

# Case for a temporally and spatially expanded Mazatzal orogeny

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## ABSTRACT

The interval between 1.78 and 1.63 Ga was one of major crustal growth and assembly in southwestern Laurentia. The prevailing view is that the culminating event for this tectonism was the ca. 1.654–1.633 Ga Mazatzal orogeny. We present evidence for a continuum of deformation, magmatism, metamorphism, and new mineral growth from 1.65 to 1.58 Ga from southern Wyoming to Sonora, Mexico. We suggest that the Mazatzal orogeny may have extended in time to ca. 1580 Ma and in space to the Cheyenne belt, southern Wyoming. If our interpretation for an extended Mazatzal orogeny is correct, the duration of the orogeny may have been ~70 m.y., similar to many orogenies in Earth's history. The ca. 1.6 Ga tectonism appears to represent a shift in tectonic style from that typically associated with the Yavapai (ca. 1.70 Ga) and “classic” Mazatzal (1.65 Ga) orogenies to widespread intracontinental deformation. If correct, a corollary to our interpretation is that newly accreted Paleoproterozoic crust stabilized rapidly and facilitated stress transfer far inboard of any active plate margin.

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## INTRODUCTION

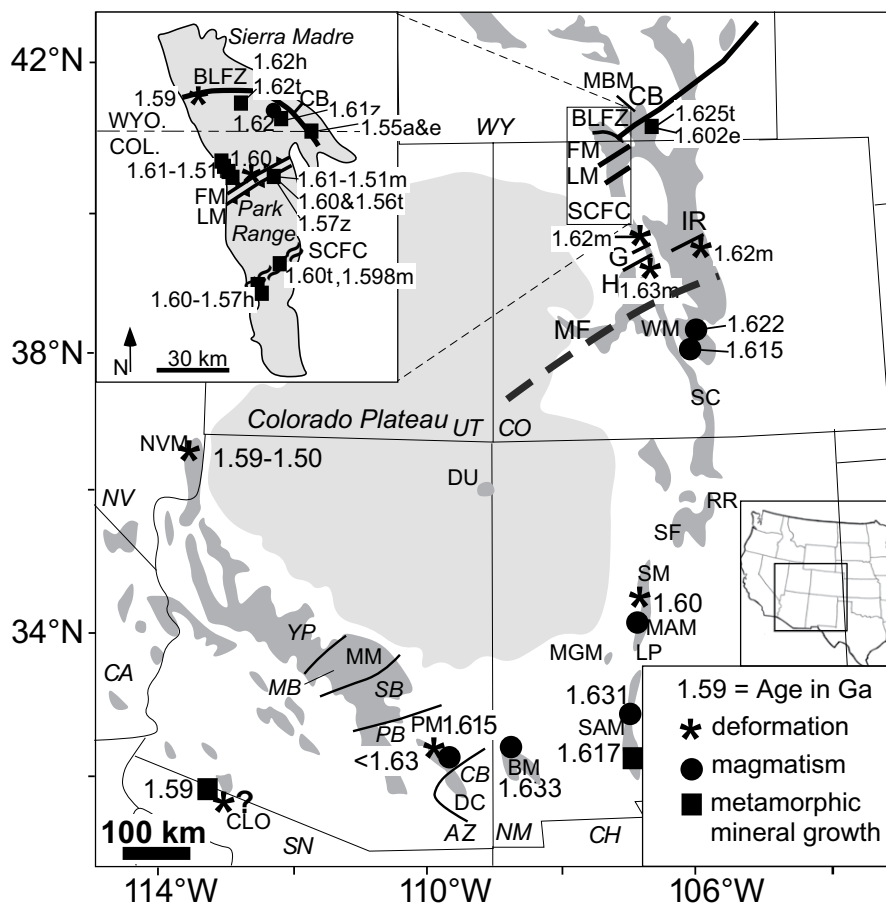
The interval between 1.78 Ga and 1.40 Ga was one of major crustal assembly in southwestern Laurentia (e.g., Condie, 1982; Karlstrom and Houston, 1984; Karlstrom and Bowring, 1988, 1993; Whitmeyer and Karlstrom, 2007) during which time a 1300-km-wide band of material was added to the southern margin of the Archean Wyoming craton during the Medicine Bow, Yavapai, Mazatzal, and Picuris orogenies. The prevailing view has been that the culminating event for accretionary tectonism was the ca. 1.65–1.63 Ga Mazatzal orogeny (Eisele and Isachsen, 2001; Amato et al., 2008), which has been interpreted to involve metamorphism, magmatism, and deformation in Arizona, New Mexico, and southern Colorado (Shaw and Karlstrom, 1999). The northernmost limit of Mazatzal deformation, the Mazatzal front of Shaw and Karlstrom (1999), has generally been considered to be in central Colorado near Salida (Fig. 1). If the Mazatzal orogeny is considered to have ceased by 1633 Ma (Amato et al., 2008), there appears to have been a >130 m.y. hiatus in deformation and magmatism prior to recently documented basin development and deformation commencing at ca. 1.49 Ga in northern New Mexico and southern Arizona (Jones et al., 2011; Andronicos et al., 2012; Doe et al., 2012; Daniel et al., 2013; Aronoff et al., 2013). In this paper, we present evidence for a temporally and spatially expanded Mazatzal orogeny that spans a time continuum from 1.65 to 1.58 Ga (herein referred to as ca. 1.6 Ga tectonism) and appears to be manifest as far north as the Cheyenne belt in southern Wyoming (Jones et al., 2010, 2013).

## BACKGROUND

The Mazatzal orogeny is a northwest-directed, thin-skinned, fold-and-thrust belt first recognized in the Mazatzal Mountains (Fig. 1), central Arizona (Wilson, 1939; Conway et al., 1982); however, at least some of the deformation in central Arizona is now known to have occurred between ca. 1474 and 1436 Ma (Doe et al., 2012, 2013). The earliest reported age

of the Mazatzal orogeny is  $1655 \pm 20$  Ma based on a U-Pb zircon date on the post-tectonic Johnny Lyon granodiorite in southeastern Arizona (Silver and Deutsch, 1963); this was redated to  $1643 \pm 5$  Ma by Eisele and Isachsen (2001). Subsequent age determinations on the Mazatzal orogeny (Erickson and Bowring, 1990; Labrenz and Karlstrom, 1991; Powicki et al., 1993; Amato et al., 2008) fall within the 40 m.y. time interval reported by Silver and Deutsch (1963) for the orogeny, with the most recent minimum age constraint being  $1633 \pm 8$  Ma in the Burro Mountains, southwestern New Mexico (Amato et al., 2008). Karlstrom et al. (2013) presented several arguments for separate and distinct tectonic events at ca. 1.65 and ca. 1.4 Ga in central Arizona and parts of New Mexico.

Recent work in northern and southwestern New Mexico and northern and northeastern Arizona, however, has documented widespread tectonism (basin development, deformation, and metamorphism) at 1.49–1.40 Ga. In northern New Mexico, the Marqueñas Formation, previously thought to be part of the ca. 1700 Ma Vadito Group, contains Mesoproterozoic detrital zircons with weighted averages of  $1477 \pm 13$  Ma and  $1453 \pm 10$  Ma (Jones et al., 2011; Daniel et al., 2013) for the middle and upper Marqueñas Formation, respectively. In south-central Arizona, Doe et al. (2012, 2013) documented basin formation between  $1474 \pm 13$  Ma and  $1436 \pm 2$  Ma, the latter being the age of the crosscutting Ruin Granite. Detrital zircons from quartzites in the Defiance uplift area of northeastern Arizona indicate a maximum depositional age of 1476 Ma (Doe et al., 2013). Several workers have documented widespread 1.47–1.42 Ga deformation and metamorphism in northern and southwestern New Mexico (Williams et al., 1999; Daniel and Pyle, 2006; Amato et al., 2008, 2011; Daniel et al., 2013; Aronoff et al., 2013). These events were previously attributed to the Mazatzal orogeny. The 1.46–1.40 Ga deformation and metamorphism in northern New Mexico have been termed the Picuris orogeny (Daniel et al., 2013), and some workers (Daniel and Pyle, 2006; Andronicos et al., 2012; Daniel et al., 2013; Aronoff et al., 2013) have proposed that all of the deformation and metamorphism in northern New Mexico occurred between 1460 and 1400 Ma. These authors, however, do not dispute evi-



**Figure 1.** Map of the southwestern United States showing geographical features, major structures, and distribution of ca. 1.6 Ga deformation (stars), magmatism (circles), and metamorphic mineral growth (boxes). Numbers represent ages in Ga for mineral growth; mineral abbreviations: a—apatite, e—epidote, h—hornblende, m—monazite, t—titanite, z—zircon (references cited in text). Inset at top left is a detail of 1.6 Ga events in the Sierra Madre and Park Range. Inset at lower right is a map of western United States; box shows area of Figure 1. Geographic features: BM—Burro Mountains, CLO—Cerro Los Ojos, DC—Dos Cabezas Mountains; DU—Defiance uplift, LP—Los Pinos Mountains, MAM—Manzano Mountains, MBM—Medicine Bow Mountains, MGM—Magdalena Mountains, MM—Mazatzal Mountains, NVM—North Virgin Mountains, PM—Pinaleno Mountains, RR—Rincon Range, SAM—San Andres Mountains, SC—Sangre de Cristo Range, SF—Santa Fe Range, SM—Sandia Mountains, WM—Wet Mountains. Tectonic blocks: CB—Cochise block, MB—Mazatzal block, PB—Pinal block, SB—Sunflower block, YP—Yavapai Province. Structures: BLFZ—Battle Lake fault zone, CB—Cheyenne belt, FMLM—Farwell Mountain–Lester Mountain suture zone, G—Gore Range shear zone, H—Homestake shear zone, IR—Idaho Springs–Ralston shear zone, MF—Mazatzal front (Shaw and Karlstrom, 1999), SCFC—Soda Creek–Fish Creek shear zone. States: AZ—Arizona, CA—California, CH—Chihuahua, Mexico, CO—Colorado, NM—New Mexico, NV—Nevada, SN—Sonora, Mexico, UT—Utah, WY—Wyoming.

dence for ca. 1650–1630 Ma deformation elsewhere in the southwestern United States (Daniel et al., 2013, p. 1438).

Andronicos et al. (2012) and Aronoff et al. (2013) proposed that southern Colorado and Arizona record both Paleoproterozoic and Mesoproterozoic deformational and metamorphic events, whereas northern New Mexico only experienced a single progressive deformational and metamorphic event between 1.46 and 1.40 Ga. These authors proposed a major Mesoproterozoic crustal boundary between these areas, perhaps coincident with the Mazatzal front. Furthermore, Daniel et al. (2013) proposed a tectonic model in which the Mazatzal Province was sutured to the Yavapai Province during a protracted 1.49–1.40 Ga event rather than at 1.65–1.63 Ga. Daniel et al. (2013) did not identify a location for this inferred suture, but if it is real, it may coincide with the crustal boundary proposed by Andronicos et al. (2012) and Aronoff et al. (2013). Because of the intensity and spatial extent of ca. 1.45 Ga tectonism, it is increasingly critical to reevaluate the spatial and temporal extent, and the general tectonic character, of the iconic Mazatzal event.

Distinguishing between Paleoproterozoic (Mazatzal) and Mesoproterozoic (Picuris) deformation and metamorphism is a significant challenge that has profound implications for crustal evolution in southwestern Laurentia. In the conventional model, where the Yavapai and Mazatzal Provinces were joined by 1.63 Ga, our documentation (discussed herein) of ca. 1.6 Ga tectonism as far north as the Cheyenne belt requires transmission of stresses far inboard (>1300 km) of any possible plate margin at that time. Conversely, if the Yavapai and Mazatzal Provinces were not joined until ca. 1.4 Ga along a crustal boundary in southern Colorado or northernmost New Mexico, the distance over

which intracratonic stresses were transmitted is reduced considerably to 300–400 km. The tectonic “driver” for ca. 1.6 Ga deformation in the latter scenario is unknown.

#### EVIDENCE FOR CA. 1.65 GA (MAZATZAL-AGE) TECTONISM IN SOUTHWEST LAURENTIA

The conventional interpretation has been that Mazatzal-age (ca. 1.65–1.63 Ga) deformation and metamorphism in southwestern Laurentia were strongly overprinted by a 1450–1400 Ma tectonothermal event, particularly in northern New Mexico (Karlstrom et al., 1997, 2004; Pedrick et al., 1998; Read et al., 1999; Williams et al., 1999). In the following section, we summarize the major constraints on the existence and age range of Mazatzal tectonism. Then, we summarize evidence for an expanded regional extent and age range for the Mazatzal orogeny. Evidence for the Mazatzal orogeny provided herein is not comprehensive but includes some of the better age constraints on this deformational event.

#### New Mexico

In the Rincon Range, northern New Mexico, Read et al. (1999) observed a spatial association among the  $1682 \pm 6.5$  Ma Guadalupita pluton, high-grade metamorphism, and deformational fabrics that they concluded documented deformation at that time. The age of 1682 Ma is “old” for the Mazatzal orogeny, but if the interpretation of Read et al. (1999) is correct, it indicates that pre-1.45–1.40 Ga deformation may be preserved locally in northern New Mexico.

The Manzano thrust belt, central New Mexico, “was active ca. 1650 Ma based on the synkinematic nature of the 1.64 Ga Manzanita pluton and growth of 1.65 Ga syntectonic monazite in the aureole of the 1.66 Ga Ojito pluton” (Baer et al., 2003, p. 42). Williams et al. (2001, p. 4) documented that monazite crystals “from the contact aureole of the Ojito pluton have ca. 1.65 Ga cores and distinct slightly younger rims that overgrow the matrix foliation, indicating 1.65 Ga metamorphism and deformation.” In the Los Pinos Mountains, southwest of the Manzano Mountains, a strong foliation in the  $1662 \pm 1$  Ma (Shastri, 1993) Sevilleta metarhyolite is truncated by the weakly foliated,  $1655 \pm 3$  Ma Los Pinos pluton (Luther et al., 2005), suggesting deformation within that time interval. Shastri and Bowring (1992) also concluded that deformation, plutonism, and possibly the peak of metamorphism were coeval at 1.66 Ga in the Los Pinos Mountains of central New Mexico.

In the Magdalena Mountains, central New Mexico, the undeformed  $1654 \pm 1$  Ma Magdalena granite (U-Pb zircon; Bowring et al., 1983) truncates strongly deformed  $1664 \pm 3$  Ma metarhyolites (U-Pb zircon; Bowring et al., 1983; Bauer and Williams, 1994), tightly bracketing deformation in that region between 1664 and 1654 Ma.

Amato et al. (2008, p. 331) noted that “Paleoproterozoic igneous rocks of the Mazatzal Province in southern New Mexico can be divided into two broad age groups,” 1680–1650 Ma rocks that are pervasively deformed and a younger group (1630–1620 Ma) of rocks that are generally undeformed or only locally deformed, suggesting deformation between 1650 and 1630 Ma.

The primary rock types in northern and central New Mexico (e.g., Santa Fe Range, Sandia Mountains, Manzano Mountains, Los Pinos Mountains, Magdalena Mountains; Karlstrom et al., 2004) include 1.68–1.65 Ga volcanic and plutonic rocks that are considered to be juvenile arc rocks based on Nd isotopic and trace-element geochemical studies (Condie, 1982; Nelson and DePaolo, 1985; Bennett and DePaolo, 1987), indicating magmatism of Mazatzal age. In the San Andres Mountains, southwestern New Mexico, Vollbrecht (1997) bracketed the age of foliation formation in granites and metasedimentary rocks to 1650–1630 Ma based on deformed ca. 1650 Ma metavolcanic rocks and a late syntectonic granite emplacement at 1630 Ma.

## Arizona

In central Arizona, undeformed ca. 1660 Ma granite dikes crosscut a  $1668 \pm 5$  Ma mylonitic diorite of the Four Peaks shear zone (Powicki et al., 1993; Mako et al., 2013). In the Mazatzal, Sunflower, and Pinal blocks of central and southeastern Arizona, deformation continued until ca. 1630 Ma (Karlstrom and Bowring, 1988). In southeastern Arizona, the late syntectonic to post-tectonic Young Granite (ca. 1630 Ma; Conway and Silver, 1988) crosscuts the Slate Creek shear zone and deformational fabrics in the Alder Group (Karlstrom et al., 1990), indicating deformation prior to 1630 Ma. The Cochise block, southeastern Arizona, has been interpreted as a juvenile magmatic arc at 1647–1630 Ma (Eisele and Isachsen, 2001). In the western Dos Cabezas Mountains (Pinal block), the late synkinematic Sommer orthogneiss yielded a U-Pb zircon date of 1.65 Ga (Erickson and Bowring, 1990; uncertainties not reported). Juvenile (based on Nd isotopes) granitoids intruded the Pinal block from  $1654 \pm 6$  Ma to  $1638 \pm 1$  Ma (Isachsen et al., 1999).

## Colorado

Within the Homestake shear zone of central Colorado, Shaw et al. (2001) obtained in situ U-Th-Pb electron microprobe monazite dates of  $1668 \pm 8$  Ma,  $1658 \pm 5$  Ma, and  $1637 \pm 13$  Ma on high-temperature fabrics within the shear zone. In situ U-Th-Pb monazite dates of  $1691 \pm 13$  Ma,

$1653 \pm 13$  Ma, and  $1623 \pm 12$  Ma were obtained from syndeformational fabrics within the Idaho Springs–Ralston shear zone (McCoy et al., 2005). It should be noted that both the Homestake and Idaho Springs–Ralston shear zones contain mylonites that also yield U-Th-Pb monazite dates in the 1.45–1.38 Ga range (Shaw et al., 2001; McCoy et al., 2005). In the Sangre de Cristo Mountains, southern Colorado, Jones and Connelly (2006) documented titanite growth at  $1637 \pm 6$  Ma that they linked to northwest-directed shortening associated with late Mazatzal deformation.

## EVIDENCE FOR POST-1.63 GA TECTONISM IN SOUTHWESTERN LAURENTIA

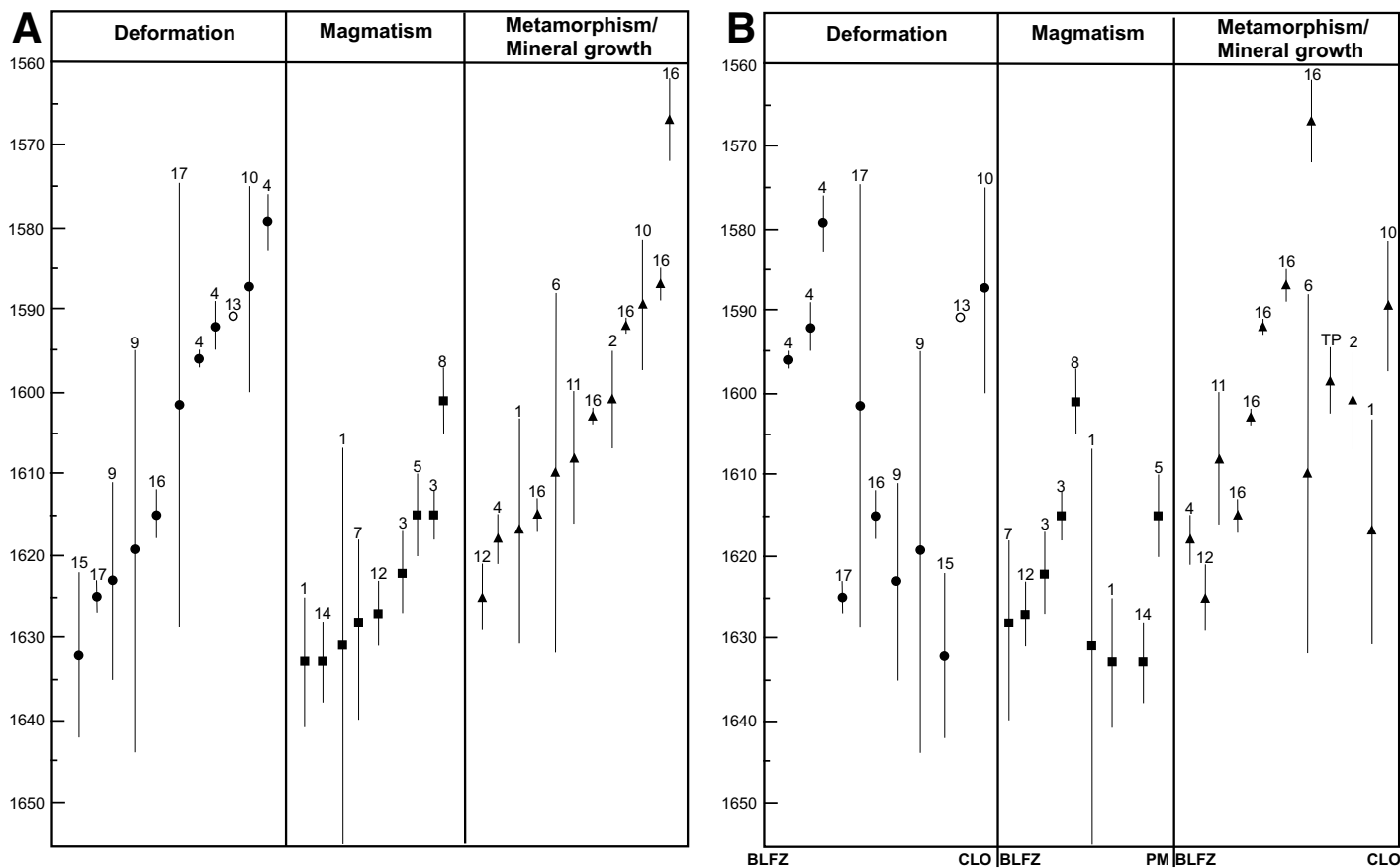
### Deformation

The best-documented ca. 1.6 Ga deformational event is associated with the cataclastic Battle Lake fault zone in the Sierra Madre, southern Wyoming. The Battle Lake fault zone is a north-northwest–vergent, thrust-tear fault system that truncated and overrode the ca. 1760 Ma Cheyenne belt (Archean–Proterozoic suture; Duebendorfer and Houston, 1990; Duebendorfer et al., 2006). The fault zone extends for  $>45$  km from the westernmost Sierra Madre to the Wyoming–Colorado border, where it is buried beneath alluvium (Fig. 1). The presence of isolated, dismembered mylonites of the Cheyenne belt within the fault zone requires at least 30 km of northwest-directed slip. The Battle Lake fault zone is imaged on the CD-ROM seismic-reflection profile of Morozova et al. (2002, 2005) and originally extended to a crustal depth of at least 15 km (possibly 22 km) with a minimum downdip length of 40 km. Three synkinematic muscovite crystals from the fault zone yielded  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $1596.5 \pm 1.4$  Ma,  $1579 \pm 3$  Ma, and  $1592 \pm 3$  Ma (Figs. 1 and 2A). The sample that yielded the ca. 1597 Ma date has a completely flat spectrum (Duebendorfer et al., 2006) and thus is interpreted as the best determination of the age of deformation.

To the east in the Medicine Bow Mountains, amphibolite-facies mylonites of the Cheyenne belt are overprinted by nonpenetrative, subvertical slip surfaces with subhorizontal, epidote-chlorite-tremolite lineations (Strickland, 2004; Strickland et al., 2004). Kinematic analysis of these slip surfaces records northwest-southeast shortening accommodated by conjugate strike-slip faults (Strickland, 2004). Northwest-southeast shortening is compatible with the kinematics of the Battle Lake fault zone. U-Pb analysis of synkinematic epidote and titanite yielded dates of  $1602 \pm 27$  Ma and  $1625 \pm 2$  Ma, respectively (Figs. 1 and 2A; Strickland, 2004).

The 1.6 Ga deformational event is not restricted to southern Wyoming. In the northern Park Range, north-central Colorado, Sigler (2008) documented greenschist-grade, steeply plunging folds with dextral asymmetry that correlate structurally with ca. 1.61 Ga structures in the Medicine Bow Mountains and have been dated by U-Pb sensitive high-resolution ion microprobe (SHRIMP) on monazite rims to ca.  $1615 \pm 3$  Ma. In the Gore Range and the Idaho Springs–Ralston shear zone, central Colorado, McCoy et al. (2005) documented synkinematic monazite growth (rims) associated with northeast-trending folds at  $1619 \pm 24$  Ma and  $1623 \pm 12$  Ma, respectively. Shaw et al. (2001) reported in situ U-Th-Pb dates of  $1637 \pm 13$  Ma,  $1632 \pm 10$  Ma, and  $1625 \pm 12$  Ma on synkinematic monazite rims from northeast-striking high-strain zones in the Homestake shear zone of central Colorado. Their  $S_2$  high-temperature shear zones record northwest-southeast shortening.

In the Manzano Mountains, central New Mexico (Fig. 1), Luther et al. (2005, 2006) obtained a U-Pb zircon date of  $1601 \pm 4$ –3 Ma on the Blue Springs Rhyolite of the Manzano Group. This metarhyolite contains a strong northeast-striking, steeply southeast-dipping foliation indicating a maximum age of deformation at ca. 1600 Ma. This fabric is distinct from ca. 1.4 Ga fabrics in the Manzano Mountains, which are concen-



**Figure 2.** Dates on ca. 1.6 Ga deformation, magmatism, and metamorphism/mineral growth in southwestern Laurentia. Symbols indicate reported ages; lines show uncertainties. Open symbols indicate no uncertainty reported. Numbers above date refer to sources of data. Sources: 1—Amato et al. (2008), 2—Aronoff et al. (2013), 3—Bickford et al. (1989), 4—Duebendorfer et al. (2006), 5—Eisele and Isachsen (2001), 6—Foster (personal commun. to Tyson, 2002), 7—Jones et al. (2013), 8—Luther et al. (2005, 2006), 9—McCoy et al. (2005), 10—Nourse et al. (2005), 11—Premo and Fanning (2000), 12—Premo and Van Schmus (1989), 13—Quigley et al. (2002a, 2002b), 14—Rämö et al. (2003), 15—Shaw et al. (2001), 16—Sigler (2008), 17—Strickland (2004), TP—this paper. (A) Dates plotted from oldest to youngest for ca. 1.6 Ga deformation, magmatism, and metamorphism/mineral growth. (B) Dates plotted according to distance south of the Battle Lake fault zone (BLFZ). CLO—Cerro Los Ojos, Sonora, Mexico; PM—Pinaleno Mountains, southeastern Arizona. There is no systematic variation in dates with position south of the Battle Lake fault zone (BLFZ).

trated near the 1.43 Ga Priest pluton (Thompson et al., 1996; Luther et al., 2005). In the north Virgin Mountains, southern Nevada (Fig. 1), Quigley et al. (2002a, 2002b) determined U-Pb ages of 1591–1508 Ma on monazite rims (uncertainties not reported) that they linked to tectonic fabric development within the northwest-side-up Virgin Mountains shear zone. In southeastern Arizona, suturing between the Pinal and Cochise blocks occurred after 1.63 Ga (Eisele and Isachsen, 2001), but these authors did not report a minimum age constraint.

Near Cerro Los Ojos in northern Sonora, Mexico (Fig. 1), an extensive folding and fabric-forming event occurred between 1645 and 1432 Ma and may have coincided with metamorphism at 1600–1575 Ma (Nourse et al., 2005). Nourse et al. (2005) attributed these structures to northwest- or west-directed shear. There is no systematic variation in timing of deformation with position south of the Battle Lake fault zone (Fig. 2B).

### Magmatism

Known magmatism within the time interval 1630 and 1600 Ma is volumetrically minor but widely distributed (Figs. 1 and 2). Premo and

Van Schmus (1989) and Jones et al. (2013) obtained U-Pb zircon dates of  $1627 \pm 4$  Ma and  $1628 \pm 11$  Ma, respectively, on a white quartz monzonite from the Sierra Madre, Wyoming. Bickford et al. (1989) obtained U-Pb zircon dates of  $1622 \pm 5$  Ma and  $1615 \pm 3$  Ma on two granitic plutons from the Wet Mountains, central Colorado. In the Manzano Mountains, central New Mexico, Luther et al. (2005) obtained a U-Pb date of  $1601 \pm 3$  Ma on the Blue Springs Rhyolite in the upper part of the Manzano Group. Rämö et al. (2003) obtained a  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon date of  $1633 \pm 5$  Ma on the Redrock diabase in the Burro Mountains, southwestern New Mexico. Amato et al. (2008) obtained a  $^{207}\text{Pb}/^{206}\text{Pb}$  SHRIMP zircon age of  $1631 \pm 21$  Ma on a foliated granite from the San Andres Mountains, southern New Mexico, and a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1633 \pm 8$  Ma on a metavolcanic rock from the Burro Mountains. In the Pinaleno Mountains, southeastern Arizona (Fig. 1), magmatism in the Cochise block continued until  $1615 \pm 5$  Ma (Eisele and Isachsen, 2001). There does not appear to be any spatial or temporal distribution of these plutons that can be interpreted in the context of tectonic setting, nor is there any systematic variation in timing of magmatism with position south of the Battle Lake fault zone (Fig. 2B).

## Metamorphism and New Mineral Growth

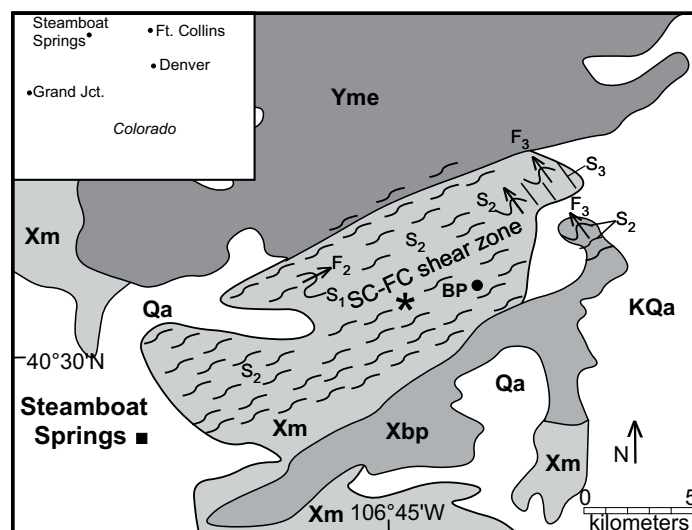
There is widespread evidence for 1.63–1.58 Ga (or younger) metamorphism and mineral growth in the western United States (Figs. 1 and 2). Premo and Van Schmus (1989) obtained two  $^{207}\text{Pb}/^{206}\text{Pb}$  dates that averaged  $1625 \pm 4$  Ma from zircon overgrowths in the Big Creek Gneiss in the southeastern Sierra Madre. Premo and Fanning (2000) reported a SHRIMP  $^{207}\text{Pb}/^{206}\text{Pb}$  date of  $1608 \pm 8.4$  Ma on a zircon overgrowth in the Big Creek Gneiss (less than 3% discordant). A hornblende sample from an amphibolite within the Green Mountain Formation, south of the Battle Lake fault zone, yielded a well-defined weighted mean  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $1618 \pm 3$  Ma (Duebendorfer et al., 2006). This amphibolite has a granoblastic texture indicative of static recrystallization. We therefore interpret the  $1618 \pm 3$  Ma date as the time of hornblende growth or total recrystallization.

In the northern Park Range, Colorado, Sigler (2008) reported slightly discordant  $^{207}\text{Pb}/^{206}\text{Pb}$  dates of  $1587 \pm 2$  Ma,  $1592 \pm 1$  Ma, and  $1603 \pm 1$  Ma from titanite in a metamorphosed calc-silicate rock. These titanite dates are interpreted to be metamorphic ages rather than cooling ages because thermobarometry indicates that pressure-temperature conditions of metamorphism at ca. 1.6 Ga in the northern Park Range were  $\sim 400$  MPa and  $650^\circ\text{C}$  (Sigler, 2008), suggesting that the titanite grew below the closure temperature of  $\sim 700^\circ\text{C}$  (Cherniak, 1993; Corfu, 1996). Sigler (2008) also obtained a weighted mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1567 \pm 5$  Ma on titanite from an amphibolite. In the same area, monazite grains from a pelitic schist yielded U-Pb SHRIMP ages of  $1753 \pm 7$  Ma and  $1615 \pm 2$  Ma. The latter age is interpreted as mineral growth during a period of metamorphism. In the southern Park Range, Colorado, within the Soda Creek–Fish Creek shear zone, a schist yielded a U-Th-Pb monazite date of  $1610 \pm 22$  Ma (Foster personal commun. to Tyson, 2002).

In the northern Wet Mountains, central Colorado, an orthogneiss yielded a Lu-Hf age on garnet of  $1601 \pm 5.7$  Ma (Aronoff et al., 2013), indicating metamorphism at that time. In the San Andres Mountains, southern New Mexico (Fig. 1), Amato et al. (2008) obtained a U-Pb date of  $1617 \pm 11$  Ma from the metamorphic rims of zircon grains in a gneiss. Finally, SHRIMP zircon analyses from three metagranitoids from Cerro Los Ojos, northern Sonora, yielded a weighted mean  $^{207}\text{Pb}/^{206}\text{Pb}$  date of  $1590 \pm 8$  Ma, which Nourse et al. (2005) interpreted as recording a metamorphic event. There is no systematic variation in timing of metamorphism or mineral growth with position south of the Battle Lake fault zone (Fig. 2B).

## New In Situ Monazite U-Th-Pb Geochronology

In the Soda Creek–Fish Creek shear zone (Buffalo Pass area), Park Range, northern Colorado, three metapelitic rocks were sampled for in situ (electron microprobe) monazite geochronology (Figs. 3 and 4). The deformational history of the shear zone is summarized in Table 1. In sample BP12-19 (Fig. 4), four domains (core, intermediate, inner rim, and outer rim) generally yielded either three or four distinct monazite dates (Figs. 4A and 4B). Cores yielded a weighted mean date of  $1724 \pm 6$  Ma; the intermediate domain yielded a weighted mean date of  $1660 \pm 14$  Ma (Figs. 4C and 4D). Inner rims and outer rims yielded similar dates, with a weighted mean of  $1598 \pm 8$  Ma, although two poorly resolved dates may be present (ca. 1605 and ca. 1590 Ma; Fig. 4C). The consistently low- and high-Y inner and outer rims (respectively) suggest that there was a second metamorphic pressure-temperature-time loop at ca. 1.60 Ga involving garnet growth (low-Y inner rim) and then garnet resorption (high-Y outer rim). The fact that the intermediate domain and the two rim domains all tend to be elongate and aligned with the main fabric (Figs. 4C and 4D) suggests that both the ca. 1660 Ma and the ca. 1600 Ma monazite



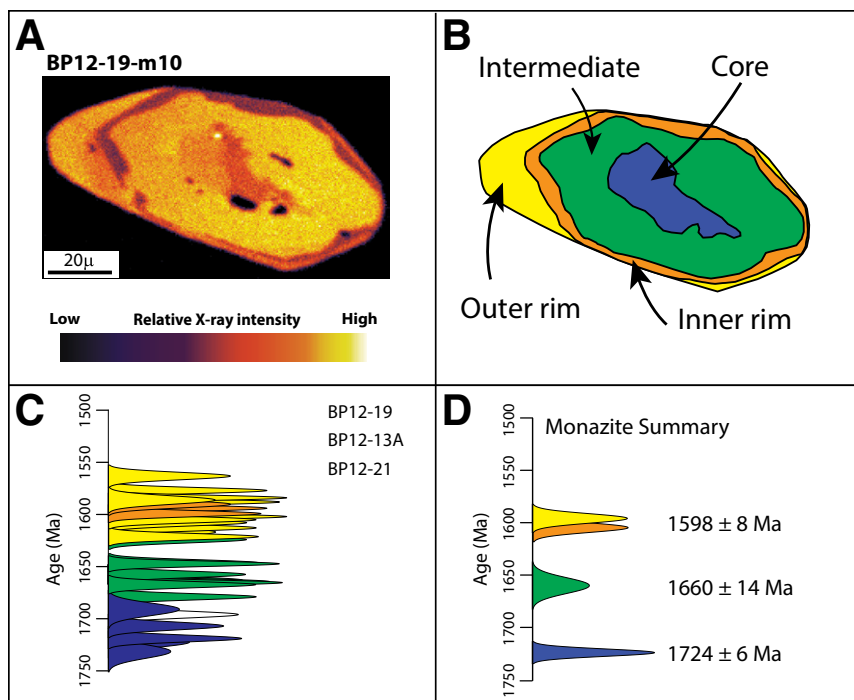
**Figure 3.** Highly generalized geologic map of the Soda Creek–Fish Creek shear zone (SC-FC shear zone) Park Range, northern Colorado. Inset shows state of Colorado and location of Steamboat Springs (shown on main map). Abbreviations: BP—Buffalo Pass; KQa—exposures of Cretaceous rocks and Quaternary alluvium, colluvium, and glacial deposits; Qa—Quaternary alluvium, colluvium, and glacial deposits; Xbp—1746  $\pm$  6 Ma Buffalo Pass pluton (Premo and Van Schmus, 1989); Xm—undifferentiated Paleoproterozoic metamorphic rocks; Yme—ca. 1.42 Ga Mount Ethel pluton (Snyder, 1980). Structural symbols:  $S_1$ —foliation associated with the earliest deformation,  $S_2$ —foliation associated with the second deformation (main fabric of the Soda Creek–Fish Creek shear zone),  $S_3$ —foliation associated with the third deformational event. Note that in the eastern part of the Soda Creek–Fish Creek shear zone,  $S_3$  strikes northwest; in the main part of the shear zone,  $S_3$  overprints and locally crosscuts  $S_2$  at a low angle (Hamlin, 2013).  $F_2$ —folds associated with the second deformation,  $F_3$ —folds associated with the third deformation. Asterisk shows locality of sample BP12-19, which was dated using in situ (electron microprobe) monazite geochronology (Fig. 4).

growth events were syntectonic. In summary, in the eastern part of the Soda Creek–Fish Creek shear zone, the principal peaks in U-Th-Pb monazite ages are  $1724 \pm 6$  Ma,  $1660 \pm 14$  Ma, and  $1598 \pm 8$  Ma, corresponding to at least three periods of mineral growth, the latter two of which are interpreted to have been associated with deformation.

## DISCUSSION

The Mazatzal orogeny was interpreted to have ended before 1643 Ma in southern Arizona and before 1633 Ma in southwestern New Mexico (Amato et al., 2008). This may be correct for the specific localities in those studies: however, when viewing the entire southwestern United States, there is a time continuum of tectonism well past 1633 Ma. For example, when uncertainties in ages are taken into account, there is a continuum of deformation from 1642 to 1575 Ma; for magmatism from 1655 to 1607 Ma; and for metamorphism/mineral growth from 1632 to 1581 Ma. The dates document a near continuum from 1655 to 1581 Ma, with only minor gaps that are generally less than 10 m.y.

Because of the near continuum of tectonism since the onset of the Mazatzal orogeny (ca. 1.65 Ma), we suggest that the Mazatzal orogeny may have extended in time to ca. 1580 Ma and in space to the Cheyenne belt (i.e., the Cheyenne belt is the “new” Mazatzal front) as suggested by Jones et al. (2013). In New Mexico and Arizona, the Mazatzal orogeny is



**Figure 4.** Compositional map ( $Y M\alpha$ ) for a typical monazite grain from the Buffalo Pass area, Soda Creek–Fish Creek shear zone, southern Park Range, Colorado. (A and B) Monazite grains from three samples of metapelitic schist typically have four compositional domains from core to rim with alternating low- and high- $Y$  domains. Inner and outer rim domains yield similar ages. Dramatic  $Y$  differences suggest that garnet may have grown during inner rim crystallization and broken down during outer rim crystallization. (C) Raw data for all grains analyzed. (D) Weighted mean ages for the four domains.

characterized by north-northwest/south-southeast shortening (e.g., Shaw and Karlstrom, 1999). All ca. 1.6 Ga structures and deformational fabrics cited here either directly record northwest-southeast shortening or are consistent with this shortening direction, further supporting a temporally and spatially expanded Mazatzal orogeny.

If our interpretation for an extended Mazatzal orogeny is correct, the duration of the orogeny may have been ~70 m.y. This is similar to time scales of many orogenies, both present and past. For example, the Himalayan–Tibetan orogen initiated >50 Ma, could be as old as 70 Ma (Yin and Harrison, 2000), and is still ongoing. In the Grenville orogeny in eastern Canada, collisional orogenesis persisted for at least 40 m.y. from ca. 1090 to 1050 Ma (Rivers, 2008, 2012; Wong et al., 2012). When viewed broadly, Cordilleran retroarc thrusting initiated in the Late Jurassic (ca. 150 Ma) and persisted for >100 m.y. although the locus of deformation shifted through time (DeCelles, 2004).

## SUMMARY AND CONCLUSIONS

Our compilation of data on the timing of tectonism, as well as the new in situ (electron microprobe) monazite date of  $1598 \pm 8$  Ma from the Soda Creek–Fish Creek shear zone, supports the concept of a Mazatzal orogeny that is greatly expanded in space and time as compared to previous inter-

pretations. Duebendorfer et al. (2006) proposed that ca. 1.6 Ga deformation in southern Wyoming may represent a previously unrecognized event in southwest Laurentia, and this possibility cannot be ruled out. The time continuum of the ca. 1.6 Ga events documented in this paper, however, leads us to favor a protracted and spatially expanded Mazatzal orogeny rather than an event that was separate and distinct. This continuum of deformation from 1650 to 1580 Ma, coupled with the recent recognition of basin development and deformation in northern New Mexico and southern Arizona at ca. 1490 Ma as discussed in the “Background” section, narrows the “tectonic gap” to 90 m.y.

If the conventional model in which the Yavapai and Mazatzal Provinces were joined by 1.63 Ga is correct, our documentation of ca. 1.6 Ga tectonism as far north as the Cheyenne belt requires transmission of stresses far inboard (>1300 km) of the southern margin of southwestern Laurentia at this time, perhaps analogous to the Laramide orogeny in the United States or the Tibetan Plateau. Inboard modification of crust 50–150 m.y. after accretion suggests a lithosphere that is strong enough to transmit stress, implying stabilization of new crust not long after accretion. Ca. 1.6 Ga tectonism appears to represent a shift in tectonic style from the narrower orogenic-belt style typically associated with the “juvenile” Yavapai (ca. 1.70 Ga) and “classic” Mazatzal (1.65 Ga) orogenies to widespread intracontinental deformation. If correct, a cor-

TABLE 1. FABRIC ELEMENTS, KINEMATICS, AND AGE OF DEFORMATION, SODA CREEK–FISH CREEK SHEAR ZONE

Deformational event	Foliations	Lineations	Folds	Kinematics	Age of deformation
D1	328°/90°	55° → 322°	None	Unknown	1774 ± 2 Ma*
D2	241°/77°	69° → 325°	79° → 266°	North side up	1774 ± 2–1739 ± 4 Ma*
D3	NE-striking (western shear zone) NW-striking (eastern shear zone)	Variable None	None 59° → 272°	Variable Unknown	1598 ± 8 Ma† Unknown

Note: Modified after Hamlin (2013).

\*K.R. Chamberlain, (personal commun., 2014).

†This study.

ollary to our interpretation is that newly accreted Paleoproterozoic crust stabilized rapidly and facilitated stress transfer far inboard of any active plate margin.

If the Yavapai and Mazatzal Provinces were not joined until ca. 1.4 Ga along a crustal boundary in southern Colorado or northernmost New Mexico (Andronicos et al., 2012; Aronoff et al., 2013; Daniel et al., 2013), the distance over which the 1.6 Ga intracratonic stresses were transmitted is reduced considerably to 300–400 km. If this scenario is correct, the southern margin of southwestern Laurentia at ca. 1.6 Ga would coincide with the southern margin of the Yavapai Province, but the regional extent and age range of the ca. 1.6 Ga tectono-metamorphism are nonetheless significantly expanded. In the latter scenario, either a noncollisional tectonic setting or one involving collision with an unspecified Colorado Paleoproterozoic tectonic block would need to be invoked to account for the 1.6 Ga tectonism to the north.

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