to 1.502 Ga. Importantly, if the lower units are older than 1.650 Ga and the upper unit is younger than 1.502 Ma, a significant unconformity or disconformity exists at the upper contact of the Four Peaks Quartzite with a time gap of 100–140 m.y. No angular relationship was observed between the Four Peaks Quartzite and the upper pelite. However, work to date does not preclude the possibility of a subtle angular unconformity between the Four Peaks Quartzite and upper pelite. If there is such an unconformity, the angular difference is relatively minor and may have been diminished during folding (Mako, 2014).
Regional Correlations

Strata at Four Peaks can be directly correlated with rocks of the surrounding Tonto Basin, including the Paleoproterozoic Redmond Formation, Hess Canyon Group, and the Mesoproterozoic Yankee Joe Formation. The 1.657 ± 0.003 Ga Redmond Formation is correlated with the Four Peaks rhyolite. The Four Peaks Quartzite is likely correlatable with the White Ledges Formation (quartzite) of the Hess Canyon Group and with the Mazatzal Peak Quartzite in the northern Mazatzal Mountains (1.660–1.630 Ga; Doe, 2014). However, it is somewhat problematic that the Maverick Shale, beneath the Mazatzal Peak Quartzite, has a maximum depositional age of 1.631 ± 0.022 Ga. This is younger than, but still within error of, the constraints at Four Peaks. The lowermost White Ledges Formation is intercalated with the Redmond Formation (Livingston, 1969), a relationship that was not observed at Four Peaks but is expected to exist given the strength of the correlation. Doe (2014), studying the Proterozoic stratigraphy of the Hess Canyon Group in the nearby Salt River Canyon, correlated the upper pelite at Four Peaks with the Yankee Joe Group and interpreted a depositional age of 1.502–1.490 Ga. The uppermost units of the Yankee Joe Formation have detrital zircon as young as ca. 1.470 Ga (Doe et al., 2013), while the lower units have interbedded ash layers dated at ca. 1.502 Ga (Bristol et al. 2014). Thus, the upper pelite at Four Peaks is probably equivalent to lowermost Yankee Joe Group (Doe, 2014). The contact between the Paleoproterozoic White Ledges Formation and the Yankee Joe Group is a well-exposed disconformity for ~20 km along the upper Salt River Canyon ~50 km to the east of Four Peaks. The apparent lack of an angular unconformity between the Mazatzal and Yankee Joe Groups appears to be a regional feature of that contact.

Magmatic Source and Crustal Evolution

The Mazatzal Province has previously been defined as composed of 1.70–1.60 Ga juvenile arc rocks (Whitmeyer and Karlstrom, 2007; and references therein). However, our new Hf isotopic data suggest some involvement of older crustal material in the petrogenesis of Paleoproterozoic rocks in the Four Peaks region (Fig. 7). Ideally, juvenile contributions would be represented by rocks that yield εHf(t) values equal to the depleted mantle array at the time of crystallization. From our data, 33% (20 zircon grains) of all Paleoproterozoic zircon grains yielded εHf(t) values that overlap with the depleted mantle array at the time of crystallization. The remaining two thirds of Paleoproterozoic zircon grains yielded εHf(t) values that may suggest the involvement of 2.0–1.75 Ga crust (Fig. 7). The nature of older crustal contributions is ambiguous in the data, and results from modern oceanic arcs, which show substantial variability in epsilon Hf space (Dhuime et al., 2011), may not preclude formation of these rocks in a juvenile arc setting. Thus, a conservative interpretation of the data is that the Paleoproterozoic rocks of the Four Peaks region were derived in part from a juvenile source that experienced some mixing with crustal components as old as 2.0 Ga. However, εHf(t) values from the Mesoproterozoic granite dike (K13-FPKS-15) suggest derivation from a ca. 1.75 Ga crustal reservoir (Fig. 7). Combined with the presence of >1.7 Ga xenocrystic zircons in our data set, and Nd isotopic data from Paleoproterozoic gneisses in the southern Mazatzal Province that show similar evidence for 2.0–1.78 Ga crustal components (Amato et al., 2008), these data may suggest that lower crust older than 1.7 Ga is present in the Mazatzal Province.

The evolved εHf(t) values of zircon grains from the Mesoproterozoic granitic dike (K13-FPKS-15) suggest that they were derived primarily from recycling of a Paleoproterozoic crust. These results are in line with previous studies of 1.48–1.35 Ga Laurentian granites (Frost and Frost, 1997; Goode and Vervoort, 2006; Bickford et al., 2015). The apparent 1.85–1.75 Ga model ages of the source region for many of the grains do not fit well with other interpreted crustal ages in Arizona, such as the 1.75 Ga crustal model age for the Jerome region of the Yavapai crust (Doe, 2014), or the Archean model ages seen beneath Mojave crust (Holland et al., 2015). However, the apparent 1.85–1.75 Ga crustal age is compatible with the observed ca. 1.8 Ga Nd model ages obtained from the Payson ophiolite (Dann, 1992) farther north in the Tonto Basin area.

Timing of Deformation

Four distinct deformation fabrics are recognized in the Four Peaks area. The first deformation event (D1) occurred ca. 1.680–1.675 Ga and formed north-east-striking S1 foliations that are present in the Buckhorn granodiorite. The age of this event is constrained by the crystallization age of the granodiorite (1.677 ± 0.014 Ga, 1.685 ± 0.004 Ga) and the age of a rhyolitic dike (1.675 ± 0.015 Ga) that crosscuts the solid-state S1 foliation (Figs. 5A and 5D).

The second episode (D2) formed weak to moderate east-west-striking foliation (S2) in the granites of Soldier Camp, the rhyolite, and the Buckhorn granodiorite. The age of D2 is partially constrained by the ages of a deformed sample K13-FPKS-14 (1.658 ± 0.015 Ga) and low-strain sample K13-4PKS-5 (1.652 ± 0.014 Ga) of granite. Because of the significant variation in fabric intensity from granite to granite, it seems likely that the suite was emplaced syntectonically at ca. 1.660–1.655 Ga. The dates that constrain both D1 and D2 are within uncertainty of one another, but crosscutting relationships clearly separate these fabrics in time. It is possible that the rhyolitic dikes in the granodiorite are related to the larger rhyolite body, and such a relationship would permit that D1 and D2 were a single progressive event. However, the high temperature (feldspar ductility) of S2, and the probably extrusive nature of the rhyolite suggest that there was a period of time (exhumation) between D1 and D2.

The Young granite brackets deformation in the Slate Creek shear zone 50 km to the northeast of the Four Peaks area. Labrenze and Karlstrom (1991) noted that penetrative fabrics in the Slate Creek zone shear are crosscut by the granite, suggesting intrusion was late or postdeformation. Our new Young granite date brackets Slate Creek shear zone deformation to after 1.70 Ga (the age of the deformed Red Rock Rhyolite; Conway and Silver 1989) and before 1.684 ± 0.017 Ga (the crystallization age of the Young granite). The timing and orientation of the Slate Creek shear zone deformation correlate well with D3 in the Four Peaks area.
The absolute age of S3 (bedding-parallel fabric; Fig. 5E) is difficult to resolve because S3 occurs in sedimentary rocks intruded by the granites of Soldier Camp. It is not clear from field evidence whether the granites crosscut S3. Because the lower sedimentary units were deposited by ca. 1.660 Ga, S3 can broadly be constrained to 1.650–1.450 Ga. We entertain three possibilities: (1) S3 may have been roughly synchronous with S2 and reflect deformation partitioning between the granitic and metasedimentary packages. (2) S3 may have been synchronous with S2 and large-scale folding as strain was partitioned around the rheologically stiff granites of Soldier Camp. This would provide an explanation for the absence of northeast-striking fabrics in the granites. (3) S3 may represent penetrative deformation at ca. 1.660–1.655 Ga associated with a regional Mazatzal orogeny.

The youngest and most significant regional deformation event recorded in the Four Peaks area (D4) occurred 1.490–1.450 Ga and resulted in the kilometer-scale Four Peaks syncline. D4 is bracketed between the deposition of the upper pelite (1.502–1.490 Ga) and the intrusion of the El Oso Granite (1.449 ± 0.013 Ga). S4 foliations, spaced cleavage, and slatey axial plane cleavage, especially in the uppermost unit, were formed during this folding event. In the past, this fold was considered a classic Mazatzal (i.e., Paleoproterozoic) structure. The new age constraints from the upper pelite require that the slatey cleavage in the upper units is a Mesoproterozoic fabric. Zones of intense shear south of the Four Peaks syncline probably formed during this event and were related to folding.

Mesoproterozoic (D3) deformation was accompanied by crustal thickening and monazite growth. By the time of intrusion of the El Oso Granite (ca. 1.450 Ga), the metasedimentary rocks in the Four Peaks area had been buried to a depth of 11–15 km, and significant anatexis had occurred in rocks within ~1 km of the El Oso Granite (Mako, 2014). At least one phase of monazite growth preceded the intrusion of the El Oso Granite and thus is attributed to crustal thickening and orogenesis. Small, meter-scale shear zones are present in the El Oso Granite, and monazite growth continued on to ca. 1.400 Ga. Significant tectonism generally ceased in the Four Peaks area by ca. 1.450 Ga.

**Tectonic History—Three Orogenic Cycles Recorded in the Four Peaks Area**

Three cycles of burial–pluton emplacement–deformation–exhumation are recorded in the Four Peaks area. The first cycle involved the emplacement of the ca. 1.680 Ga Buckhorn granodiorite and the production of the S1 foliation. No older host rocks have been recognized, but the medium-grained nature of the granodiorite and the ductile nature of S1 (~500 °C) suggest some significant depth of burial, probably on the order ~10 km. The rocks were exhumed by approximately ca. 1.660 Ga, when the rhyolite and lower three metasedimentary units were deposited. The second cycle involves burial, emplacement of the granites of Soldier Camp (1.658 ± 0.015 Ga), and development of the S2 foliation. D2 is interpreted to have occurred at ca. 1.655 Ga. The formation of S2 foliations may have been part of this event and, if so, could reflect a period of thrusting and tectonic burial. The coarse-grained nature of the granite and the ductile penetrative nature of S2 suggest at least some amount of burial, probably greater than the currently exposed 600–800 m Paleoproterozoic metasedimentary package.

We suggest that burial of at least several kilometers would be required for emplacement of the generally medium-grained granites of Soldier Camp. Between ca. 1.655 Ga and ca. 1.570 Ga (or possibly 1.502 Ga), the Four Peaks area was once again exhumed to the surface. The lack of a recognizable angular unconformity at this time is puzzling.

The third tectonic cycle involved deposition of the (1.502–1.490 Ga) upper pelite, deformation and burial to midcrustal (petrologically constrained, 11–15 km) depths, emplacement of the 1.450 Ga El Oso Granite, and regional metamorphism to at least greenschist facies, with higher temperatures associated with plutons. The Four Peaks syncline was developed at this time, presumably associated with regional thrusting and tectonic burial. The rocks at Four Peaks were exhumed by ca. 1.33 Ma, when the regional deposition of the flat-lying Apache Group sediments occurred (Cuffney, 1977; Stewart et al., 2001). However, the growth of monazite as young as 1.400 Ga suggests that the rocks remained at some depth after 1.450 Ga granite emplacement.

**Testing Alternative Models**

There are a few alternative possibilities to this tectonic history that warrant examination. First, because the contact relationships among the rhyolite, lower quartzite, and Buckhorn granodiorite have not been documented in detail, we consider whether the Paleoproterozoic sedimentary package was actually intruded by the granodiorite. This would make the sedimentary rocks older than the Mazatzal Group (>1.68 Ga), and it would remove one of the “tectonic cycles” from the history. However, the maximum depositional age of the Four Peaks Quartzite is 1.684 ± 0.016 Ga, which would still make the deposition of the sedimentary package rapid. Additionally, rocks of this depositional age are unknown in the Tonto Basin area; the Mazatzal Group was deposited 1.66–1.63 Ga, and the next older Alder Group was deposited 1.72–1.70 Ga (Doe, 2014). The fact that the younger granites of Soldier Camp (1.658 ± 0.015 Ga) intrude the sedimentary package, that the rhyolite (1.657 ± 0.014 Ga) underlies the sedimentary package, and the reasonable correlation with the Hess Canyon Group to the south argue against this alternative model. Additionally, the sedimentary package would have been deformed during D4 at ~500 °C (feldspar plasticity), if the diorite intruded the sediments. High-temperature, localized deformation structures or microstructures (S3; Fig. 5A) in the lower sedimentary units have not been recognized.

We also consider whether the entire sedimentary package at Four Peaks may be Mesoproterozoic in age. Such a situation is permissive based on the detrital zircon data. It is conceivable that during the deposition of the lower sedimentary units, the basin received little or no 1.660–1.490 Ga detritus. Again, however, the granites of Soldier Camp (1.658 ± 0.015 Ga) appear to
intrude the lower parts of the sedimentary section, and the rhyolite appears to form the base of the stratigraphic section. Given the critical nature of this contact relationship, future work should focus on the granites of Soldier Camp. The conundrum of the present data is that there is an apparently continuous stratigraphic section that contains Paleoproterozoic strata (1.66 Ga) at the bottom and Mesoproterozoic strata at the top, with the lower parts of the section intruded by Paleoproterozoic granites.

Readers may notice that the lower sedimentary package is deposited on a 1.657 ± 0.014 Ga rhyolite and intruded by 1.658 ± 0.015 Ga granite, which is problematic if the mean ages are taken as absolute. The relatively large uncertainty (95% confidence) on these ages (~15 m.y.) must be taken into account. Additionally, if the granites of Soldier Camp sample includes a significant number of assimilated detrital zircon grains, this could make the age of the granites appear older (and given the presence of ca. 1.75 Ga grains, this is certainly possible). A correlation with the Beeline Granite may in fact be valid. Clearly, better age constraints are needed for this suite of granites. Additionally, Brady (1987) documented caldera-related rhyolites in the nearby Sheep Basin Mountain area, which might explain the similar age of granite plutons and rhyolites.

Regional Implications: The Mazatzal and Picuris Orogenies and the Mazatzal Province in Southwestern Laurentia

Deformation in central Arizona, including the Tonto Basin region and more specifically the northern Mazatzal Mountains, has generally been associated with the ca. 1.65 Ga Mazatzal orogeny (Karlstrom and Bowring, 1988; Labrenze and Karlstrom, 1991; Eisele and Isachsen, 2001). Recent detrital U-Pb zircon data from both New Mexico and Arizona have suggested that previously unrecognized Mesoproterozoic rocks, disconformably deposited on Paleoproterozoic successions, were deformed by northwest-directed folding and thrusting during Mesoproterozoic time, previously thought to be ca. 1.66 Ga (Labrenze and Karlstrom, 1991; Conway and Silver, 1989). Taken to the extreme, these results led some workers to cast doubt on the very existence of the Mazatzal orogeny (Daniel et al., 2013; Daniel and Pyle, 2006). The large syncline in the Four Peaks area is one such structure, and indeed, data presented here suggest that it formed during the Mesoproterozoic (ca. 1.490–1.460 Ga). Rocks in the Four Peaks area, however, also preserve evidence for two periods of Paleoproterozoic deformation, one at ca. 1.680 Ga and another at ca. 1.660 Ga, or perhaps a continuum of tectonism during this broader time frame. Both of these events fall into the window of Mazatzal tectonism and may represent two stages in a progressive Mazatzal orogeny. D (1.680–1.675 Ga) also overlaps in time with the end of the Yavapai orogeny in the Grand Canyon (Karlstrom et al., 2003). At least two, and possibly three, tectonic foliations in the Four Peaks area are consistent with the Mazatzal orogeny. There is only one foliation generation at Four Peaks that definitively fits within the current 1.660–1.600 Ga Mazatzal orogeny.

Our results require that some elements of the model for Paleoproterozoic tectonism in central Arizona be revised. Classically, it was suggested that the rocks were buried to middle-crustal levels during the Mazatzal orogeny and possibly remained in the midcrust until at least 1.400 Ga (Williams and Karlstrom, 1996). Based on detrital zircon data, the region was exhumed by 1.57–1.50 Ga, when new sediments were deposited. Regional metamorphic grades were probably in the greenschist facies during the Mazatzal orogeny, with higher grades possible near some syntectonic plutons (Williams, 1991b). Our new U-Pb-Hf isotopic data suggest that the Four Peaks region may be underlain by a component of 1.75–2.0 Ga crust that is not directly related either to juvenile Yavapai (1.8–1.7 Ga) or juvenile 1.7–1.6 Ga crust. The age of the crustal source region for the Four Peaks granites is similar to that of granitoids intruded by the Payson ophiolite further north in the Tonto Basin area. The Slate Creek shear zone, which runs between these two locales, has previously been proposed as a crustal age boundary (Wessels and Karlstrom, 1991), but the similarity in crustal age across the shear zone casts doubt on this interpretation and suggests a need for more detailed “mapping” of the Hf characteristics of lower-crustal source regions.

Jones et al. (2009) concluded that thick rhyolite-quartzite packages of northern New Mexico and Colorado were deposited in relatively short-lived syntectonic basins during regional collisional orogenesis. This type of model is consistent with ca. 1.65 Ga Mazatzal orogenesis in the Four Peaks area, where sedimentary deposition appears to have been rapid and closely followed by granite emplacement and deformation. We suggest that the cycles of deposition and tectonism in the Four Peaks area reflect syncollisional basin formation and basin closure events. The fact that no clear angular unconformity has been recognized between Paleoproterozoic and Mesoproterozoic sediments in the Four Peaks or throughout the Tonto Basin area remains an unresolved challenge for models of crustal dynamics in this long-lived accretionary margin.

Significant Mesoproterozoic tectonism has been recognized for several decades as evidence for the age of structures, fabrics, and metamorphic events has emerged throughout southwest Laurentia (Grambling and Dalimeyer, 1993; Nyman et al., 1994; Nyman and Karlstrom, 1997; Williams et al., 1999; Shaw et al., 2001; Amato et al., 2011; Daniel et al., 2013). The Four Peaks area is another example of the importance of more recently recognized Mesoproterozoic sedimentation. The classic fold-and-thrust belt in the Barnhart Canyon area further north in the Mazatzal Mountains (Doe and Karlstrom, 1991) was originally interpreted to have deformed at 1.66–1.65 Ga synchronous with the Slate Creek shear zone (Karlstrom and Bowring, 1991). Based on similarities in the stratigraphy and structural style, this fold-and-thrust belt may also be primarily or partly of Mesoproterozoic age.

An additional challenge for understanding the Proterozoic growth of Laurentia revolves around determining the nature and location of crustal province boundaries. The term Mazatzal orogeny has been used in the literature as a 1.7–1.8 Ga crustal age province, as well as a magmatic and deformational event. Our new results are in agreement with published geochronologic boundaries (e.g., Karlstrom and Humphreys, 1998) that show no pre–1.7 Ga rocks south of the Slate Creek shear zone. However, the new Hf data show that the deep crust involves rocks older than 1.8–2.0 Ga, such that the deep crust...
does not conform to published notions of progressive addition of juvenile 1.75 Ga “Yavapai” crust followed by addition of juvenile 1.7–1.6 Ga Mazatzal crust (e.g., Whitmeyer and Karlstrom, 2007). Instead, this crustal block differs from both, and additional Hf and Nd data are needed to understand the extent of older crustal substrates within different parts of the orogen.

These new results, highlighting the importance of Mesoproterozoic tectonism in southwestern Laurentia, call into question the nature of previously proposed province boundaries. It is clear from our results that at least in central Arizona, deformation related to the Picuris orogeny overprints Mazatzal deformation of even older crust (Fig. 9). Examples across the southwestern United States are similar (Grambling and Dallmeyer, 1993; Williams et al., 1999; Amato et al., 2011; Daniel et al., 2013; Jones et al., 2011). Mesoproterozoic deformation in the southwestern United States tends to rework older crust. Given that there may be a component of older basement in the Four Peaks area (pre–1.7 Ga), Mazatzal deformation might also rework older (Yavapai or slightly older) crust in this area.

## CONCLUSIONS

Rocks in the Four Peaks area record evidence for a polyphase history that includes three periods of burial-deformation-exhumation. Two periods occurred in the Paleoproterozoic and were part of the Mazatzal orogeny. The second of these (ca. 1.660 Ga) included the rapid deposition of a classic rhyolite-quartzite sequence (including the Four Peaks Quartzite) that appears correlative with similar trachyandesite-quartzite packages to the south in the rhyolite-quartzite sequence (including the Four Peaks Quartzite) that appears similar to the Four Peaks Quartzite. shale (pre–1.7 Ga), Mazatzal deformation might also rework older (Yavapai or slightly older) crust in this area.

Figure 9. Summary of deposition, plutonism, and monazite growth. Black boxes designate crystallization ages with associated uncertainty. Gray boxes designate brackets on sedimentary deposition. Open boxes designate pulses of monazite growth. The numbers are as follows: 1—Buckhorn granodiorite, 2—crosscutting rhyolite dike, 3—Young granite, 4—rhyolite, 5—Mazatzal Group sediments, 6—gritstones of Soldier Camp, 7—megacrystic granite, 8—Yanneke Joe Group sediments, 9—monazite cores, 10—monazite rims, 11—young monazite cores, 12—El Oso Granite, 13—El Oso-related intrusion.


Burrett, C., and Berry, R., 2000, Proterozoic Australia–western United States (AUSWUS) fit be-


Doe, M.F., 1991, Structural Geology of a foreland thrust-system in the vicinity of Barnhardt Can-

Doe, M.F., 2014, Reassessment of Pale- and Mesoproterozoic Basin Sediments of Arizona: Implica-


Ludwig, K.R., 1974, Precambrian Geology of the Central Mazatzal Mountains, Arizona (Part II) and Lassen Volcanic Center, California (Part III) [M.S. thesis]: Flagstaff, Arizona, Northern Arizona University, 102 p.


Ludwig, K.R., 1974, Precambrian Geology of the Central Mazatzal Mountains, Arizona (Part II) and Lassen Volcanic Center, California (Part III) [M.S. dissertation]: Pasadena, California, California Institute of Technology, 363 p.


