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# Detrital Zircon Evidence for Mixing of Mazatzal Province Age Detritus With Yavapai Age (ca. 1700-1740 Ma) and Older Detritus in the ca. 1650 Ma Mazatzal Province of Central New Mexico, USA

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**DETRITAL ZIRCON EVIDENCE FOR MIXING OF MAZATZAL  
PROVINCE AGE DETRITUS WITH YAVAPAI AGE (CA. 1700-1740 MA.)  
AND OLDER DETRITUS IN THE CA. 1650 MA. MAZATZAL PROVINCE OF  
CENTRAL NEW MEXICO, USA**

By

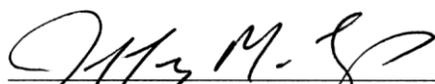
**Daniel P. Wallace**

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 2014

Approved : 

Christopher G. Daniel  
Thesis Advisor, Department of Geology, Bucknell University



Jeffrey M. Trop  
Chair, Department of Geology, Bucknell University



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## ABSTRACT

Preliminary detrital zircon age distributions from Mazatzal crustal province quartzite and schist exposed in the Manzano Mountains and Pedernal Hills of central New Mexico are consistent with a mixture of detritus from Mazatzal age (ca. 1650 Ma), Yavapai age (ca. 1720 Ma.), and older sources. A quartzite sample from the Blue Springs Formation in the Manzano Mountains yielding 67 concordant grain analyses shows two dominant age peaks of 1737 Ma and 1791 Ma with a minimum peak age of 1652 Ma. Quartzite and micaceous quartzite samples from near Pedernal Peak give unimodal peak ages of ca. 1695 Ma and 1738 Ma with minimum detrital zircon ages of ca. 1625 Ma and 1680 Ma, respectively. A schist sample from the southern exposures of the Pedernal Hills area gives a unimodal peak age of 1680 Ma with a minimum age of ca. 1635 Ma. Minor amounts of older detritus (>1800 Ma) possibly reflect Trans-Hudson, Wyoming, Mojave Province, and older Archean sources and aid in locating potential source terrains for these detrital zircon. The Blue Springs Formation metarhyolite from near the top of the Proterozoic section in the Manzano Mountains yields 71 concordant grains that show a preliminary U-Pb zircon crystallization age of  $1621 \pm 5$  Ma, which provides a minimum age constraint for deposition in the Manzano Mountains.

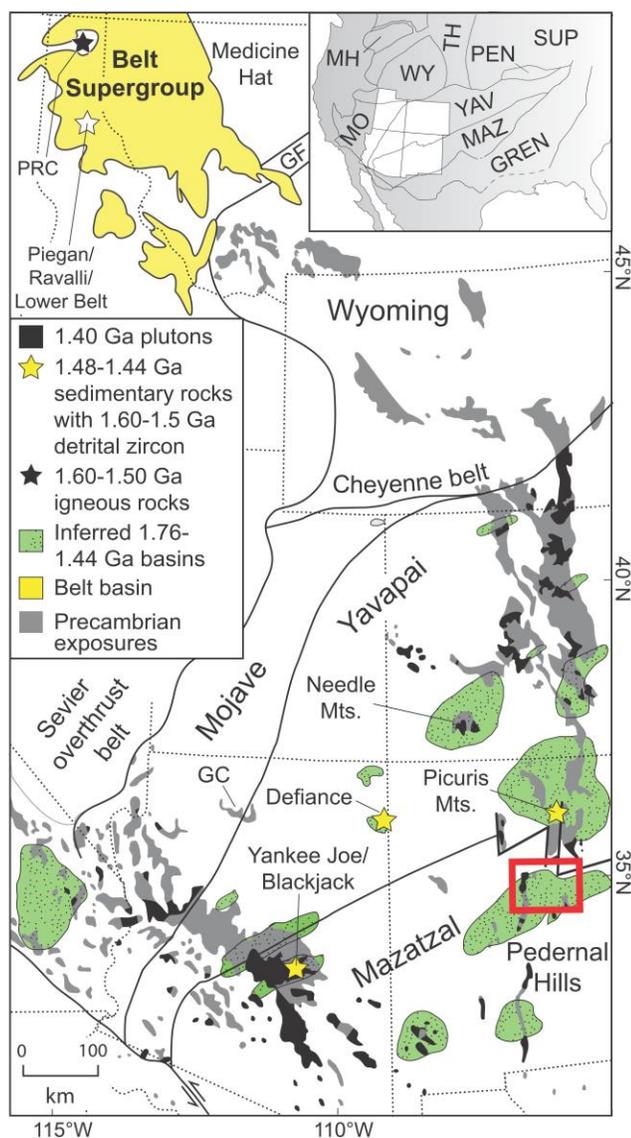
Normalized probability plots from this study are similar to previously reported age distributions in the Burro and San Andres Mountains in southern New Mexico and suggest that Yavapai Province age detritus was deposited and intermingled with Mazatzal Province age detritus across much of the Mazatzal crustal province in New Mexico. This data shows that the tectonic evolution of southwestern Laurentia is associated with

multiple orogenic events. Regional metamorphism and deformation in the area must postdate the Mazatzal Orogeny and ca. 1610 Ma – 1620 Ma rhyolite crystallization and is attributed to the Mesoproterozoic ca. 1400 – 1480 Ma Picuris Orogeny.

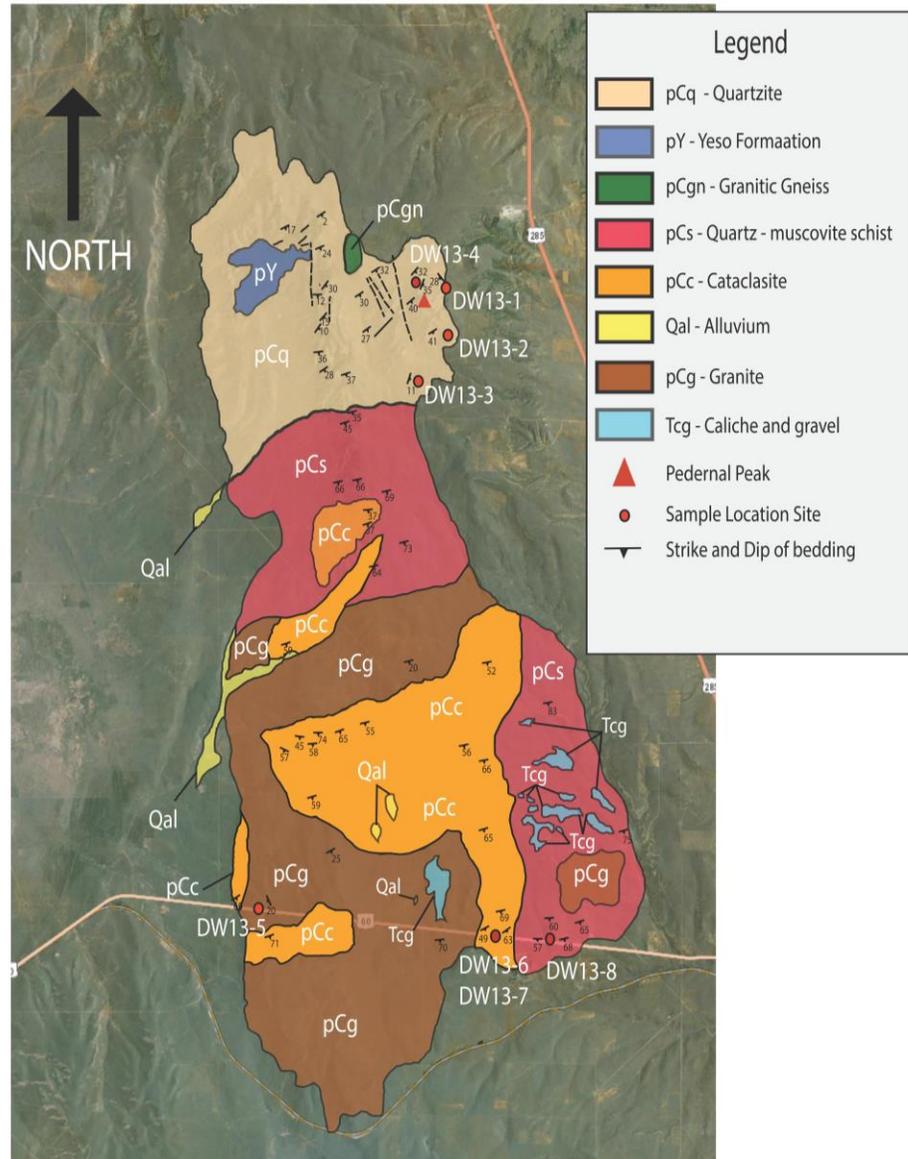
## **INTRODUCTION**

Whitmeyer and Karlstrom (2007) present a tectonic model for the evolutionary history of North America that suggests that during the Proterozoic Eon (specifically 1.60 Ga – 1.80 Ga) multiple micro continents and island arcs, called “provinces”, were accreted onto Laurentia from the south and southeast. Two of these provinces in particular are the Yavapai Province (1.70 – 1.78 billion years old) and the Mazatzal Province (1.60 – 1.69 billion years old). Between about 1.60 and 1.80 billion years ago these provinces were accreted along the continental margin across the central United States and Great Lakes, and into northeastern Canada (Figure 1). The Proterozoic sediments deposited along the Yavapai – Mazatzal crustal boundary during the ca. 1650 Ma Mazatzal Orogeny contain detrital zircon, and U-Pb dating of these zircon aid in determining the maximum depositional age and provenance of these metasedimentary rocks.

The Pedernal Hills are located about 54 km south of the boundary between the Yavapai and Mazatzal Provinces, and east of Albuquerque in Torrance County, New Mexico. A metaquartzite, granitic gneiss, schist, cataclasite, and granite are among the common rock types found in the Pedernal Hills (Gonzales and Woodward, 1972) (Figure 2). Age relations of the metaquartzite, granitic gneiss, and schist cannot



**Figure 1:** Regional map of Proterozoic rocks in the western United States. Gray color indicates Proterozoic exposures of rock. Black areas represent Proterozoic plutons. Green patterned areas represent inferred Proterozoic basins. Yellow stars represent locations of recently discovered Mesoproterozoic metasedimentary rock similar to the Belt Supergroup shown in yellow. Major Proterozoic crustal province boundaries are shown by solid curved lines. Inset map shows regional distribution of Precambrian province boundaries across the western and central United States. Red box shows the general location of the Manzano Mountains and Pedernal Hills. Figure modified from Doe et al. (2013).



**Figure 2:** Bedrock map of the Pedernal Hills. Four samples were taken from the northern Quartzite Terrain while four others were taken in the southern reaches of the Pedernal Hills along HWY 60. Representative strike and dip measurements, sample location sites, and lithologies are shown on this map. Geology modified from Gonzalez, 1968.

be definitely stated (Armstrong and Holcombe, 1982). With the increasing grade of metamorphism from north to south in the Pedernal Hills there is also an increase in intensity of the foliations in these rocks in outcrop, which makes the interpretation of the stratigraphic sequence very difficult (Armstrong and Holcombe, 1982).

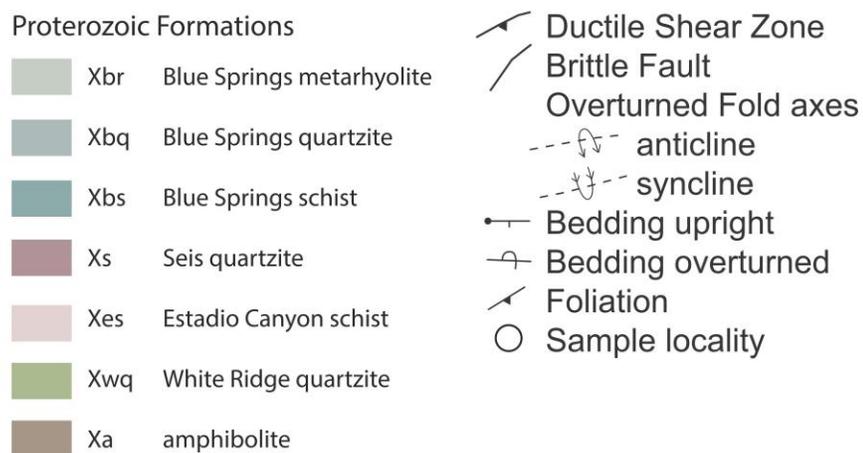
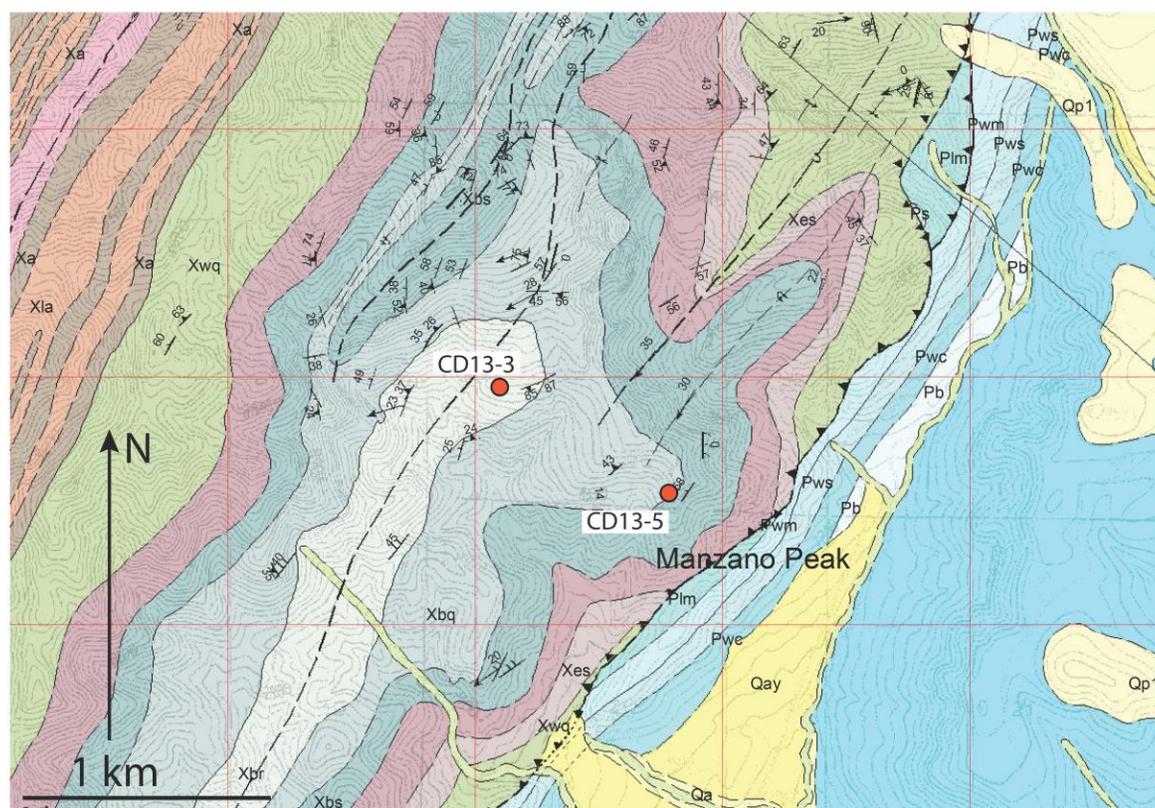
## **PREVIOUS RESEARCH**

Geologic mapping has previously been done in the Pedernal Hills to examine the various lithologies present. Armstrong and Holcombe (1982) recognized three dominant lithologic groups in the Pedernal Hills including the Northern Quartzite Terrain, T-Phase Volcanics, and M2 Volcanics. The Northern Quartzite Terrain consists of a massive layer of quartzite with iron oxides that define compositional layering, and could have been deposited during a fluctuation in seawater oxygen levels (Armstrong and Holcombe, 1982). Immediately south of the Northern Quartzite Terrain are an assortment of volcanic rocks which mainly include laharic breccia with interbedded rhyolite (Armstrong and Holcombe, 1982). Further south are the M2 Volcanics that consist of andesite, mafic laharic breccia, and silicic pyroclastic rhyolite (Armstrong and Holcombe, 1982). Armstrong and Holcombe (1982) and Gonzalez (1968) state that throughout the Pedernal Hills there are granite units which crosscut the metasedimentary rocks and can be used to infer relative ages of these rocks.

About 80 km east of the Pedernal Hills are the Manzano Mountains, which are a north-south trending mountain range on the eastern flank of the Rio Grande Rift. The lithologies in the Manzano Mountains consist of the three separate quartzite units (Blue

Springs Quartzite, Seis Quartzite, and White Ridge Quartzite), two separate schist units (Blue Springs Schist and Estadio Canyon Schist), a metarhyolite unit (Blue Springs Metarhyolite), and an amphibolite unit (Figure 3). These rocks sit in the middle of a ~ 2.5 km – 3 km wide syncline and represent relatively young Paleoproterozoic rocks in the Manzano Mountains. Each of these units is intruded locally by the Ojita, Monte Largo, and Priest granite plutons. The Ojita Pluton is ca. 1527 Ma whereas the Monte Largo and Priest Plutons are ca. 1656 Ma and 1427 Ma respectively (Bauer et al., 1993). These intrusions crop out throughout the Manzano Mountains.

McKee (1988) conducted geochemical analyses of the various lithologies in the Manzano Mountains and Pedernal Hills. The Pedernal Hills mafic volcanic rocks are calc-alkaline in nature and range from basalt to andesite in composition while the felsic volcanic rocks from the Pedernal Hills and Manzano Mountains range from rhyodacite to silica-rich rhyolite (McKee, 1988). In both the Pedernal Hills and Manzano Mountains, felsic volcanic samples exhibit a decrease in amounts of  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{MgO}$  with increasing amounts of  $\text{SiO}_2$  (McKee, 1988). McKee also found that Zr and Hf concentrations vary more in the Pedernal Hills than they do in the Manzano Mountains, which could suggest different amounts of zircon in the rocks from these two localities. Felsic volcanic rocks show a higher concentration of Nb, Y, and Ta in the Pedernal Hills than in the Manzano Mountains (McKee, 1988). Mafic volcanic rocks in the Pedernal Hills showed concentrations between 50 wt%  $\text{SiO}_2$  and



**Figure 3:** Geologic map of Manzano Mountains, New Mexico. Sample CD13-3 is taken from the Blue Springs metarhyolite and sample CD13-5 is taken from the Blue Springs quartzite. The Blue Springs metarhyolite (Xbr) is in the middle of a 2.5 – 3 km syncline and represents some of the youngest Proterozoic rocks exposed in the Manzano Mountains. Modified from Baer et al. (2004).

80 wt% SiO<sub>2</sub> (McKee, 1988).

From the geochemical data of the mafic and andesitic rocks in the Pedernal Hills tectonic interpretations can be made. On a TiO<sub>2</sub> – V plot the mafic and andesitic rocks from the Pedernal Hills plot in areas corresponding to arc volcanics, back-arc basin volcanics, and mid ocean ridge basalts (MORB) (McKee, 1988). On a La – Ta, plot the andesites and calc-alkaline basalts fall into the continental arc field (McKee, 1988). Concentrations of Th/Yb were plotted against Ta/Yb for all basalt and andesite samples from the Pedernal Hills. Fields on this plot are broken down into continental arc, island arc, mid ocean ridge basalt, and “within plate” basalt. Every sample plotted on this diagram falls in the continental arc field (McKee, 1988).

### *Significance of Research*

My research examines detrital zircon extracted from quartzite, schist, and metarhyolite from the Pedernal Hills and Manzano Mountains of New Mexico in order to determine the maximum depositional age and provenance of these rocks. This study is the first application of detrital zircon geochronology on the metasedimentary rocks in the Pedernal Hills. Information on the maximum depositional age and provenance will help us understand the evolutionary history of North America between 1.60 and 1.80 billion years ago in southwest Laurentia. By comparing the detrital ages of the metasedimentary rocks in the Pedernal Hills with the ages of rocks from the surrounding region it is possible that sediment sources for these zircon will be found. Previous detrital zircon geochronology from southern New Mexico infers that these sediments are largely

derived from the Mazatzal Province (Amato et al., 2008).

## **METHODS**

### *Sample collection and preparation*

Oriented samples DW13-3, DW13-4, and DW13-8 were collected near Pedernal Peak and south of Pedernal Peak along HWY 60. Samples CD13-3 and CD13-5 were collected by Dr. Daniel in the Manzano Mountains (Table 1) (Figure 4.1 – 4.5). Thin sections of each of these samples were cut for light microscope imaging to determine the size and abundance of the various minerals in each sample. Light microscope images of the zircon were assembled into a detailed photo mosaic that allowed for efficient location of various grains during analysis. Rock chips were cut, mounted in epoxy, and polished with multiple cycles using 15  $\mu\text{m}$ , 9  $\mu\text{m}$ , 3  $\mu\text{m}$ , and 1  $\mu\text{m}$  diamond suspension.



**Figure 4.1:** Outcrop photo of sample DW13-3 micaceous quartzite.



**Figure 4.2:** Outcrop photo of sample DW13-4 quartzite.



**Figure 4.3:** Outcrop photo of sample CD13-3 metarhyolite.



**Figure 4.4:** Outcrop photo of sample CD13-5 quartzite. Compositional layering of quartz and iron oxide grains on the centimeter scale exhibited in this sample.



**Figure 4.5:** Outcrop photo of sample DW13-8 micaceous schist.

### *Hand sample and thin section descriptions*

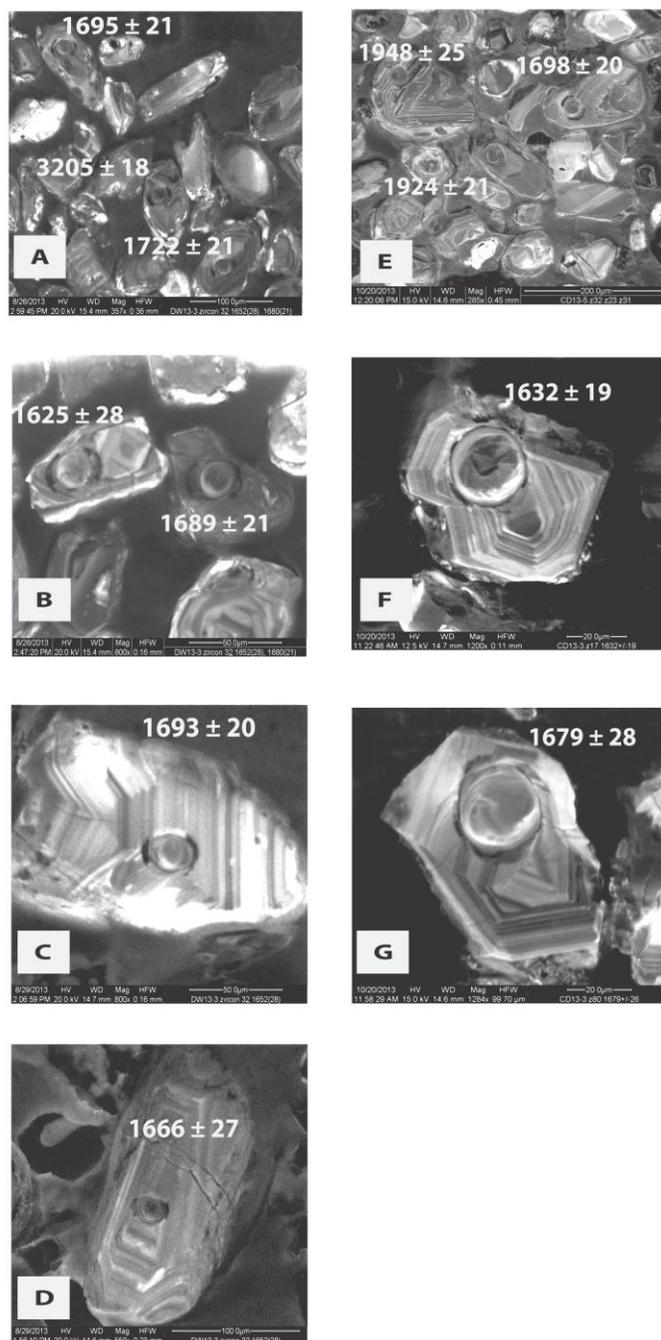
Two oriented samples were collected from near Pedernal Peak. Sample DW13-3 is a micaceous quartzite that has a preferred orientation of micas. The exposed surface of this sample exhibits lichens and oxidation rind while a fresh surface exhibits roughly parallel spaced cleavage. Compositional layering and schistosity are exhibited in this sample where schistosity is sub parallel to the compositional layering. Thin section images of sample DW13-3 show compositional layering of muscovite and quartz grains. Iron oxides (< 5%) are present in this sample. Quartz grains are equal in size (0.1 – 0.4 mm) throughout most of this sample. Sample DW13-4 is a massive quartzite that exhibits compositional layering of quartz and iron oxide on the centimeter scale. Oxidation rind is present on the exposed surface as well as minor amounts (< 10%) of muscovite present. Thin section images of sample DW13-4 show equal size quartz grains (0.1 – 0.4 mm) and muscovite in a space-preferred orientation. Iron oxides (< 5%) are also present in thin section. Sample DW13-8 is a schist collected south of Pedernal Peak along HWY 60. Large quartz veins are present in this sample locality. Thin section images of sample DW13-8 show ~50% equal size quartz grains (0.3 – 0.5 mm), ~50% muscovite, and some magnetite (<2%). Muscovite is seen inside of these magnetite grains, which suggests that magnetite crystallized after the muscovite. DW13-8 exhibits compositional layering, schistosity, and elongation lineations. All of these features in DW13-8 are sub parallel to each other. This sample is consistent with the hypothesis that the intensity of foliations and metamorphism increase from north to south in the Pedernal Hills.

Two oriented samples were collected in the Manzano Mountains. Sample CD13-5

is a quartzite that exhibits compositional layering of quartz and iron oxide on the centimeter scale. Thin section images of this sample show quartz grains (~95%) of equal size with the remaining 5% being muscovite and iron oxides. Sample CD13-3 is a metarhyolite collected from the Blue Springs metarhyolite. Thin section images of this sample show muscovite in a crenulation foliation style with garnet inclusions inside the muscovite. The inclusions of garnet suggest that the garnet crystals in this sample grew after the muscovite was formed.

### *Zircon morphology*

Light microscope images and cathodoluminescence images were taken for samples DW13-3, DW13-4, DW13-8, CD13-3, and CD13-5 (Figure 5). Light microscope images for DW13-3 show that zircon grains are clear to flesh colored and rounded (~95%). Grains are uniform in shape and color and the average size for grains in this sample are ~ 100  $\mu\text{m}$  across. About 5% of grains are euhedral and are 100  $\mu\text{m}$  across. Light microscope images for sample DW13-4 show that zircon grains are flesh to brown colored and are subhedral to euhedral. About 80% of grains are subhedral and 20% are euhedral. Light microscope images for DW13-8 show that grains are clear to pink colored and have a subhedral to euhedral grain boundaries. The average grain size for this sample is 50 $\mu\text{m}$ . All zircon from samples DW13-3, DW13-4,



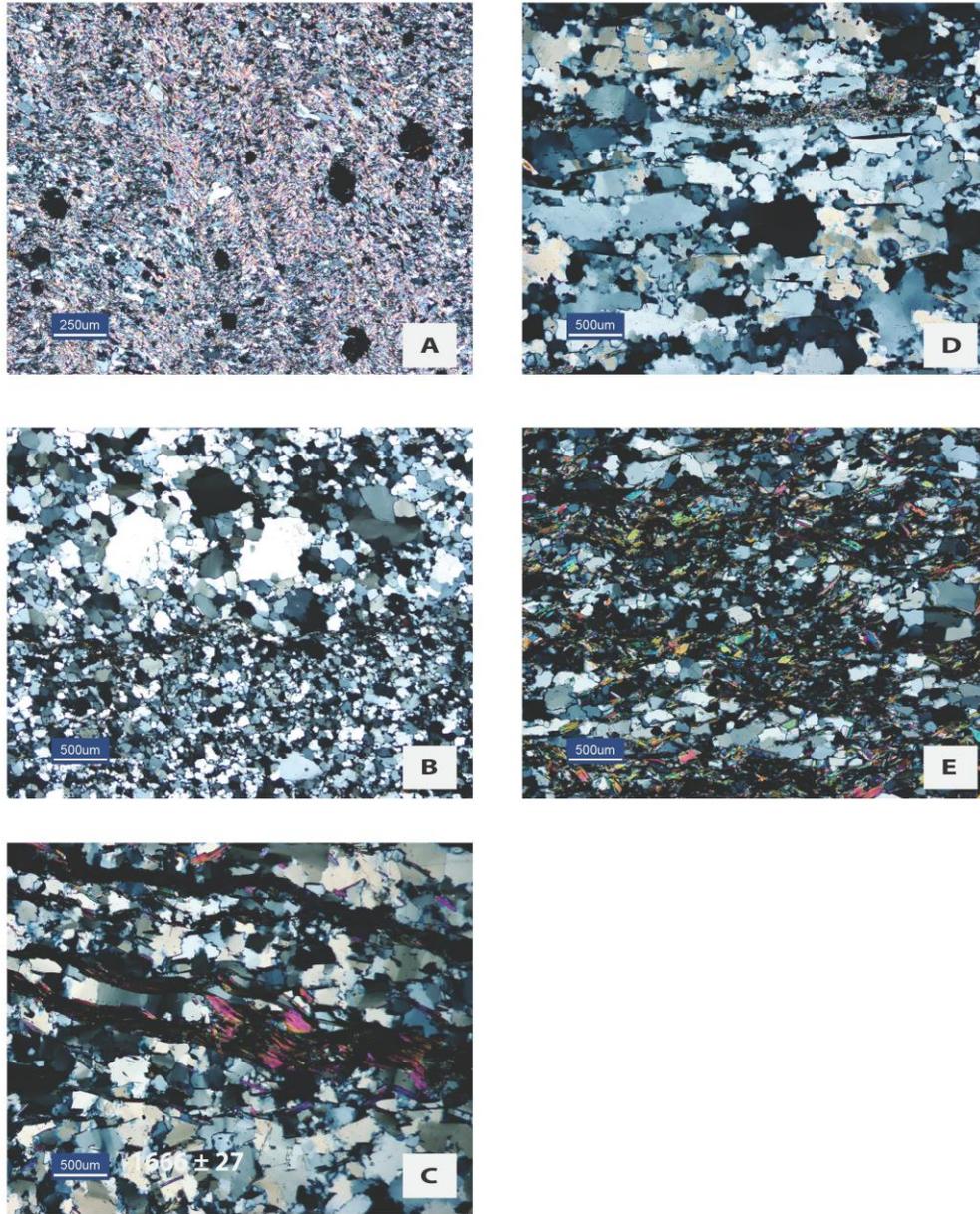
**Figure 5:** Post-ablation cathodoluminescence images of detrital zircon recovered from near Pedernal Peak and the Manzano Mountains. Zoning is characteristic of igneous crystallization and euhedral crystals show little evidence of sedimentary reworking. A and B) Sample DW13-3. C and D) Sample DW13-4. E) Sample CD13-5. Craters are 19-24  $\mu\text{m}$  in diameter. F and G) Igneous zircon from CD13-3. Ages are in Ma. Craters in each sample are 19-24  $\mu\text{m}$  across.

and DW13-8 are igneous derived and show concentric igneous zoning with little evidence of sedimentary reworking. Images from samples CD13-3 and CD13-5 are also igneous derived and show concentric igneous zoning. Thin section photomicrographs of each sample were taken of each of these samples (Figure 6).

Cathodoluminescence images of detrital zircon from both study areas show igneous zoning characteristics. Zircon grains range in size from 50 to 200  $\mu\text{m}$  with a majority of the grains being sub-angular to well rounded. Angular to euhedral to subhedral grains are less common. Igneous zircon from metarhyolite CD13-3 are euhedral to subhedral and range in size from 100 to 200  $\mu\text{m}$ .

#### *Detrital zircon geochronology methods*

Zircon crystals are extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples are processed such that all zircon are retained in the final heavy mineral fraction. A large split of these grains (hundreds to thousands of grains) is incorporated into a 1" epoxy mount. The mounts are sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis. Detrital samples DW13-3, DW13-4, DW13-8, CD13-5 and igneous sample CD13-3 were analyzed with LA-ICP-MS at the University of New Brunswick Department Of Earth Sciences. About 100 grains were randomly chosen for all detrital zircon samples and about 50 grains were analyzed for the igneous sample. Grains with obvious cracks were avoided for igneous



**Figure 6:** Thin section photomicrographs of samples analyzed in this study. A) Garnet-bearing metarhyolite, CD13-3. B) Quartzite, CD13-5. C) Micaceous quartzite, DW13-3. D) Quartzite, DW13-4. E) Schist, DW13-8.

sample CD13-3. All grains were characterized and optically evaluated using reflected light and CL imaging prior to and following analysis. Zircon grains were ablated and analyzed using a Resonetics M-50 193nm Excimer laser system connected, via Nylon tubing, to an Agilent 7700x quadrupole ICP-MS equipped with dual external rotary pumps. Zircon were ablated using 19  $\mu\text{m}$  craters and a 5 Hz repetition with the laser energy at the target (fluence) regulated at 4 J/cm<sup>2</sup>. Each analysis comprised 25 sec of background gas collection followed by 30 sec of ablation. Ablated aerosols were entrained in a He cell gas flow (800 mL/min) and subsequently mixed with N<sub>2</sub> (2.8 mL/min) and Ar (750 mL/min) prior to entering the ICP-MS torch. High-capacity Vici Metronics Hg traps on all gas lines ensure <sup>204</sup>(Hg+Pb) gas background  $\leq$  150 cps under maximum sensitivity conditions. The ICP-MS was operated at 1300W and a torch depth of 5.0 mm. Ion lens settings were tuned, while rastering on NIST610 glass, to achieve maximum sensitivity on <sup>207</sup>Pb while maintaining oxide production (<sup>248</sup>ThO/<sup>232</sup>Th) < 0.4% and <sup>238</sup>U/<sup>232</sup>Th  $\sim$ 1.05. Dwell times for <sup>91</sup>Zr (10ms), <sup>204</sup>Pb (60ms), <sup>206</sup>Pb (50ms), <sup>207</sup>Pb(75ms) <sup>208</sup>Pb(10ms), <sup>232</sup>Th(10ms) and <sup>238</sup>U(15ms) were set to achieve a total quadrupole sweep time of  $\sim$ 0.25sec yielding  $\sim$ 120 individual measurements in 30sec of ablation. Each sample was analyzed by defining a laser ablation sequence of standards (91500 and Temora zircon, NIST610) and unknowns that were run automatically while the ICP-MS collected data over the same period of time. All sequences comprised 15–20 analyses of 91500 zircon, evenly distributed among the unknowns, that were used as external standards to correct for laser-induced element fractionation (LIEF) and mass bias in the ICP-MS. Temora zircon grains (416 Ma) were also analyzed in each sequence to

verify the accuracy of the acquisition and data reduction schemes. All data were reduced offline using a combination of Iolite v2.15 (Paton et al., 2011) and VisualAge v2011-08-29 (Petrus and Kamber, 2012) running under Wavemetrics IgorPro v6.22™.

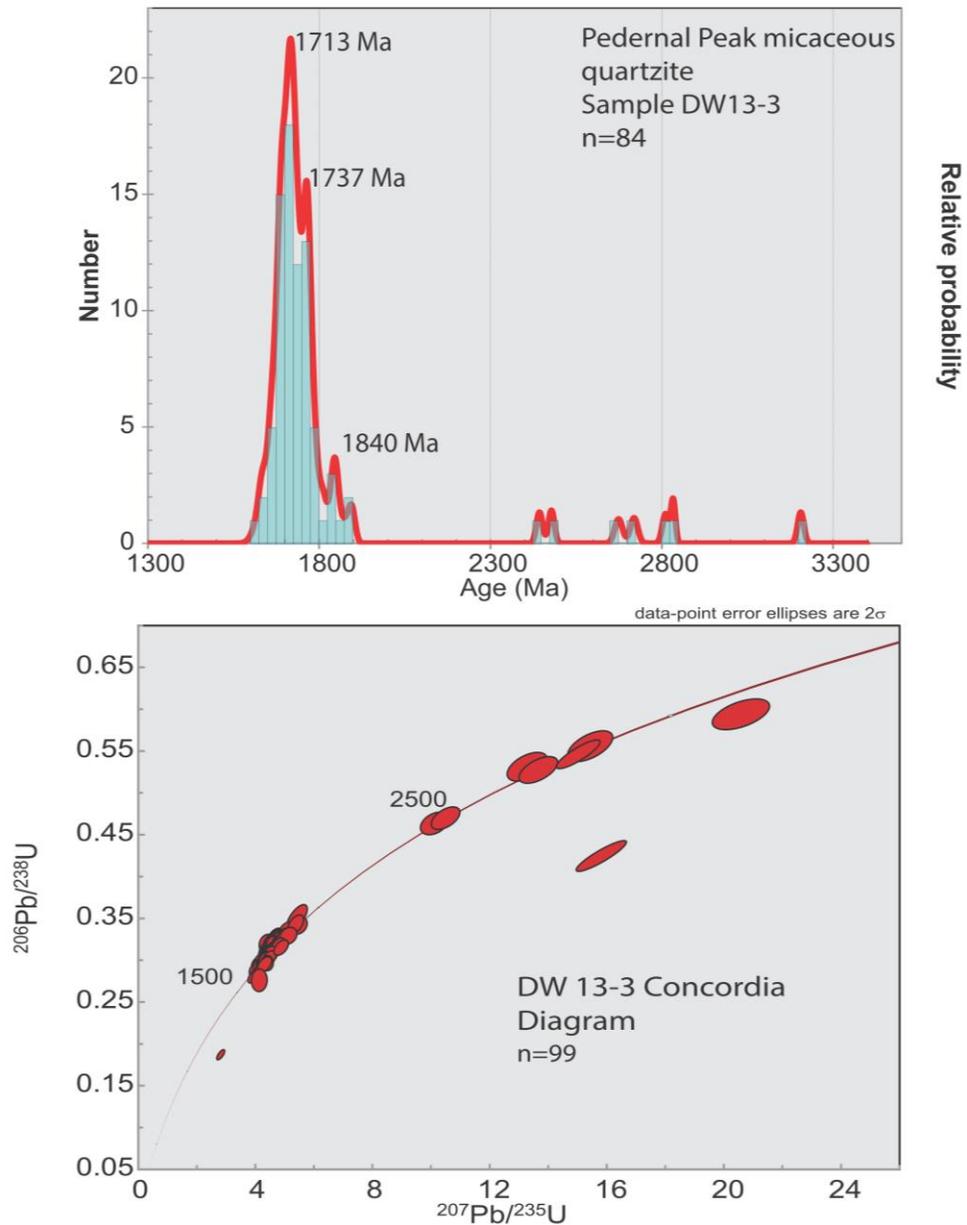
The resulting  $^{207}\text{Pb}/^{206}\text{Pb}$  ages are shown on Pb\*/U concordia diagrams and relative age-probability diagrams using the routines in Isoplot (Ludwig, 2008). The age-probability diagrams show each age and its uncertainty (for measurement error only) as a normal distribution, and sum all ages from a sample into a single curve. Composite age probability plots are made from an in-house Excel program that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves. Complete analytical results are presented together with sample location coordinates in the Data Repository (Tables 2-6). Analyses that were >20% discordant or >5% reverse discordant (by comparison of  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages) were eliminated and are not reported.

## RESULTS

### *U-Pb detrital zircon ages*

Detrital zircon data that were >5% reverse discordant and >20% discordant (by comparison of  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages) were eliminated from the age probability distribution plots. Uncertainties for calculated mean igneous ages and detrital zircon population ages are reported as 2-sigma or twice the standard error.

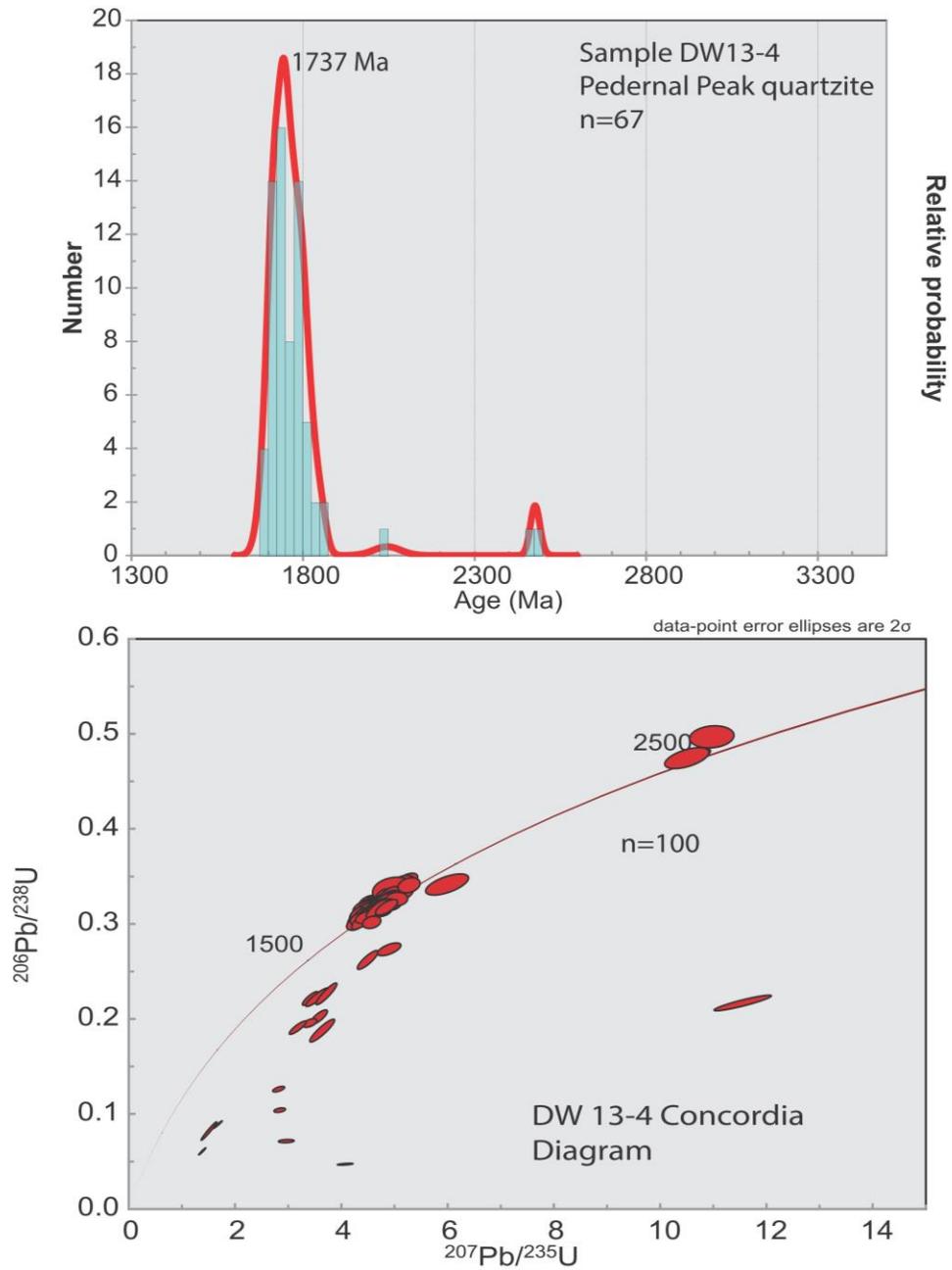
Isotopic analysis of micaceous quartzite DW13-3 (Figure 7) shows 84 concordant



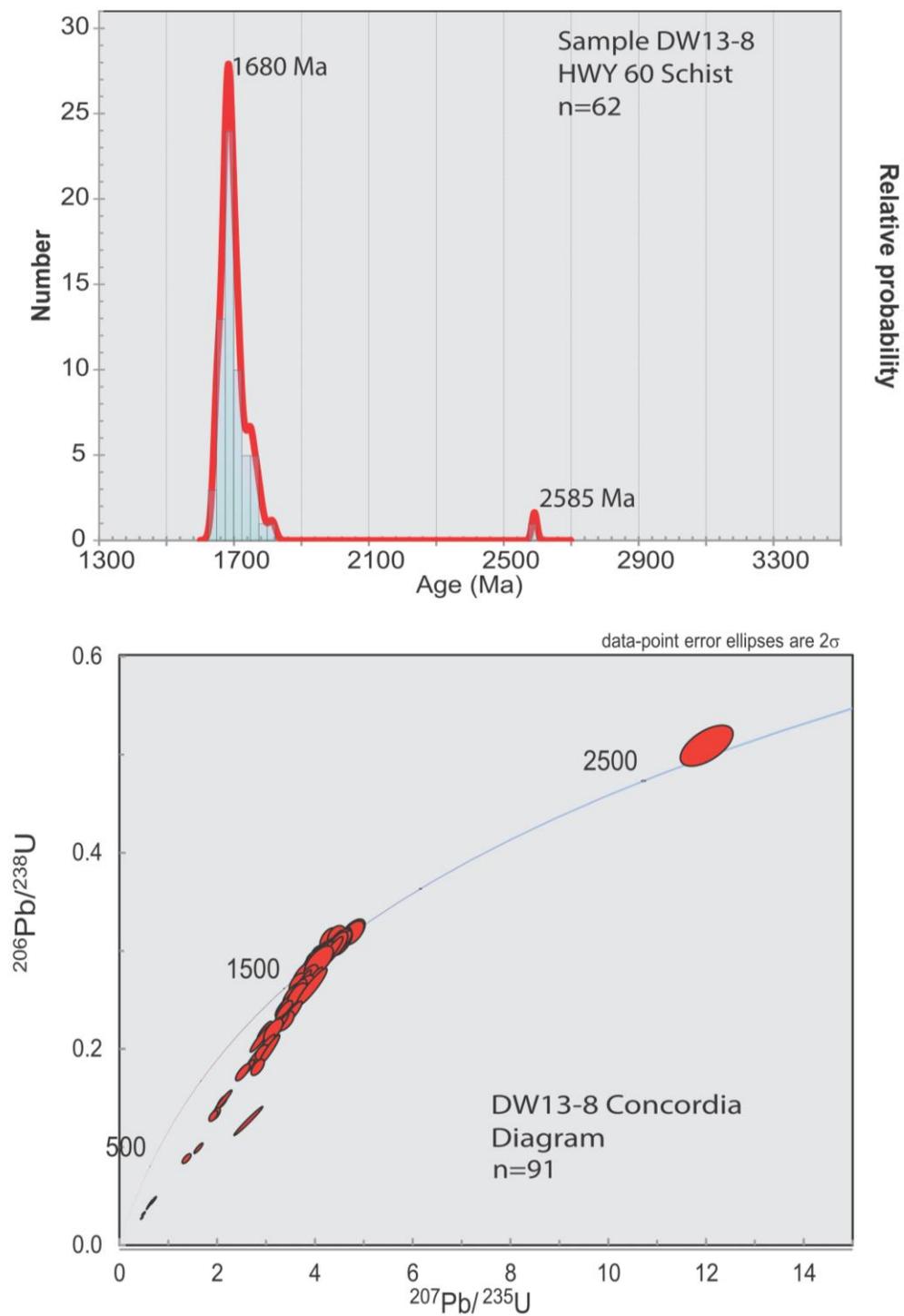
**Figure 7:** Normalized probability density distribution plot and corresponding concordia diagram for sample DW13-3. The normalized probability density distribution plot shows all concordant grains while concordia shows all grains analyzed for this sample. Histogram bins are 25 m.y. wide. Ellipse sizes on concordia diagrams vary due to the error on the  $\text{Pb}^{206}/\text{U}^{238}$  and  $\text{Pb}^{207}/\text{U}^{235}$  “clocks.” Large ellipses represent larger errors while small ellipses represent smaller errors.

grains with main peaks at 1713 Ma, 1737 Ma, and 1840 Ma. Smaller peaks are shown in this sample at ~ 2500 Ma, ~2800 Ma, and ~2900 Ma. Isotopic analysis of quartzite DW13-4 (Figure 8) shows 67 concordant grains and has a dominant peak age at 1737 Ma. A smaller peak age is shown at ~2500 Ma. Isotopic analysis of schist DW13-8 (Figure 9) shows 62 concordant grains with a dominant unimodal peak age at 1680 Ma. Isotopic analysis of quartzite sample CD13-5 (Figure 10) shows 67 concordant grains with a wide range of age distributions. Dominant peak ages are at 1737 Ma, 1791 Ma, and 1863 Ma while smaller peaks are between ~2300 Ma and 3000 Ma. The youngest peak in this quartzite member is shown at 1652 Ma. Isotopic analysis of metarhyolite sample CD13-3 shows some of the youngest Proterozoic ages in the Manzano Mountains and yields 70 concordant grains (Figure 11). A weighted mean age plot was produced for these zircon instead of a probability density distribution plot, and yields an average age of  $1626 \pm 5.7$  Ma (Figure 12). A weighted mean age plot was made for the three youngest zircon grains in this sample. The age from this new weighted mean age plot (Figure 13) shows an average age of  $1599 \pm 8$  Ma.

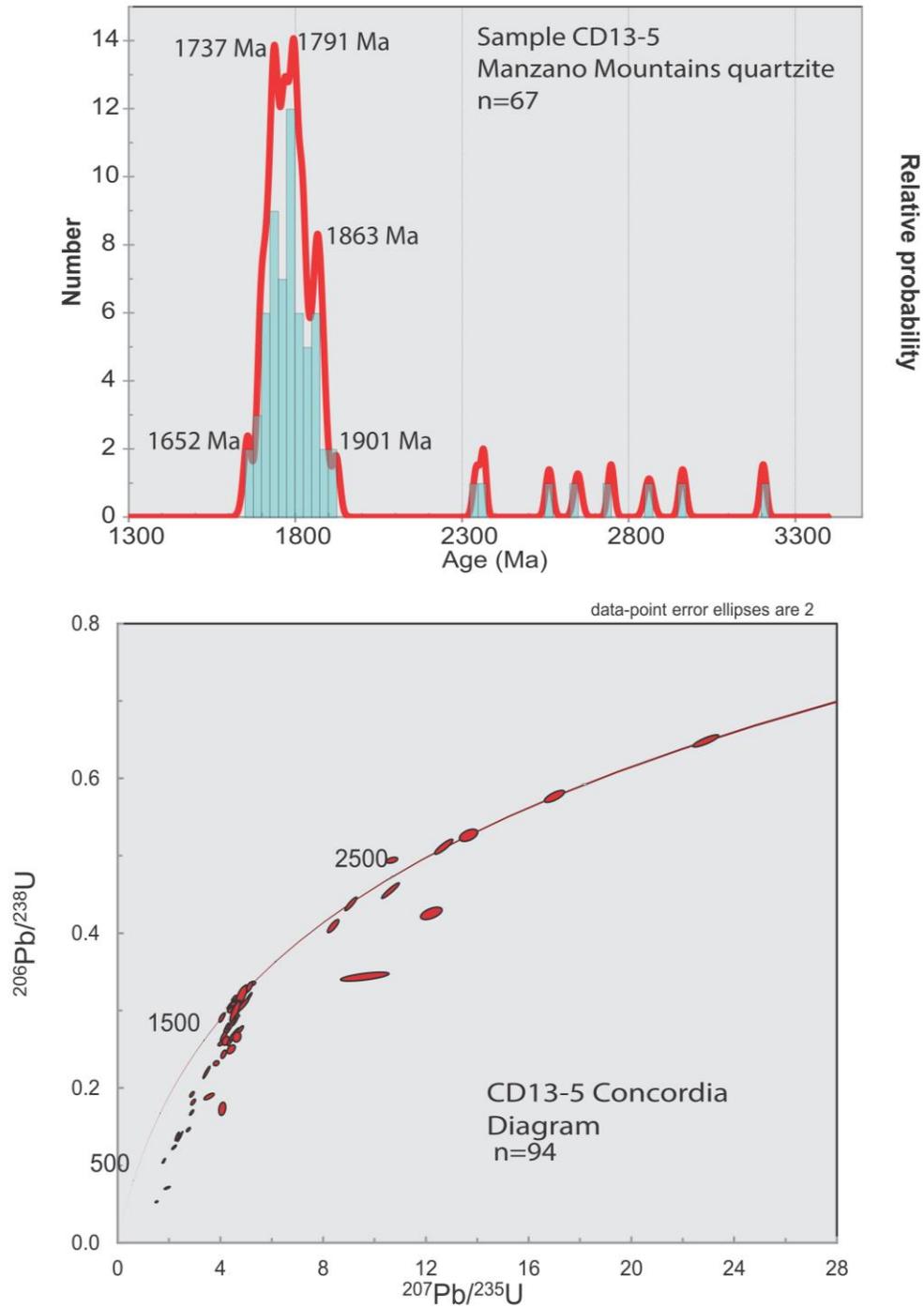
Zircons that grow due to metamorphism commonly show U/Th ratios greater than 10 while igneous zircon show U/Th ratios less than 10 (Gehrels et al., 2012). U/Th ratios for all samples are plotted in Figure 14. Of the 355 data points shown in the U/Th plot, 353 data points are below a ratio of 10 (~ 99.4%). Ratios are especially low in samples DW13-8 and CD13-3. The low U/Th ratios and concentric zoning in all samples confirm



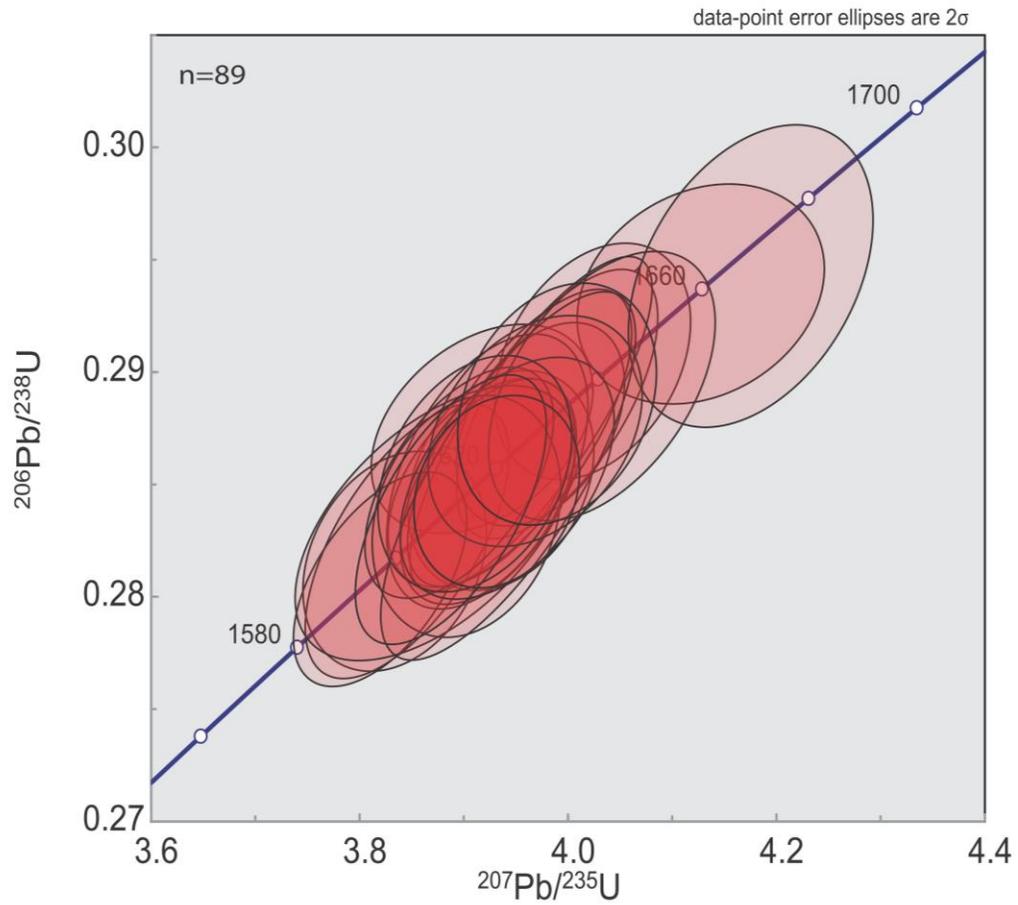
**Figure 8:** Normalized probability density distribution plot and corresponding concordia diagram for sample DW13-4. Histogram bins are 25 m.y. wide.



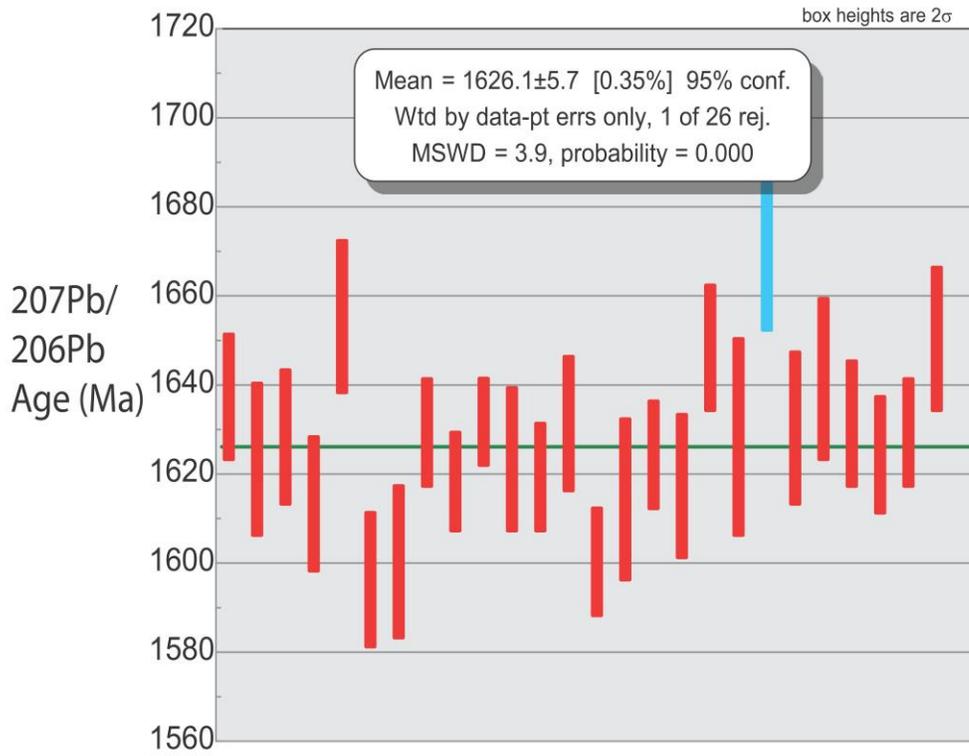
**Figure 9:** Normalized probability density distribution plot and corresponding concordia diagram for sample DW13-8. Histogram bins are 25 m.y. wide.



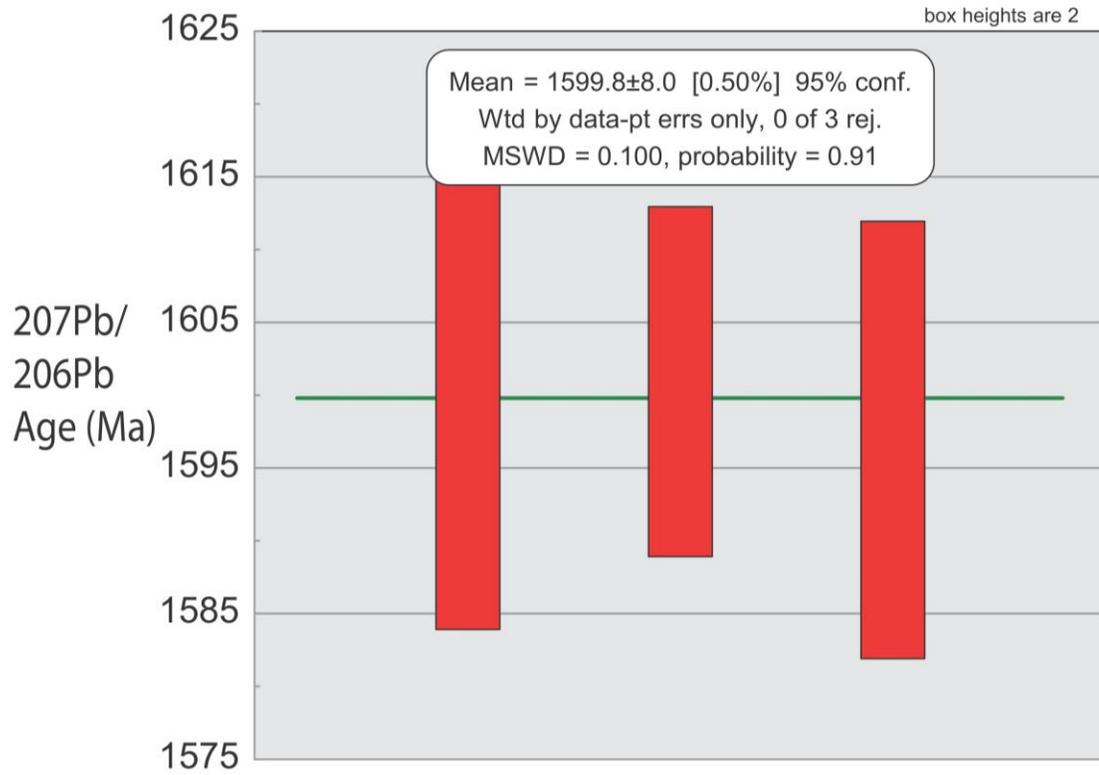
**Figure 10:** Normalized probability density distribution plot and corresponding concordia diagram for sample CD13-5. Histogram bins are 25 m.y. wide.



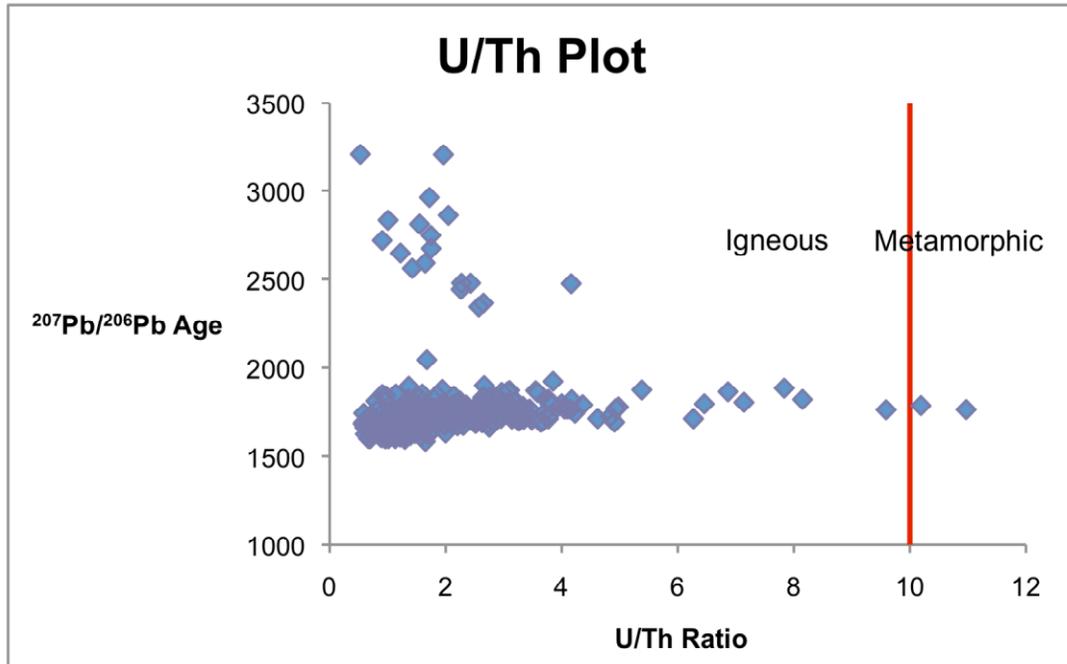
**Figure 11:** Concordia plot for metarhyolite sample CD13-3.



**Figure 12:** Weighted mean age plot for zircon from metarhyolite sample CD13-3. The blue line represents a grain that was not included in the age calculation.



**Figure 13:** Weighted mean age plot for the three youngest concordant analyses in sample CD13-3.



**Figure 14:** U/Th against  $^{207}\text{Pb}/^{206}\text{Pb}$  age. Values less than 10 (left of red line) for all samples are consistent with igneous zircon while value greater than 10 (right of red line) are consistent with metamorphic zircon. CL zoning and low U/Th ratio are consistent with an igneous origin for detrital zircon.

igneous origins for all detrital zircon samples.

## DISCUSSION

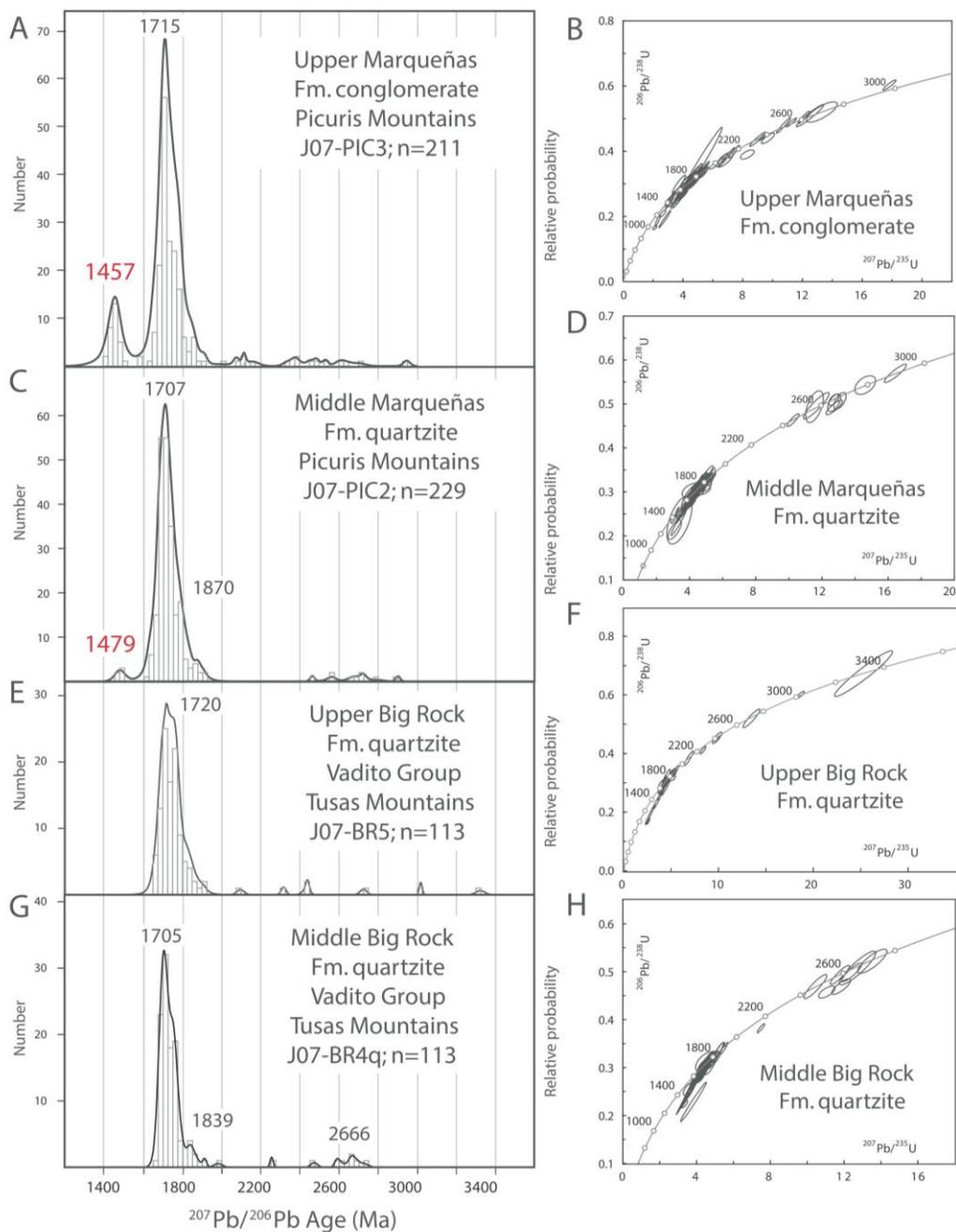
### *Detrital zircon ages*

The detrital zircon age spectrum for samples DW13-3 and DW13-4 in the Pedernal Hills match well with sample CD13-5 from the Manzano Mountains. Both DW13-3 and DW13-4 show peak ages of 1713 Ma and 1737 Ma respectively while CD13-5 shows peak ages at 1737 Ma and 1791 Ma. Sample DW13-8 has a younger age population than the Pedernal Peak quartzites. DW13-8 in the southern reaches of the Pedernal Hills shows a unimodal age distribution of 1680 Ma, which suggests that the detrital zircon in this sample are locally derived. The detrital zircon ages from DW13-8 suggest that the rocks young to the south. A weighted mean age plot for the three youngest grains in metarhyolite sample CD13-3 show an age of  $1599 \pm 8$  Ma while the youngest grains in CD13-5 are 1652 Ma. This data suggests that the Blue Springs Quartzite in the Manzano Mountains was deposited between roughly 1652 Ma and 1600 Ma with deformation and metamorphism of the Blue Springs Quartzite and Blue Springs Metarhyolite occurring after 1600 Ma. In our experience in the Pedernal Hills we did not find any granite units significant enough to state that there were cross cutting relationships, and therefore were not able to constrain a depositional age for the Pedernal Hills samples.

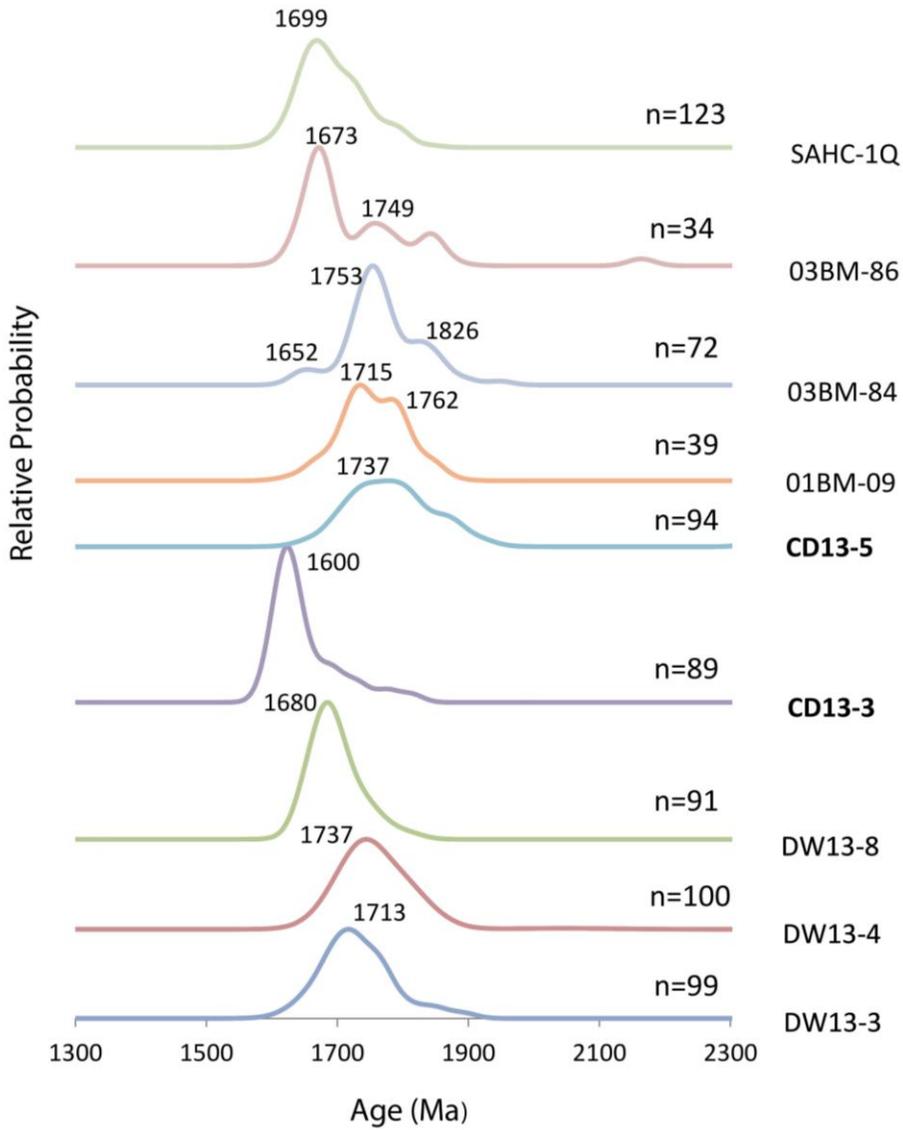
Detrital zircon geochronologic studies have been conducted on rocks in regions

surrounding the Pedernal Hills such as the Tusas and Picuris Mountains of northern New Mexico and have shown ages providing critical information for regional correlations (Figure 15). Samples from the Vadito and Hondo groups shows ages with probability peaks from 1765 Ma to 1704 Ma respectively while detrital samples from the Marquenas Formation show age peaks at 1707 Ma and 1715 Ma (Jones et al., 2011). Unpublished U/Pb data from a metarhyolite in the Marquenas Formation yield an age of 1450 Ma.

Detrital zircon ages from the Pedernal Hills and Manzano Mountains were compared with detrital zircon ages obtained from Amato (2008, 2011) using a normalized probability plot (Figure 16). Detrital zircon ages obtained by Amato (2008, 2011) are from samples collected in southern New Mexico in the Burro Mountains. The overall trend of ages in Amato's 2008 and 2011 studies show ages that are very similar to the ages obtained in the Pedernal Hills and Manzano Mountains sections. Sample 03BM-83 is a gabbro and a Concordia diagram shows a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1631 \pm 14$  Ma (Amato, 2011). Sample 01BM-09 is a biotite-garnet schist that yielded 48 concordant grains with bimodal peak ages at 1715 Ma, 1762 Ma, and an older peak at 1835 Ma (Amato, 2008). Sample 03BM-84 is a quartz muscovite schist that yielded 73 concordant grains with bimodal peak ages at 1732 Ma, 1753 Ma, and 1826 Ma (Amato, 2008). Sample 03BM-86 is a quartz muscovite schist that yielded 44 concordant grains with bimodal peak ages at 1673 Ma, 1701 Ma, and 1845 Ma (Amato, 2008). Sample SAHC-1Q is a lithic quartzite that yielded 131 concordant grains with a unimodal peak age at 1669 Ma. The data presented from both Amato (2008, 2011) add significant insight to the provenance and tectonic setting of the Pedernal Hills and Manzano Mountains ca. 1.6-1.8 Ga. It is in the



**Figure 15:** Age distribution diagrams for  $^{207}\text{Pb}/^{206}\text{Pb}$  ages and concordia diagrams for detrital zircon from the Marquenás and Big Rock formations, Picuris and Tusas Mountains, New Mexico. Plots represent all grains analyzed. Histogram bins are 25 m.y. wide (Jones et al., 2011).



**Figure 16:** Normalized probability plot comparing detrital zircon ages from samples taken from the Pedernal Hills and Manzano Mountains with samples taken from the Burro Mountains of southern New Mexico.

Burro Mountains that we still see a mix of Yavapai age and Mazatzal age detritus, which is very similar to what is encountered near the Yavapai-Mazatzal crustal boundary.

### *Regional Tectonic Implications*

U/Pb ages recorded by detrital zircon, lithological descriptions, and geochemical data (McKee, 1988) allow for interpretation about the depositional environments and provenance of the rocks in the Pedernal Hills. This information is essential in understanding the regional tectonic history and implications of central New Mexico during the Paleoproterozoic. Detrital zircon ages, mineralogical and textural observations of the Pedernal Hills samples, and ages of detrital grains from the Burro and San Andres Mountains (Amato et al., 2008, 2011) to the south of the Pedernal Hills help to determine provenance for the rocks in the Pedernal Hills.

Petrology of hand samples and previously reported geochemical data (McKee, 1988) in the Northern Quartzite Terrain and the volcanic rocks in the Pedernal Hills indicate that these rocks formed subaqueously (McKee, 1988). The mafic volcanic rocks in the Pedernal Hills consist of mafic pyroclastics and exhibit little to no evidence of any pillow basalts or pillow breccias (McKee, 1988). Mafic pyroclastic rocks do not travel far from their source of eruptions. This evidence indicates a subaerial eruption of the mafic volcanic rocks followed by rapid subaqueous deposition of these rocks (McKee, 1988). Samples DW13-3 and DW13-4 are both poorly sorted and have a lack of mature sediment that indicates little evidence of sedimentary reworking. The lack of deep-sea lithologies such as bedded cherts and deep-sea mudstones indicates that the

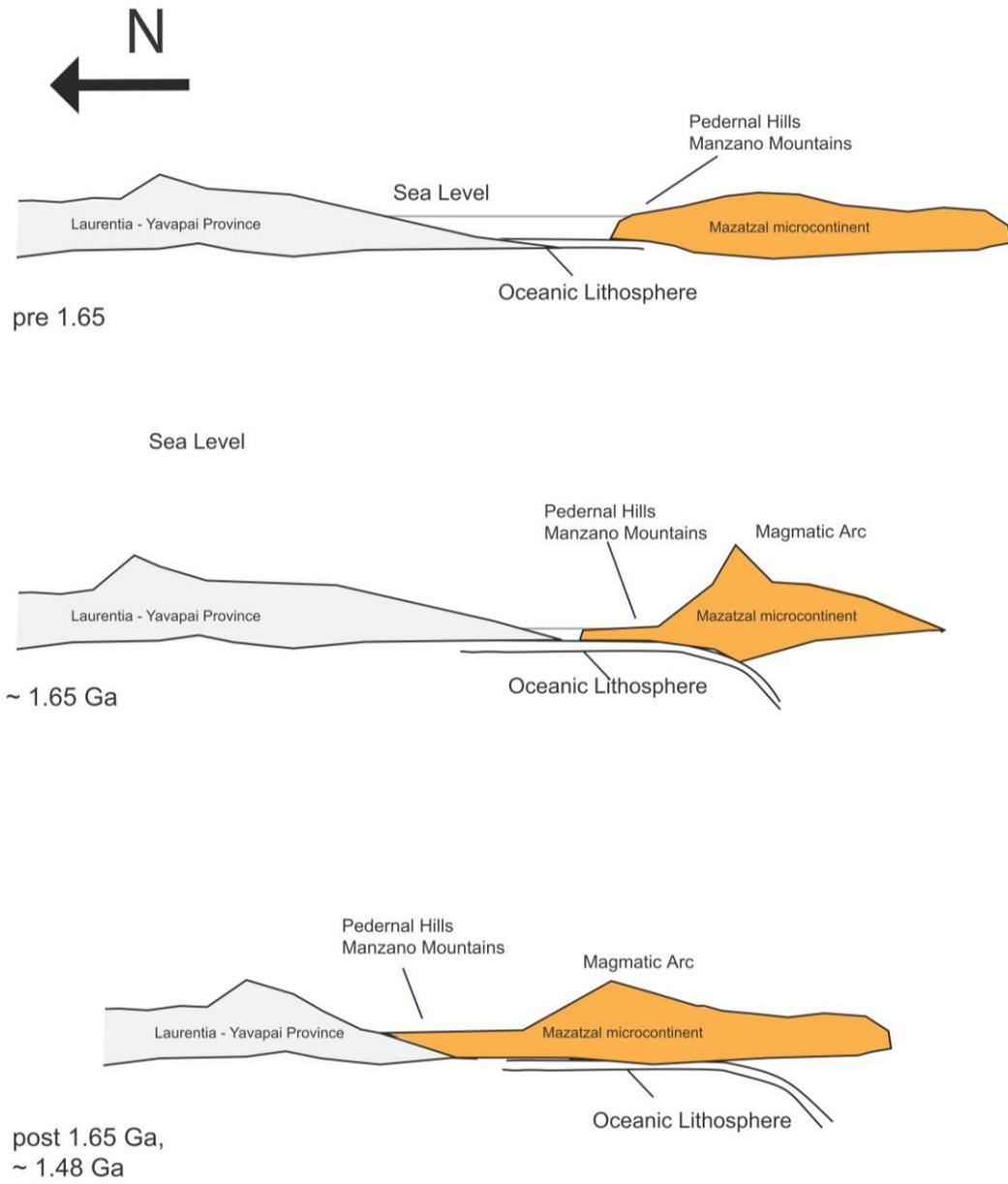
quartzite unit was not deposited in the deeper areas of the basin, but could represent shallow marine sediment accumulation (McKee, 1988). The geochemical data on these samples show that they are tholeiitic and calc-alkaline in nature, and this plays an important role in the tectonic interpretation.

Detrital samples DW13-3 and DW13-4 both yield peak ages at 1713 Ma and 1737 Ma respectively. In sample DW13-3 there are minor amount of older grains that yield ages between 2300 Ma and 3000 Ma. Sample DW13-4 is very similar in this respect. There are only two grains that yield an age of 2400 Ma to 2600 Ma. Ages from detrital sample CD13-5 are very similar to DW13-3 and DW13-4. This sample yields main peak ages at 1737 Ma and 1791 Ma with older grains showing smaller peaks between 2300 Ma and 3000 Ma. In each of these three detrital samples there are small peaks showing ages not representative of Mazatzal age sediment. The similarity in ages between detrital samples DW13-3 and DW13-4 from the Pedernal Hills and detrital sample CD13-5 from the Manzano Mountains also suggests that these two localities could have the same source terrain. The older detrital zircon ( $> 1.7$  Ga) is a mixture of Yavapai and Mazatzal age detritus with the much older grains ( $> 2.3$  Ga) possibly reflecting Trans-Hudson, Wyoming, Mojave Province, or older Archean sources.

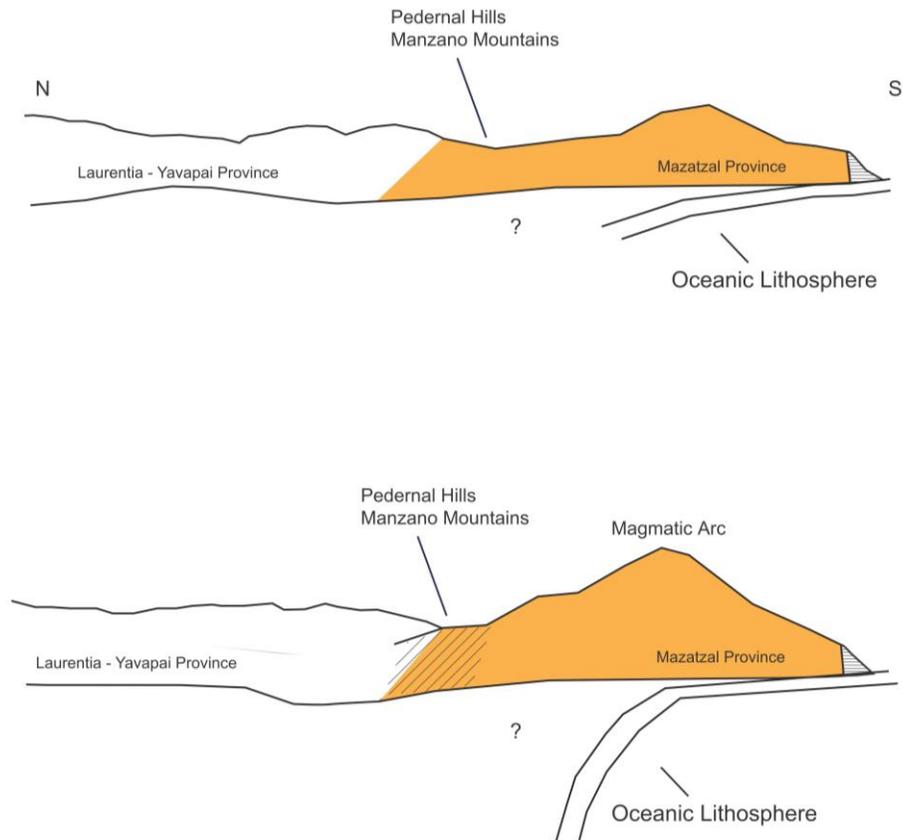
There are multiple basin interpretations for the metasedimentary rocks in the Pedernal Hills of New Mexico (Figure 17). One interpretation is that subduction of oceanic crust under the Mazatzal Province occurred ca. 1650 Ma in an event called the Mazatzal Orogeny and created a volcanic arc in the study area. This explains the assortment of volcanic lithologies scattered throughout the Pedernal Hills. During this

orogenic event a basin was formed in which there was an intermingling of detritus from the Yavapai and Mazatzal Provinces. This interpretation calls for a forearc or intra-arc basin on the front side of the arc (McKee, 1988). Tholeiitic rocks are characteristic to front arc settings (McKee, 1988), consistent with tholeiitic and calc-alkaline rocks in the Pedernal Hills (McKee, 1988).

Another interpretation of basin type for these rocks is a retroarc foreland basin. This basin setting for the Pedernal Hills is the most likely option. Geochemical data (McKee, 1988) tells us about the geochemistry of the rocks in the Pedernal Hills but does not tell us from which direction subduction was occurring. It is possible that as the Mazatzal Province was colliding with the Yavapai Province, oceanic crust to the south of the Mazatzal Province was subducting under the Mazatzal Province (Figure 17). This direction of subduction still explains the arc related volcanics that are present in the Pedernal Hills. This basin interpretation also better explains the intermingling of detritus from the Yavapai and Mazatzal Provinces. In a forearc setting sediment would have had to travel down gradient from the Yavapai Province and then back up gradient and deposited into the Pedernal Hills. The retroarc foreland basin interpretation allows for the Pedernal Hills to be in the lowest point of the basin between these two provinces, allowing sediment from both provinces to easily intermingle with each other. A modern tectonic analog for the Mazatzal Orogeny and the Pedernal Hills, assuming a retroarc foreland basin setting, would be China and Taiwan. Subduction of oceanic crust east of Taiwan is currently subducting under Taiwan creating arc related volcanic rocks. Over time the island of Taiwan will move closer to China due to this



**Figure 17.1:** Tectonic interpretation of the Mazatzal Orogeny if the inferred basin type were a forearc basin.



**Figure 17.2:** Tectonic interpretation of the Mazatzal Orogeny if the inferred basin type were a retroarc foreland basin. In the top cartoon the oceanic lithosphere is just starting to subduct under the Mazatzal Province from the south. In the bottom cartoon the oceanic lithosphere has fully subducted under the Mazatzal Province and has created a magmatic arc.

subduction, will close the Strait of Taiwan, and collide with China and the rest of mainland Asia where arc derived sediments from Taiwan and sediments from China will be intermingled in a collisional basin setting.

There are two alternative caveats to these models that do not require sediment transport from the north. The first is the possibility of the recycling of sediment off the magmatic arc in the Pedernal Hills area. It is possible that after detrital zircon was transported from the Yavapai Province and deposited into the Pedernal Hills, it was then uplifted and eroded back into this basin and transported back north. The second is the possibility of 1.7 Ga and older plutons south of the Pedernal Hills in Mexico. If 1.7 Ga and older plutons were found in Mexico then this could also be a potential source terrain for the detrital zircon in the Pedernal Hills. These two caveats are purely speculative and would require additional investigation to what has already been done in this study.

In order to improve this study a few things are necessary. It is necessary to return to the Pedernal Hills and walk the entirety of the sections present. Due to lack of time we only had one day to conduct fieldwork in the Pedernal Hills, which is why sample locations are only in the most northern and most southern reaches of the area. Sampling the volcanic rocks in the middle section (T-Phase Volcanics and M2 Volcanics) for igneous zircon would add more data to this study. I would go back to this area to sample these rocks in hopes of finding cross cutting relationships, and in turn determine a time constraint for deposition of the metasedimentary rocks. It is also necessary to conduct U/Pb dating of the monazite grains extracted from these rocks.

Monazite ages would give us absolute timing of metamorphism, which could help us better understand the Mazatzal Orogeny.

## **CONCLUSION**

Based on detrital zircon age populations from the Pedernal Hills and Manzano Mountains we were able to locate potential source terrains for the metasedimentary rocks in these locations and also constrain a depositional age for the Blue Springs Quartzite. Samples DW13-3, DW13-4, and CD13-5 show peak ages at 1713 Ma, 1737 Ma, and 1737 Ma/1791 Ma respectively and all show smaller peak ages between 2300 Ma and 3000 Ma which reflect Trans-Hudson, Wyoming, Mojave Province, or older Archean sources. While we were able to constrain a depositional age for the Blue Springs Quartzite between 1652 Ma and 1600 Ma, we were unable to constrain depositional ages for the Pedernal Hills samples due to the lack of cross cutting relationships found in this area. Although we did not constrain a depositional age for these samples we did find what we had expected, which is a mixture of Yavapai and Mazatzal aged detritus with some signatures of older Archean detritus in the northern reaches of the Mazatzal Province. This data led us to ask what kind of basin were these sediments being deposited in and what could be a possible tectonic setting for southwest Laurentia ca. 1.60 Ga – 1.80 Ga. Based on the geochemical data from McKee (1988) and detrital zircon age populations from this study and Amato's study (2008, 2011) the basin type for the metasedimentary rocks in the Pedernal Hills could be interpreted as either a forearc basin or a retroarc foreland basin. Sediment was transported into this basin during the ca. 1650 Ma Mazatzal Orogeny from both the north and south. Metamorphism of the metasedimentary rocks in

this area post 1.65 Ga as well as 1.40 Ga plutonism in northern and central New Mexico are not associated with the metamorphism and magmatism of Mazatzal Orogeny, but instead were (Daniel et al., 2013) caused by the 1.40 Ga- 1.48 Ga Picuris Orogeny.

**Table 1.** Location of samples included in this study.

Sample Number	Lat, Long	Orientation	Litologies	Analysis
DW13-3	N 34° 50.9969' W 105° 38.8289'	022°, 11° E	Micaceous quartzite	Detrital zircon
DW13-4	N 34° 50.8999' W 105° 38.0832'	025°, 35° SE	Quartzite	Detrital Zircon
DW13-8	N 34° 40.2921' W 105° 35.6200'	091°, 57° S	Muscovite schist	Detrital Zircon
CD13-3	N 34° 34.1087' W 106° 26.9453		Metarhyolite	Igneous Zircon
CD13-5	N 34° 33.8609' W 106° 26.5100'		Quartzite	Detrital Zircon

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