2016

Do Proterozoic Metamorphic Rocks in Northern New Mexico Record One Metamorphic Event At 1.4 Ga, or Two Overprinting Events At 1.65 GA and 1.4 GA

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DO PROTEROZOIC METAMORPHIC ROCKS IN NORTHERN NEW MEXICO RECORD ONE METAMORPHIC EVENT AT 1.4 GA, OR TWO OVERPRINTING EVENTS AT 1.65 GA AND 1.4 GA?

By

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A Thesis

Presented to the Honors Committee
In Partial Fulfillment of the Requirements for the Degree
of Bachelor of Science with Honors in Geology
Bucknell University
May 2016

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ACKNOWLEDGEMENTS

I would first like to thank my thesis advisor, Dr. Chris Daniel, for his unwavering guidance, encouragement, patience, and support throughout the course of my research project. Sophomore year, when I first started doing work with Dr. Daniel, I never imagined that I would accomplish and learn so much, and I am truly grateful for his insight and mentoring. He always pushed me to do my best, and continually challenged me to think critically which allowed me to reach my goals and excel beyond them. I would also like to thank Dr. Mary Beth Gray for her kind words and endless motivation that kept me going even in the most stressful of times. Similarly, I want to extend thanks to all of the geology faculty, as they helped further cultivate my passion for the geosciences, and helped me grow both as a student and a person over the course of my undergraduate career. I would like to give a special thanks to Brad Jordan and Carliee Dill for organizing trips as well as assisting me with gear and the equipment at Bucknell University.

I would also like to thank Chris Macfarlane and his staff at the LA ICP-MS lab at the University of New Brunswick for helping me in conducting geochronological analyses as well as assisting me in data processing. I am furthermore especially grateful for my peers and fellow seniors, Alex Mackay, Izzy Bristol, and Rae Donofrio for spending long nights in the O'Leary computer lab with me and for their relentless and unwavering support. I would also like to give special thanks to Kim Nagotko for mentoring me and guiding me throughout the entire honors thesis process. Also to my fellow "Geopals", I can't imagine where I would be today without your constant support and encouragement. As stressful as it may have been at times, I will miss our late night second home in the O'Leary computer lab, and I will always remember the countless laughs and memories that we shared there.

Finally, I would like to thank my family for supporting me through all of these years, especially during my time at Bucknell. To my mom, you are one of the strongest people I know, and you kept me sane and kept me going even through the most difficult times. To my brother Alex, thanks for being my source of comic relief, as well as for the late night phone calls when I needed a break after working consecutive hours on my research. Lastly, I would like to thank my Dad for cultivating a love for the natural world in me at a young age that eventually led me to pursue geology. I know that he would be extremely proud of me and my work.

Support for this project is funded by the National Science Foundation grant EAR – 1250220.

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ABSTRACT

In-situ LA-ICPMS U-Pb monazite geochronology was used to determine the timing of regional metamorphism in the Picuris Mountains and northern Taos range, New Mexico. Monazite ages from aluminous quartzite and sillimanite-kspar bearing gneisses in Cedro Canyon, northern Taos Range, yield intercept ages of ca. 1380 Ma. Subhedral to anhedral monazite range in size between 10 µm and 50 µm, are typically aligned parallel/sub-parallel to the foliation, and generally occur along mineral grain boundaries; a few grains occur as inclusions within Fe-Ti oxides. Backscatter electron imaging revealed zoning in several monazite grains, but little to no compositional zoning is exhibited in the analyzed grains. Monazite do not appear to preserve any record of ca. 1650 Ma near-granulite facies metamorphism as previously proposed for this region.

Monazite in the Picuris Mountains, northern New Mexico, yield LA-ICPMS, U-Pb intercept growth ages from a variety of bulk compositions: a metarhyolite clast from the Marqueñas Fm. (1386 ± 11 Ma), a micaceous quartzite from the underlying Vadito Fm. (1362 ± 3 Ma), a garnet-biotite-staurolite schist from the Piedra Lumbre Fm. (1357 ± 6 Ma), and a metatuff layer from the Pilar Fm. (1359 ± 19 Ma). The majority of monazite grains are euhedral though some irregular boundaries are apparent due to the partial inclusion of matrix grains. Backscatter electron imaging showed little to no compositional zoning within the grains. Monazite in all samples are generally aligned parallel to the dominant regional foliation, but some clearly overgrow the foliation at a high angle and are interpreted as post-tectonic.

Monazite record no evidence of an older, 1.65 Ga metamorphic and deformational event as proposed by previous studies. Younger, ca. 1430-1360 Ma monazite across northern New Mexico are interpreted to reflect a single regional high temperature metamorphic event and/or pervasive mid-crustal fluid flow event. All monazite growth events are associated with the Picuris Orogeny. Although some monazite in Colorado record multiple age domains, corresponding to at least two monazite growth events, northern New Mexico only records Mesoproterozoic metamorphism and deformation.

INTRODUCTION

The southern portion of the North American continent was progressively assembled through a series of two major accretionary events, including the amalgamation of oceanic terranes and juvenile island arcs associated with the 1.78-1.70 Ga Yavapai and 1.68-1.60 Ga Mazatzal orogenies (Whitmeyer and Karlstrom, 2007). The Mazatzal Orogeny is interpreted as the last major orogenic event recorded in Proterozoic Rocks of the southwestern US (Whitmeyer and Karlstrom, 2007; Bowring and Karlstrom, 1990). However, the areal extent and nature of deformation and metamorphism associated with the Mazatzal Orogeny is under debate (Pedrick et al., 1998; Daniel and Pyle, 2006; Daniel et. al., 2013). In New Mexico and Arizona, deformation of Mesoproterozoic and Paleoproterozoic rocks previously attributed to the Mazatzal Orogeny is now known to be associated with a younger, ca. 1.45-1.36 Ga event, the Picuris Orogeny (Doe et al., 2013; Daniel et al., 2013).

Monazite can be used to date the age of metamorphism in metamorphic rocks, and can record numerous growth events preserved as compositional zoning within an individual grain (Parrish, 1990). In this study, I present new monazite U-Pb ages from the Picuris and northern Taos mountains, two study areas that experienced different peak metamorphic conditions at different crustal levels. Monazite were analyzed from four separate formations in the Picuris Mountains representing different depositional ages and bulk compositions. The northern Taos Range monazite from aluminous quartzite and sillimanite-kspar bearing gneisses were analyzed. Previous work in the region proposed that these areas experienced two overprinting metamorphic events at ca. 1.65 Ga and again at ca. 1.4 Ga (Pedrick et al., 1998; Karlstrom et al., 2004) (Figure 1). My research is designed to test this model using monazite geochronology. If two metamorphic events occurred we would expect to see two monazite populations at both 1.65 Ga and 1.4 Ga. If one metamorphic event occurred, we would expect to see a single monazite population ca. 1.4 Ga. The goal of this work is to determine if metamorphism and deformation is related to the Paleoproterozoic Mazatzal Orogeny, or the Mesoproterozoic Picuris Orogeny, or possibly both as proposed by previous studies (Pedrick et al., 1998; Read et al., 1999; Karlstrom et al., 2004).

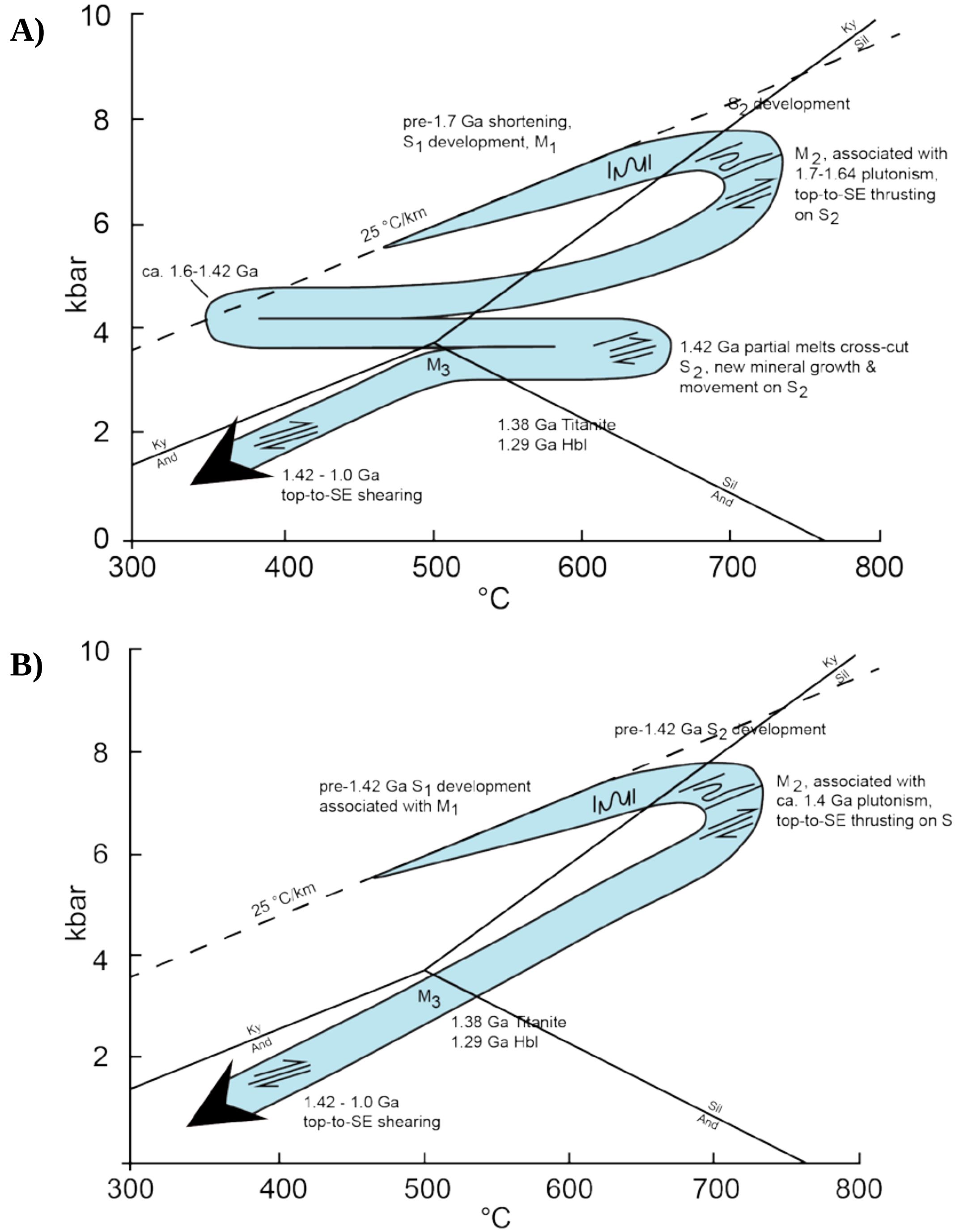


Figure 1: Two potential P-T-t-D diagrams for the Taos Range proposed by Pedrick et al., 1998. A) Preferred model proposed two metamorphic events, one at 1.65 Ga and one at 1.42 Ga. B) Alternate model proposed the region only underwent a single metamorphic event at 1.42 Ga.

GEOLOGIC BACKGROUND

Proterozoic Geology of the southwestern United States

The assembly of the Archean and Paleoproterozoic core of the North American continent was completed by 1.8 Ga, and was followed by the accretion of multiple island arcs and oceanic terranes to the southwestern portion of the juvenile crust between 1.8-1.6 Ga (Whitmeyer et al., 2007). Two major provinces attributed to the growth of southwestern Laurentia: the 1.68-1.60 Ga Yavapai province and the 1.68-1.60 Mazatzal province (Whitmeyer et al., 2007) (Figure 2).

The Yavapai crustal province predominantly extends from Arizona to southern Colorado, and successively stretches northeastward into the center of the continent (Figure 3) (Whitmeyer et al., 2007). The Yavapai province is a product of the accretion of juvenile island arc crust between 1.80 to 1.68 Ga, which collided with the southwestern margin of Laurentia through a series of discrete pulses between 1.71 to 1.68 Ga during the Yavapai Orogeny (Whitmeyer et al., 2007). The province is dominated by greenstone series, consisting of metabasalt, metaandesite, metarhyolite, and other associated volcanogenic metasedimentary rocks intrude by various plutons (Whitmeyer et al., 2007). Pb isotopes from the Yavapai suggest that the province is primarily derived from juvenile mantle material (Whitmeyer et al., 2007). A small portion of zircon from the region show evidence of the incorporation of older crustal material with ages of 2.0-1.8 Ga, which is just slightly older than crystallization ages of 1.8-1.7 Ga (Whitmeyer et al., 2007).

The Mazatzal crustal province is thought to have formed as a result of the accretion of various island arcs between 1.68 and 1.60 Ga (Whitmeyer et al., 2007).

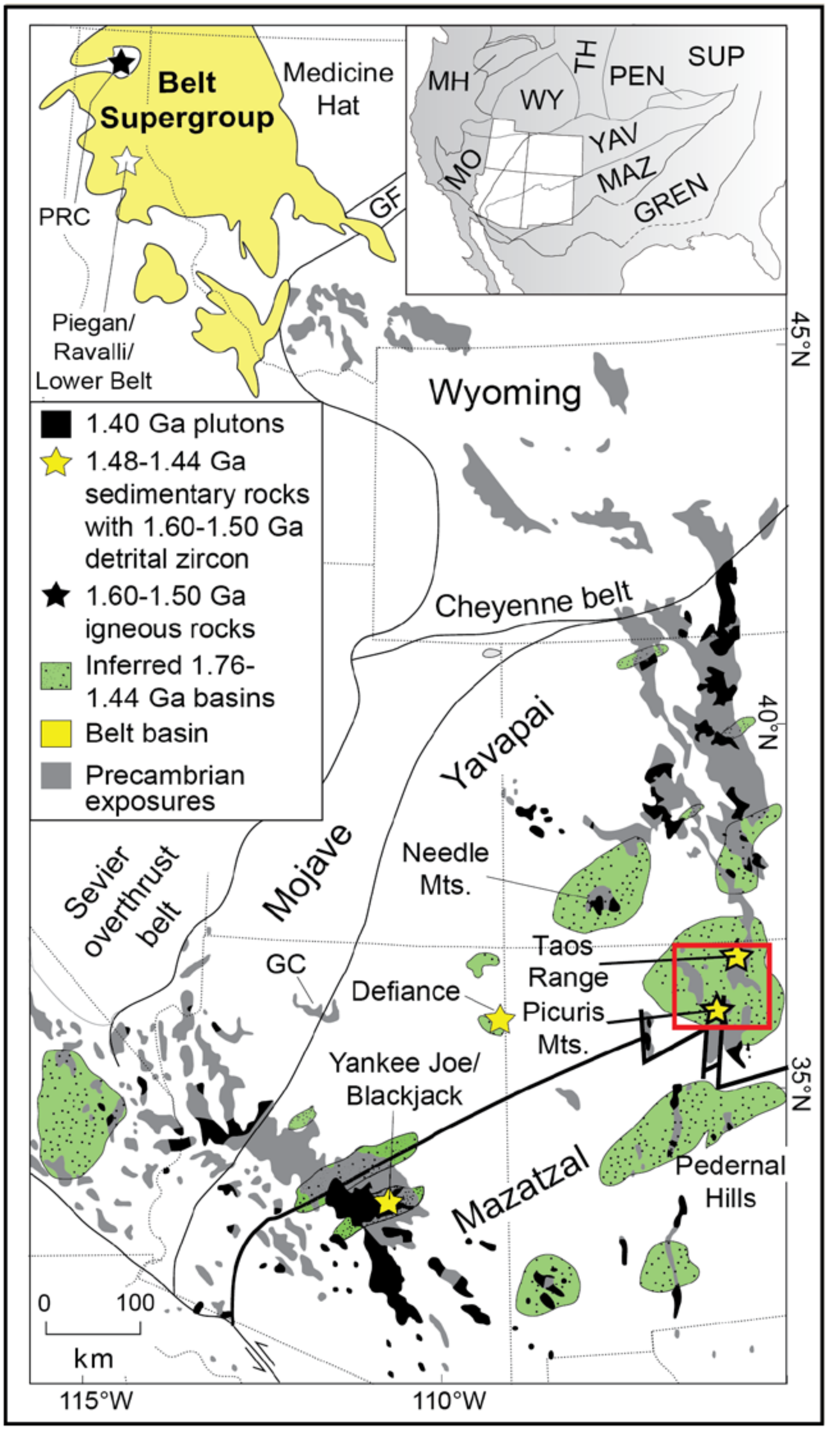


Figure 2: Gray shaded regions represent exposed Proterozoic rock in the western United States. Crustal province boundaries shown by the solid lines and Proterozoic 1.4 Ga plutons are shown in black. Note the red box is the study area, located at the Picuris Mountains and Taos Range. Modified from Doe et al. (2013).

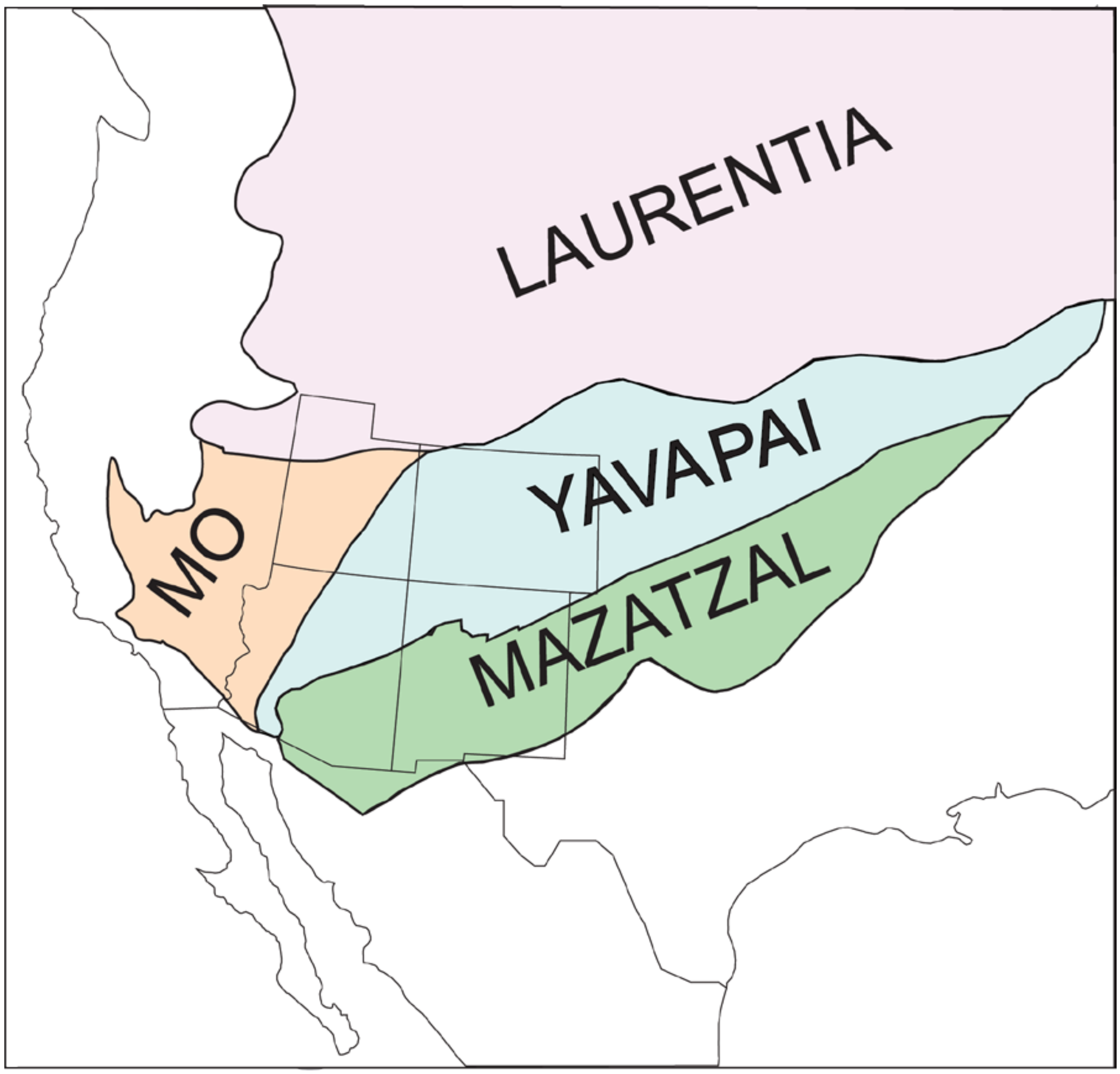


Figure 3: Simplified Paleoproterozoic map of Paleocontinent Laurentia and Precambrian crustal provinces (Mojave, Yavapai, and Mazatzal) superimposed on a map of the modern day North American continent, modified from Daniel et al. (2013).

The major rock types that dominate the Mazatzal province include a succession of volcanogenic greenstones, basalt, basaltic andesite, dacitic tuff, and rhyolite (Whitmeyer et al., 2007). It has been proposed that the Mazatzal province accreted to the Yavapai province during the Mazatzal Orogeny, but the timing and areal extent of deformation associated with the event has been controversial (Bowring and Karlstrom, 1990). It has been suggested that the Mazatzal Orogeny lasted from 1.65-1.60 Ga (Whitmeyer et al., 2007), where others have suggested that there was a continuous series of deformation that lasted from 1.70-1.65 Ga (Williams et al., 1999). The rocks associated with the orogeny experienced either greenschist or amphibolite facies metamorphism, but it is hard to pinpoint exactly when the various phases of deformation occurred (Whitmeyer et al., 2007).

The Picuris Orogeny, proposed by Daniel et al. (2013), includes the deposition of 1490-1450 Ma sediment followed by subsequent burial and regional triple-point metamorphism at depths of 12-18 km (Daniel et al., 2013). Previously, Daniel and Pyle (2006) proposed that the dominant regional foliation and structures in northern New Mexico were established during the Mesoproterozoic, based upon ca. 1435-1400 Ma metamorphic monazite grains included within kyanite, sillimanite, and andalusite. This has been supported by detrital zircon data from Jones et al. (2011), and Doe et al. (2012, 2013) which show that rocks previously presumed to have Paleoproterozoic metamorphic ages actually have Mesoproterozoic protolith ages (Daniel et al., 2013). This suggests that Proterozoic rocks in northern New Mexico experienced only one major regional deformational and upper-amphibolite-facies metamorphism during the Mesoproterozoic: the Picuris Orogeny (Daniel et al., 2013).

Regional Geologic Setting of the Taos Range and Picuris Mountains

The northern Taos Range exposes amphibolite facies to near granulite facies metamorphic rocks that reflect a higher degree of metamorphism than observed in adjacent mountain ranges of northern New Mexico. It is comprised of six lithologic units: an amphibolite gneiss, a felsic gneiss, a lower coarse-grained gneissic granite, an upper fine-grained gneissic granite, a sillimanite-kspar bearing gneiss, and an aluminous quartzite unit (Figures 4A, 4B). The rocks in the region are crosscut by high-angle faults near the Questa Caldera as well as north-rending faults along the western front of the mountain range (Smith, 1988).

Pedrick et al. (1998) identified an S_1 foliation that include bedding-parallel layers of kyanite, which are folded into F_2 intrafolial isoclinal folds, which produce the main S_2 fabric. The S_2 foliation is folded by F_3, which are upright northeast trending folds (Pedrick et al., 1998). S_2 shifts from a northeast striking fabric with variable dips in the southern portion of the Taos Range, to an east striking steeply dipping fabric that contains an east-west L_2 lineation (Pedrick et al., 1998). The Picuris are composed of six distinct Mesoproterozoic and Paleoproterozoic stratigraphic units: the Marqueñas Formation metaconglomerate, the Piedra Lumbre Formation graphitic garnet-biotite-staurolite schist, the Pilar Formation dark grey to black fine-grained graphitic phyllite, the

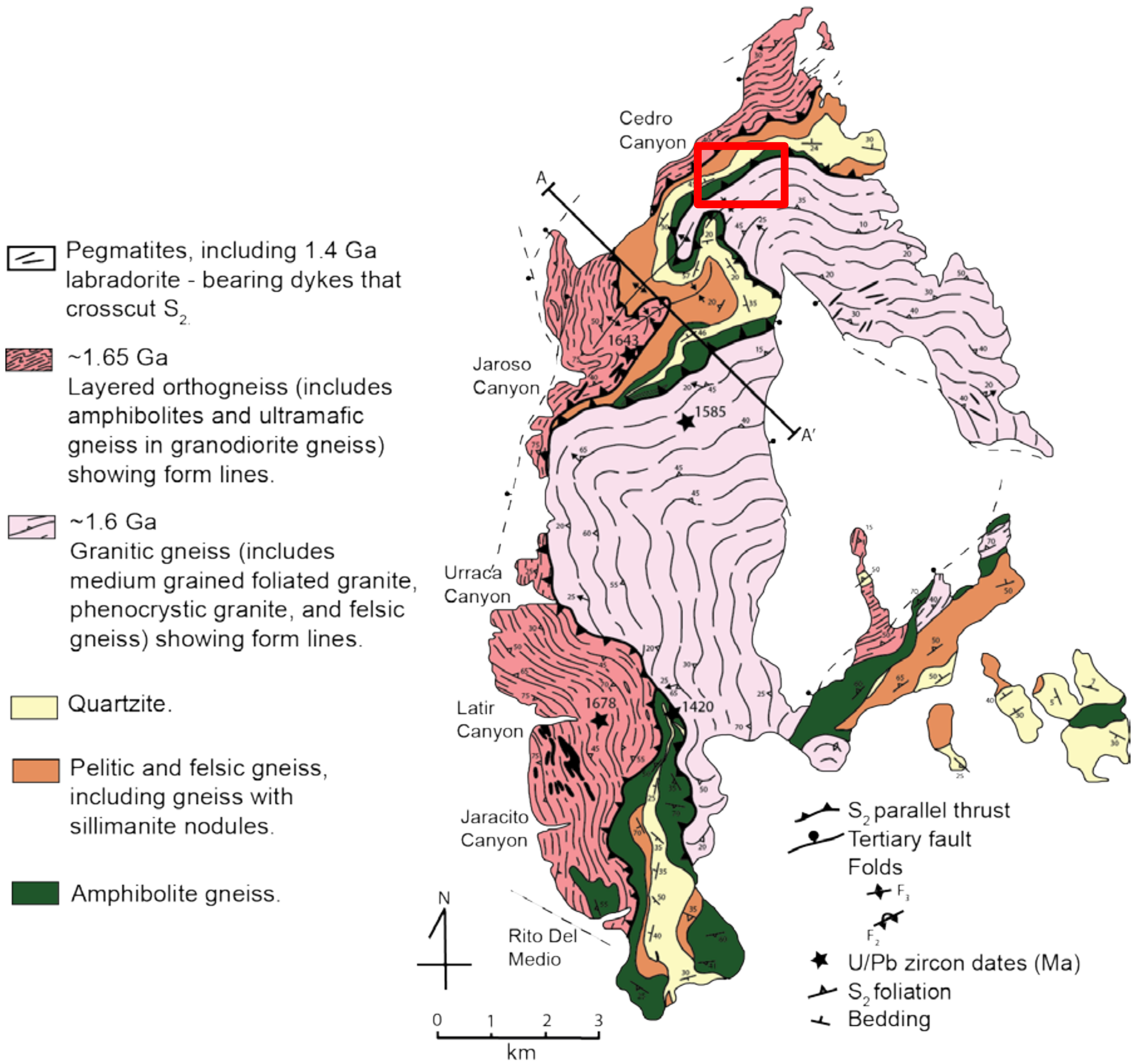


Figure 4A. Simplified geologic map of the northern Taos Range, showing tectonic interleaving of supracrustal rocks between large packages of felsic gneiss (Pedrick et al., 1998). The red box outlines the area of Cedro Canyon in Figure 4B.

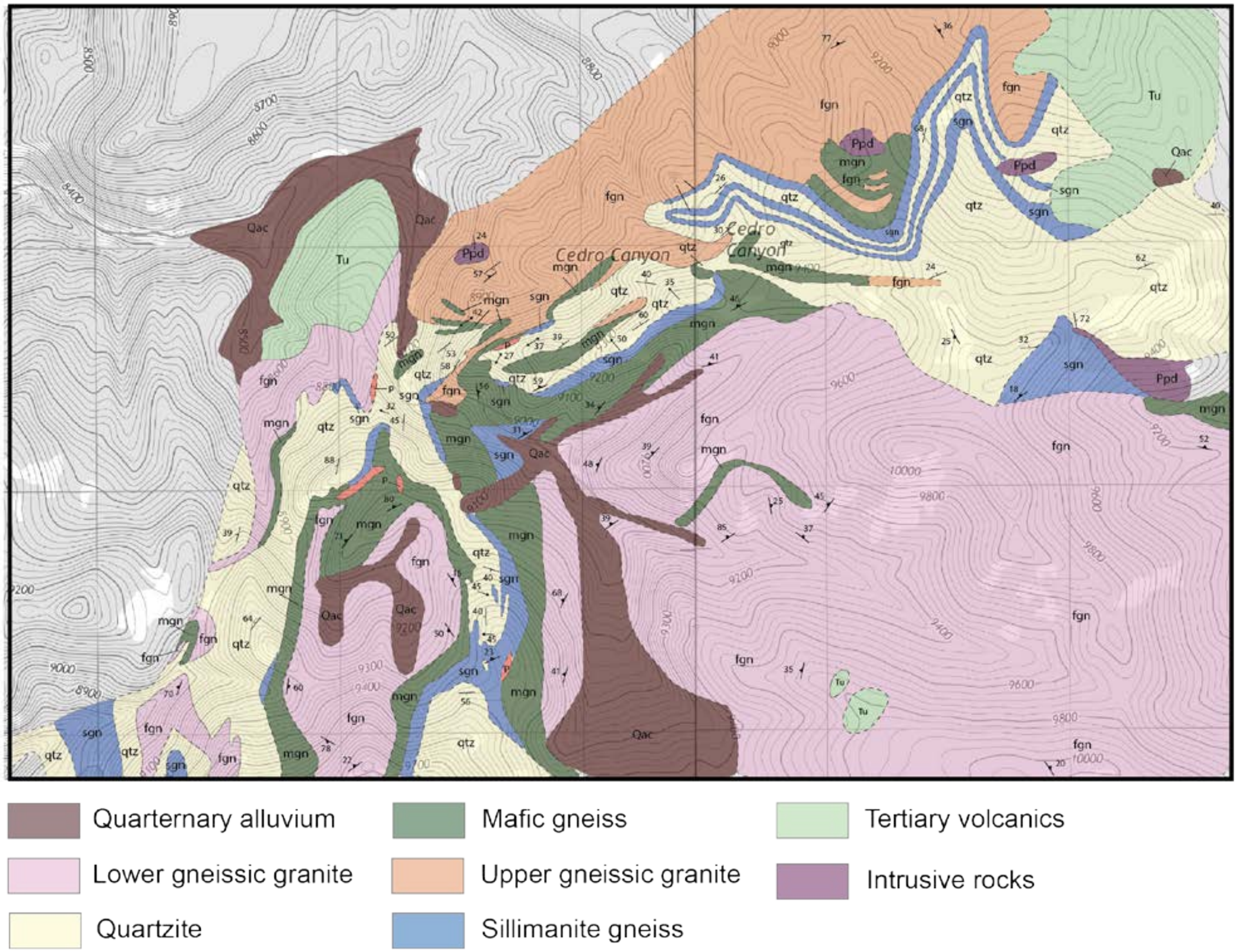


Figure 4B: Detailed geologic map of the study area in Cedro Canyon, Taos Range, northern New Mexico (after Smith, 1988).

Rinconada Formation interbedded quartzite and schist, the Ortega Formation massive to cross-bedded quartzite, and the basal Vadito group (Figure 5). The Marqueñas Formation, Piedra Lumbre Formation, and Pilar Formations have Mesoproterozoic protolith ages of ca. 1.50-1.45 Ga (Daniel et al., 2013). The underlying Rinconada and Ortega Formations protolith age is not known, but is between 1.50 and 1.70 Ga. The lowermost Vadito Group has a Paleoproterozoic protolith age ca. 1.70 to 1.72 Ga. Metamorphic P-T conditions in the Picuris Mountains are estimated to be 530 °C at 4 kbar (Daniel and Pyle, 2006).

In the Picuris, bedding, S_0, is well preserved within the Ortega cross-bedded quartzite, as well as the overlying Rinconada Formation (Bauer, 1993). S_1 is associated with a schistosity that is near parallel to S_0, as well as a down-dip L_1 lineation, and may be related to small-scale isoclinal folds preserved within the Rinconada schists (Daniel and Pyle, 2006). S_0, S_1, and L_1 are consequently affected by F_2 folds (Daniel and Pyle, 2006). The Hondo syncline is a representative fold from the F_2 generation, exhibiting km-scale fold geometry with an east striking axial surface with a 65° S dip (Bauer, 1993) (Figure 5). S_1 becomes altered to a steeply south-dipping foliation, defined as S_2, which transects the F_2 folds, and is interpreted as forming relatively late in the F_2 fold development (Daniel and Pyle, 2006). Regional deformation and metamorphism in the Picuris Mountains is attributed to the Mesoproterozoic (ca. 1.5-1.4 Ga) Picuris Orogeny.

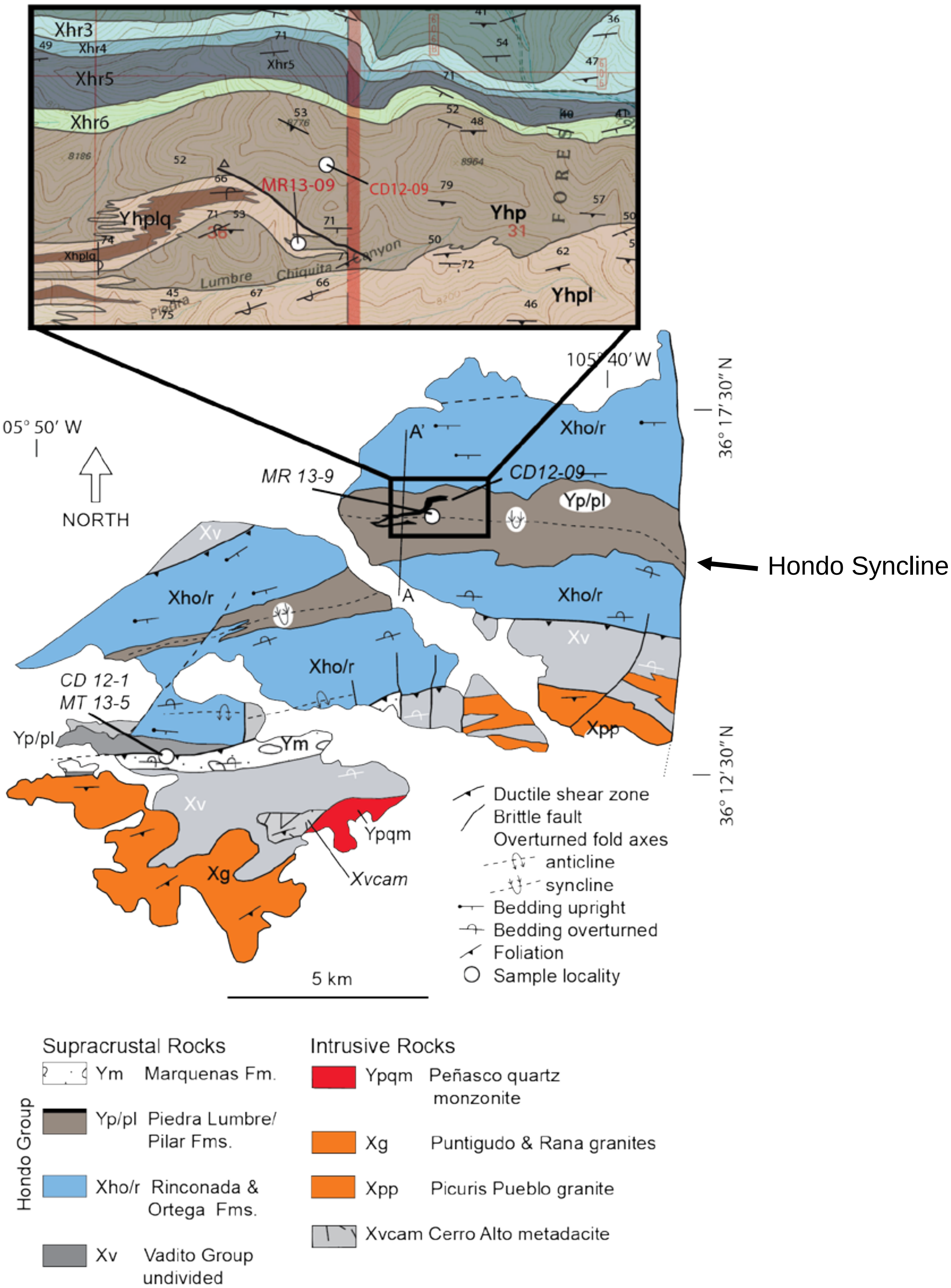


Figure 5. Simplified geologic map of the Picuris Mountains with sample localities (after Daniel et al., 2013). Inset figure is detailed geologic map of the study area in the northern Picuris Mountains showing sample locations (after Bauer and Helper 1994).

METHODS

Sample Collection

Samples CD12-01, CD12-09 MR13-09, and MT13-05 were previously collected from the Vadito Group, the Pilar Formation, Piedra Lumbre Formation, and the Marqueñas metaconglomerate from the Picuris Mountains, respectively (Table 1, Figure 5, Figure 6).

Samples SS15-01, SS15-03, and SS15-08 were collected from aluminous quartzite and sillimanite kspar bearing gneiss from the Taos Range, respectively (Table 2, Figure 5, Figure 6). Thin sections for each of the samples from the Picuris Range were cut for monazite geochronology and scanning electron microscope study. For the samples from the Taos Range, rock chips were cut from the collected hand samples using a rock saw, and fashioned into pieces that were approximately 1.3 cm by 1.3 cm. The small rock chips were then mounted into epoxy and polished for in-situ monazite geochronology and scanning electron microscope study. Backscatter electron and light photomicrographs were taken of all samples for investigation of sample foliation, characteristics, monazite textures, and monazite zoning (Figure 7 and Figure 8).

Monazite U-Pb Geochronology Methods

Monazite U-Pb analyses were conducted in-situ using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICPMS). All samples from both the Picuris Mountains and the Taos Range were analyzed at the University of New Brunswick.

Table 1. Locations of samples from the Picuris Mountains, see Figure 3 for locations.

Number	Lat, Long	Orientation	Formation	Lithology
CD12-01	N 36° 12’ 12.96” W 105° 48’ 45”	-	Vadito Group	Micaceous quartzite
CD12-09	N 36° 16’ 23.16” W 105° 43’ 7.68”	250, 58 S	Pilar	Graphitic phyllite
MR13-09	N 36° 16’ 11.28” W 105° 43’ 14.16”	-	Piedra Lumbre	Graphitic garnet-biotite-staurolite schist
MT13-05	N 36° 12’ 4.32” W 105° 48’ 29.88”	266, 66 S	Marqueñas	Metarhyolite clast within metaconglomerate

Table 2. Locations of samples from the Taos Range, see Figure 4 for locations.

Number	Lat, Long	Orientation	Formation	Lithology
SS15-01	N 36° 55’ 22.14” W 105° 30’ 46.53”	062, 42 NW	N/A	Aluminous quartzite
SS15-03	N 36° 55’ 20.49” W 105° 30’ 45.32”	305, 59 S	N/A	Sillimanite kspar bearing gneiss
SS15-08	N 36° 55’ 26.78” W 105° 28’ 57.52”	055, 26 W	N/A	Sillimanite kspar bearing gneiss

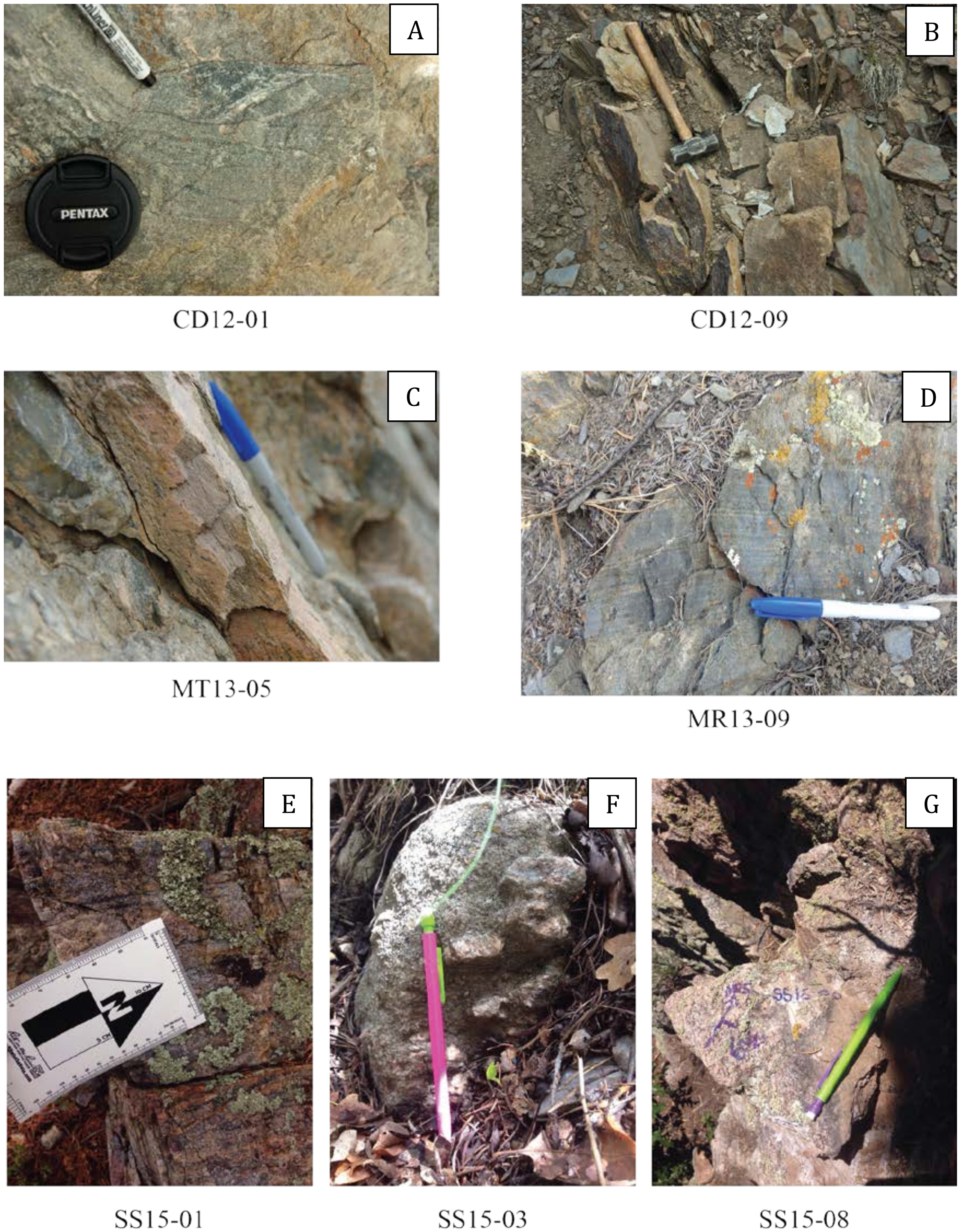


Figure 6 A-G: Field outcrop photographs of the A. Vadito Formation, B. Pilar Formation, C. metarhyolite clast from Marqueñas metaconglomerate, D. Piedra Lumbre Formation, E. aluminous quartzite, F. sillimanite kspar bearing gneiss, G. sillimanite kspar bearing gneiss.

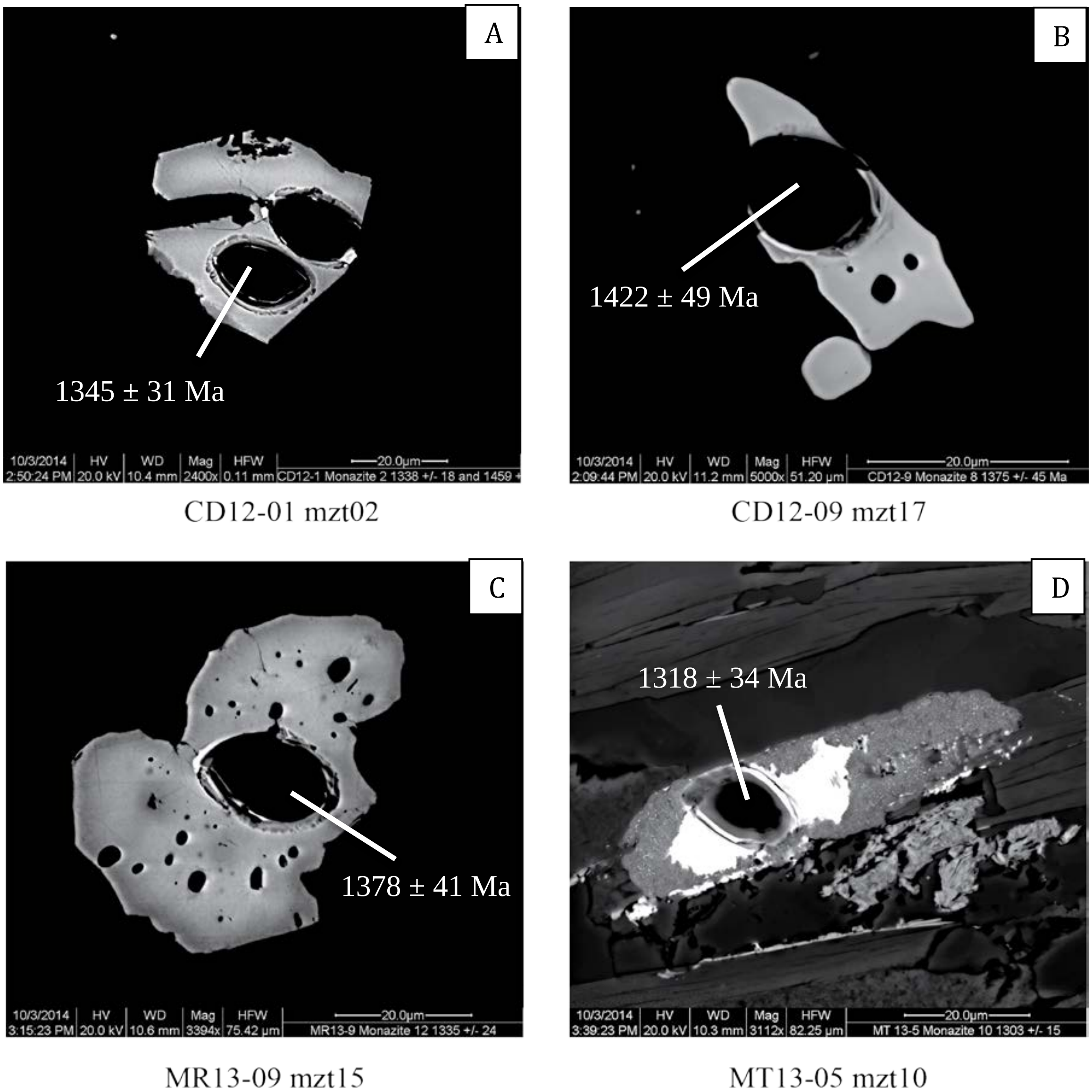


Figure 7 A-D: Backscatter electron photomicrographs of monazite within A) CD12-01, B) CD12-09, C) MR13-09, and D) MT13-05. All samples show the age of the representative monazite grain close to the spot of ablation.

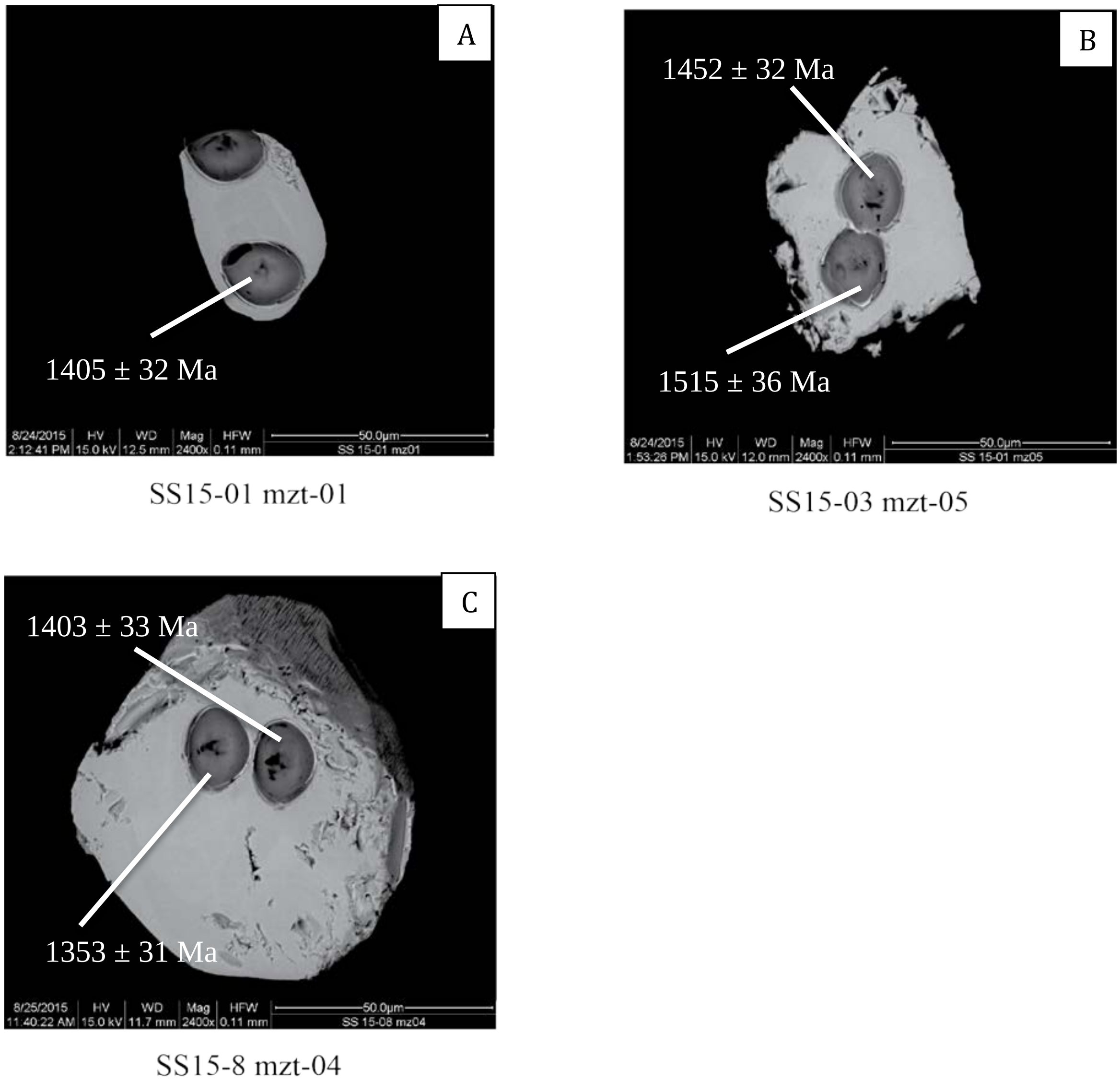


Figure 8 A-C: Backscatter electron photomicrographs of monazite within A) SS15-01, B) SS15-03, and C) SS15-08. All samples show the age of the representative monazite grain close to the spot of ablation.

The scanning electron microscope was used to locate individual monazite grains on the polished surface of thin section and epoxy round surfaces. Images were taken prior to analysis in order to screen the grains for fractures or inclusions and to help with laser placement. Monazite were generally ablated near the core of the grain; some grains only contained one analysis, while others were large enough to collect multiple spots. Monazite were ablated with an average crater diameter of 10-13 µm, a 3.5 Hz pulse rate, and a laser fluence of ~3.5 J/cm^2 (Petrus et al., 2011). Once material is ablated off of the surface of the monazite grain, it passes through plasma at high temperatures which allows for the separation of U and Pb isotopes. After the ions pass through the plasma, the various isotopes of U and Pb are carried into the mass spectrometer for isotopic analysis. The number of analyses taken per sample ranged from 8-30 analyses.

Grains that contained large inclusions or cracks were purposefully avoided in order to avoid contamination and poor analyses. Generally, grains with greater than 1% discordant or 1% reverse discordant were eliminated from all monazite samples, with few exceptions. The data was put into excel using the Berkley Geochronology Center's Isoplot program to generate concordia diagrams and ^{206}Pb/^{207}Pb age diagrams. Excel was also used to generate age vs. ^{238}U concentration and age vs. Th concentration.

RESULTS

Age summaries are given in Table 3 and 4. Detailed results for each study are presented in the following text.

Picuris Mountains in-situ U-Pb monazite geochronology and textural analysis

Figure 9 presents U-Pb monazite analyses from a metarhyolite clast within the Marqueñas Fm. (MT13-05), the Piedra Lumbre Fm. graphitic garnet-biotite-staurolite schist (MR13-09), the Pilar Fm. graphitic phyllite (CD12-09), and the Vadito Group micaceous quartzite (CD12-01) (Table 3).

Marqueñas Formation MT13-05

MT13-05 is a cobble sized metarhyolite clast from a polymictic boulder to cobble conglomerate overlain by a chlorite-epidote-biotite-muscovite quartzite (Soegaard and Eriksson, 1986) (Figure 6A). The clast exhibits a strong elongation lineation and foliation, S2, defined by quartz, muscovite, microcline, and chlorite. Grains are generally euhedral to subhedral, and are aligned parallel to subparallel to the dominant regional foliation. Some grains exhibit significant replacement by apatite. MT13-05 yielded an intercept age of 1342 ± 58 Ma, and a $^{206}Pb/^{207}Pb$ age of 1354 ± 53 Ma (Figure 9A-B). Only 4 of 10 grains analyzed yielded acceptable results.

Piedra Lumbre Formation MR13-09

MR13-09 is a fine-grained graphitic, garnet-biotite-staurolite schist. The sample is very fine grained and strongly foliated (Figure 6B). Monazite are generally subhedral to anhedral, and commonly aligned subparallel to the foliation, with the exception of a few grains that cross cut the foliation at a high angle. Some monazite grains also exhibit aligned inclusions. MR13-09 yielded a concordia age of 1362 ± 6 Ma, and a $^{206}Pb/^{207}Pb$

Table 3: Age summaries from the Picuris Mountains.

Sample	Concordia Age (Ma)	Intercept Age (Ma)	2 S.E. (Ma)	$^{206}Pb/^{207}Pb$ (Ma)	2 S.E. (Ma)
MT13-05	-	1342	58	1354	53
MR13-09	1362	-	6	1365	17
CD12-09	-	1460	160	1411	20
CD12-01	-	1380	41	1368	9

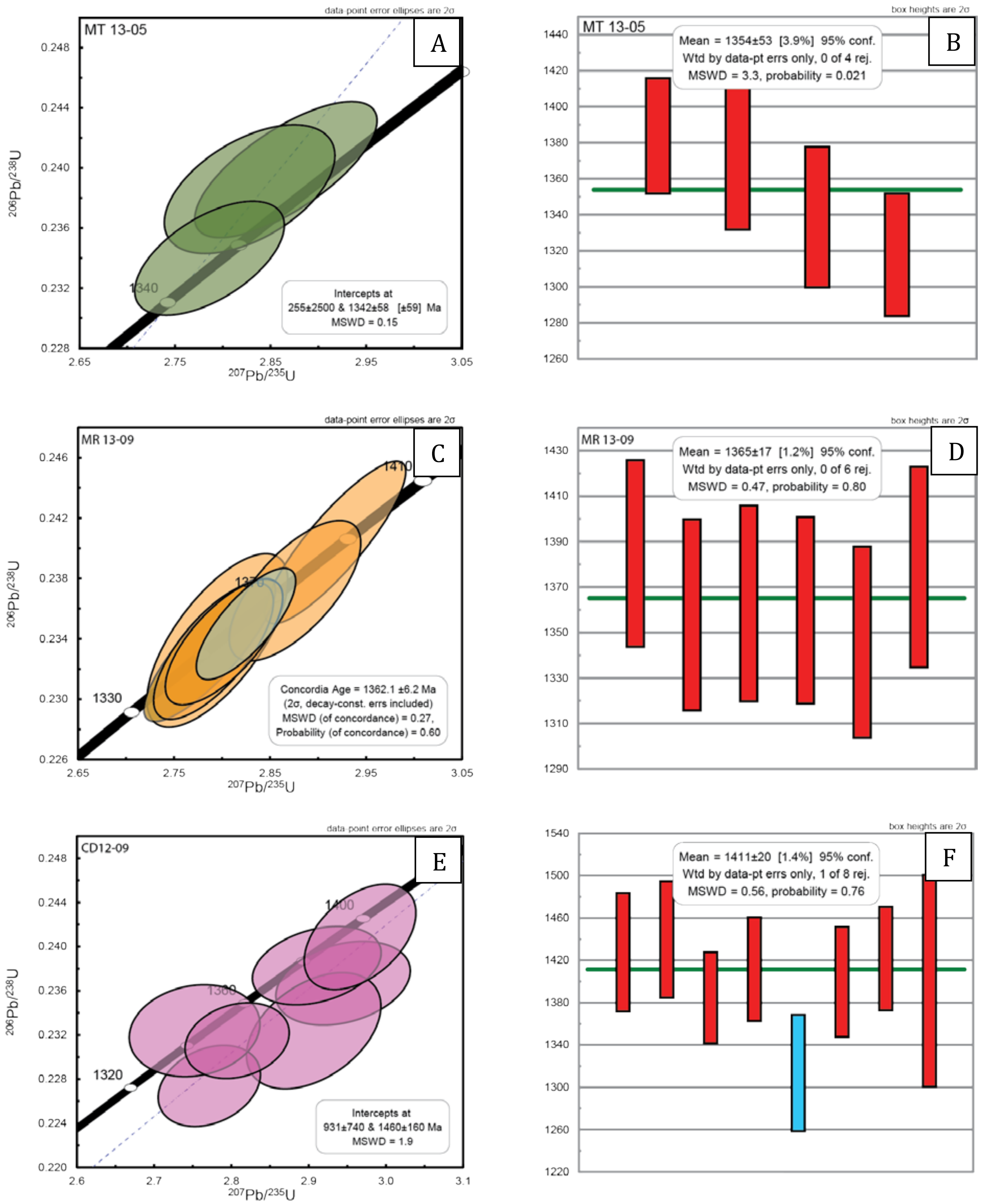
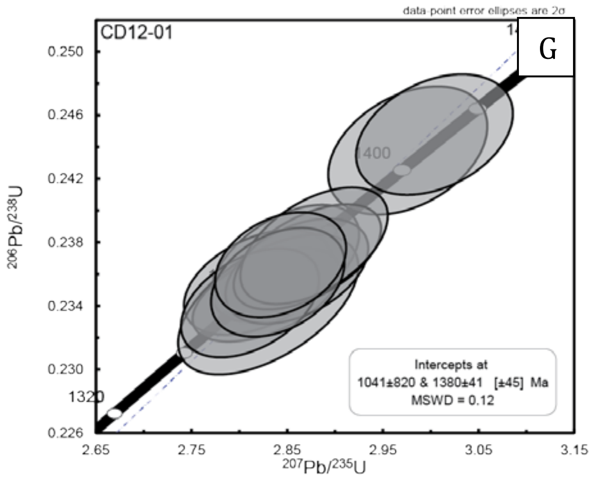


Figure 9 A-F: Concordia plot and $^{206}Pb/^{207}Pb$ weighted mean age plot for sample A-B) MT13-05 metarhyolite clast from the Marqueñas Fm. C-D) MR13-09 Piedra Lumbre Fm. E-F) CD12-09 metatuff within the Pilar Fm.



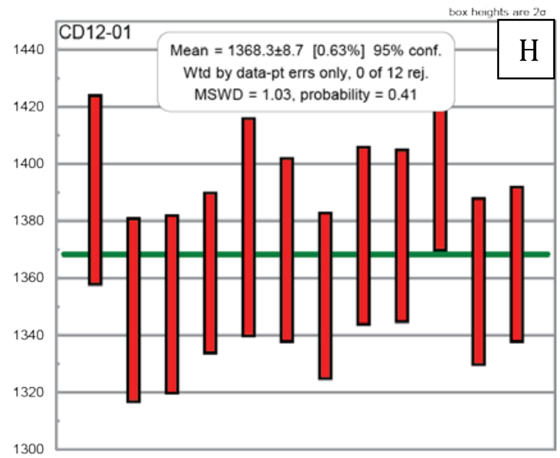


Figure 9 G-H (cont.): Concordia plot and $^{206}Pb/^{207}Pb$ weighted mean age plot for sample G-H) CD12-01 micaceous quartzite from the Vadito Group.

age of 1365 ± 17 Ma (Figure 9C-D). 11 grains analyzed out of 27 total yielded concordant results.

Pilar Formation CD12-09

CD12-09 is a metatuff with microporphyroblasts of microcline deposited within a dark grey to black fine-grained graphitic phyllite (Figure 6C). The sample exhibits a strong foliation, which is defined by aligned quartz, muscovite, and biotite. Grains are generally anhedral, and most are aligned parallel to subparallel to the foliation with the exception of a few grains that cross cut the foliation at a high angle. Some monazite grains from this sample also exhibited aligned inclusions. CD12-09 yielded an intercept age of 1460 ± 160 Ma, and a $^{206}Pb/^{207}Pb$ age of 1411 ± 20 Ma (Figure 9E-F).

Vadito Group CD12-01

CD12-01 is from a micaceous quartzite, dominated by muscovite, biotite, quartz, and chlorite grains (Figure 6D). The sample exhibits a moderate foliation, and is a mix of fine and coarser grained material. Grains were generally large as well as euhedral to anhedral, and most are aligned parallel to subparallel to the foliation with the exception of a few grains that cross cut the foliation at a high angle. CD12-01 yielded an intercept age of 1380 ± 41 Ma, and a $^{206}Pb/^{207}Pb$ age of 1368 ± 9 Ma (Figure 9G-H).

Taos Range in-situ U-Pb monazite geochronology and textural analysis

Figure 10 presents U-Pb monazite analyses from an aluminous quartzite (SS15-01, and two samples of sillimanite kspar bearing gneiss (SS15-03 and SS15-08) (Table 4). Initially, we did not find evidence of monazite ages associated with the Paleoproterozoic and Mazatzal Orogeny, but recent reexamination showed zoning in a majority of grains from all three analyzed samples. Because of this we can't definitively rule out the possibility of an older monazite growth event.

Aluminous Quartzite SS15-01

SS15-01 is from a coarse grained aluminous quartzite with alternating quartz rich layers and oxide rich layers (Figure 6E). The sample exhibits a strong foliation defined by compositional layering and aligned orientation of iron oxides. Monazite grains are subhedral to anhedral, and are generally aligned subparallel to the foliation with the exception of a few grains that are included within iron oxides and a few that cross cut the foliation at a high angle. SS15-01 yielded an intercept age of 1421 ± 45 Ma, and a $^{206}Pb/^{207}Pb$ age of 1400 ± 38 Ma (Figure 10A-B).

Sillimanite Kspar Bearing Gneiss SS15-03

SS15-03 is from a coarse grained sillimanite kspar bearing gneiss with large kspar knobs in hand sample (Figure 6F). The sample exhibits a weak foliation defined by quartz, muscovite, and kspar. All monazite are generally rounded and anhedral and are

Table 4. Age summaries from the Taos Range.

Sample	Concordia Age (Ma)	Intercept Age (Ma)	2 S.E. (Ma)	$^{206}Pb/^{207}Pb$ (Ma)	2 S.E. (Ma)
SS15-01	-	1421	45	1400	38
SS15-03	-	1375	33	1371	18
SS15-08	1376	-	8	1381	55

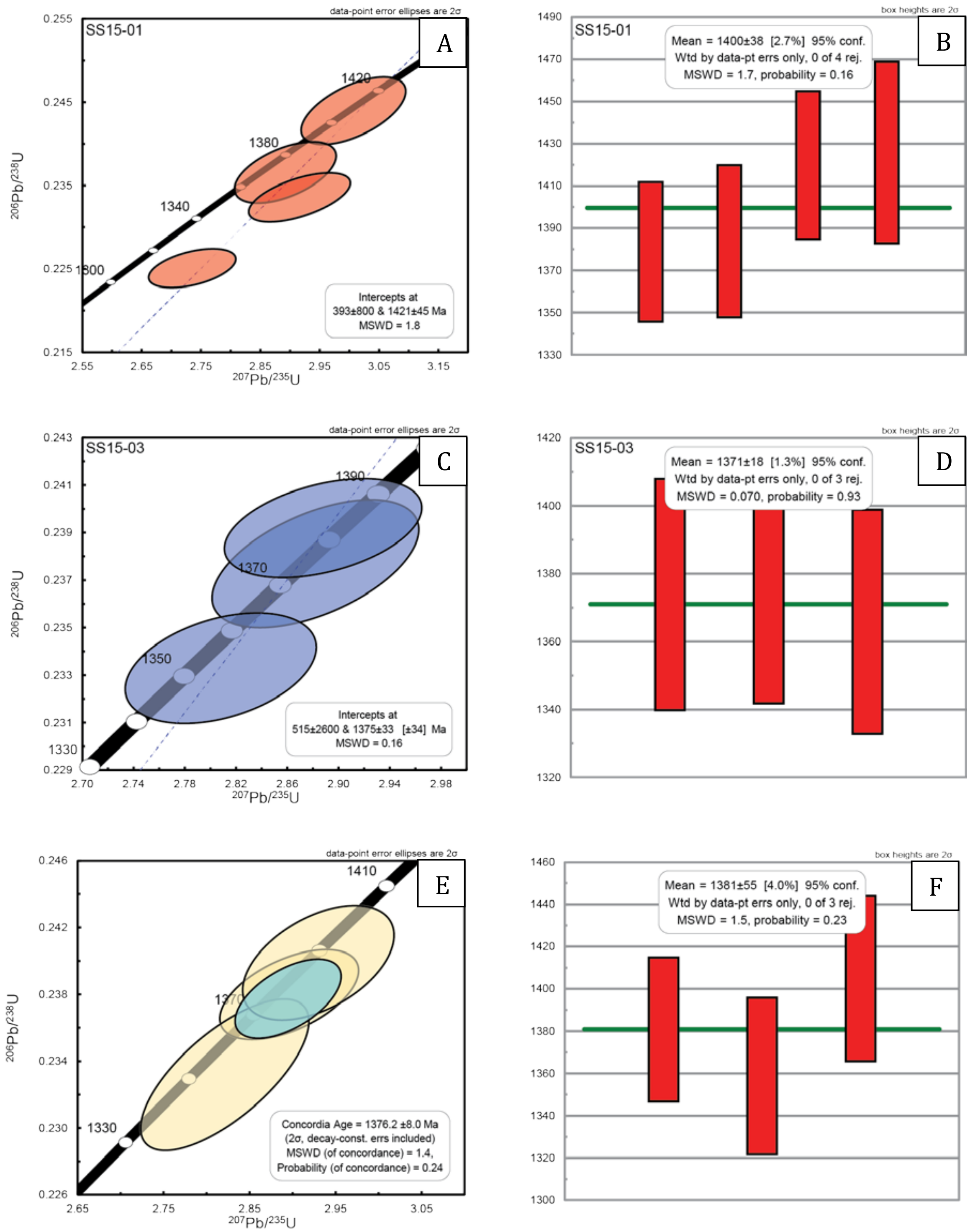


Figure 10 A-F: Concordia diagrams and $^{206}Pb/^{207}Pb$ age plots for the Taos Range; A-B. aluminous quartzite (SS15-01), C-D. sillimanite kspar bearing gneiss (SS15-03), E-F. sillimanite kspar bearing gneiss (SS15-08).

aligned subparallel to the foliation. SS15-03 yielded an intercept age of 1375 ± 33 Ma and a ^{206}Pb/^{207}Pb age of 1371 ± 18 Ma (Figure 10C-D).

Sillimanite Kspar Bearing Gneiss SS15-08

SS15-08 is from a coarse grained sillimanite kspar bearing gneiss with large kspar knobs in hand sample (Figure 6G). The sample exhibits a weak foliation defined by quartz, muscovite, and kspar. All monazite are generally rounded and anhedral and are aligned subparallel to the foliation. SS15-08 yielded a concordia age of 1376 ± 8 Ma and a ^{206}Pb/^{207}Pb age of 1381 ± 55 Ma (Figure 10A-F).

DISCUSSION

1.4 Ga monazite growth is consistent with 1.4 Ga metamorphism and deformation, and therefore does not support the occurrence of high grade metamorphism and deformation at 1.65 Ga. This new data calls for the reevaluation of the polymetamorphic model favored by Pedrick et al. (1998), Read et al. (1999), and Karlstrom et al. (2004). Older, 1430-1400 Ma monazite in the Picuris Range are interpreted to record prograde and peak metamorphic monazite growth (Daniel and Pyle, 2006). Younger ca. 1380 Ma monazite across northern New Mexico may reflect a second regional metamorphic event or pervasive mid-crustal fluid flow event. Both monazite growth events are associated with the Picuris Orogeny.

Monazite Geochronology in the Picuris Mountains and Taos Range

Previous work conducted in the Picuris Mountains by Daniel and Pyle (2006) examined Al_2SiO_5 triple-point reaction textures and monazite geochronology in aluminous schist and quartzite from the Ortega Formation. Most of the monazite examined in Daniel and Pyle (2006) occurred as inclusions within kyanite, sillimanite, and andalusite. These monazite, yielded in-situ ion microprobe ages ranging from of 1434 ± 12 Ma to 1390 ± 20 Ma (Daniel and Pyle, 2006) (Figure 11). The monazite from Daniel and Pyle (2006) exhibit distinct growth zoning, which has been characterized into three compositional growth domains; the core, intermediate, and rim. No data from this study suggest evidence of an older metamorphic event related to the proposed ca. 1650 Ma Mazatzal Orogeny, but instead suggest that deformation in the region is due singularly to a ca. 1450 Ma orogenic event (Daniel and Pyle, 2006).

Concordia/intercept ages range from 1342 ± 58 Ma to 1460 ± 160 Ma, and $^{206}Pb/^{207}Pb$ ages range from 1354 ± 53 to 1411 ± 20 Ma. The four samples represent different protolith ages and bulk compositions, but yield similar monazite ages that are approximately 20-50 Ma younger than previously reported ages of Daniel and Pyle (2006). Monazite partially-to-completely overgrow matrix minerals and aligned inclusions are observed in all samples. Monazite show little evidence of internal deformation, no pressure shadows, and apatite pseudomorphs after monazite show no evidence of deformation. The grains in this study also lack evidence of compositional or growth zoning based upon backscatter electron images. Based on these lines of evidence, the monazite is interpreted to generally post-date tectonic activity. It is also important to

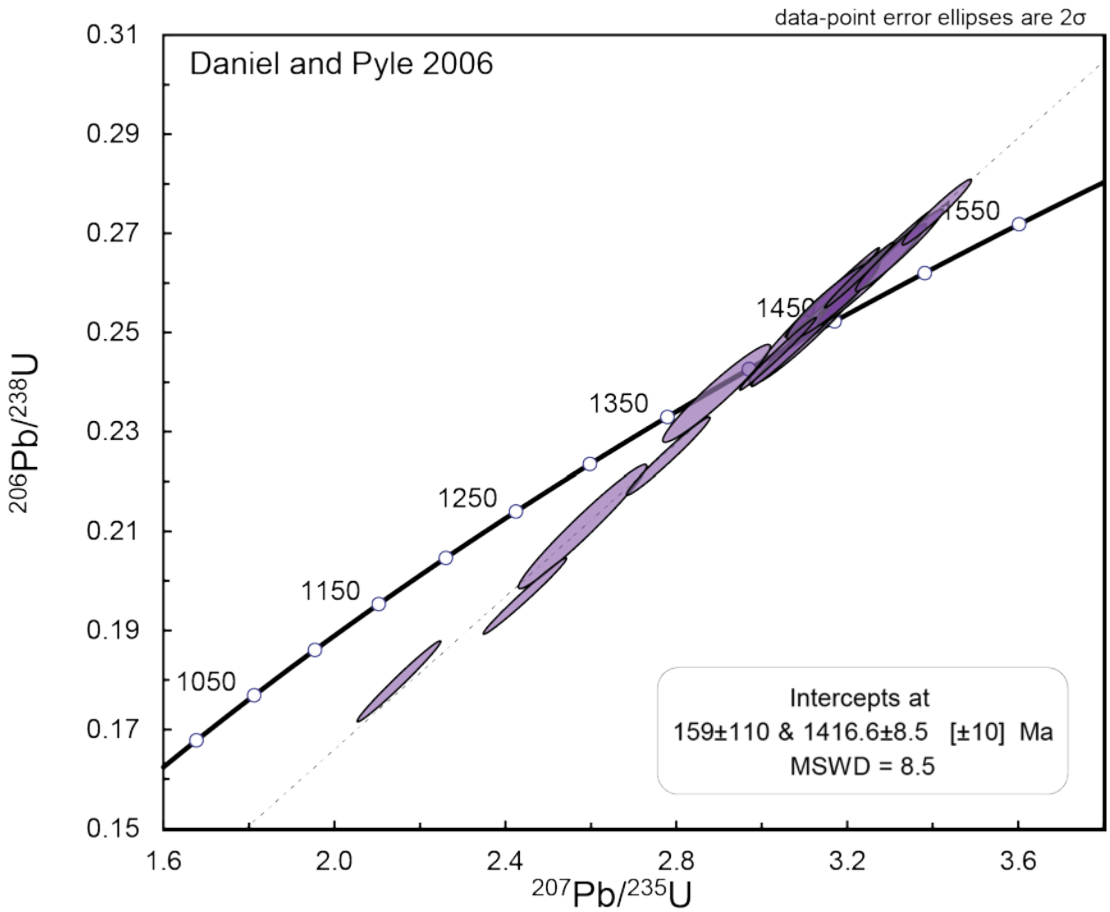


Figure 11: Concordia age data from Daniel and Pyle (2006), yielding an average upper intercept age of 1416.6 ± 8.5 Ma. Data was collected from the Ortega Formation in the Picuris Mountains using an ion microprobe.

note that the Vadito Group has a Paleoproterozoic protolith age ca. 1.70-1.72 Ga which pre-dates the Mazatzal Orogeny, and there is no observed evidence in the monazite from the Vadito indicative of a 1.65-1.60 Ga event.

In both Daniel and Pyle (2006) and this study, there is no evidence of monazite that date back to the proposed Mazatzal Orogeny at ca. 1650 Ma. It is possible that both studies simply missed the older monazite grains, or that evidence of an older metamorphic event has been completely overprinted by ca. 1450-1400 Ma metamorphism. Regardless, Daniel and Pyle (2006) interpreted these Mesoproterozoic ages as a singular event responsible for deformation and metamorphism in northern New Mexico, as opposed to the bulk of deformation occurring during the Paleoproterozoic. The 20-50 Ma difference between the ages yielded in this study and the Daniel and Pyle (2006) study might be accounted for by analytical differences between the ion microprobe and the LA-ICP-MS method. Alternatively, it is also possible that the monazite from Daniel and Pyle (2006) record prograde and peak metamorphic monazite growth during the Picuris Orogeny, whereas the younger monazite record a post-tectonic pervasive fluid flow event providing a definite lower bound to metamorphism and deformation associated with the Picuris Orogeny.

Upper concordia/intercept ages from the Taos Range range from 1375 ± 33 Ma to 1421 ± 45 Ma, and $^{206}Pb/^{207}Pb$ ages range from 1371 ± 18 Ma to 1400 ± 38 Ma. Subhedral to anhedral monazite range in size between 10 µm and 50 µm, are typically aligned parallel to sub-parallel, and generally occur along mineral grain boundaries; a few grains occur as inclusions within Fe-Ti oxides. Preliminary backscatter electron imaging revealed little to no compositional zoning, but further thin section investigation showed extensive zoning in some of the grains. The new crystallization ages from this study are similar to the ages found in the Picuris Range from both this study and the Daniel and Pyle (2006), and also lack evidence of 1650 Ma monazite (Figure 12). This helps to support the idea that both the Taos Range and Picuris Mountains experienced a single metamorphic event between ca. 1420 Ma and 1360 Ma rather than polymetamorphism at ca. 1650 Ma and 1400 Ma (Figure 13).

Comparison of Monazite Ages Across New Mexico and Colorado

I next compared monazite data from previous studies in New Mexico and Colorado to data from this study and the Daniel and Pyle (2006) data, in order to look for common monazite populations across the region (Figure 14). These data sets include monazite ages from the Tusas Range (Kopera, 2003), the Burro Mountains (Amato et al. 2011), the Rincon Range (Hallett, 2002), the southern Santa Fe Range (Short, 2006), and the northern Santa Fe Range (Heuer, 2007). Data analyzed from Colorado include monazite from the Homestake shear zone, the Gore Range shear zone, the St. Louis Lake shear zone, the Idaho Springs-Ralston shear zone, and the Black Canyon shear zone (Shaw et al., 2001; McCoy 1999; Jessup et al., 2005) (Figure 14).

Kopera (2003) conducted in-situ monazite geochronology with the electron microprobe on monazite grains from the Ortega Formation in the northern Tusas Mountains, northern New Mexico in 2003 (Figure 14). He found that monazite ages reveal a gradient from north to south, with an increase in younger ~1400 Ma ages

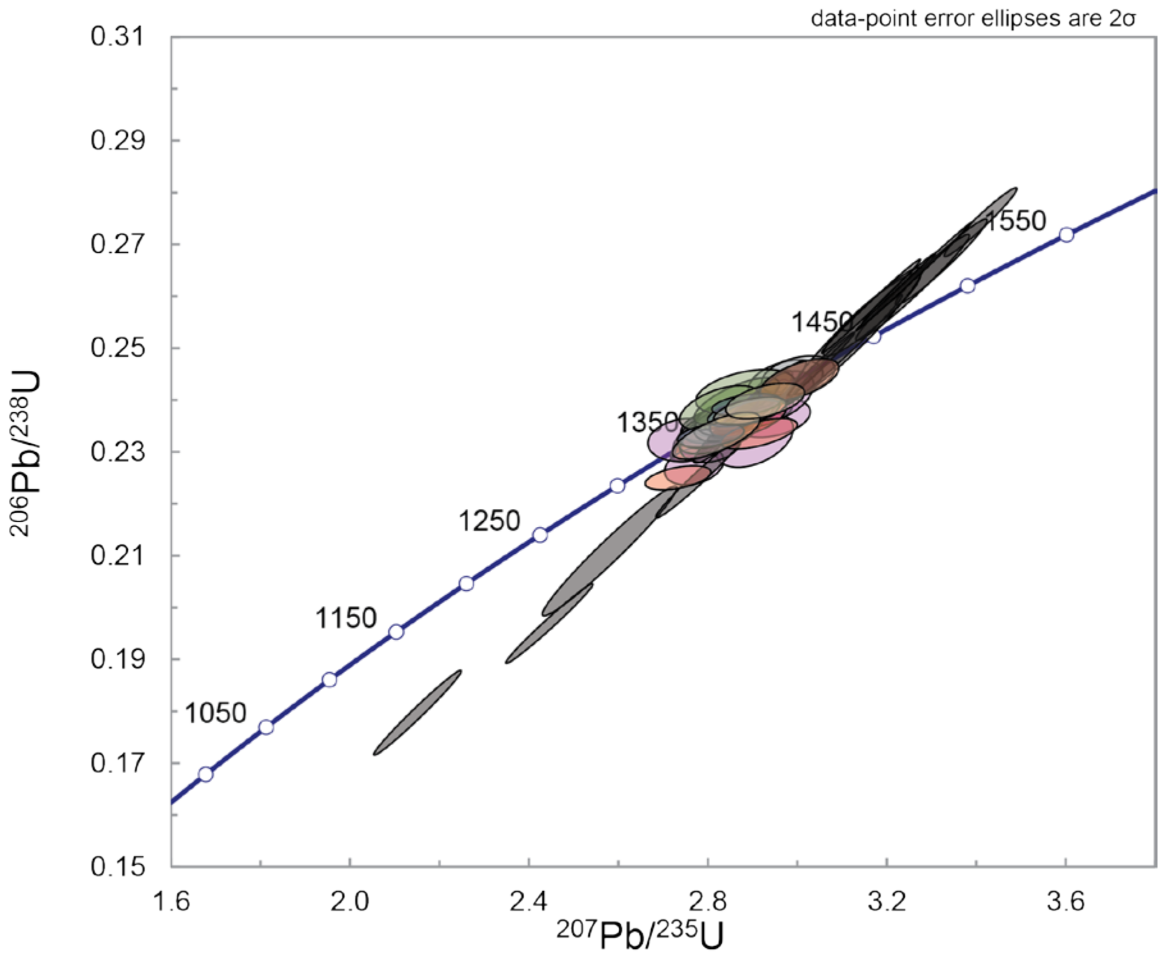


Figure 12: Concordia diagram for monazite from this study and Daniel and Pyle (2006). This plot suggests that a pervasive metamorphic and deformational event occurred in the northern New Mexico Region between 1360 and 1420 Ma.

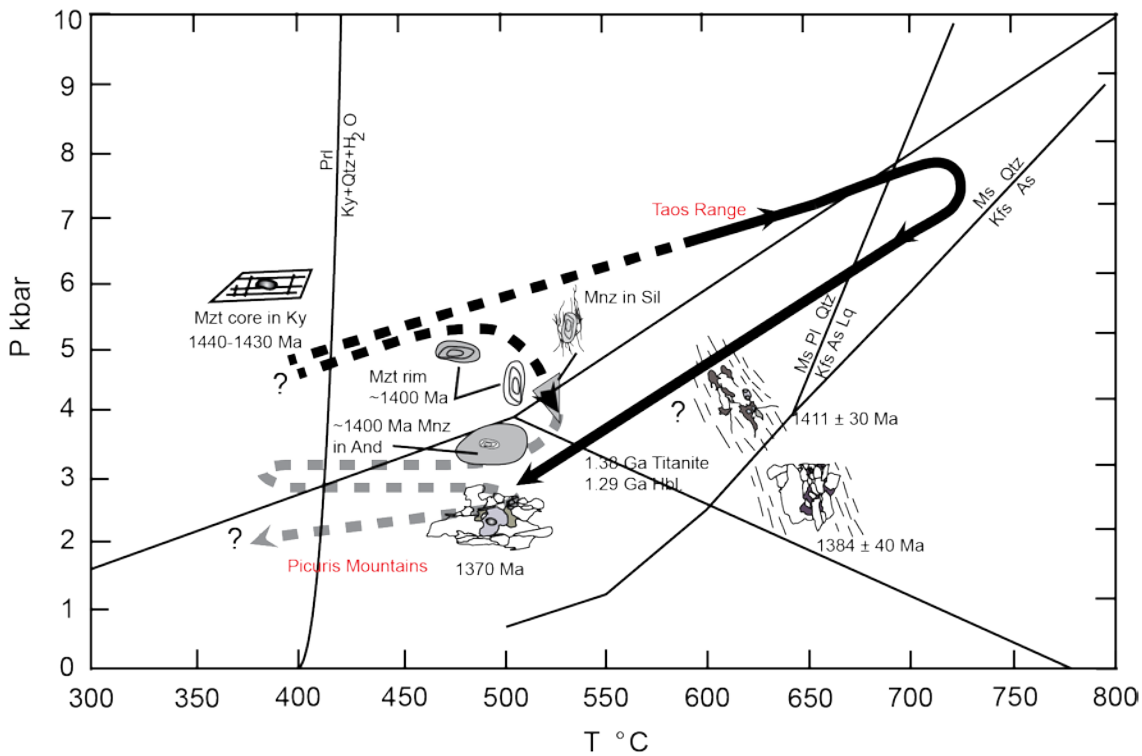
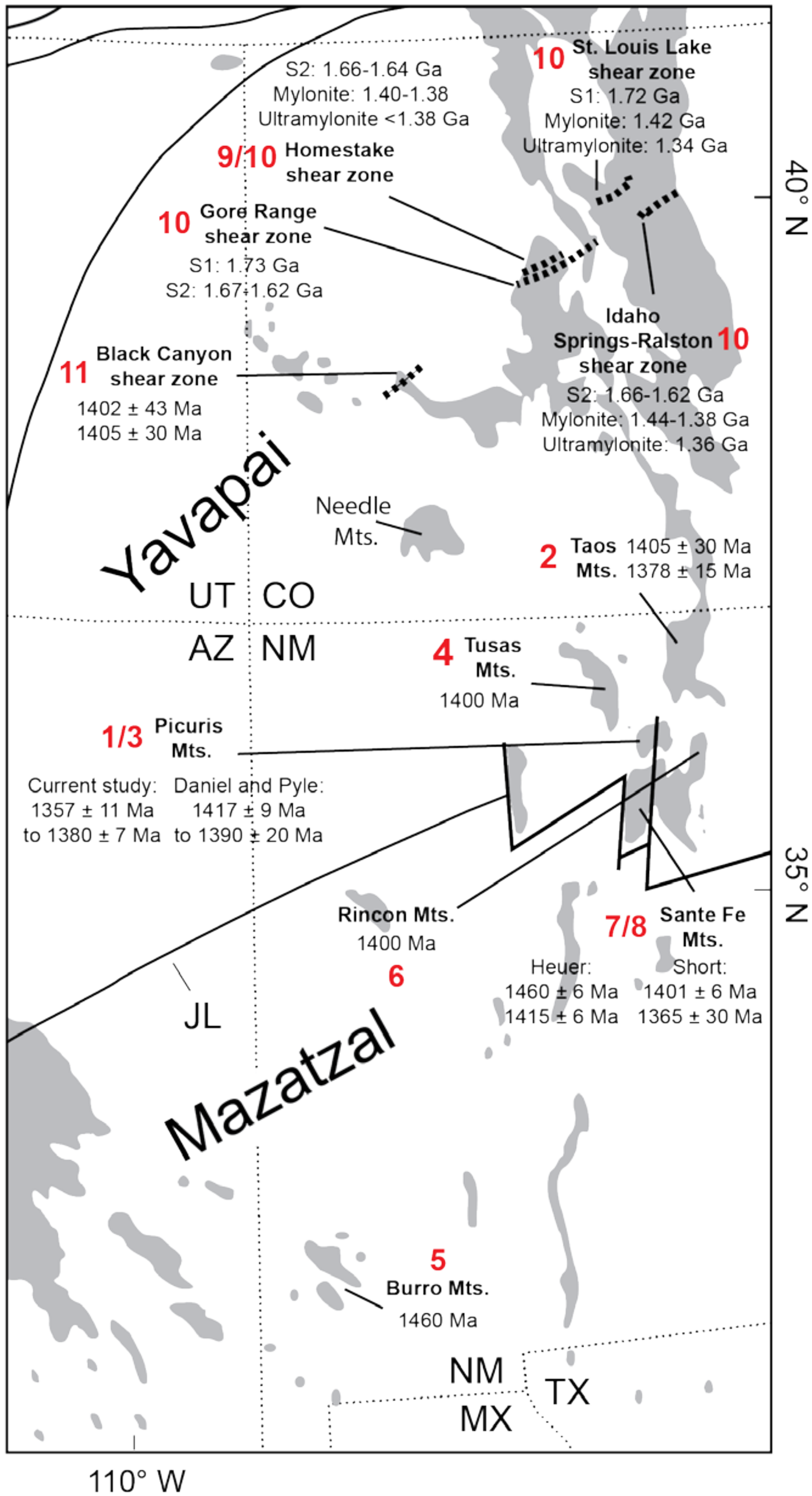


Figure 13: Summary P-T-t-D diagram showing paths for both the Picuris Mountains and Taos Range based on monazite-xenotime temperature estimates and mineral assemblages/thermobarometry, respectively. Data from the current study has been superimposed onto the graph to show how the grains would fit into the proposed P-T-t-D path (Daniel and Pyle, 2006; Pedrick et al., 1998).



S2: 1.66-1.64 Ga
Mylonite: 1.40-1.38
Ultramylonite <1.38 Ga
10 St. Louis Lake shear zone
S1: 1.72 Ga
Mylonite: 1.42 Ga
Ultramylonite: 1.34 Ga
9/10 Homestake shear zone
10 Gore Range shear zone
S1: 1.73 Ga
S2: 1.67-1.62 Ga
40° N
Idaho Springs-Ralston shear zone 10
S2: 1.66-1.62 Ga
Mylonite: 1.44-1.38 Ga
Ultramylonite: 1.36 Ga
11 Black Canyon shear zone
1402 ± 43 Ma
1405 ± 30 Ma
Yavapai
Needle Mts.
2 Taos Mts. 1405 ± 30 Ma 1378 ± 15 Ma
UT CO
AZ NM
4 Tusas Mts.
1400 Ma
1/3 Picuris Mts.
Current study: 1357 ± 11 Ma to 1380 ± 7 Ma
Daniel and Pyle: 1417 ± 9 Ma to 1390 ± 20 Ma
35° N
Rincon Mts.
1400 Ma
6
7/8 Sante Fe Mts.
Heuer: 1460 ± 6 Ma 1415 ± 6 Ma
Short: 1401 ± 6 Ma 1365 ± 30 Ma
JL
Mazatzal
5 Burro Mts.
1460 Ma
NM
MX
TX
110° W

Figure 14: Map of the four corners area showing exposed Precambrian outcrops and locations of study areas used for comparison in this study: 1 and 3. Picuris Mts., this study and Daniel and Pyle (2006) respectively, 2. Taos Range, this study, 4. Tusas Mts., Kopera (2003), 5. Burro Mts., Amato (2011), 6. Rincon Mts., Hallett (2002), 7. Southern Santa Fe Mts., Short (2006), 8. Northern Santa Fe Mts., Heuer (2007), 9. Homestake shear zone, Shaw et al. (2011), 10. Homestake shear zone, Gore Range shear zone, St. Louis Lake shear zone, and Idaho Springs Ralston shear zone, McCoy (2005), and 11. Black Canyon shear zone, Jessup (2005).

towards the southern end of the Tusas (Kopera, 2003). From two localities in the northern portion of the range, monazite ages are predominantly older than ~1700 Ma, which have been interpreted to be detrital grains seeing that they postdate the known depositional age of the Ortega Formation (Kopera, 2003). In the southern portion of the Tusas, all dated monazite grains are completely ~1400 Ma or younger in age (Kopera, 2003). There are a few grains that yielded ages of approximately ~1670 to 1690 Ma, which would lend support to deformation associated with the Mazatzal Orogeny, but Kopera concluded that the dominant ~1400 Ma ages favor a single metamorphic event around that time rather than primary deformation and metamorphism occurring during the Mazatzal Orogeny (Kopera, 2003).

Amato et al. (2011) published electron microprobe in-situ monazite geochronology data from the Burro Mountains in southern New Mexico (Figure 14). From the calculated ages for each sample, he assessed zones and age clusters and calculated one or several weighted averages for each grain (Amato et al. 2011). Amato et al. (2011) found that their samples have a dominant monazite population concentrated around ~1460-1470 Ma associated with localized plutonism, and any older grains that were analyzed were interpreted as being detrital in origin. No metamorphic monazite ages were determined to yield ages between the 1680-1630 Ma range, which would have corresponded to the Mazatzal Orogeny (Amato et al. 2011).

Hallett (2002) examined monazite from migmatites in the Rincon Range in northern New Mexico, using in-situ monazite geochronology with the electron microprobe (Figure 14). From each sample, 1-8 points were analyzed per 6-10 monazite grains, and high resolution x-ray maps of grains were also collected from each sample (Hallett, 2002). Analyzed monazite grains from the Guadalupita Pluton exhibit crystallization ages centered approximately around 1400 Ma (Hallett, 2002). X-ray mapping of monazite from these samples show that a large majority of monazite grains exhibit zoning patterns in yttrium, uranium, thorium, and lead (Hallett, 2002). These suggest that the grains from the pluton underwent multiple stages of growth and resorption only around ~1400 Ma because there was no evidence of ~1680 Ma monazite ages (Hallett, 2002).

Short (2006) calculated a total of 118 ages from three samples from the southern Santa Fe Mountains (Figure 14). To collect these ages she used in-situ monazite geochronology with the electron microprobe (Short, 2006). Analyses from three plagioclase schists yielded unweighted averages of 1400 ± 60 Ma, 1401 ± 6 Ma, and 1365 ± 30 Ma, respectively (Short, 2006). The monazite from Short (2006) did not yield any 1.65 Ga ages, and Short noted that there are no plutons in the study area that could provide the heat and pressure necessary to allow for amphibolite grade metamorphism and deformation to occur (Short, 2006). Therefore, a single metamorphic event at ~1400 Ma is favored over a polymetamorphic model.

Heuer (2007) investigated monazite from migmatites from the northern Santa Fe Range using in-situ electron microprobe dating (Figure 14). High resolution x-ray maps of individual grains revealed four domains of compositional yttrium zoning: a yttrium-low core, a yttrium-intermediate domain, a yttrium-rich domain, and a yttrium-depleted rim (Heuer, 2007). Heuer (2007) determined that there was a link between the U-Pb ages and yttrium concentration, which led him to conclude that each of the domains represented a discrete monazite growth event (Heuer, 2007). The Y-low core yielded an age of 1730 ± 20 Ma, the Y-intermediate domain yielded an age of 1699 ± 6 Ma, the Y-rich domain yielded an age of 1460 ± 6 Ma, and the Y-depleted rim yielded an age of 1415 ± 6 Ma (Heuer, 2007). Heuer interpreted the first generation as representative of the Yavapai Orogeny, the second domain representative of the Mazatzal Orogeny, the third domain representative of partial melting, and that the fourth generation is representative of retrograde monazite growth (Heuer, 2007). The second domain, with an age of 1699 ± 6 Ma, most likely does not represent the Mazatzal Orogeny, seeing that it is actually too old to be considered to crystallize during the orogeny proposed during that time. There has been extensive evidence of plutonism occurring in the Santa Fe Range during this time, which can explain observed monazite growth (Metcalf, 2011).

Shaw et al. (2001) analyzed monazite from the Homestake shear zone in Colorado using in-situ U-Pb lead dating with the electron microprobe (Figure 14). In his work, Shaw et al. (2001) recognized two distinct growth episodes of monazite growth: one that lasted from ca. 1760-1630 Ma, and a second that lasted from ca. 1540-1370 Ma. The first, older major episode identified involved the progression from mid-crustal sub-horizontal growth to heterogeneous crustal shortening (Shaw et al. 2001). The second, younger episode has been interpreted as representing dextral slip associated with ca. 1.4 Ga transpression and deformation (Shaw et al. 2001). Shaw concluded that Homestake shear zone is an example of low angle fabrics evolving into a steep mylonitic shear zone, subsequently followed by repeated reactivation during exhumation of the middle crust (Shaw, 2001).

McCoy (1999) dated monazite from the Homestake shear zone, the Gore Range shear zone, the St. Louis Lake shear zone, and the Idaho Springs-Ralston shear zone from Colorado using U-Pb in-situ monazite electron microprobe analyses. She found two distinct populations of monazite growth, the first being from 1.7-1.62 Ga, and the second from 1.45-1.38 Ga, corresponding with older rims and younger cores of the monazite grains (McCoy, 1999). She concludes that the older cores coincide with the Mazatzal Orogeny in southeastern Arizona, and the younger deformation is associated with the Mesoproterozoic Colorado shear zones that overprint Paleoproterozoic metamorphism (McCoy, 1999).

Jessup et al. (2005) examined rocks exposed in the Black Canyon of Gunnison, Colorado, and dated monazite from the area using U-Pb in-situ geochronology with the electron microprobe. Only two monazite grains were analyzed: one grain is an inclusion in a cordierite porphyroblast with an age of 1390 ± 6 Ma, and the second is an inclusion in a garnet porphyroblast that yielded a similar age of 1390 ± 6 Ma (Jessup et al., 2005). Neither grain exhibited any evidence of growth zoning (Jessup et al., 2005). Jessup concluded that because both grains are inclusions within other minerals, they can act as a timing constraint on metamorphic assemblages, indicating that metamorphism lasted longer than plutonism associated with the Vernal Mesa pluton (1434 ± 2 Ma) during the Mesoproterozoic intercratonic tectonism in the area (Jessup et al. 2005).

In Colorado, generally, each mylonitic shear zone segment strikes east to northeast, ranging from 028° to 090°, with dips ranging from 74° NW to 66° SE (McCoy, 2005). The movement on these shear zones are predominantly dip slip, with a slight dextral ductile slip component (McCoy, 2005). The Colorado Mineral Belt shear zone is a Mesoproterozoic mylonitic system that moved between 1.45 and 1.3 Ga as part of a period of orogenesis that overprints an older Paleoproterozoic orogenic episode (McCoy, 2005).

Implications

The age comparison chart clearly shows an age trend centered near ~1400 Ma (Figure 15). The only evidence of older monazite data comes from Colorado, which is associated with a known monazite growth event during the Paleoproterozoic (Shaw et al., 2001; McCoy, 1999). The probability distribution plot also supports evidence of a pervasive ~1400 Ma metamorphic event with a strong probability peak at an age of 1382 Ma (Figure 16). It has been generally agreed that Colorado experienced deformation as result of metamorphism at both ca. 1650 Ma and 1400 Ma e.g., (Shaw, 2001). In New Mexico, the story appears to be different due to the lack of monazite bearing any ages that could be associated with deformation as a result of the Mazatzal Orogeny.

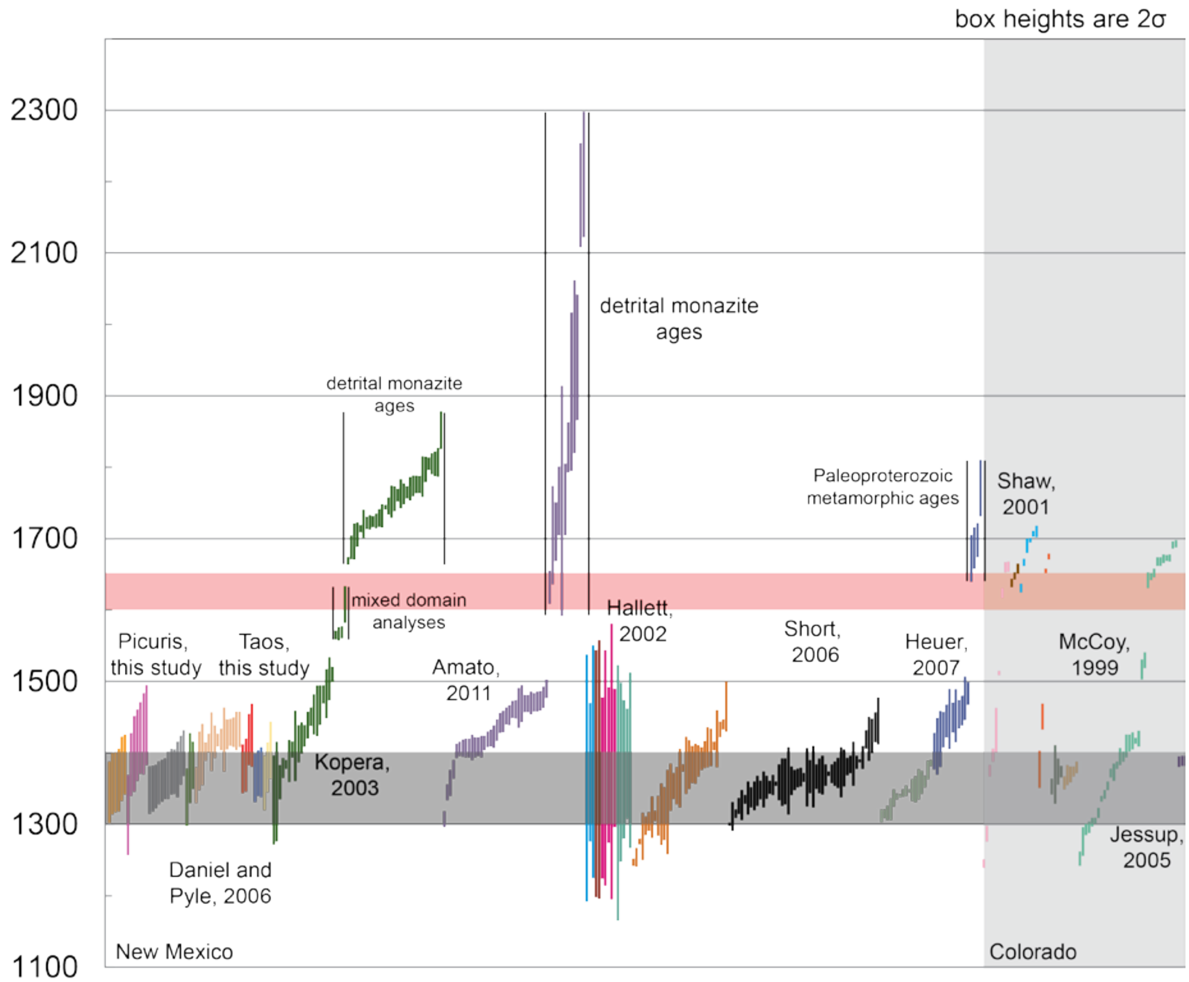


Figure 15: Comparison age chart including monazite age data from this study, and previous studies in the southwestern United States (McCoy, 1999; Shaw, 2001; Hallett, 2002; Kopera, 2003; Jessup, 2005; Daniel and Pyle, 2006; Short, 2006; Amato, 2011). The grey horizontal bracket represents an age range from 1300-1450 Ma, which corresponds with the Mesoproterozoic Picuris Orogeny. The red horizontal bracket represents an age range from 1600-1650 Ma, which corresponds with the Paleoproterozoic Mazatzal Orogeny. The data from New Mexico is in the white block on the left of the graph, and the data from Colorado is in the light grey block on the right of the graph. Each color represents a discreet data set from each of the various studies.

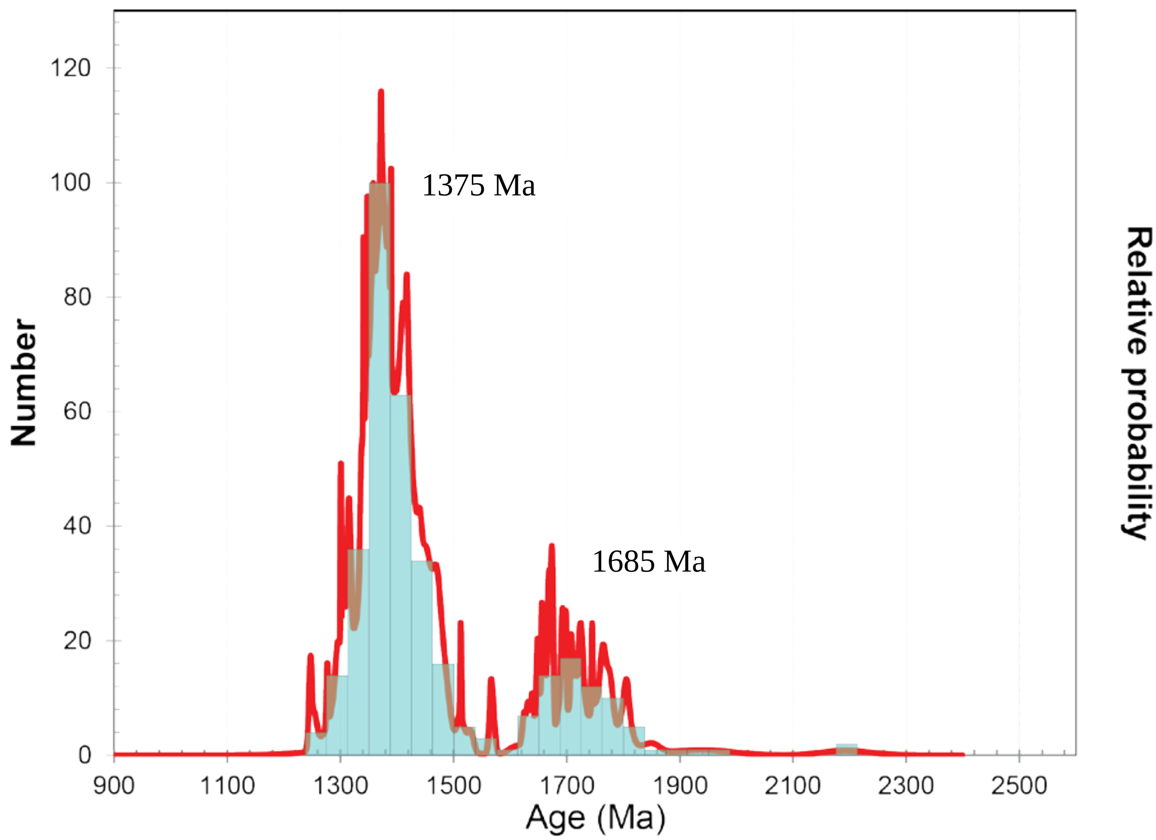


Figure 16: Relative probability distribution plot with all data from New Mexico and Colorado, including detrital grains (McCoy, 1999; Shaw, 2001; Hallett, 2002; Kopera, 2003; Jessup, 2005; Daniel and Pyle, 2006; Short, 2006; Amato, 2011). Here, the peak age is ca. 1382 Ma, and the smaller peak is representative of detrital grains and an older deformational event reflected in the Colorado data.

Metcalf (2011) presented U-Pb SIMS ages from zircon grains in the Santa Fe Range from a megacrystic granite, tonalite, and migmatite. The megacrystic granite yielded a concordant U-Pb age of 1633 ± 12 Ma, and the tonalite yielded a concordant U-Pb age of 1395 ± 13 Ma (Metcalf, 2011). The migmatite yielded two populations of zircon cores with U-Pb ages of 1635 ± 17 Ma and overgrowth rims with U-Pb ages of 1399 ± 15 Ma, and two grains with an older U-Pb age of 1792 ± 24 Ma (Metcalf, 2011). Metcalf interprets monazite grains as young as 1633 Ma to be detrital in age, which agrees with conclusions drawn regarding older grains from Kopera (2003) and Amato (2011).

This implies that deformation and metamorphism previously associated with the Paleoproterozoic Mazatzal Orogeny is instead Mesoproterozoic in age. My data shows that monazite growth in the Picuris Mountains and Taos Range is restricted to the Mesoproterozoic, between ca. 1380-1420 Ma. My data also lacks evidence of monazite growth ages that are Paleoproterozoic in age. Data from other various studies in New Mexico support a pervasive deformational and metamorphic event occurring around ~1400 Ma, and also lack metamorphic monazite growth ages from ca. 1650 Ma (Figure 15 and Figure 16). In Colorado, the observed reactivation of steeply dipping ductile shear zones are coincident with the deformation detected further south in New Mexico.

SUMMARY AND CONCLUSION

Monazite growth ages from various bulk compositions from the Picuris Mountains and Taos Range record the occurrence of a metamorphic and deformational event between ca. 1420-1380 Ma. Monazite from the region have failed to produce growth ages from the Paleoproterozoic ca. 1.65 Ga coincident with the Mazatzal Orogeny. It is possible that there was contact metamorphism and deformation associated with 1630-1680 Ma plutons, but it is not responsible for the amphibolite facies to near granulite facies temperatures and triple point metamorphism associated with the rocks in northern New Mexico and southern Colorado. Deformation of Mesoproterozoic and Paleoproterozoic rocks previously attributed to the Mazatzal Orogeny is now known to be associated with a younger, ca. 1.45-1.36 Ga event, the Picuris Orogeny. Regional monazite data from New Mexico and Colorado show a peak monazite age distribution focused ca. 1420 to 1360 Ma and also fail to produce Paleoproterozoic ages, inferring a widespread Mesoproterozoic metamorphic and deformational event. The data from this study as well as others do not support a polymetamorphic model for the southwestern US with two respective separate events at 1.65 Ga and 1.42 Ga as previously proposed for the region.

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