



Revised location for the Yavapai-Mazatzal crustal province boundary in New Mexico: Hf isotopic data from Proterozoic rocks of the Nacimiento Mountains

T. A. Grambling, M. Holland, K. E. Karlstrom, G. E. Gehrels, and M. Pecha
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REVISED LOCATION FOR THE YAVAPAI-MAZATZAL CRUSTAL PROVINCE BOUNDARY IN NEW MEXICO: HF ISOTOPIC DATA FROM PROTEROZOIC ROCKS OF THE NACIMIENTO MOUNTAINS

TYLER A. GRAMBLING¹, MARK HOLLAND¹, KARL E. KARLSTROM¹, GEORGE E. GEHRELS²,
AND MARK PECHA²

¹ Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, tgrambling@unm.edu

² Department of Geosciences, University of Arizona, Tucson, AZ

ABSTRACT—Lithospheric growth of southwestern Laurentia during the Paleoproterozoic has been hypothesized to have involved addition of two dominantly juvenile crustal provinces: the 1.8–1.7 Ga Yavapai province and the 1.7–1.6 Ga Mazatzal province. Timing of assembly of these two crustal provinces has been stated to have occurred during the 1.72–1.68 Ga Yavapai orogeny and 1.65–1.60 Ga Mazatzal orogeny, with both provinces undergoing high temperature deformation and metamorphism at middle crustal depths accompanying Mesoproterozoic intrusions from 1.45–1.35 Ga. The boundary between provinces remains poorly understood, but has been inferred to lie along the northern edge of the Jemez volcanic lineament and through the Nacimiento uplift in northern New Mexico. This basement-cored Laramide uplift exposes a 53-km-long north-south transect dominated by Paleoproterozoic and Mesoproterozoic granite, providing an ideal locality to examine age and origin of continental lithosphere across this proposed boundary on a local scale. A quartzite metasedimentary unit from the northern Nacimiento that is intruded by ca. 1696 Ma granite was analyzed with U-Pb and Hf isotopic analyses of zircons. The detrital zircon data show a narrow unimodal age peak at 1720 Ma and a maximum depositional age of ~1.7 Ga. Detrital zircons from this sample yield initial epsilon Hf ($\epsilon\text{Hf}_{(t)}$) values ranging from +6.4 to +14.2 suggesting an isotopically juvenile ca. 1.7–1.8 Ga source region for the quartzites. Detrital zircon ages suggest a correlation with the greater Hondo Group and equivalents of northern New Mexico. A 1449 ± 12 Ma granite from the southern Nacimiento Mountains has initial epsilon Hf ($\epsilon\text{Hf}_{(t)}$) values of +2.6 to +10.5 suggesting that the lower crustal melt source region contained 1.7–1.8 Ga (Yavapai) crust that was partially melted by and may have mixed with juvenile 1.4 Ga melt. Together these data suggest that >1.7 Ga (Yavapai) crustal province rocks extend in the subsurface south of the southern Nacimiento Mountains.

INTRODUCTION

Growth of continental crust along the southwestern margin of Laurentia by accretion and stabilization of arc terranes throughout the Proterozoic has been postulated for over 30 years (e.g. Condie, 1982; Karlstrom et al., 1987; Karlstrom et al., 2001). In New Mexico, two crustal age provinces have been proposed based largely on geophysical lineaments, U-Pb ages, and isotopic character of surface outcrops: Yavapai (1.8–1.7 Ga) and Mazatzal (1.7–1.6 Ga). A northeast-trending boundary between the age provinces has been defined as the north edge of a zone of positive aeromagnetic anomalies associated with the Jemez lineament (Karlstrom and Daniel, 1993) and the southern extent of pre-1.7 Ga basement rock exposures (Karlstrom and Humphreys, 1998). This boundary has been drawn through the Nacimiento Mountains in the northern part of New Mexico (Karlstrom and Daniel, 1993; Karlstrom et al., 2004).

A plate scale model for progressive southwards growth of Proterozoic lithosphere was presented by Whitmeyer and Karlstrom (2007). Several aspects of this model are debated:

1) The boundary between the age provinces has been variably defined as a relatively discrete suture between age provinces (Fig. 1; Magnani et al., 2004; 2005; Karlstrom et al., 2005) and/or as part of a wide distributed transitional zone of terrane imbrication that extends north into southern Colorado

(Karlstrom and Humphreys, 1998; Shaw and Karlstrom, 1999; Karlstrom and Williams, 2006).

- 2) Some models suggest the provinces are made up of dominantly juvenile additions to the lithosphere (1.7–1.8 Ga for Yavapai and 1.7–1.6 Ga for Mazatzal; Bowring and Karlstrom, 1990), while others have proposed there is significant older crust in the subsurface, i.e. pre-1.8 Ga for the Yavapai (Bickford and Hill, 2007; Karlstrom et al., 2007) and pre-1.7 Ga for the Mazatzal province (Amato, 2008).
- 3) The timing of accretionary deformation(s) and location of any accretionary sutures is debated. Some models envision suturing of terranes to have accompanied and closely followed lithospheric growth during the 1.72–1.68 Ga Yavapai and 1.65–1.60 Ga Mazatzal orogenies (Whitmeyer and Karlstrom, 2007); others question the arc accretion model as the mechanism for crustal growth (Bickford and Hill, 2007; c.f. Karlstrom et al., 2007); and some suggest final suturing of the Mazatzal terrane in northern New Mexico may have taken place later, during the 1.45 Ga Picuris orogeny (Daniel et al., 2013).

Northern New Mexico is an important locality to continue to refine and test models of crustal growth throughout the Proterozoic. Various datasets that need improving include the delineation and definition of surface and subsurface crustal age provinces, timing and nature of magmatic events, and more precise geochronologic constraints on timing of basin formation, deformation, and metamorphism. The purpose of this paper is to evaluate

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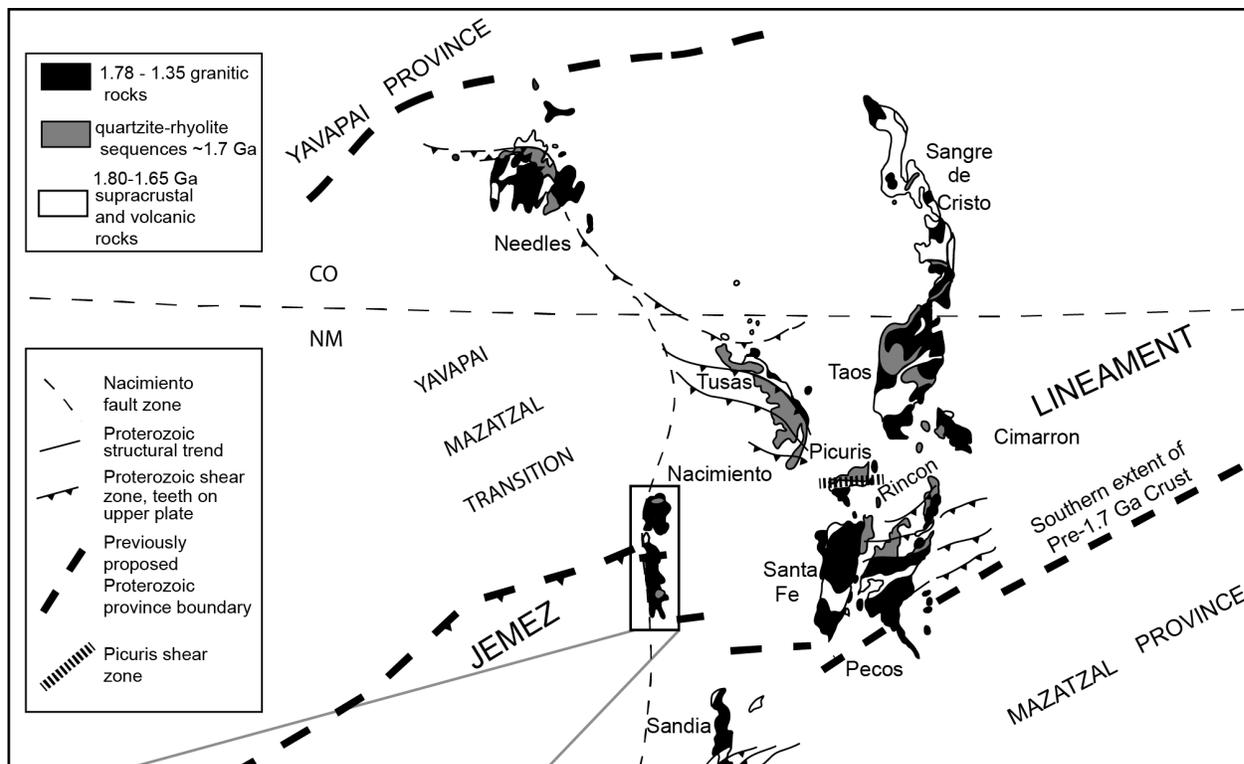
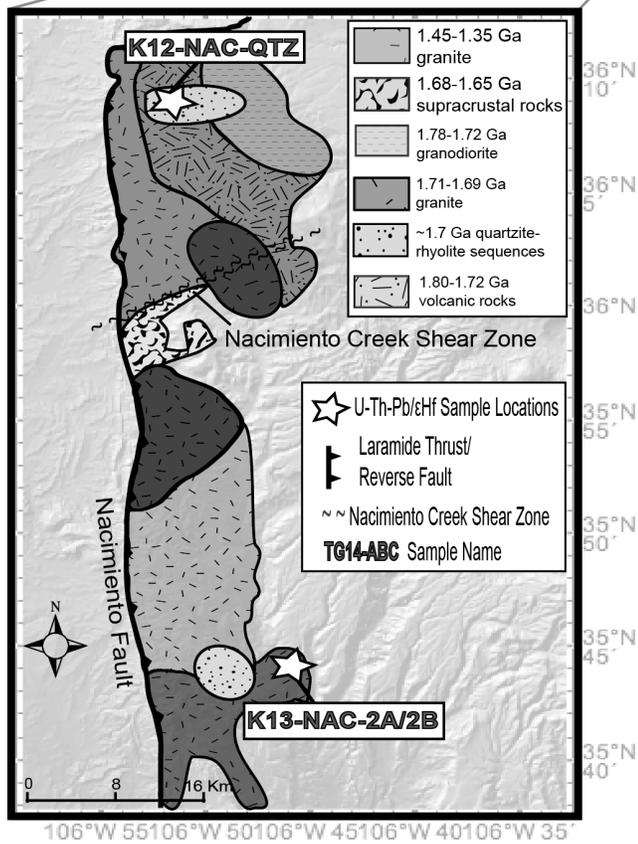


FIGURE 1. Simplified geologic map of northern New Mexico and southern Colorado showing Proterozoic outcrops and mountain range names, modified after Karlstrom et al. (2004). Location of proposed Yavapai-Mazatzal age province boundary and location of Picuris orogeny (~1.45 Ga) shear zones shown with heavy dashed lines. Detail map shows area of study with sample locations shown, starred locations indicate samples with new U-Pb-Hf data.



the previously defined crustal boundary posited to pass through the Naciminto uplift using paired U-Pb-Hf isotopic data from igneous and detrital zircon. We use the Hf isotopic composition of zircons separated from 1.4 Ga granites in the Naciminto Mountains to probe lower crustal composition and help delineate lower crustal age provinces (e.g. Cecil et al., 2011; Foster et al., 2012). U-Pb and Hf isotopic data from detrital zircon in quartzites in the Naciminto uplift are also examined to help test regional stratigraphic correlations. Our new data are the first published Hf isotopic data obtained from Proterozoic rocks of northern New Mexico.

GEOLOGIC BACKGROUND

Limited outcrop, and a history of subsequent deformations (1.5–1.4 Ga and Phanerozoic), complicates the goal of identifying any boundary delineating the Yavapai from Mazatzal provinces in New Mexico. However, the proposed Yavapai-Mazatzal province boundary in northern New Mexico (Fig. 1) is shown as parallel to the Jemez lineament (Aldrich, 1986)—a NE-SW striking locus of Cenozoic tectonic activity, volcanism, and aeromagnetic lineaments that transect the state from near Springerville, AZ, in the west, to Raton, NM, in the northeast

(Karlstrom et al., 2004, Magnani et al., 2004, Cather et al., 2006). This boundary also represents the southernmost extent of Yavapai-age rocks with U-Pb ages >1.7 Ga (Karlstrom and Humphreys, 1998). The Jemez lineament overlies a zone of lower crustal reflectors which were interpreted as both a bivergent orogenic suture and a lithospheric boundary (Magnani et al., 2004, 2005). Shaw and Karlstrom (1999) interpreted this boundary as an age province boundary that formed the southern extent of a wide transitional zone that represented diffuse Mazatzal-age deformation (1.65–1.6 Ga) extending into southern Colorado that affected Yavapai-age (pre-1.7 Ga) rocks. Northern New Mexico is also a domain of intense ~ 1.4 Ga deformation and amphibolite facies metamorphism (Williams et al., 1999, 2009; Shaw et al., 2005, Daniel and Pyle, 2006) that is associated with development of a 1.5–1.45 Ga sedimentary basin (Jones et al., 2011, Daniel et al., 2013, Doe et al., 2013), and arguably either a 1.4 Ga suture zone (Daniel et al., 2013) or a zone of penetrative 1.4 Ga reactivation along an older lithospheric boundary (Williams et al., 1999; Shaw et al., 2005).

The Nacimiento and San Pedro Mountains form a north-south Laramide-aged basement cored uplift, collectively referred to as the Nacimiento uplift (Woodward, 1974; Woodward et al., 1977; Karlstrom et al., 2004). The Nacimiento uplift exposes Proterozoic rocks spanning an age range of 1.73 to 1.4 Ga that are dominated by granites, but also include metavolcanic and metasedimentary rocks (Woodward et al., 1977, Woodward, 1987, and references therein) (Fig. 1). In the northern Nacimiento uplift, 1730 Ma and 1700 Ma U-Pb ages were reported without accompanying analytical data, on the San Pedro quartz monzonite (Woodward, 1987, based on analyses by L.T. Silver), and a granite (Karlstrom et al., 2004, based on analyses by L.T. Silver in 1984). Minimum age constraints on metasedimentary units in the northern section of the San Pedro Mountains were given as ca. 1696 ± 10 Ma based on a U-Pb zircon age reported in an abstract by Premo and Kellogg (2005). Numerous granites in the southern Nacimiento Mountains have been interpreted to be ~ 1.45 Ga based on their megacrystic texture, general lack of penetrative foliation, and an unpublished U-Pb zircon age of ca. 1460 Ma on the Joaquin quartz monzonite (Karlstrom et al., 2004, based on analyses by L.T. Silver in 1984). Thus, the northern Nacimiento Mountains were inferred to be in the Yavapai province and a boundary was drawn either just south of the San Pedro Mountains (Karlstrom and Daniel, 1993, Karlstrom and Humphreys, 1998) or south of the Nacimiento uplift (Karlstrom et al., 2004). The Nacimiento Creek shear zone is a discrete mylonite zone that separates the San Pedro block from the Nacimiento block and may represent part of, or a reactivation of, a lithospheric crustal boundary zone (Fig. 1, Cather et al., 2006, Magnani et al., 2004, Karlstrom et al., 2004, Premo and Kellogg, 2005, Woodward, 1987).

SAMPLING AND METHODS

Samples were collected from the northern and southern sections of the Nacimiento Mountains. Field sampling involved breaking samples into fist sized pieces and visual inspection of

the pieces to avoid any weathered samples. Approximately two gallons of rock were collected for each sample. Rock samples were then shipped to the Arizona Laserchron Center (ALC) at the University of Arizona, Tucson for processing and sample preparation. Sample preparation involved standard heavy mineral separation techniques, mounting zircon separates in epoxy, and hand polishing before cathodoluminescent (CL) and/or back scatter SEM imaging. Additional details are available at the ALC website (www.laserchron.org). U-Pb and Hf analyses were conducted during 3 sessions in January of 2013, March of 2014, and May of 2014.

At the ALC, U-Pb geochronology of zircons is conducted *in situ* by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) on a Nu Plasma HR ICPMS coupled to a Photon Machines Analyte G2 excimer laser. U-Pb geochronologic analyses were conducted using a 30 μm spot size and typically yield a ~ 15 μm ablation pit depth. To account for inter-elemental fractionation of U, Th, and Pb, during laser ablation, in-run analysis of a known standard is conducted between every three to five unknowns. Typical uncertainties resulting from the standard correction for each zircon age determination range from 1–2% at the 2-sigma confidence level. Data are filtered to exclude analyses with $>10\%$ uncertainty in $^{206}\text{Pb}^*/^{238}\text{U}$ and $^{206}\text{Pb}^*/^{207}\text{Pb}^*$ ages (with * indicating radiogenic lead generated from the breakdown of ^{235}U and ^{238}U , respectively), analyses that yield >500 counts per second ^{204}Pb , ages that are $>20\%$ discordant, and $>5\%$ reverse discordant. For detailed analytical methods see Gehrels et al. (2006), Gehrels et al. (2008), and Gehrels et al. (2014).

CL images documenting the internal textures of grains were used in igneous samples to guide spot selection for analysis. Metamict zones, fractures, and inclusions were avoided during analysis. For detrital samples, care was taken to analyze grains of all morphologies and internal textures, excluding only those that were clearly metamict or fractured.

Hf isotopic analyses were also conducted *in situ* by LA-MC-ICP-MS on a Nu Plasma HR ICPMS coupled to a Photon Machines Analyte G2 excimer laser. Hf isotopic analyses were conducted using a 40 μm spot size placed directly over the U-Pb ablation pit to ensure that the same material from which the age determination was reached is analyzed for Hf isotopic composition. As advocated by Woodhead et al. (2004), interference from ^{176}Yb and ^{176}Lu , is accounted for by calculating βYb and βYb assuming $^{173}\text{Yb}/^{171}\text{Yb} = 1.132338$ (Vervoort et al., 2004) and $^{176}\text{Lu}/^{175}\text{Lu} = 0.02653$ (Patchett, 1983) respectively. Reference zircon standards Mud Tank, Plesovice, 91500, FC-1, Temora2, Sri Lanka, and R33 were analyzed in-run with unknowns every 15–20 analyses as standards and corrections with the most weight put on Temora2, 91500, Mud Tank, FC-1, and Plesovice. In the event that standard values are shifted systematically from the value of known solutions, an Yb bias correction factor was applied to the unknown $^{176}\text{Hf}/^{177}\text{Hf}$ values. For example, the correction factor for unknowns analyzed during the May 2014 session had all values decreased by 0.2 epsilon units. In order that unknown values are calibrated based on the same standards analyzed during the session, data reduction of all solutions,

standards, and unknowns is performed together. All $\epsilon\text{Hf}(t)$ values were calculated using the ^{176}Lu decay constant of Scherer et al. (2001) ($\lambda = 1.867 \times 10^{-11}$), and the bulk silicate earth composition of Bouvier et al. (2008). We compare our results to the depleted mantle (DM) composition of Vervoort and Blichert-Toft (1999). Additional details for analytical methods of Hf isotopic analysis at the ALC are detailed in Cecil et al. (2011), and Gehrels et al. (2014).

Due to the importance of the correct age assignment in calculations of $\epsilon\text{Hf}(t)$, selection of igneous zircon for subsequent Hf isotopic analysis was based on their CL texture, age uncertainty, and size. Analyses were conducted on spots that yielded the narrowest age uncertainties, and were unlikely to result in the ablation of distinct age domains. Selection of detrital zircon for subsequent Hf isotopic analysis was based on age peaks composed of >3 overlapping ages (at 2-sigma uncertainty) determined by the AgePick excel macro (Gehrels, 2009). Our sample yielded only one significant age peak (1720 Ma), so grains were selected for Hf analysis based on age uncertainty, size, and internal texture in the same manner as igneous zircon.

RESULTS

We report paired U-Pb-Hf isotopic data from detrital zircon separated from the San Pedro quartzite (K12-NAC-QTZ), and plutonic zircon separated from the monzogranite of the Guadalupe Box in the southern Nacimiento Mountains (K13-NAC-2A, K13-NAC-2B) (Fig. 1). The results of individual U-Pb analyses are reported in Appendix Table 1, and Lu-Hf isotopic data are reported in Appendix Table 2. All ages reported below were calculated using the AgePick excel macro

(Gehrels, 2009) and include internal and external errors, and age uncertainties are expressed at 2-sigma.

Sample K12-NAC-QTZ

K12-NAC-QTZ is a low grade, grey, fine-grained micaceous quartzite that preserves well defined cross bedding, a pervasive NW striking foliation, and some centimeter to millimeter scale folds. This unit is crosscut by the pink to red porphyritic ca. 1696 Ma Clear Creek monzogranite (Premo and Kellogg, 2005), and described as roughly coeval with the adjacent metavolcanic sequence due to spatial association and crosscutting relationships (Woodward et al., 1974, Wobus, 1984). The metavolcanic rocks spatially associated with the quartzite include quartz-eye metarhyolites. Other supracrustal rocks are present as poorly exposed outcrops of limited extent. The entire area appears to be within a mixed zone of metasedimentary-metavolcanic-and intrusive rocks, dubbed the “hybrid zone” by Woodward (1987). This sample yielded a population of euhedral to subhedral detrital zircon grains that exhibited concentric zonation and minor rounding of grain rims, with sizes ranging from $20\mu\text{m}$ to $220\mu\text{m}$, and aspect ratios ranging from 1:1 to 1:4 (Fig. 2A).

U-Th-Pb Results

We obtained 107 $^{206}\text{Pb}^*/^{207}\text{Pb}^*$ detrital zircon ages from the San Pedro quartzite. Our results define a narrow unimodal age peak at 1720 Ma (Fig. 3A). Ages within this peak ranged from 1698 ± 40 Ma to 1760 ± 60 Ma, with 1 grain yielding an age of 2681 ± 11 Ma (Fig. 3A, Appendix Table 1). Individual zircon analyses ranged from 82% to 105% concordant, with 102 $>90\%$ concordant grains. Average concordance of all zircon analyses

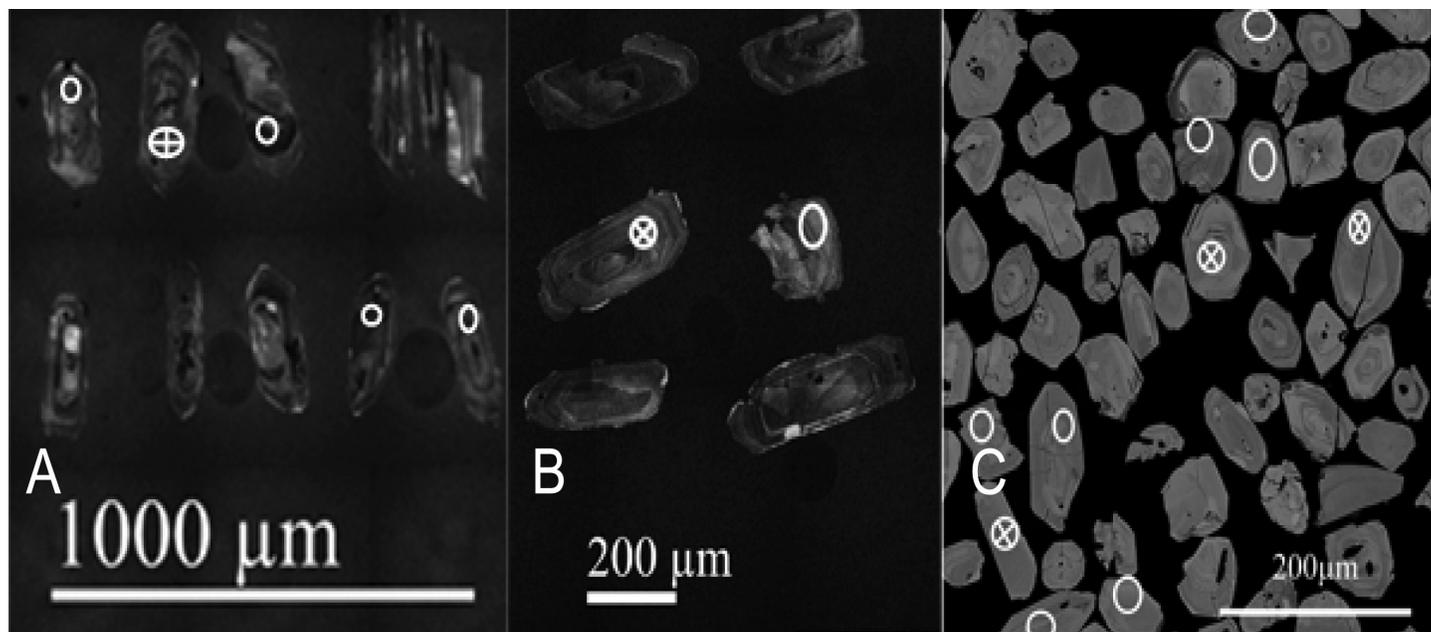


FIGURE 2. Images of igneous and detrital zircon analyzed in this study. A. CL images of igneous zircons from samples K13-NAC-2A and K13-NAC-2B B. and backscatter scanning electron microscope image of detrital zircons representative of sample K12-NAC-QTZ C. White circles show spot analyses for U-Pb data only, circles with cross hairs indicate spots subsequently analyzed for Hf isotopic data. Circle sizes are exaggerated to allow viewing of examined region.

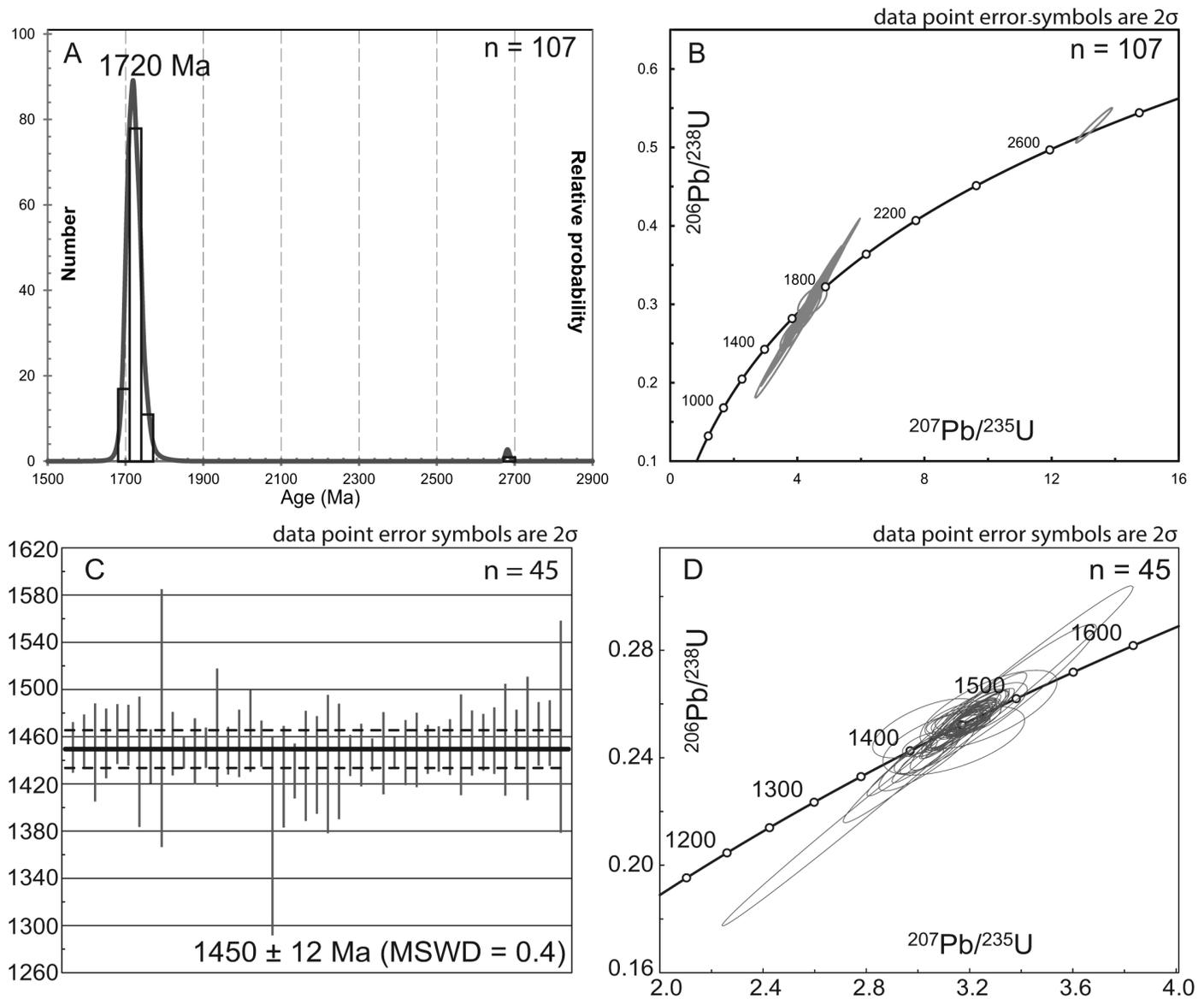


FIGURE 3. Detrital zircon age probability (A) and concordance (B) plots for the San Pedro quartzite (K12-NAC-QTZ). This sample yielded a unimodal age peak of $1720 \text{ Ma} \pm 14 \text{ Ma}$ from 106 analyses. Summary of zircon U-Pb age data for the monzogranite of Guadalupe Box. C. Weighted mean of all U-Pb zircon ages. Solid line shows weighted mean age of 1450 Ma and the dashed line shows the uncertainty envelope of $\pm 12 \text{ Ma}$ at 2-sigma. D. Concordia plot of all igneous U-Pb data.

was 99%. The U concentration of individual zircons ranged from 55 to 458 ppm, with an average value of 153 ppm and U/Th ratios for individual grains ranged from 0.9 to 3.6, with an average value of 1.8. A weighted mean of 106 Paleoproterozoic grains yields an age of $1720 \pm 14 \text{ Ma}$ (MSWD = 1.6).

Lu-Hf Results

Subsequent Hf isotopic analyses were conducted on 28 zircons from sample K12-NAC-QTZ. $\epsilon\text{Hf}(t_0)$ values calculated from measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranged from +6.4 to +14.2. The lowest $\epsilon\text{Hf}(t_0)$ value (+6.4) was calculated from the single Archean grain. All other Paleoproterozoic zircon grains yielded $\epsilon\text{Hf}(t_0)$ values ranging from +7.1 to +14.2 (Fig. 3C).

Samples K13-NAC-2A/B

Sample K13-NAC-2 includes two separate samples, K13-NAC-2A and K13-NAC-2B. These samples were labeled separately due to a substantial contrast in textures sampled within a continuous outcrop of the monzogranite of the Guadalupe Box, which lies approximately 45 km south of the Clear Creek monzogranite that intrudes sample K12-NAC-QTZ (Fig. 1), and approximately 30 km south of the Nacimiento Creek shear zone. K13-NAC-2A is a megacrystic, weakly to non-foliated, red to pink monzogranite with an abundance of 3–5 mm potassium feldspar phenocrysts and 1–2 mm biotite lenses. Sample K13-NAC-2B was a similar porphyritic red to pink monzogranite, but also contained abundant 5–10 cm mafic enclaves. These two samples, belonging

to the monzogranite of the Guadalupe Box (Woodward 1987), were collected near the Gilman Tunnels and Mesa Pinabeta fault zone in southeastern-most Nacimiento Mountains. These samples were collected within 10 m of one another and had field relations that showed K13-NAC-2B was a zone of mafic enclaves within K13-NAC-2A and hence likely to be co-magmatic. Zircon grains from this sample were euhedral zircons with well-defined concentric zonation, ranging in size from 70 μm to 600 μm , with aspect ratios of 1:2 to 1:5 (Fig. 2B,C).

U-Th-Pb Results

Due to the observed co-magmatic relationship between these samples, U-Th-Pb data for both were processed together. U concentrations for the zircon ranged from 32 to 310 ppm with an average value of 122 ppm, and U/Th ratios ranged from 1.0 to 2.8 with an average of 1.4, consistent with magmatic origin for these grains (Hoskin and Schaltegger, 2003). We obtained 41 $^{206}\text{Pb}^*/^{207}\text{Pb}^*$ ages, 18 from sample K13-NAC-2A, and 27 from sample K13-NAC-2B. Ages ranged from 1376 \pm 82 Ma to 1476 \pm 109 Ma, and all but one age was >90% concordant. A weighted mean of 41 ages yielded an age of 1450 \pm 12 Ma (MSWD = 0.4) is interpreted as the time of crystallization of the pluton (Fig. 3C).

Lu-Hf Results

Lu-Hf isotopic analyses were conducted on 30 grains (15 from K13-NAC-2A and 15 from K13-NAC-2B). Similar to their U-Pb isotopic results, these two samples yielded indistinguishable Hf isotopic results despite their contrasting textures and

different proportions of mafic enclaves. $\epsilon\text{Hf}(t)$ values yield a near continuous range from +2.6 to +7.8 with one grain (K13-NAC-2A-12) yielded a higher value of +10.5 at 1.45 Ga. With the exception of K13-NAC-2A-12, $\epsilon\text{Hf}(t)$ values from all grains overlap at 2σ . (Appendix Table 2, Fig. 4).

DISCUSSION OF AGE AND ISOTOPIC DATA

The strong unimodal peak of 1720 Ma from sample K12-NAC-QTZ is consistent with derivation from the 1.8–1.7 Ga Yavapai crustal province. The depositional age of this metasedimentary unit is constrained by the weighted mean age of detrital zircons at 1720 \pm 14 Ma and Clear Creek monzogranite, which intrudes the San Pedro quartzite at ca. 1696 Ma (Premo and Kellogg, 2005). The narrow range of detrital zircon ages indicates a uniform-age source region. Hf isotopic values from detrital zircons of the San Pedro quartzite are within error of the depleted mantle model array at 1.72 Ga, and hence, the zircon was derived from an isotopically juvenile source region. Of the 28 Paleoproterozoic aged grains we obtained Hf isotopic data for, 26 grains yielded $\epsilon\text{Hf}(t)$ values that overlap with the depleted mantle array at 1720 Ma (Fig. 4). The two grains that did not overlap with the depleted mantle array yielded $\epsilon\text{Hf}(t)$ values higher than that of the depleted mantle at 1.72 Ga. These grains may appear theoretically problematic; however, numerous studies have documented heterogeneities in the depleted mantle reservoir (Hamelin et al., 2013 and references therein). As such, we do not suggest that these data reflect analytical issues, but rather that the San Pedro

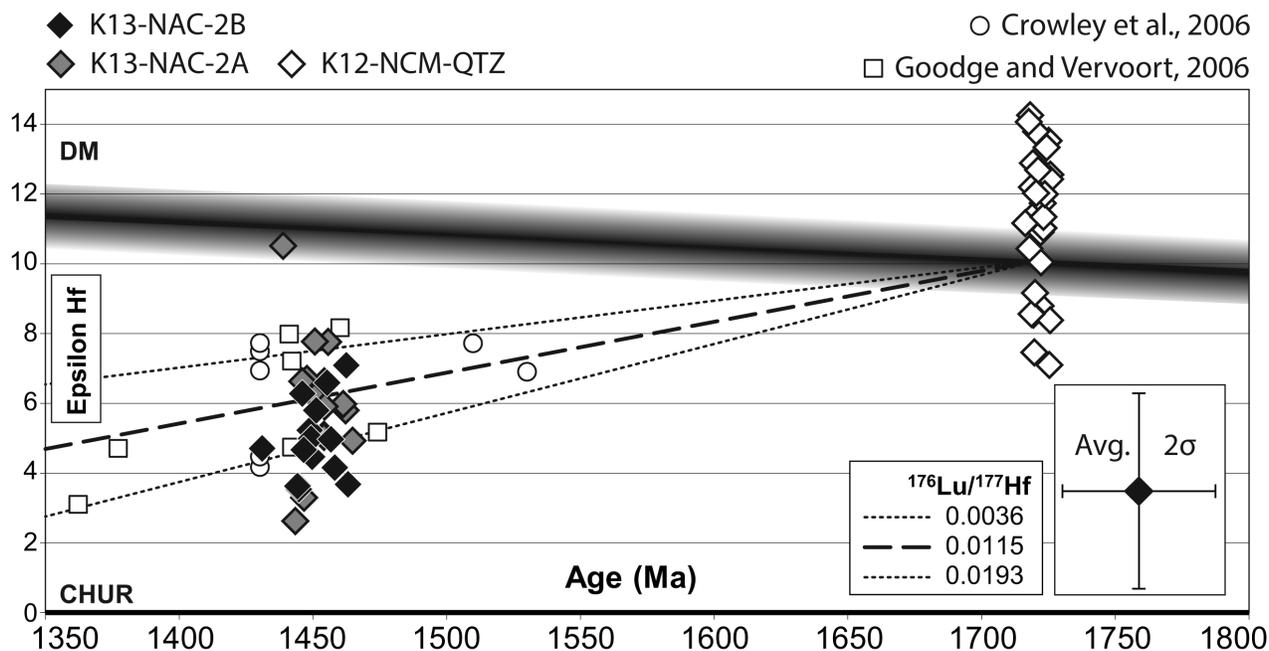


FIGURE 4. Summary of paired U-Pb-Hf zircon isotopic data from the Nacimiento Mountains. Each diamond represents a zircon for which we have a U-Pb crystallization age and initial $^{176}\text{Lu}/^{177}\text{Hf}$ isotopic data, while squares and circles indicate values for Yavapai-sourced zircon from other studies for comparison. Average 2-sigma uncertainty for each kind of analysis is shown in the bottom right. Dashed lines denote the crustal evolution path for crust separated from the depleted mantle (DM) at ca. 1.72 Ga. The slopes of these paths are based on Lu/Hf ratios of crustal rocks from Vervoort and Patchett, 1996. The shaded black region transecting the plot indicates the depleted mantle (DM) reservoir path based on values established by Vervoort and Blichert-Toft, 1999, and the solid black line along the x-axis indicates the chondritic uniform reservoir (CHUR) of primordial mantle.

quartzite was derived from a juvenile 1720 Ma source. These data support the presence of juvenile crust in the local source area available for deposition in basins in the Nacimiento region at 1720 Ma, and are consistent with the tectonic model put forth by Jones et al. (2009) suggesting relatively local derivation of quartzites and rapid progression from basin formation to closure needed to explain the unimodal peaks. No paleocurrent indicators were observed in the field, but 1720 Ma rocks that could have sourced these sediments outcrop throughout northern New Mexico in the Pecos and Taos ranges, and locally in the northeastern San Pedro Mountains. More distant transport from ~1.72 Ga rocks in central to southern Colorado such as those near Salida, Big Thompson Canyon, Beaver Creek areas, and the Needle Mountains and southern Sangre de Cristos (Reed et al., 1987, Karlstrom et al., 2004) is also possible, but not favored, because more distant transport would presumably have led to incorporation of the wider range of zircon ages (e.g. 1.78–1.70 Ga) found in southern Colorado.

Combined with field observations, previously proposed petrogenetic models, and paired U-Pb-Hf isotopic data from detrital zircon of the San Pedro quartzite, the Hf isotopic composition of samples K13-NAC-2A and K13-NAC-2B provide valuable insight into the provenance of lower crust in the southern Nacimiento Mountains. The ~1.4 Ga suite of A-type granites in southern Laurentia have been suggested to be derived from partial melting of pre-existing crust by underplating of mantle derived melts (Anderson, 1983; Barnes et al., 2002; Frost and Frost, 1997; 2013). The presence of a substantial volume of mafic enclaves within the granites of the southern Nacimiento Mountains provides field evidence to support this model (Frost and Frost, 1997). Moreover, it has been suggested that some granitic melts of the A-type granite suite were mixed with juvenile mantle derived melts based on the presence of mafic enclaves and spread in $\epsilon\text{Hf}(t)$ values from near juvenile to non-juvenile values at the 1.46 Ga crystallization age (Goodge and Vervoort, 2006; Bickford and Hill, 2007).

Within the context of these field observations and petrogenetic models, we interpret the Hf isotopic data obtained from samples K13-NAC-2A and 2B to indicate that the monzogranite of the Guadalupe Box was derived from ~1.72 Ga Yavapai province crust (Fig. 4), which is also manifested as detrital grains in the San Pedro quartzite. The $\epsilon\text{Hf}(t)$ values obtained from the granitic samples are consistent with derivation from >1.7 Ga crust, as shown by their position relative to the crustal evolution paths shown in Figure 4. Additional support of a Yavapai province parentage for this rock is offered by the similarity between $\epsilon\text{Hf}(t)$ values obtained in this study and those reported by Goodge and Vervoort (2006) for Mesoproterozoic granites from Yavapai crust in Colorado, and igneous zircon from lower crustal xenoliths in the Four Corners region (Crowley et al., 2006) (Fig. 4).

Regional Implications

The results from this study have implications of regional significance. The unimodal nature and juvenile Hf signature of the San Pedro quartzite suggests a correlation with similar-aged

(~1.7 Ga), unimodal, first cycle quartzites from throughout northern New Mexico and southern Colorado (Jones et al., 2009, Fig. 5). The unimodal age peak of K12-NAC-QTZ is more age restricted than potentially correlative units of the region (Fig. 5).

A visual comparison to age plots of several samples from Jones et al. (2009, 2011) and Daniel et al. (2013) that are representative of the Hondo Group show a similar age peak of ~1710 Ma (Fig. 5). The cumulative Vadito Group sample is noted to have a wider age spectra, which is negatively skewed. Additionally, the shoulders of the peak extend out to 1900 Ma, with input from 2.0 Ga to 2.75 Ga grains. Nevertheless, the sharp unimodal spectrum and age are very similar to individual quartzite samples of the Vadito Group collected from the Picuris Mountains (Daniel et al., 2013), which show more restricted age distributions.

Ortega Formation samples (Jones et al., 2009, 2011) show a similar unimodal age spectrum with an age range of ~1650 Ma to ~1890 Ma and a major peak similar to that of the Nacimiento quartzite at 1720 Ma. However, the Ortega Formation is a distinctive clean quartzite unlike the San Pedro quartzite, which is closely associated with metavolcanic deposits more like the Vadito Group. The Uncompahgre Group quartzites (Jones et al., 2009) also show a similar general age trend from ~1690 Ma to ~1910 Ma, with a peak at 1742 Ma and minor Archean input (Fig. 5).

The unimodal age distributions of all these Paleoproterozoic quartzites are distinctive and are interpreted to reflect acidic weathering conditions—which are required in order to rapidly remove feldspars—and extreme recycling in extensional basins along the leading edge of the Laurentian continent at 1.7–1.6 Ga (Jones et al., 2009). The juvenile nature and restricted time range of zircon in our sample suggests first-cycle reworking of just-older volcanic and plutonic rocks at the margins of the basin. Our preferred correlation is that the Nacimiento metasedimentary package correlates with the transitional Vadito-Ortega quartzites seen in the Tusas and Picuris Ranges to the northeast (Bauer, 1984). This is based on similar micaceous quartzites, similar maximum depositional age, similar age spectra to individual samples in the Picuris (Daniel et al., 2013) and similar close association with metarhyolites seen in the Tusas and Picuris Mountains (Wobus, 1984) (Fig. 6).

CONCLUSIONS

New geochronologic and isotopic data from the Nacimiento Mountains suggest that quartzites from the northern part of the range may correlate with the 1.7 Ga parts of the Hondo Group of the Tusas and Picuris Mountains. $\epsilon\text{Hf}(t)$ data from 1.46 Ga plutons in the southern Nacimiento Mountains suggest that pre-1.7 Ga crust extends in the subsurface further south than the Nacimiento Mountains and that, if age province boundaries are steeply dipping, the boundary between pre-1.7 Ga Yavapai crust and 1.7–1.6 Ga Mazatzal age crust would lie farther south of the Nacimientos. The detrital zircon age and overall characteristics of the San Pedro quartzite argue for extending the large-scale quartzite basin along the southwestern margin of Laurentia at 1.7 Ga proposed by Jones et al. (2011) to include the units exposed in the Nacimiento uplift (Fig. 6).

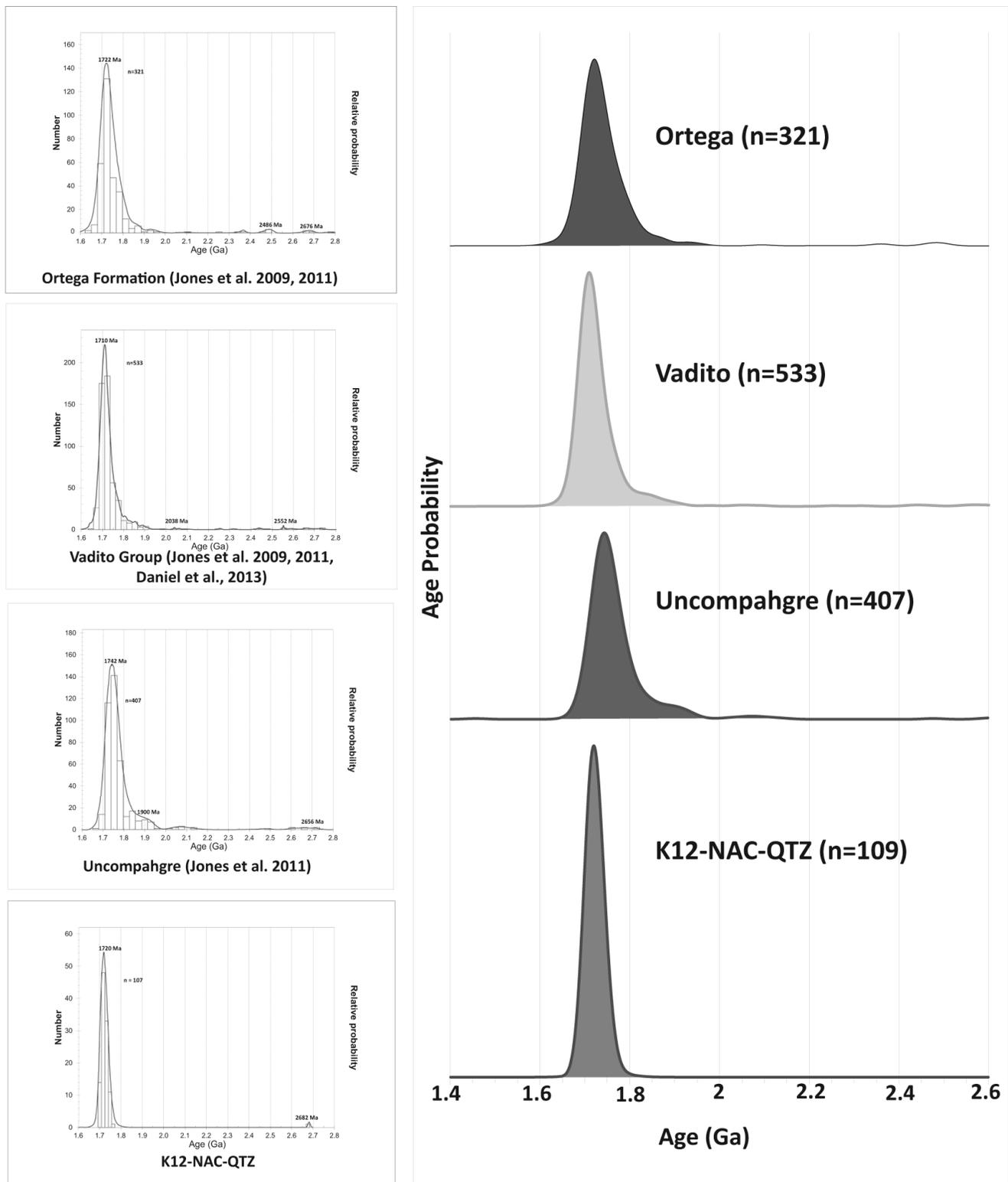


FIGURE 5. Comparisons of the detrital zircon age distributions of the San Pedro Quartzite (bottom) with major quartzite successions in northern New Mexico and southern Colorado. Left side shows histogram, age probability curve and peak age. Right side shows probability distribution functions normalized by the number of ages in each sample set such that the area beneath each curve is the same. Data are from Jones et al. (2009; 2011), Daniel et al. (2013) and this study. Eight >2600 Ma grains from the Vadito, four >2600 Ma grains from the Ortega, and three >2600 Ma grains from the Uncompahgre are not shown in normalized probability plot.

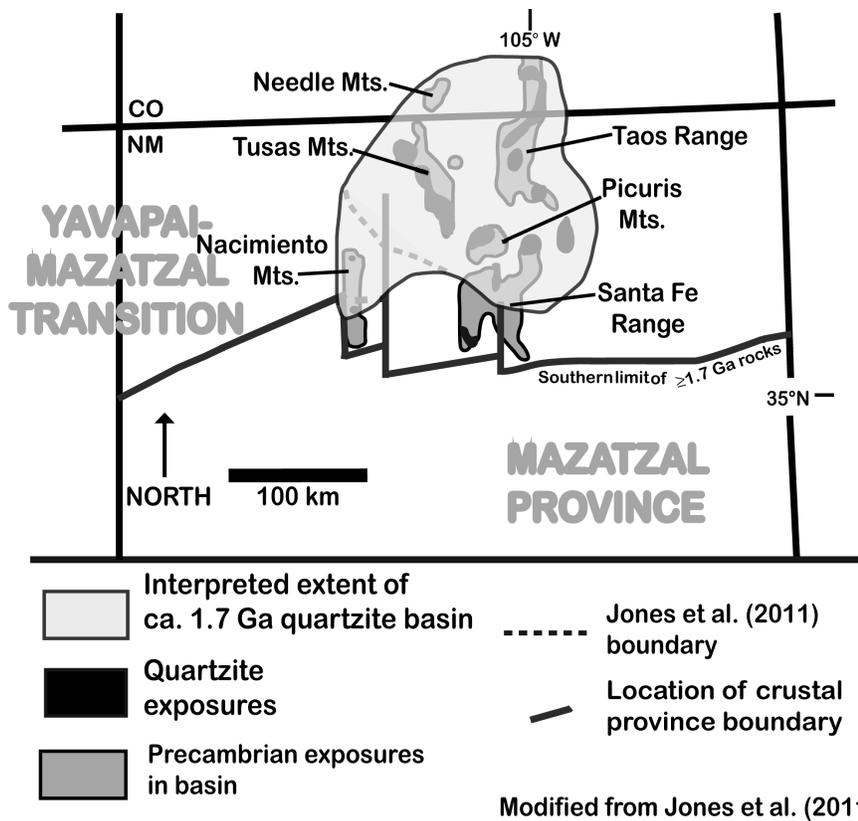


FIGURE 6. Extent of quartzite basin development along the SW Laurentian margin ca. 1.7 Ga, modified from Jones et al. (2011) whose original SW basin boundary is represented by a dashed line. Revised Yavapai-Mazatzal boundary and uplifts with Precambrian exposures are shown.

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