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The Timing of Deformation in the Four Peaks Area, central Arizona, and relevance for the Mazatzal Orogeny

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**THE TIMING OF DEFORMATION IN THE FOUR PEAKS AREA, CENTRAL
ARIZONA, AND RELEVANCE FOR THE MAZATZAL OROGENY**

A Thesis Presented

by

CALVIN A. MAKO

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
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Department of Geosciences

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Ad Majorem Dei Gloriam

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ABSTRACT

TIMING OF DEFORMATION IN THE FOUR PEAKS AREA, CENTRAL ARIZONA, AND RELEVANCE FOR THE MAZATZAL OROGENY

SEPTEMBER 2014

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The Mazatzal orogeny (1.66-1.60 Ga) is a key element of the tectonic evolution of the North American continent during the Proterozoic (Whitmeyer and Karlstrom, 2007). Recently, Mesoproterozoic detrital zircon grains (1.55-1.45 Ga) have been found in metasedimentary rocks that were thought to have been deformed during the Paleoproterozoic Mazatzal orogeny (Jones et al. 2011; Doe et al. 2012, 2013; Daniel et al. 2013). Some type examples Mazatzal deformation now seem to be too young to have been deformed in the accepted time of that orogeny (1.66-1.60 Ga) and may have been deformed in the younger, newly defined, Picuris orogeny. This leads to questions regarding the timing and nature of the Mazatzal orogeny and its importance in the evolution of the North American continent. The object of this research is to constrain the timing of deformation related to the Mazatzal and Picuris orogenies and clarify the Proterozoic history of the North American continent.

The Four Peaks area in central Arizona has been selected as an ideal location to tightly constrain the timing of deformation. The area hosts a package of Proterozoic metasedimentary rocks that are folded into a kilometer-scale syncline, surrounded by

Mesoproterozoic to Paleoproterozoic granitoids. The Four Peaks syncline has been considered a type example of Mazatzal-age deformation (Karlstrom and Bowring, 1988). Zircon and monazite geochronology are presented along with structural and petrologic data in order to understand the geologic history of the Four Peaks area. The evidence suggests that three deformation events occurred at ~1675 Ma, 1665-1655 Ma and 1490-1450 Ma. Sedimentary deposition occurred 1665-1655 Ma and 1520-1490 Ma with a significant disconformity in between these episodes. Both the Mazatzal and Picuris orogenies can be associated with periods of deformation, sedimentary deposition and pluton emplacement. The most significant shortening event, which formed the Four Peaks syncline, occurred during Mesoproterozoic time and was related to the Picuris orogeny.

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CHAPTER 1

INTRODUCTION

The Proterozoic basement of southwestern North America is interpreted to represent a protracted history of accretionary orogenesis from ca. 1.8 -1.0 Ga. Distinct belts of Proterozoic rocks extend from southern California to Northern Labrador and are divided into the Yavapai, Mazatzal, Granite-Rhyolite and Grenville provinces (Figure 1) (Whitmeyer and Karlstrom, 2007). The Yavapai province is composed of 1.8-1.7 Ga crust, deformed during the ca. 1.7 Ga Yavapai orogeny. The extensive Mazatzal province consists of 1.7-1.6 Ga crustal material and sedimentary successions that are interpreted to have been accreted to the margin of the Laurentian craton with significant deformation and metamorphism between and 1.66 and 1.60 Ga (Bennett and DePaolo, 1987; Bowring and Karlstrom, 1990; Luther, 2006). The Mazatzal orogeny has been a long-standing element of North American geologic history and the Mazatzal province has been used as an important piercing point for supercontinent reconstructions (Karlstrom et al. 2001; Li et al. 2008; Betts et al. 2008).

Detrital zircon data from Proterozoic metasediments in Arizona and New Mexico have given reason to doubt elements of the classic understanding of the Mazatzal orogeny in the southwestern United States. Mesoproterozoic (1.55-1.45 Ga) zircon grains have been discovered in the Marquenas, Pilar and Piedra Lumbre Formations of northern New Mexico (Jones et al. 2011; Daniel et al. 2013) and the Hess Canyon Group and Defiance quartzite in Arizona (Doe et al. 2012, 2013). These sediments occur within the Mazatzal province and were thought to have been deformed during the Mazatzal orogeny.

However, the occurrence of Mesoproterozoic grains suggests that deformation and large scale folding had to be Mesoproterozoic or younger. Younger sediments even appear in fold and thrust localities that have classically defined Mazatzal-age deformation, suggesting that many important structures may be too young to have deformed during the Mazatzal Orogeny. Paleoproterozoic deformation may have been less important in the construction of the present basement architecture than previously thought. Daniel et al. (2013) termed this younger deformation event the Picuris orogeny.

A clarified understanding of relationship between Mesoproterozoic and Paleoproterozoic deformation (Picuris and Mazatzal orogenies) is necessary to understand how the assembly of North America is recorded in the southwestern US. It is necessary to revisit classic examples of Mazatzal sedimentation and deformation and tightly constrain the timing of these processes. The Four Peaks area in central Arizona is an ideal location to pursue these goals. There, a thick, ~1.5 km, section of folded Proterozoic metasediments is exposed, surrounded by a sea of variably deformed plutonic and volcanic rocks that range in age from 1677 Ma to 1449 Ma.

The objective of this thesis is to constrain the timing of deformation in the Four Peaks area using zircon and monazite geochronology coupled with structural and petrologic analysis. The results of recent work imply that at least some component of deformation, previously attributed to the Mazatzal orogeny, may in fact be significantly younger. Constraints from the Four Peaks area will provide an important data point for understanding of the Proterozoic evolution of the Southwest and the importance of the Mazatzal orogeny. Current work suggests that the rocks in the Four Peaks area record components of both Mesoproterozoic and Paleoproterozoic deformation.

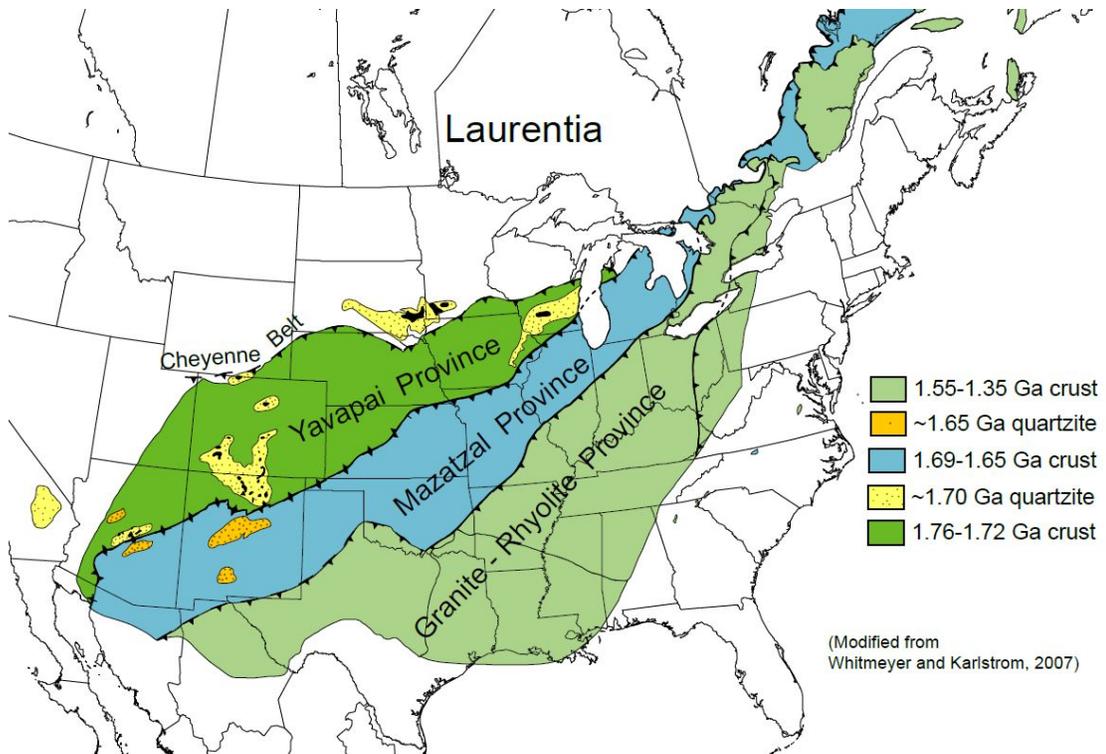


Figure 1- The Proterozoic provinces of North America. These provinces extend in wide belts across the continent. The Mazatzal province (blue) is correlated with the Labradorian province in Canada. Sedimentary basins are also shown in yellow and orange.

CHAPTER 2

GEOLOGIC BACKGROUND

Paleoproterozoic and Mesoproterozoic deformation have been documented across the North American continent. Beginning at ~1.8 Ga, the Laurentian craton grew rapidly southward by the addition of juvenile crust and older crustal components. The rocks that record this growth have been divided into several provinces on the basis of age and isotopic characteristics (Condie, 1986; Reed et al. 1987; Karlstrom et al. 1987; Bennett and DePaolo, 1987; Hoffman, 1989). The Yavapai province consists of dominantly juvenile crustal material that was accreted 1.8-1.7 Ga and extends from central Arizona through northern New Mexico and across the mid-continent (Figure 1) (Bowring and Karlstrom, 1990; Whitmeyer and Karlstrom, 2007). The younger Mazatzal province contains 1.68-1.60 Ga crust and sedimentary successions that were deformed during the Mazatzal orogeny 1.66-1.60 Ga (Karlstrom and Bowring, 1988; Karlstrom et al. 2004; Luther, 2006). Thick quartzite-rhyolite sequences are characteristic of the Mazatzal province (Whitmeyer and Karlstrom, 2007). The Mazatzal province has been correlated with crust of similar age in northwestern Canada, known as the Labradorian province (Figure 1) (Gower et al. 1997; Whitmeyer and Karlstrom, 2007; Hynes and Rivers 2010). Deformation associated with the Mazatzal orogeny has been recognized across the midcontinent and into Ontario (Romano et al. 2000; Bailey et al. 2004; Holm et al. 2007; Craddock and McKiernan 2007).

The Mazatzal orogeny was originally proposed in the Southwest based primarily on accumulated work in central Arizona and named after the “Mazatzal Revolution” of

Wilson (1939) (Karlstrom and Bowring, 1988). It has been associated across the Southwest with fold and thrust style deformation and low to moderate grade metamorphism (Doe and Karlstrom, 1991; Williams, 1991; Williams and Karlstrom, 1996; Williams et al. 1999). The timing of Mazatzal deformation has been constrained to 1660-1600 Ma, especially in New Mexico and Arizona (e.g. Labrenze and Karlstrom, 1991; Bauer and Williams, 1994; Shaw et al. 2001; Eisele and Isachsen, 2001; Amato et al. 2008).

Significant tectonism occurred across North America in the Mesoproterozoic. There is evidence of a crust formation event at 1.45 Ga, termed the Pinwarian orogeny, in the Grenville province of Ontario, Canada (Wasteneys et al. 1997). The extensive and poorly exposed Granite-Rhyolite province, south of the Mazatzal and Yavapai provinces, consists of crust with ages between 1.5 and 1.3 Ga (Figure 1) (Van Schmus et al. 1996). A suite of voluminous ferroan granites intruded across North America at 1.45-1.35 Ga associated with regional metamorphism in the Southwest (Grambling and Dallmeyer, 1993; Williams and Karlstrom, 1996). These granites were originally thought to be anorogenic (Anderson and Bender, 1989), but it has been recognized that significant deformation occurred during or after emplacement, at least locally (Nyman et al. 1994). Although ca. 1.4 Ga deformation has long been recognized (Grambling and Dallmeyer, 1993), sedimentary rocks of that age have only recently been recognized (Jones et al. 2011, Doe et al. 2012, Daniel et al. 2013, Doe et al. 2014). The relative contribution of Paleo- and Mesoproterozoic orogenesis to deformation of sedimentary successions in the Mazatzal province is not well understood (Williams et al. 1999).

The Tonto Basin area of central Arizona, where the Four Peaks Wilderness is located, has been an important location for studying the Proterozoic tectonism of the southwest. The nearby Mazatzal Mountains expose a fold and thrust system that has been interpreted as a foreland system of the Mazatzal orogeny (Doe and Karlstrom, 1991). The Slate Creek movement zone, which forms the boundary between the Sunflower and Mazatzal blocks of the Mazatzal province, is exposed in the Tonto Basin. The syn- to post-deformational Young Granite was used to constrain the timing of deformation in the Slate Creek movement zone, and thus the timing of the Mazatzal orogeny, to 1.65 Ga (Labrenze and Karlstrom, 1991). Significant work has been done on the stratigraphy and sedimentology of the Proterozoic metasediments of the Tonto Basin (Cuffney, 1977; Trevena, 1979; Doe et al. 2012) including the Mazatzal quartzite (Cox et al. 2002), which is broadly correlated with the Ortega Quartzite of northern New Mexico. Most recently, significant sequences of deformed Mesoproterozoic sediments have been recognized in the Mazatzal Mountains and near the Salt River Canyon (Doe et al. 2012; Doe, 2014).

The Four Peaks are located in the southern Mazatzal Mountains in the Tonto Basin area. This region offers the opportunity to answer questions about the timing of deformation in the Southwest. The geology of the Four Peaks area (Figure 2) consists of a kilometer-scale, doubly plunging syncline of Proterozoic metasediments, which have been interpreted to be members of the Mazatzal group (Estrada, 1987; Powicki, 1996). The syncline has been interpreted as a large roof pendant in a sea of granites (Wilson, 1939; Estrada, 1987). Igneous rocks range in age from ~1677 Ma to ~1449 Ma and are variably deformed. A major, 12 km wide, shear zone has been proposed adjacent to the southern limb of the syncline. Previous workers have attributed the major structures

present in the Four Peaks area to Mazatzal-age deformation (Karlstrom and Bowring, 1988; Powicki, 1996). This thesis presents geochronologic, structural and petrological data to better constrain the timing and character of deformation.

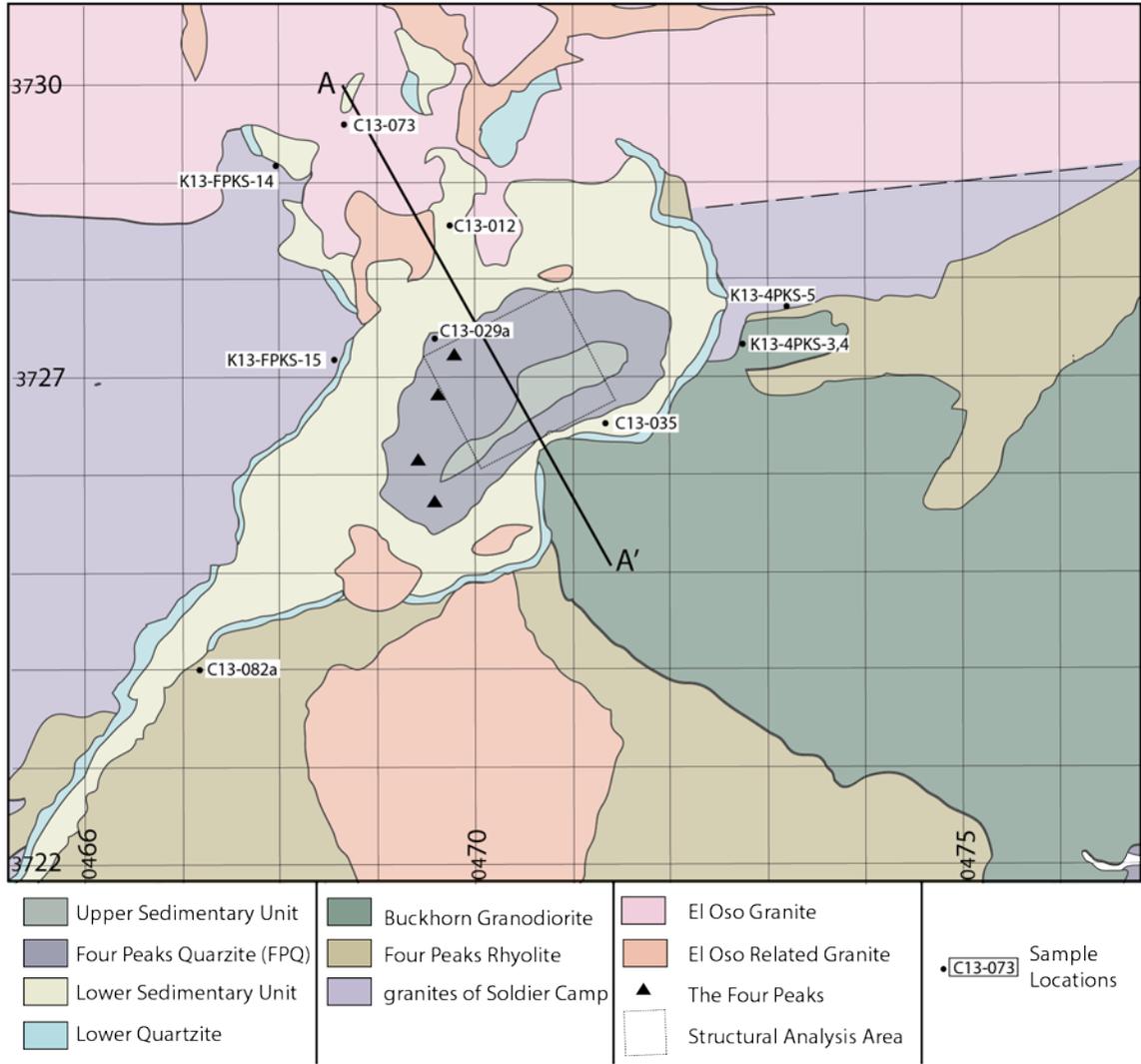


Figure 2- Geologic map of the Four Peaks area. It shows the important samples of this study. The outlined area in the center of the map is considered cylindrically folded. The gridlines are spaced 1 km apart with some labels of UTM coordinates. This map was produced by Skotnicki (2000) and modified after Powicki (1996).

CHAPTER 3

METHODS

3.1 Overview

Mapping and sample collection for this study were conducted between May, 2013 and March, 2014. Samples of all of the major metasedimentary and igneous units were collected. Thin sections were made to examine microstructures and microtextures, and to search for monazite. The X-Ray Fluorescence facility at the University of Massachusetts under the direction of Dr. Michael Rhodes was used to obtain major element compositions of two samples of the lower sediment and one of the Four Peaks rhyolite. Detrital and igneous zircon grains were analyzed at the University of Arizona Laserchron Laboratory. The petrologic modeling program Theriak-Domino (de Capitani and Petrakakis, 2010) was used to constrain pressure and temperature conditions recorded in the rocks of Four Peaks.

3.2 Monazite Geochronology

Monazite was found by making full-section Wavelength Dispersive Spectrometry (WDS) compositional maps of Ce-L α x-ray intensity of thin sections on a Cameca SX-50 electron microprobe at the University of Massachusetts. 15 kV accelerating potential, 300nA current, 25 millisecond dwell time and 35 micron pixel step size were used. Individual monazite grains were then mapped at high resolution for U, Th, Y, Ca and Nd to identify compositional domains that could be related to generations of monazite growth. 15 kV accelerating potential, 200nA current, 80 millisecond dwell time and

about 0.5 micron pixel step sizes were used to map monazite grains. Selected monazite grains were analyzed on the University of Massachusetts Ultrachron electron microprobe with 15kV accelerating potential and ~200nA beam current. Concentrations of U, Pb and Th for age calculations along with a suite of major and trace elements were determined using WDS by the methods of Williams et al. (2006) and Dumond et al. (2008). Steps were taken to model the curving pattern of the background x-ray signal below U, Pb and Th x-ray peaks to improve the accuracy of those measurements.

3.3 Zircon Geochronology

Zircon was analyzed at the University of Arizona Laserchron Center using a laser ablation- inductively coupled plasma- multicollector mass spectrometer. Zircon separates were mounted and imaged using cathodoluminescence and plane light to identify zoning and fractures in zircon grains. A random and representative population of zircon grains from each sample with domains free of fractures and with oscillatory zoning was analyzed. Effort was made to represent all crystal morphologies present in the sample. Zircon dates with 80-105% concordance were included in final age calculations and probability distributions. The final uncertainties were calculated using the following formula. $Uncertainty = \sqrt{ (standard\ error)^2 + (random\ error)^2 } / 100 * mean\ age$. Analytical methods followed that of Gehrels et al. (2008).

3.4 Whole Rock Geochemistry and Pseudosection Modeling

Whole rock geochemistry for three samples was determined at the University of Massachusetts using the X-Ray Fluorescence facilities. Samples were crushed and

powdered, mixed with a fluxing agent in appropriate proportions, melted and fused into glass discs. X-ray intensities were measured for the elements Si, Mg, Fe, Al, K, Na, Ca, Ti, P and Mn.

Bulk compositions were input into the Domino application of the Theriak-Domino modeling package (de Capitani and Petrakakis, 2010). Input compositions were set to water saturated conditions. Variable oxygen was allowed to fit the calculated assemblages. The thermodynamic database of Holland and Powell (1998) was used for all phase diagram calculations reported in this study.

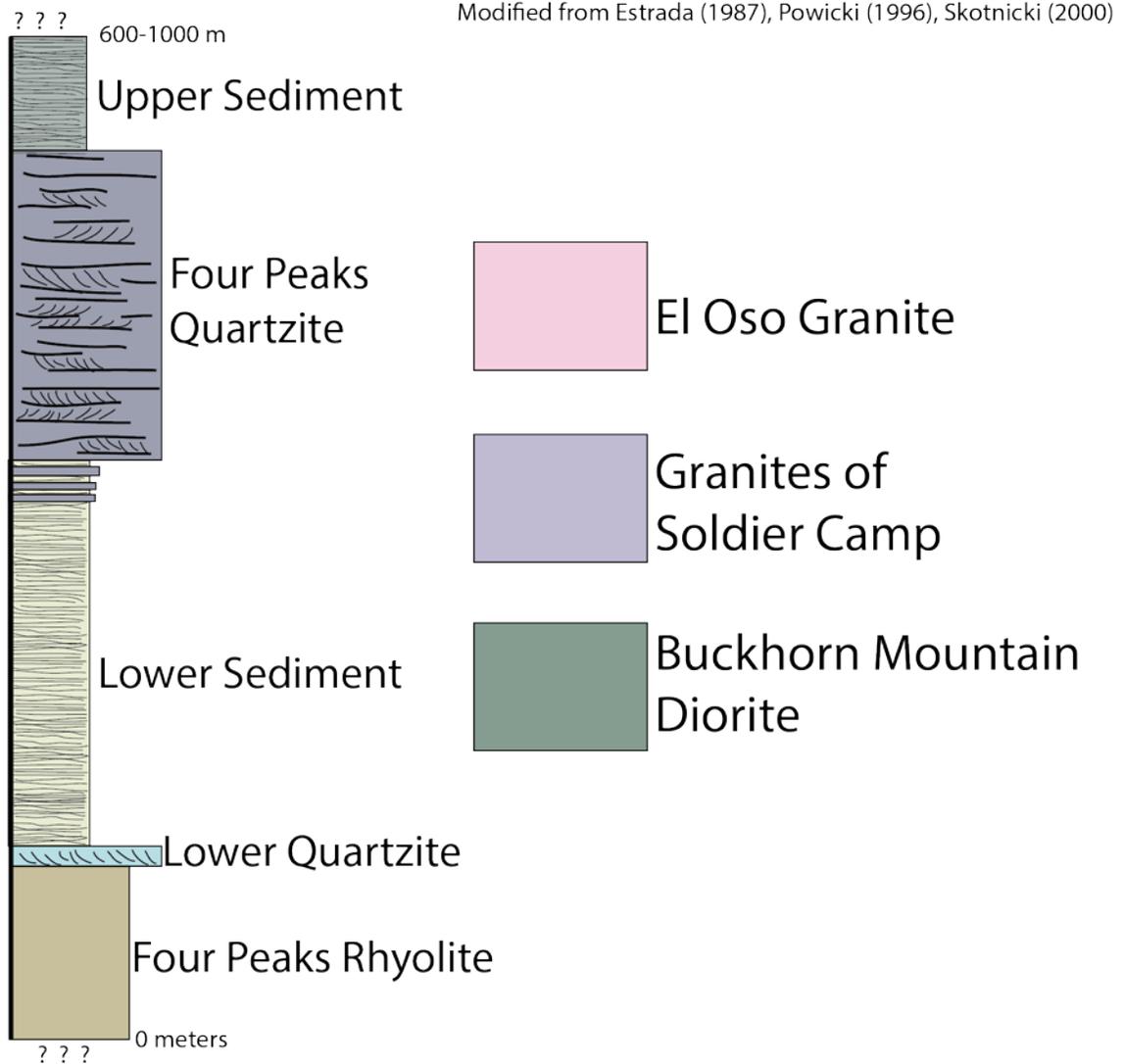


Figure 3- The stratigraphic section in the Four Peaks area. The figure is modified from Estrada (1987), Powicki (1996) and Skotnicki (2000). 600-1000 meters of stratigraphic section are present at Four Peaks.

CHAPTER 4

RESULTS

4.1 Stratigraphy

There are four distinguishable metasedimentary units in the Four Peaks area that have been folded into the large, kilometer-scale Four Peaks syncline. The lowermost unit is a thin (50-60m), extremely pure basal quartzite (Powicki, 1996), referred to as the Lower Quartzite. Above this is a lower pelitic to psammitic unit, 450m thick, (Estrada, 1987; Powicki, 1996), referred to as the Lower Sedimentary unit. On the north side of the Four Peaks syncline a large area of this unit experienced intense contact metamorphism from the adjacent El Oso granite and is now a gneissic, and commonly migmatitic, rock. The Four Peaks Quartzite is 200-400m thick and makes up the resistant ridge of the Four Peaks. It is an extremely mature, finely cross-bedded quartzite with occasional layers of pelitic phyllite to schist (Wilson, 1939; Estrada, 1987; Powicki, 1996). Finally, the syncline is cored by an upper slate unit that contains Mesoproterozoic detrital zircon (Doe, 2014), referred to as the Upper Sedimentary unit. More detailed descriptions of these units can be found in Estrada (1987), Powicki (1996) and Skotnicki (2000). The stratigraphy is summarized in Figure 3.

The three lower units of the Four Peaks stratigraphic section have gradational contacts. The very mature lower quartzite becomes interlayered with pelitic beds towards its top as it transitions to the lower sedimentary unit. The lower sedimentary unit becomes increasingly quartzite rich up-section with occasional layers of pure quartzite and finally becomes the Four Peaks Quartzite. The top half of the Four Peaks Quartzite

has several 1-10 meter thick pelitic layers that are red-brown weathering. The top few meters of the Four Peaks Quartzite become distinctively rusty weathering and quartz grains are larger (1-3mm). This is in contrast to the monotonous fine grain size and grey to purple weathering of the bulk of the Four Peaks Quartzite. The upper sedimentary unit has a sharp contact with the Four Peaks Quartzite. It is easily distinguishable from the quartzite by its tan-grey weathering, more finely-bedded nature and well defined slaty cleavage. The lithologic change is spatially very rapid, but the contact was never directly observed in the field.

Four igneous units were distinguished by Skotnicki (2000) and Powicki (1996) in their studies. The Buckhorn Mountain granodiorite is exposed southeast of the Four Peaks syncline. The granodiorite has two unpublished ages of 1685 ± 4 Ma (Skotnicki, 2000) and 1669 ± 7 Ma (Powicki, 1996). Spencer and Richards (1999) report that the Buckhorn granodiorite is gradational with other granitic rocks that are included in the more regionally extensive Buckhorn creek complex. It is variably foliated throughout the study area (Figure 4). The Four Peaks rhyolite is exposed in two bodies southwest and east of the syncline and is thought to be the lowermost unit of the stratigraphic section (Powicki, 1996; Skotnicki, 2000). In most places the rhyolite is intensely deformed, but locally it can be shown to have no deformation structures. Small bodies of the rhyolite can consistently be found below the Lower Quartzite, particularly on the northern limb of the syncline.

Skotnicki (2000) interpreted the granites exposed east of Four Peaks to be equivalent to the Beeline Granite (mapped as xg and xgm), which is exposed across a large area of the southern Mazatzal Mountains (Figures 5 and 6). A sample of this granite

from the Adams Mesa quadrangle 15 km to the west has a published age of 1632 ± 3 Ma (Isachsen et al. 1999). New data, presented below, suggest that the granite at Four Peaks is not correlative to the Beeline granite. This granite clearly intrudes the lowermost sedimentary units in places. In at least one place, a large block of what appears to be lower quartzite is included in the granite (Figure 7). There is potentially a greater variety of granites east and northeast of Four Peaks than Powicki (1996) or Skotnicki (2000) describe, or what are described in this study. For convenience, these granites are tentatively termed the granites of Soldier Camp, bearing in mind that this name distinguishes what is probably a complex of granitic intrusions.

The youngest major igneous unit is the El Oso granite, which is also exposed over a large area of the Mazatzal Mountains and is a member of the ca. 1.4 Ga suite of ferroan granites that extends across North America (Figure 8). Powicki (1996) reported an unpublished age of 1.48 Ga for this granite. It is distinguishable by the pervasive occurrence of 2-3 cm potassium feldspar megacrysts and its crumbly weathering style. There is a fine grained phase of this granite that can be found as dikes and small isolated bodies across the study area. This generation of granites cross-cut all of the other rocks in the Four Peaks area (Powicki, 1996; Skotnicki, 2000). The El Oso granite exhibits local, meter-scale shear zones, but is largely undeformed.

4.2 Structural Geology

The Four Peaks syncline is a tight to close, doubly-plunging fold that verges to the northwest and the southern limb is overturned and thin relative to the northern limb (Figure 2) (Estrada, 1987; Powicki, 1996). The single fold of the syncline covers an area



Figure 4- Example of fabrics in the Buckhorn granodiorite. Note stretched feldspar and aligned biotite grains.



Figure 5- Fabrics in the Granites of Soldier Camp. The pen (bottom center) shows the general orientation of the fabric, which is defined by biotite alignment.



Figure 6- Additional example of deformed granites of Soldier Camp. The foliation is parallel to hammer.

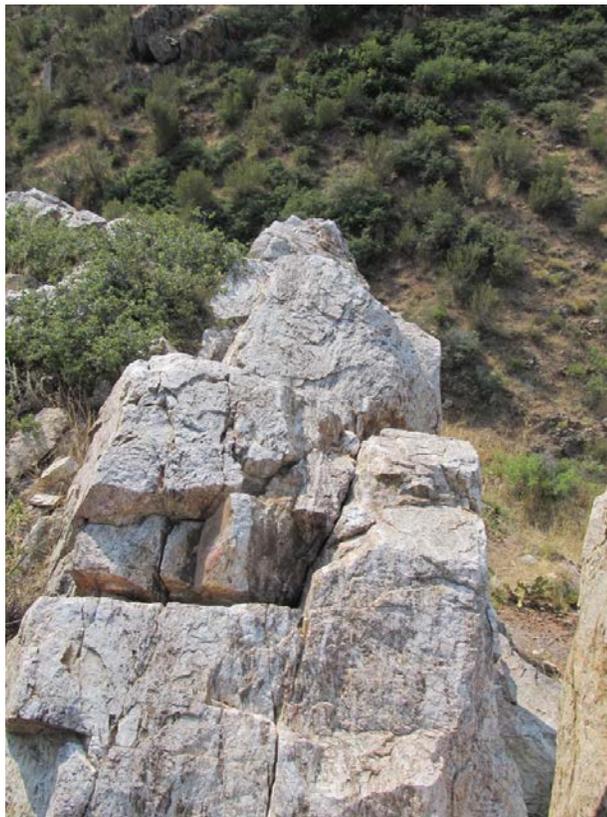


Figure 7- Block of Lower Quartzite surround by Granites of Soldier Camp. Located 1.5 km from nearest intact Lower Quartzite.



Figure 8- Typical El Oso granite. Note characteristic large feldspar grains.



Figure 9- A rhyolitic dike. This dike (dated during this study) cross-cuts S_1 fabrics in the diorite and is subsequently offset by a small shear zone.



Figure 10- Transposed bedding in the Lower Sedimentary unit. Located near the contact with Granites of Soldier Camp.



Figure 11- Additional transposed bedding in the Lower Sedimentary unit. Located near the contact with Granites of Soldier Camp.



Figure 12- Complex leucosome - fabric relationships. Located in the Lower Sedimentary unit, 1 km from El Oso granite contact.



Figure 13- Mesoscopic fold in the Four Peaks Quartzite. These may be typical of the mechanism for thickening on the northern limb of the Four Peaks syncline.



Figure 14- Abundant mesoscopic folds, at a distance. Photo looks to the northeast on the northern limb of the Four Peaks syncline in the Four Peaks Quartzite.

greater than 3 by 5 kilometers in map pattern. Powicki (1996) reported that the orientation of the fold axis is 55→210, and the axial plane averages 050,70. Estrada reported an axial plane of 050,60 and a fold axis plunging 47° to the NE. The syncline is interpreted to be a sheath fold, so no single orientation describes the orientation of the fold axis everywhere. The hinge of the fold is curved, plunging inward toward the center of the fold. The Four Peaks syncline may be a remnant member of a large-scale fold train as suggested by the map pattern of the lower quartzite, gradually shallower dips in northern limb and foliation patterns of the rhyolite in the southwest part of the area. Fabrics are generally not visible in the Four Peaks Quartzite, especially in the field, but are readily measurable in the more pelitic units. Foliations are axial planar to the Four Peaks syncline forming a distinct slatey cleavage in the Upper Sedimentary unit. In thin section, a mild crenulation of a bedding-parallel fabric by the axial planar fabric can be observed, although it is not present the central part of the Four Peaks syncline. A more strongly developed crenulation cleavage was observed in the southwestern part of the study area (Powicki, 1996).

A structural analysis of bedding, foliations and minor fold axes shows the similarity of structural features throughout folded rocks of Four Peaks (Figure 15a-f). It was hypothesized that an angular unconformity might exist between the Four Peaks Quartzite and Upper Sedimentary unit because of the presence of Mesoproterozoic zircon above the contact. To test this, the orientations of structures above and below this contact were analyzed and the contact was closely traced. Measurements from a domain of the fold that was determined to be cylindrically folded (outlined in Figure 2) were used in this analysis.

The orientations of bedding, minor folds and structural fabrics are similar above and below the upper Four Peaks Quartzite contact. Beta-axes for bedding in the Four Peaks Quartzite and Upper Sedimentary unit are 22→074 (Figure 15a, blue cross on Figure 15f) and 14→057 (Figure 15b, yellow cross on Figure 15f), respectively. Average minor fold axes for the Four Peaks Quartzite and Upper Sedimentary unit are 28→076 (Figure 15c, blue dot on figure 15f) and 30→070 (Figure 15d, yellow dot on figure 15f), respectively. The average orientation of fabrics measured in the Upper Sedimentary unit is 066,86 (Figure 15e, great circle in Figure 15f). The right hand rule applies to all of the above orientations and all others reported in this document. On a stereonet, the beta-axes and fold axes plot very close to the plane of average foliation, which suggests there is a common fold orientation observed in the rocks above and below the contact. Given the singularity of fold orientation and style, these rocks probably experienced the same folding history (Figure 15f). The general orientation of the fold axis in this cylindrically folded domain is 23→066. Notably, the Upper Sedimentary unit beta-axis is the furthest from the pelite foliation of all the orientations noted, but this difference does not seem to be significant enough to suggest two distinct fold orientations in the Four Peaks area.

The Four Peaks rhyolite, which occurs at the base of the stratigraphic section, has a strongly developed tectonic fabric that is nearly pervasive in its exposures. Mylonitic to, locally, ultramylonitic fabrics define a 100-200 meter wide zone of intense shearing with thrust and right-lateral motion along the southern limb of the Four Peaks syncline, mostly in the rhyolite (Powicki, 1996; this study). Powicki (1996) interpreted this and the strong foliations in the Buckhorn Diorite to indicate a major, crustal-scale shear zone. Skotnicki (2000) found no evidence of intense shearing at all in the Four Peaks area. The

presence of mylonites was confirmed during this study, supporting the interpretation of a shear zone. However, intensely mylonitized foliations are localized in the Four Peaks rhyolite. Where the Buckhorn granodiorite intersects the along-strike projection of ultramylonitic shear zones, it is nearly undeformed. A very large scale shear zone would be expected to cut across all the map units. Furthermore, the same rock units appear on either side of the zone of intense shearing, suggesting that offsets were minimal. Field observations during this study suggest that there is in fact a zone of more intense, thrust-sense, shearing and focused deformation along the southeast margin of the syncline, as interpreted by Powicki (1996), but a crustal-scale shear zone is beyond what the evidence in the Four Peaks area suggests.

4.3 Structural Fabrics

Four distinct, regionally extensive structural fabrics have been identified in the Four Peaks area. Given the new age controls, the foliation nomenclature presented here is different from that of Powicki (1996). The Buckhorn Granodiorite, the oldest unit in the study area (ca. 1680 Ma), has a heterogeneous, moderate to strongly developed foliation that generally strikes northeast with a steeply plunging lineation (Powicki, 1996; Skotnicki, 2000). This foliation is termed S_1 . The granodiorite is composed of quartz, feldspar, biotite and amphibole with stretched quartz, feldspar and biotite defining the foliation. Spaced protomylonite to mylonite zones can be found throughout the granodiorite alternating with areas of less intense deformation. Foliations in the granodiorite have an average orientation of 242,85 (Figure 15g) but there is significant scatter about that orientation. There is likely a composite of S_1 and subsequent foliations

present in the granodiorite. This fabric is cross-cut by rhyolitic dikes (Figure 9), which have been dated during this study. These dikes are also deformed (Figure 9).

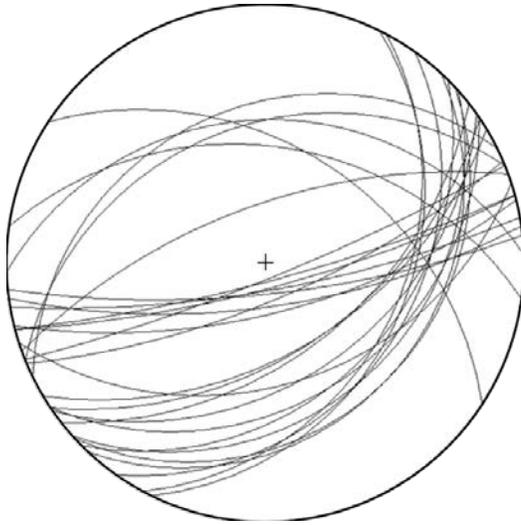
There is a pervasive, weak to moderate, fabric in the granites of Soldier Camp that is termed S_{2x} . Recrystallized, grain-size reduced, quartz observed in thin section suggests that this is a solid state fabric and not syn-magmatic. Not all of the granites exhibit this fabric, so these granites seem to be a complex composite of different intrusions. S_{2x} is different in orientation than all the other foliation orientations in the Four Peaks area with an average of 269,76 (Figure 15h). This is a distinctly E-W oriented foliation, which is atypical of Proterozoic rocks in the southwest, where most foliations are NE striking (Whitmeyer and Karlstrom, 2007). NE striking fabrics are rare in the granites of Soldier Camp. There are also a significant number of foliation measurements from the Buckhorn granodiorite that have a similar orientation. Most commonly S_{2x} is defined by the alignment and stretching of biotite with less deformed quartz and feldspar porphyroclasts.

A bedding parallel foliation is variably present in the metasedimentary rocks in the Four Peaks area, which is termed S_{2y} . In the Lower Quartzite and Lower Sedimentary unit close to the contact with the granites of Soldier Camp there is evidence of more intense deformation. Intrafolial folds within sedimentary layers suggest local transposition of bedding (Figures 10 and 11) and isoclinal folding is common. Such features have not been recognized in areas of the Four Peaks syncline further away from the granite. Fabrics in the adjacent granite do not parallel the contact with the sediments. Additionally, Powicki (1996) described a variably developed bedding parallel foliation, which is occasionally present in thin section. S_{2y} is used because this foliation is clearly distinct from S_{2x} , but the relative timing of these foliations is not clear. Additionally, S_{2y}

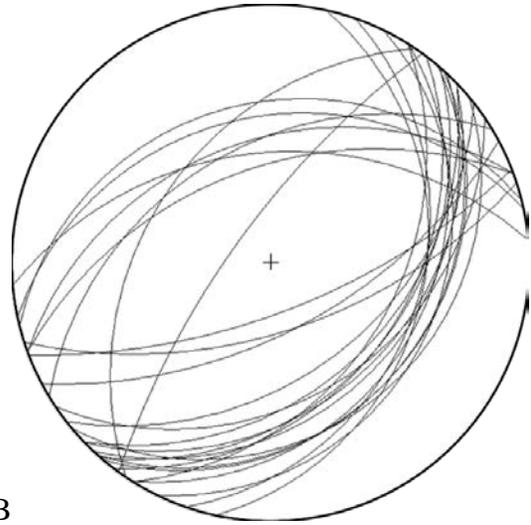
is only locally developed, whereas other foliations in the Four Peaks area are more pervasive.

The fourth recognizable foliation in the Four Peaks area is axial planar to the Four Peaks syncline, and termed S_3 . This fabric is steeply dipping and northeast striking, averaging 066,86 (Figure 15e). This orientation is very similar to S_1 in that they are both steeply dipping and NE striking, but occurs in much younger rocks. In the Upper sedimentary unit and Four Peaks Quartzite, it is manifest as dissolution surfaces or slaty cleavage. S_3 is strongly developed in the Four Peaks rhyolite, defined by the alignment of micas. In the southwestern region of the study area, near sample C13-082b (Figure 2), S_3 forms a crenulation cleavage as it interacts with the bedding parallel fabric S_{2y} . This crenulation cleavage can be observed in other parts of the syncline as well (Powicki, 1996). The ultramylonitic fabrics of the high strain zones to the southwest and east of the syncline are S_3 . Ultramylonites have an S_3 orientation and occur in rocks that are too young to contain S_1 (the Four Peaks rhyolite). It is possible that northwest striking foliations in the Buckhorn Granodiorite are a composite of S_1 , S_{2x} and S_3 . In the limbs of the fold foliations are a composite of S_{2y} and S_3 as bedding approaches parallelism with the axial plane.

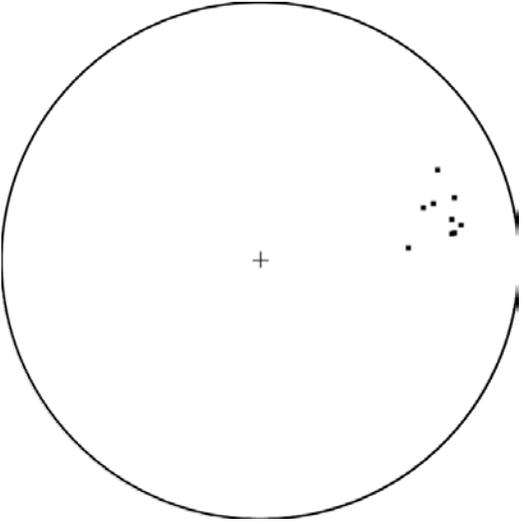
Foliations in the Four Peaks rhyolite probably represent a composite of S_{2x} and S_3 . There are two separate bodies of rhyolite to the east and southwest of the syncline. In Figure 15i, all rhyolite foliation orientations are plotted together and foliations from the east (Figure 15j) and southwest (Figure 15k) are plotted separately. Fabrics in the eastern rhyolite body are more similar to fabrics in the Buckhorn granodiorite, while southwestern rhyolite fabrics are closer to in orientation to the granites of Soldier Camp.



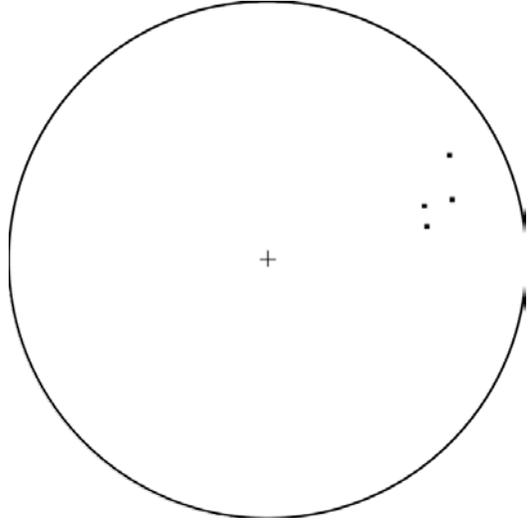
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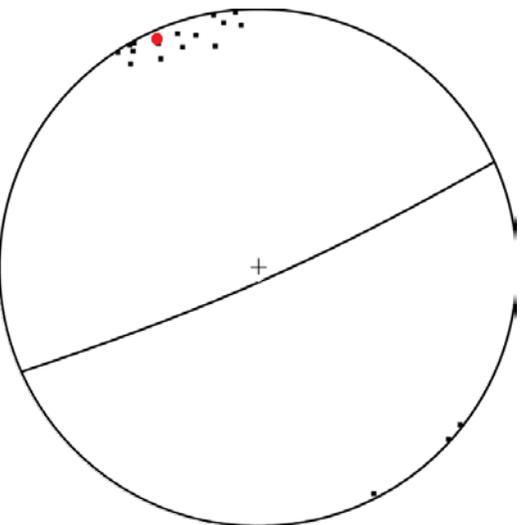
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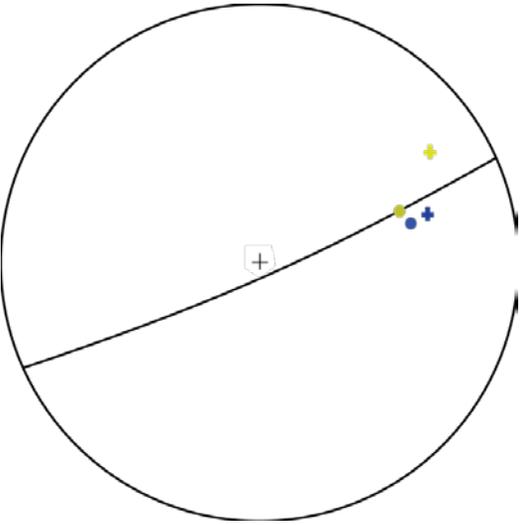
C



D



E



F

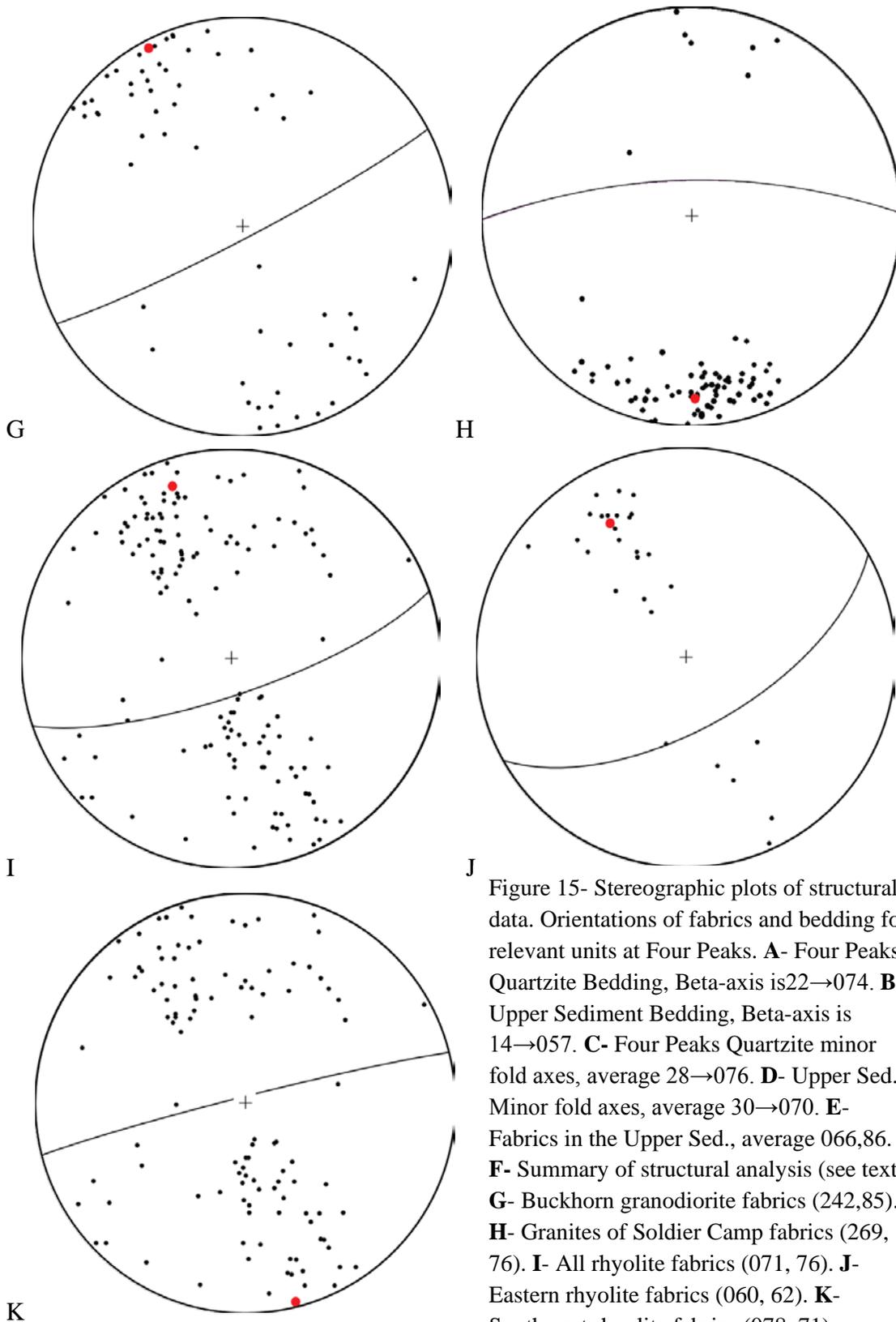


Figure 15- Stereographic plots of structural data. Orientations of fabrics and bedding for relevant units at Four Peaks. **A-** Four Peaks Quartzite Bedding, Beta-axis is 22→074. **B-** Upper Sediment Bedding, Beta-axis is 14→057. **C-** Four Peaks Quartzite minor fold axes, average 28→076. **D-** Upper Sed. Minor fold axes, average 30→070. **E-** Fabrics in the Upper Sed., average 066,86. **F-** Summary of structural analysis (see text). **G-** Buckhorn granodiorite fabrics (242,85). **H-** Granites of Soldier Camp fabrics (269, 76). **I-** All rhyolite fabrics (071, 76). **J-** Eastern rhyolite fabrics (060, 62). **K-** Southwest rhyolite fabrics (078, 71).

It is possible that the two rhyolite bodies are of different ages and thus did not experience the same deformation events. If the southwestern rhyolite was deposited after the formation of S_3 , it would only have taken S_{2x} and S_3 foliations. This would explain the scattered but generally E to ENE striking foliations in that rhyolite. Similarly, the more northeast striking foliations in the eastern rhyolite may be S_3 . If the eastern rhyolite is older, it may be related to the rhyolitic dikes that cross-cut S_1 .

Close to the contact with the El Oso granite, migmatitic leucosomes tend to form parallel to bedding. Leucosomes can be found folded into the S_3 orientation with associated axial planar fabrics defined by the growth of biotite. In the field, it is not explicitly clear whether migmatization occurred before or after folding. Leucosomes may have formed preferentially along favorable sedimentary layers that had already been folded or they may have been folded after formation (Figure 12). Local shear zones and minor foliations can be found in the young El Oso granite, so it is possible that deformation did occur after migmatization. These foliations could be termed S_4 , but no significant effort was made to characterize this foliation and it is not pervasive. Additionally, leucosomes can be found to cut across transposed bedding.

4.4 Metamorphic Petrology

Metamorphic assemblages in the Four Peaks area approach lower amphibole facies and range to lower greenschist facies. The common assemblage in the pelitic metasedimentary rocks is quartz + muscovite + biotite + aluminosilicate. Andalusite and cordierite, or pseudomorphs thereafter, can be found in most of the Four Peaks sediments. Sillimanite is common in the lower sedimentary unit within one kilometer of the El Oso

granite contact and leucocratic domains, suggesting partial melting. Kyanite has not been found in this area. Regional metamorphism in the Sunflower Block, where the Four Peaks area resides (Karlstrom and Bowring, 1988) is generally low grade. Williams (1991) suggested lower greenschist facies metamorphism occurred, which has been associated in time with the classic Mazatzal orogeny (1660-1600 Ma).

Contact metamorphism from the El Oso granite intrusion dominates the metamorphic signature of the rocks in the Four Peaks area, especially on the north limb of the syncline. Powicki (1996) defined four metamorphic zones that increase in grade northward to the granite contact. By analogy with the work of Johnson and Vernon (1995), Powicki (1996) suggested that the rocks in the Four Peaks area experienced pressures of ~3 kbar and temperatures 400-650 °C. Little contact metamorphism has been recognized in association with the granites of Soldier Camp. This, and the finer grained nature of the granite, suggests that it may have been emplaced at a shallower depth than the El Oso granite.

The results of geochemical analysis of three samples are shown in Table 1. One sample is typical of the Four Peaks rhyolite (C13-006b) and two are samples of the Lower Sedimentary unit. Sample C13-012 represents the Lower Sediment that was close to the contact aureole of the El Oso granite and experienced partial melting. C13-035 is part of the Lower Sediment that is ~3 km from the El Oso and experienced minimal contact metamorphism.

Isochemical phase diagrams (pseudosections) were calculated for samples C13-012 (Figures 16 and 17) and C13-035 (Figures 18 and 19) and have been used to constrain the pressures and temperatures recorded in the rocks and investigate the

metamorphic history of the Four Peaks area. Equilibrium assemblages were calculated over 1.5-5.5 kbar pressure and 300-1000° C. For C13-012, the assemblage observed in thin section is quartz, biotite, plagioclase, sillimanite. This assemblage plots in the highlighted field in Figure 17. Leucosomes (interpreted partial melt) are difficult to distinguish in thin section, but were observed in the rocks surrounding this sample. C13-035 contains the assemblage, chlorite, biotite, quartz, and muscovite in thin section. Relict detrital feldspar grains are altered to white mica. These assemblages plot in the highlighted fields in Figure 19, which has a calculated assemblage of chlorite, biotite, phengite and margarite. Margarite was not observed in thin section. A run of the Theriak application of the modeling package at 500° C and 3.5 kbar calculates that margarite is only 0.17 volume percent of the equilibrium assemblage, so it is not surprising none was recognized.

Pseudosection modelling suggests that these rocks reached pressures of 3-4 kbar and a range of temperatures varying with proximity to the El Oso granite. Assemblages from the partially melted sample, C13-012, suggest conditions of approximately 700°C and 3.0-5.5+ kbars. C13-035 has an assemblage that suggests conditions of 500°C and over 1.5-5.5+ kbar. Another constraint on the P-T history of the Four Peaks area is the presence of both andalusite and sillimanite. It is likely that the analyzed rocks equilibrated at the same pressure and at temperatures corresponding to proximity to the El Oso granite contact. Thus, the pressure recorded must fall in a range such that an isobaric path of temperature increase can produce both andalusite and sillimanite. According to pseudosection models, this condition can only be met between 2.5 and 4

Wt % Oxide	C13-006b	C13-012	C13-035-1
SiO2	75.182	64.335	70.951
TiO2	0.408	0.880	0.665
Al2O3	14.467	20.741	15.698
Fe2O3T	1.608	6.587	6.577
MnO	0.043	0.113	0.079
MgO	0.675	1.321	1.453
CaO	0.406	0.685	0.024
Na2O	3.209	1.079	0.140
K2O	4.122	4.265	4.353
P2O5	0.088	0.036	0.040
Total	100.208	100.042	99.979

Table 1- Geochemistry data. Summary of XRF data. Sample C13-006b is Four Peaks rhyolite from the eastern body. Sample C13-012 is Lower Sedimentary unit from close to the El Oso granite. C13-035 is Lower Sedimentary unit 2.5 km from the El Oso granite.

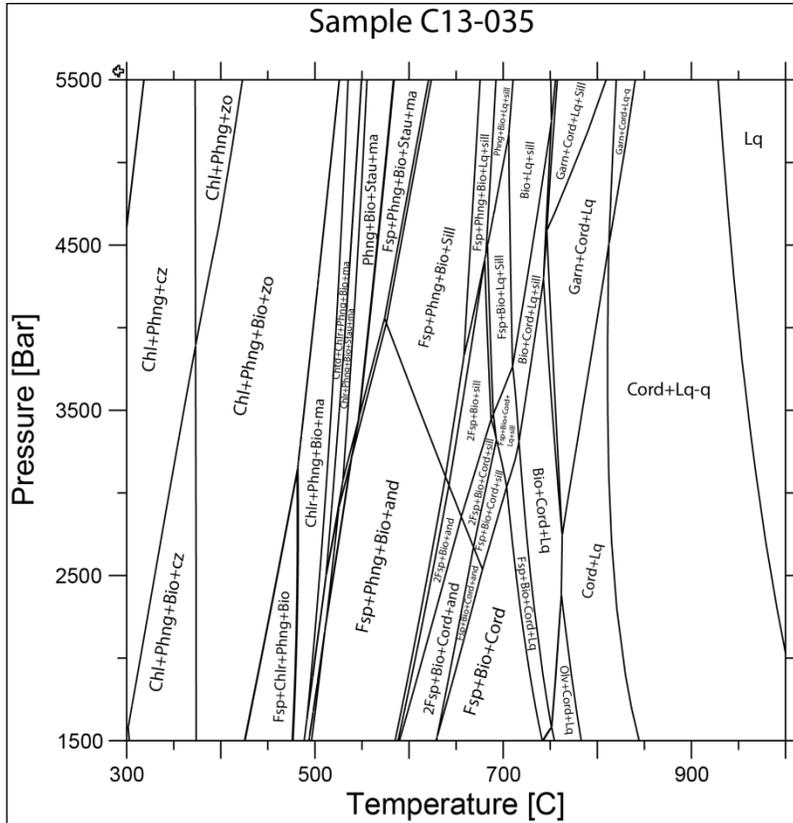


Figure 18- Mineral assemblages in P-T space, C13-035. Lower Sedimentary Unit far from the contact with El Oso granite.

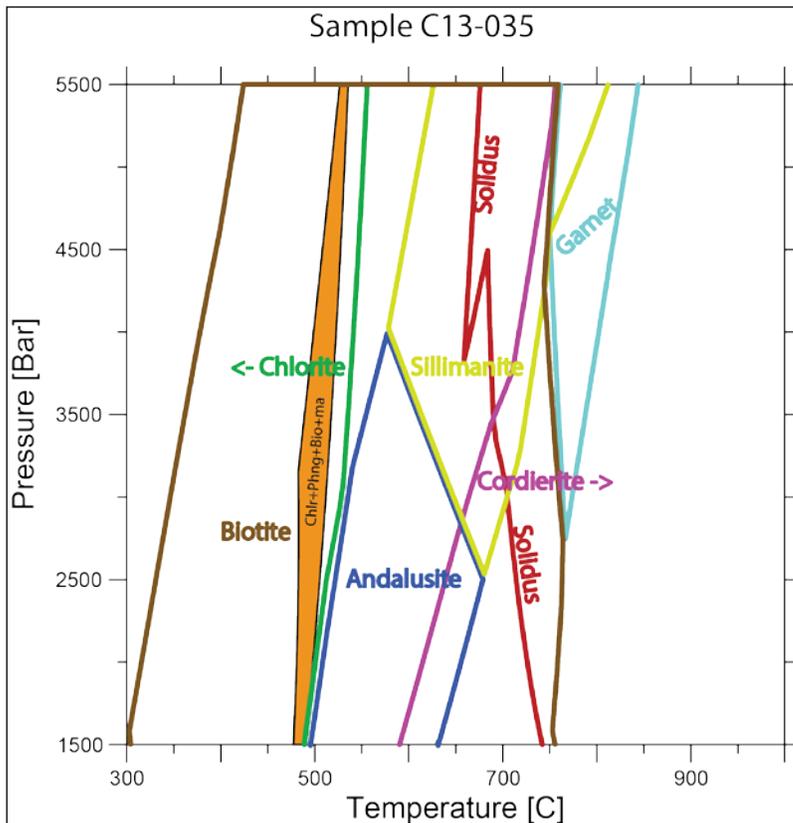


Figure 19- Relevant reactions and mineral stabilities, C13-035. The color of the label corresponds to the color of the reaction. The observed mineral assemblage is Chlorite+ Biotite+ Phengite+ margarite (highlighted in orange).

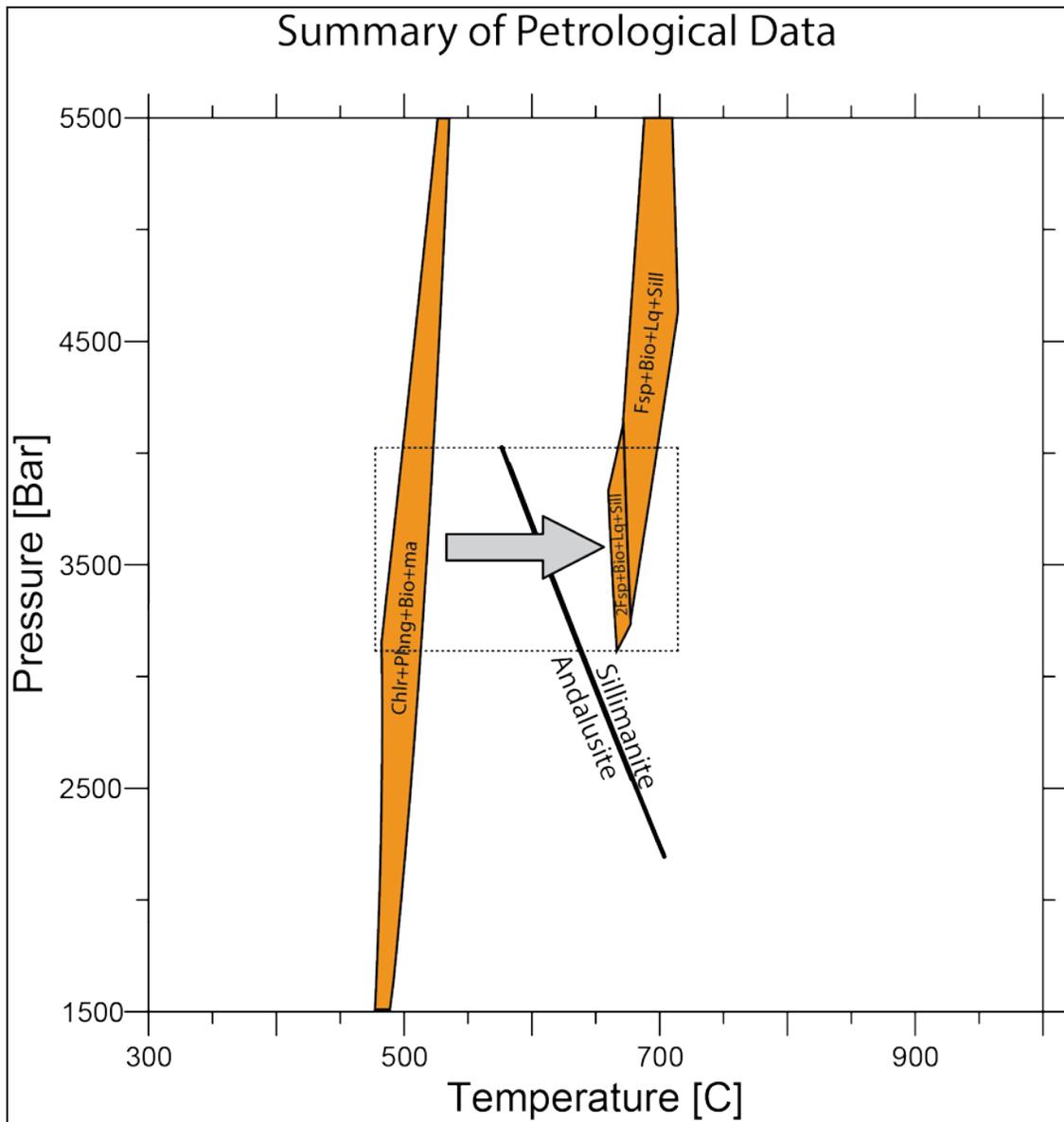


Figure 20- Summary of petrological data and interpretation. The highlighted fields are the pressure and temperature ranges of the observed assemblage if they are at equilibrium. The black line shows the andalusite-sillimanite reaction over the range that a rock could travel from andalusite directly to sillimanite stability isobarically with temperature increase. The box shows the range of pressures and temperatures that the rocks in the Four Peaks area could have equilibrated at and the arrow shows the interpreted heating path with proximity to the El Oso granite.

kbar pressure. Combining these results, a range of 3-4 kbar pressure is obtained (Figure 20). It should be noted that small changes in bulk composition or mineral solution models could have a large effect on these constraints.

The equilibrium temperature ranges for the two samples and the aluminosilicate constraint suggest a thermal gradient from 500 to at least 700 °C, within 2.5 km of El Oso granite contact. This is represented in Figure 20. The results of the present petrologic analysis are in agreement with Powicki (1996). These results suggest that the El Oso granite was emplaced at a depth of 11-15 km (given ordinary crustal densities and the range of pressures).

A Paleoproterozoic metamorphic signature is hard to discern in the rocks of the Four Peaks area. There was no discernible contact metamorphism induced by Paleoproterozoic granites that can be distinguished from the strong Mesoproterozoic metamorphism. It is likely that the Four Peaks sediments and granites were at relatively shallow depth, so it is possible that no significant metamorphism took place in the Paleoproterozoic. Assemblages far from the El Oso granite will probably record temperatures and pressures conditions from the Paleoproterozoic.

4.5 U-Pb Zircon Geochronology

New and existing zircon geochronology provides essential constraints on the geologic history of the Four Peaks area. Zircon from nine samples were analyzed and dated during this study. Several key igneous rocks that can constrain parts of the deformation history have been dated to provide. Detrital zircon populations from two samples are also reported to constrain the timing of sedimentation. The following is a

description of each of those samples and a summary of the geochronologic data. Results are shown in Table 2.

C13-029a- This is a sample of Four Peaks Quartzite from the base of the unit, a few meters above the contact with the Lower Sedimentary Unit. The location of the sample is on Brown's trail on the northern limb of the syncline. The quartzite is about 95% quartz with accessory sericite, oxides, monazite and zircon. Detrital zircon was separated and ninety-one grains were analyzed. Zircon grains in this sample were small (50-150 μ m long) and commonly fragmental. In cathodoluminescence images, oscillatory zoning and dark cores were very common. The primary age peak occurs at 1770 Ma with a subsidiary peak at 1820 Ma. The youngest grain analyzed is 1635 ± 36 Ma, but a population of ages is needed to define a maximum depositional age in a statistically valid way. The most robust maximum depositional age for the Four Peaks Quartzite is 1687 ± 11 Ma based on a weighted mean of the 5 youngest grains.

20130916-1- This is a sample collected and analyzed by Michael Doe during his doctoral work at the Colorado School of Mines (Doe, 2014) and it is included here for its great relevance for the present study. The sample was taken from the stratigraphically highest point available in the Four Peaks area in the Upper Sedimentary unit. A probability density plot of detrital zircon ages (94 grains) shows significant peaks at 1580 and 1785 Ma. There are minor age peaks at 1730 Ma, 1830 Ma and a few scattered ages stretching into the Archean. The maximum depositional age based on the 7 youngest zircon grains in the analyzed population is 1566 ± 7.6 Ma (Doe, 2014). Zircon grains 1400-1600 Ma do not have a Laurentian source and have been an important element of recent paleo-

geographic reconstructions (Doe et al. 2012). Zircon grains of this age in the Southwest are interpreted to have been sourced from the Australian continent (Doe et al. 2012).

C13-067b- This sample is not from Four Peaks, but is the Young granite from the area of Young, Arizona. The Young granite has been interpreted as post- to syn-tectonic and used to bracket the age of deformation in the Slate Creek movement zone (Labrenze and Karlstrom, 1991). This is very relevant for questions in the Four Peaks area and a better age constraint on the Young granite has been needed. Zircon (18) from this sample yield a crystallization age of 1664 ± 17 Ma.

C13-073- This is a typical sample of El Oso granite. The sample location is very close to Long Pine trailhead at the end of Forest Road 648. Zircon grains were 200-300 μ m and elongate, occasionally with fractured cores (not analyzed). Large 1-3 cm feldspar phenocrysts are common, along with quartz and biotite. Twenty-seven zircon grains yield a crystallization age of 1449 ± 14 Ma.

C13-082b- This is a sample of the Four Peaks rhyolite in the southwestern part of the study area. Zircon was 100-200 μ m and tabular to irregular in shape. The rhyolite in this location exhibits mylonitic to ultramylonitic, northeast striking fabrics and steeply plunging lineations. This rhyolite is interpreted to be the base of the stratigraphic section in the Four Peaks area, but fine-grained granites (with very similar ages to the Four Peaks rhyolite) are observed to intrude the lowermost units. Zircon yield a crystallization age of 1657 ± 16 Ma.

K13-4PKS-3- This is a sample of a rhyolitic dike that cuts across foliations (S_1) in the Buckhorn granodiorite. It is a critical constraint on the timing of deformation. Sixteen zircon grains were 80-105% concordant. The sample is fine-grained and located at

3727500N, 0472500E (UTM coordinates). This dike and others are exposed in a stream bed near the Chillicut (or Rock Creek) trail. These dikes are also deformed by small shear zones but clearly cut across S_1 . It is possible that these dikes were syn-tectonic with respect to the S_1 forming event or subsequently deformed by a later event. Zircon yield a crystallization age of 1675 ± 18 Ma. Powicki (1996) reported an age of ~ 1660 Ma for one of these dikes. These rhyolitic dikes should not be correlated with the Four Peaks rhyolite as previously thought (Mako et al. 2013) given the difference in age.

K13-4PKS-4- This is a sample of the Buckhorn granodiorite that is cross-cut by rhyolitic dikes. Thirty zircon grains were 80-105% concordant. The tectonic foliation must be younger than the crystallization age of this sample. Zircon yield an age of 1677 ± 16 Ma. This is within the error of an unpublished date of this granodiorite, 1685 ± 4 Ma (Skotnicki, 2000). Powicki (1996) reported a date of 1669 ± 6 Ma (citing Bowring, personal communication) for the granodiorite from this same location.

K13-4PKS-5- A sample of megacrystic granite from the Chillicut trail, west of the Four Peaks syncline. The granite in this location is weakly sheared. The age of this sample was expected to be close to that of the El Oso granite but in fact it is Paleoproterozoic. This lends credence to the interpretation of Powicki (1996) that there are two bodies of Paleoproterozoic granite on either side of the syncline, cut by the large El Oso pluton. Visually this granite is indistinguishable from the El Oso granite. Twenty-two zircon grains yield an age of 1655 ± 18 Ma.

K13-FPKS-14- This sample is described as foliated (S_{2x}), biotite-bearing granite (Karlstrom, personal communication, 2013). It is mapped as 'xgm' by Skotnicki (2000) and is one of the granites of Soldier Camp. This granite was previously correlated with

the Beeline granite, which was sampled on the Beeline Highway in the Adams Mesa quadrangle and dated at 1632 ± 3 Ma (Isachsen et al. 1999). Zircon from this sample yield an age of $1667 \pm$ Ma (32 grains). If grains furthest from the mean are eliminated to reduce MSWD, a mean age of 1658 ± 17 Ma (28 grains) is calculated (MSWD = 1.02 vs. 8.4). Based on the new data, a correlation of the granites in the Four Peaks area with the Beeline granite is incorrect.

K13-FPKS-15- This granite sample is undeformed and muscovite-bearing (Karlstrom, personal communication, 2013). This granite is mapped as 'ygm' by Skotnicki (2000). It is relatively fine-grained and commonly contains stray 2-4cm feldspar megacrysts. It is most likely related to the El Oso granite and cuts across all other units. Zircon analysis yields distinct Mesoproterozoic and Paleoproterozoic age populations. Only 15 grains were analyzed in this sample. Ten have a mean age of 1437 ± 16 Ma and four have a mean age of 1651 ± 25 Ma. This is an unsurprising result given that this is a small dike in Paleoproterozoic country rock. The Paleoproterozoic zircon grains were probably incorporated into the melt during dike emplacement in the Mesoproterozoic.

Summary

There are essentially three age ranges of igneous rocks exposed in the Four Peaks area. The oldest of these include the Buckhorn granodiorite and rhyolitic dikes, which are close in age at 1680-1670 Ma. The accepted age of the Buckhorn Diorite should be revised to 1677 ± 14 Ma, or ca. 1680 Ma. The second age group ranges from 1665-1655 Ma and includes the Four Peaks rhyolite (1657 ± 16 Ma), the granites of Soldier Camp and the megacrystic granite (1655 ± 18 Ma). The granites of Soldier Camp cannot be

Table 2- Zircon Geochronology

Sample	Description	n	Mean Age (Ma)	Uncertainty (Ma)	MSWD	Derital Peak	Max Age (Ma)
C13-029a	Four Peaks Quartzite	91	-		-	1770 Ma	1687 +/- 11
						1820 Ma	
20130916-1	Upper Sedimentary Unit	94				1580 Ma	1566 +/- 8
						1730 Ma	
						1785 Ma	
						1830 Ma	
C13-067b	Young Granite	18	1664	17	0.28		
C13-073	El Oso Granite	27	1449	14	0.71		
C13-082b	Four Peaks Rhyolite	27	1657	16	0.44		
K13-4PKS-3	Rhyolitic Dike	16	1675	18	1.9		
K13-4PKS-4	Buckhorn Granodiorite	30	1677	17	0.39		
K13-4PKS-5	Megacrystic Granite	22	1655	18	2		
K13-FPKS-14	granite of Soldier Camp	30	1667	19	8.4		
K13-FPKS-15	Fine Granite El Oso	10	1437	16	1.5		
		4	1651	25	1.8		

correlated with the 1632 Ma Beeline Granite given the age of K13-FPKS-14 (1667 ± 15 Ma) and the inherited ages of K13-FPKS-15 (~ 1651 Ma). The third group includes the El Oso granite and related intrusions, which crystallized 1450-1440 Ma. The El Oso granite is 1449 ± 14 Ma and its fine grained component is ~ 1437 Ma (sample K13-FPKS-15).

Detrital zircon grains in the sedimentary section in the Four Peaks area include Paleoproterozoic to Mesoproterozoic ages. The Four Peaks Quartzite exhibits a strong 1770 Ma peak in zircon age, as is typical of many Proterozoic quartzites in the southwest, including the Ortega (NM), White Ledge and Mazatzal Peak (AZ). The Upper Sediment in the Four Peaks area has a maximum depositional age of ~ 1566 Ma, which indicates that that unit may be a member of the Yankee Joe depositional system (1520-1490 Ma) (Doe, 2014).

4.6 Monazite Geochronology

Approximately 30 thin sections were mapped using Wavelength Dispersive Spectrometry to identify monazite for dating. None of the igneous rocks in the Four Peaks area yielded monazite, but in many of the metasedimentary rocks, monazite was identified. Most of the monazite that was found was heavily altered, very small, and unsuitable for dating. Dating attempts on monazite from the Four Peaks Quartzite, Upper Sedimentary unit and Lower Sedimentary unit yielded large errors and inconsistent ages within compositional domains. The monazite grains had many holes and appeared to have undergone breakdown reactions after crystallization.

Monazite was successfully dated in two samples of Lower Sediment (C13-012 and C13-011-1) and in one sample of the Lower Quartzite (C13-056a-1), all very close to

the contact with the El Oso granite. Sample C13-012 is the same that was analyzed for whole rock geochemistry, reported above. There are essentially three age groups of monazite that have weight means of 1483.9 ± 2.5 Ma, 1462.8 ± 5.4 Ma and 1414.1 ± 9.4 Ma (see Appendix C for details). Nine monazite grains were analyzed in a polished thin section of this sample. Cores (n=3) have a weighted mean age of 1482.7 ± 4.4 Ma and rims have a mean age of 1466.2 ± 5.1 Ma (Figure 21). A high Th domain of monazite 'm1' yielded a date of 1510 ± 4.4 Ma. Although this sample was heavily metamorphosed by the El Oso granite monazite is well preserved. Most monazite growth apparently occurred earlier than the crystallization age of the granite.

Two monazite grains were successfully dated in sample C13-011-1. This sample was taken very close to C13-012 and displays the same mineralogy, though C13-011-1 is more psammitic in composition. Three monazite dates from 'm7' and 'm2' have a weight mean of 1456.7 ± 6.8 Ma (Figure 21). These monazite do not appear to be aligned in any mineral fabric or foliation.

Sample C13-056a-1 is from the Lower Quartzite and is very close to the El Oso granite and granites of Soldier Camp. It yielded three datable monazite, m3, m4 and m8. A central, moderate concentration Y domain, of m3 was dated at 1458 ± 3 Ma. Monazite m4 has a moderate Y domain dated at 1410 ± 2.7 Ma and a high Y domain dated at 1416 ± 2.2 Ma. Monazite m8 gave dates of 1386 ± 3.8 Ma and 1418 ± 4.6 Ma for a moderate and a very high Y domain, respectively (Figure 21).

It is worth noting that the only monazite that was preserved from alteration occurs very close to the hot El Oso granite. Monazite within the Four Peaks Quartzite and Upper

Sediment, and furthest away from the granite are heavily altered. Monazite appears to have been more stable at higher temperatures close to the El Oso granite.

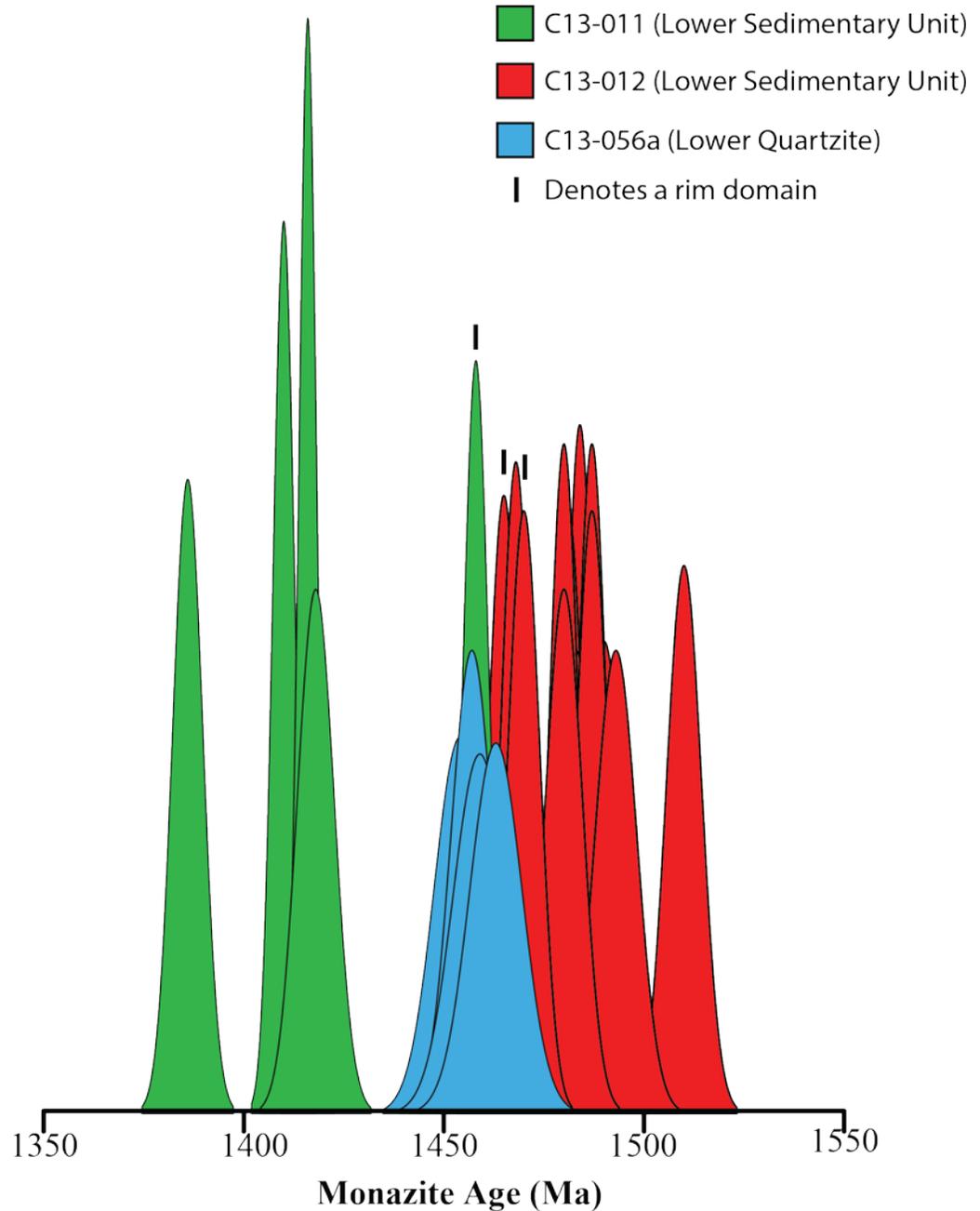


Figure 21- The ages of dated monazite. Major age groups include 1485 Ma, 1465-1460 Ma and 1415 Ma. All monazite dated are from within 1 km of the El Oso granite contact. Each bell-curve in the plot above represents a normal distribution of probable monazite age for a single compositional domain in a monazite grain. Each histogram is centered on the calculated U-Pb-Th age and the analytical uncertainty is used to plot the probability distribution. The histograms are normalized to each have the same area.

CHAPTER 5

DISCUSSION

5.1 Introduction

The objective of the present research was to constrain the timing of deformation in the Four Peaks area with the goal of assessing the style and significance of Paleoproterozoic and Mesoproterozoic tectonic events. The above data, in conjunction with previous data from Powicki (1996) and Skotnicki (2000), will help to address the question of when deformation occurred in the Four Peaks area, as well as the timing of sedimentary deposition and uplift. The work of Doe (2014) has also been very important to this study. Interpretations on the timing of deposition and deformation are presented below, and followed by a proposed geologic history of the Four Peaks area. The regional significance of the geologic record at Four Peaks is then evaluated.

5.2 Timing of Deposition

The data presented above allow constraints to be placed on the timing of sedimentary deposition of the metasedimentary rocks in the Four Peaks area. The Four Peaks rhyolite (1657 ± 16 Ma) is interpreted to be the base of the stratigraphic section, bracketing the onset of deposition to <1657 Ma. However, the lowermost sediments are intruded by the Granites of Soldier Camp, which has an overlapping age (1686-1649 Ma). These observations suggest that at least the Lower Quartzite and lower parts of the Lower Sedimentary Unit were deposited and lithified before ~ 1660 Ma. The Lower Sedimentary unit does not have any recognizable unconformities and is in gradational

contact with the Four Peaks Quartzite directly above it. If the lower parts of the sedimentary section were deposited and lithified by ~1660 Ma, it follows that the Four Peaks Quartzite was as well. This is consistent with the maximum depositional age for the Four Peaks Quartzite of 1687 ± 11 Ma. Thus, the timing of deposition of the Four Peaks sediments below the Upper Sedimentary unit can be loosely constrained to 1665-1655 Ma. The dates used to constrain this period have uncertainties that are probably greater than the duration of sedimentation, so this is an approximate constraint.

The highest unit in the stratigraphic section in the Four Peaks area is part of a Mesoproterozoic depositional system. The Upper Sedimentary unit has a maximum depositional age of ~1566 Ma, based on detrital zircon ages (Doe, 2014). If only data from Four Peaks are considered, the sediments must have been deposited 1566-1449 Ma, the younger constraint being the intrusion of the El Oso granite (1449 Ma). Doe et al. (2014), studying the Proterozoic stratigraphy of the Hess Canyon Group in the nearby Salt River Canyon, concluded that the presence of zircon of the age found in the Four Peaks area indicated a transition into the Yankee Joe depositional system. The Yankee Joe system contains zircon populations with age peaks as young as 1488 Ma. Doe (2014) interpreted the timing of this depositional system to be 1520-1490 Ma. It is likely that the Four Peaks Upper Sedimentary unit was deposited in this age range. If the Lower Sedimentary Unit, Lower Quartzite and Four Peaks Quartzite are >1655 Ma and the Upper Sediment is < 1520 Ma, an unconformity must exist in the sedimentary section. This unconformity represents at least 100 Ma, and as much as 140 Ma, of non-deposition and erosion.

Given the presence of Mesoproterozoic detrital zircon grains in the Upper Sedimentary unit and a lack of them in the other units, it was hypothesized that the unconformity in the section might be angular in nature. If two significant deformation events folded the Four Peaks sediments in the Paleoproterozoic and Mesoproterozoic, we would expect an angular unconformity between the Four Peaks Quartzite and the Upper Sedimentary unit and differences in structural style and orientation across that same contact. A concerted effort was made to identify any angular relationship between the two uppermost units. Though the contact was not directly observed, no such unconformity could be discerned. Measurements of bedding orientation across the contact were similar and the orientations of structural features were also similar. Structural analysis of bedding and foliation planes supports this conclusion (as discussed above), in that the same style and orientation of folding occurs above and below the unconformity.

Work to date does not preclude the possibility of a subtle angular unconformity between the Four Peaks Quartzite and Upper Sedimentary unit. If there is such an unconformity, it is minor. There is no substantial difference between the structural orientation across the contact and no evidence to suggest that the quartzite has experienced multiple significant folding events. It is conceivable that two deformation events of the same orientation could have led to these results, however no direct evidence suggests that conclusion. A period of bedding parallel shear is possible that did not result in significant folding or rotation of bedding.

The character of the granites of Soldier Camp lends credence to the existence of an unconformity, and suggests that a significant amount of sediment could have been

eroded above the unconformity before the deposition of the Upper Sediment. The granites of Soldier Camp range from coarse- to fine-grained and very little contact metamorphism has been recognized in the adjacent metasediments. It is therefore likely that these granites were emplaced within a few kilometers of the surface, intruding into cooler crust that would allow less heating of the surrounding rock. Previous workers have suggested that the stratigraphic section exposed in the Four Peaks area is ~1000-900 meters thick (Estrada, 1987; Powicki, 1996) and based on the present study it could be as little as 800-600 meters thick at the time of intrusion. A much thicker sedimentary package is generally required to produce lithified sediments. Although the Granites of Soldier Camp were shallowly emplaced, a depth of only 1000-600 meters seems too shallow to produce a coarse-grained granite.

Without a significantly thicker section of Paleoproterozoic sediments in the Four Peaks area, normal granites would not be found intruding lithified sediments. This points to the conclusion that between ~1655 Ma and ~1566 Ma (likely, ca. 1520 Ma), a significant amount of uplift and erosion took place. It is noteworthy that no angular relationship between the Four Peaks Quartzite and the Upper Sedimentary unit has been recognized and the unconformity does not have significant topography. There is strong evidence that a significant unconformity exists in the metasedimentary section in the Four Peaks area, but, surprisingly, the uplift and erosion that it represents must have taken place with little or no rotation of bedding from horizontal. Thus, the Four Peaks unconformity represents a 140-100 million year disconformity.

Field relationships suggest that the Four Peaks rhyolite is older than the granites of Soldier Camp. The rhyolite is found almost all the way around the syncline in contact

with the Lower Quartzite (see Figure 2). In many places there are small meters-scale bodies of rhyolite close to the quartzite. This suggests a stratigraphic relationship such that the quartzite was deposited on top of the rhyolite. The granites of Soldier Camp cross-cut the lower sediments in outcrop and even map scale (Figure 2, northwest of the syncline). Most importantly, 1:24,000 mapping of the Four Peaks quadrangle (Skotnicki, 2000) shows dikes of 'xg' (granites of Soldier Camp) intruding the rhyolite (near 3723500N, 0465500E in UTM coordinates). If the rhyolite (for the sake of argument) had an intrusive relationship to the sediments, the age constrains would suggest a depositional period of 1675-1665 Ma (between Buckhorn granodiorite and Soldier Camp granites), a relatively minor difference.

It should be noted that the area northwest of the Four Peaks syncline has a complex array of granitic rocks and it is suspected that there are multiple ages of intrusions. Given the closeness in age of the Four Peaks rhyolite, the granites of Soldier Camp and the Paleoproterozoic megacrystic granite these could be considered a granite-rhyolite complex of related intrusions.

5.3 Regional Correlations

Deposition of sedimentary rocks in the Four Peaks area fits within the context of the Mazatzal and Yankee Joe depositional systems (Doe, 2014). The Mazatzal system, which includes the White Ledge formation and the Mazatzal Peak Quartzite, was deposited 1660-1630 Ma (Doe, 2014). The Lower Quartzite, Lower Pelite and Four Peaks Quartzite were deposited 1665-1655 Ma. This is outside, but still fairly close to the timing of the Mazatzal depositional system. The White Ledge formation and

Mazatzal Peak Quartzite, which are members of the Mazatzal system, are likely correlative with the Four Peaks Quartzite (Doe, 2014). The Upper Sedimentary unit in the Four Peaks area was deposited after 1566 ± 8 Ma and earlier than 1449 ± 14 Ma (the age of the El Oso Granite). The age of the Yankee Joe depositional system is 1520-1490 Ma, which is in agreement with the depositional age of the Upper Sediment. Thus, the Upper Sediment is likely correlative with the Yankee Joe Formation.

The Hess Canyon group, exposed in the Salt River Canyon, includes the Redmond rhyolite, White Ledges Formation and Yankee Joe Formation. An apparent disconformity of greater than 100 Ma also exists in the Hess Canyon group between the White Ledges and Yankee Joe Formations (Doe et al. 2012). Thus, the metasedimentary package in the Four Peaks area is strongly correlative with the Hess Canyon Group. It is also noteworthy that the orientation of folds in the Yankee Joe Formation near the Salt River Canyon is extremely similar to that in the Four Peaks area (Doe, personal communication, 2013).

The White Ledge formation has a trachyandesite at its base (the Redmond formation) (Cuffney, 1977), in contrast to the rhyolite in the Four Peaks area. The Four Peaks rhyolite has a silica content of about 75 wt % SiO_2 and wt % $\text{Na}_2\text{O}+\text{K}_2\text{O}$ of about 7.3. This composition plots decidedly in the rhyolite field on a plot of total alkalis vs. silica (Le Bas et al. 1986). Despite the difference in composition, the similarity in age of the Four Peaks rhyolite (1657 ± 16 Ma) and the Redmond rhyolite (1657 ± 3 Ma) suggests a strong correlation between the White Ledge-Redmond Formation and the Four Peaks Quartzite-rhyolite package. The Hess Canyon group has many striking similarities to the Four Peaks stratigraphy.

Powicki (1996) suggested that it was possible that the Four Peaks Quartzite is correlative with the Houdon Quartzite, which is found in the Tonto Basin area, however this is not supported by the newest data. The Houdon Quartzite is a member of the Alder Group, deposited 1720-1700 Ma (Doe, 2014).

5.4 Timing of Deformation

Three episodes of fabric forming deformation are distinguishable in the Four Peaks area. The first (D_1) occurred at ca. 1675 Ma and formed northeast striking S_1 foliations that are present in the Buckhorn granodiorite. This episode of deformation is constrained by the crystallization age of the granodiorite (1677 ± 14 Ma) and the age of a rhyolitic dike (1675 ± 14 Ma) that cross-cuts S_1 fabric. Powicki (1996) reported that the spaced, mylonitic character of S_1 is characteristic of plutons that cooled significantly after emplacement, before deformation (citing Gapais, 1989). If that is the case, there may have been some amount of exhumation that occurred between the granodiorite emplacement and D_1 .

The second episode (D_2) formed weak to moderate east-west striking fabrics (S_{2x}) in the granites of Soldier Camp, Four Peaks rhyolite and the Buckhorn granodiorite. D_2 is bracketed by the ages of sample K13-FPKS-14 (1667 ± 14 Ma), a granite of Soldier Camp, and sample K13-4PKS-5, which is mostly undeformed and younger (1655 ± 4 Ma). Thus, D_2 occurred at ca. 1665-1655 Ma. A significant period of deformation is constrained by the ages of these two samples. Some of the granites of Soldier Camp are undeformed, which suggests this complex of granites was emplaced syn-deformationally.

The absolute age of S_{2y} is somewhat ambiguous and it is difficult to constrain its age relative to S_{2x} . S_{2y} occurs in sediments that are intruded by the Granites of Soldier Camp but no clear relationship was observed that suggested whether the granites cross-cut S_{2y} . Because the lower sedimentary units were deposited by ca. 1660 Ma, S_{2y} can broadly be constrained to 1660-1450 Ma. However, it may have formed any time after sedimentary deposition and could be ca. 1665-1655 Ma. S_{2y} may be related to D_2 or part of progressive deformation in another event.

The youngest significant deformation event recorded in the Four Peaks area (D_3) occurred 1490-1450 Ma and resulted in large-scale folding of the Four Peaks sedimentary section. D_3 is bracketed between the lithification of the Upper Sedimentary unit (after final deposition at ca. 1490 Ma) and the intrusion of the El Oso granite (~1450 Ma). S_3 foliations and slaty cleavage were formed during this deformation event. This is the most significant deformation event recorded in the Four Peaks area and produced the highest degree of shortening, represented by the Four Peaks syncline.

It is possible that S_{2y} foliations formed during D_3 or D_2 deformation. D_3 produced minimal NE striking fabrics in the granites of Soldier Camp but strong foliations in the nearby metasedimentary rocks. Strain may have been partitioned into the lower sediments producing non-coaxial shear close to the rheologically stiff granite while the large fold was being formed. The cool granite may have acted as a buttress to localize the syncline. This contradicts what was presented by Mako et al. 2013; that the Paleoproterozoic granites in the Four Peaks area bracketed the time of folding. S_{2y} may also have formed during the Paleoproterozoic in a period of thrusting that did not produce significant folding or misorientation of bedding (this is a speculative hypothesis). Strain partitioning

between the granites and metasedimentary rocks during D_3 is the preferred model. In any case, the age of intrusion of the granites of Soldier Camp cannot be used to bracket the major folding event in the Four Peaks area given that significant strains are observed at this contact.

Mesoproterozoic, D_3 , deformation was accompanied by significant crustal thickening and monazite growth. By the intrusion of the El Oso granite at the end of D_3 , the metasedimentary rocks in the Four Peaks area had been buried to a depth of 11-15 km. A large portion of the monazite grains that were dated during this study grew during the D_3 time period. A first pulse of monazite grew at ca. 1485 Ma, shortly after the start of deformation, followed by the growth of rims and other new monazite at ca. 1465 Ma. These ages are generally older than the El Oso granite (although some are within uncertainty) and probably did not grow as a result of contact metamorphism, but rather resulted from metamorphic changes produced by significant crustal shortening and thickening. Renewed growth at 1415 Ma and on to 1386 Ma indicates continuing thermo-tectonic activity, however it does not appear that deformation was significant at that time since the El Oso granite is almost totally undeformed. Mesoproterozoic deformation was indeed significant in this area as evidenced by petrological and monazite constraints.

These conclusions are not consistent with some previous results from the Four Peaks area. Estrada (1987) reported that deformation in the Mazatzal group, which was associated with the metasediments in the Four Peaks area, occurred between 1700 and 1630 Ma. The work of Powicki (1996) supported this interpretation with a tight constraint on folding and major deformation to 1669-1660 Ma. The cross-cutting rhyolitic dike was used to make this conclusion, but new data suggests that this does not correspond to

folding. Skotnicki (2000) found the timing of deformation in the Four Peaks area to be ambiguous given contact relationships and previous geochronology. One of the periods of deformation discussed in the present study (D_2) is consistent with the conclusions of Powicki (1996), but the evidence suggests that the major folding event was much younger.

5.5 A Geologic and Tectonic History of the Four Peaks area

A history of tectonism from ca. 1680 Ma to 1450 Ma is recorded in the Four Peaks area. The first event was the emplacement of the Buckhorn granodiorite at ca. 1680 Ma. Whatever crust that the granodiorite was emplaced into is not exposed in the Four Peaks area. D_1 occurred at ca. 1675 Ma. It is recorded in the granodiorite, forming as S_1 foliations. The timing is constrained by the cross-cutting rhyolitic dike (1675 ± 18 Ma). Following deformation, the diorite must have been exhumed so that the sedimentary units could be deposited. The Lower Quartzite, Lower Sediment and Four Peaks Quartzite were probably deposited and lithified by ca. 1660 Ma. The granites of Soldier Camp (1667 ± 19 Ma) were emplaced soon after deposition and clearly cut across the lowermost sediments.

D_2 took place within the range 1665-1655 Ma. Fabrics of this age are weak to moderate and east-west striking, S_{2x} . The granites of Soldier Camp (1667 ± 19 Ma) are variably deformed and a sample of minimally deformed megacrystic granite gives an age of 1655 ± 18 Ma. The Four Peaks rhyolite was deposited at 1657 ± 16 Ma. The variably present bedding parallel fabrics (S_{2y}) may be related to this deformation event, but there is no clear evidence for this. Deformation may have occurred 1655-1450 Ma.

Between ~1655 Ma and ~1570 Ma (or possibly 1520 Ma) uplift and erosion occurred, removing a significant amount of stratigraphy from the Four Peaks section. This is supported by the gap in depositional ages of the Four Peaks Quartzite and Upper Sediment as well as the granites that intrude the lowermost sediments. We would expect a depth greater than 600-1000 meters (the thickness of the Paleoproterozoic sediments) for a medium to coarse grained granite to be emplaced. There is no measureable angular relationship between older and younger sediments and no topography has been recognized at the unconformity in the Four Peaks area. Perhaps erosion of the sediment occurred down to the flat and resistant quartzite. Somehow, these sediments remained near horizontal after 140-100 Ma of uplift, erosion and deposition.

Mesoproterozoic tectonism in the Four Peaks area included deposition, deformation and plutonism. Renewed deposition began at ca. 1520 Ma and continued until 1490 Ma, based on regional interpretations (Doe, 2014). The most major deformation event (D_3) in the Four Peaks area took place between 1490 and 1450 Ma. The kilometer-scale Four Peaks syncline and S_3 formed during this time. The fold records deformation of sedimentary rocks that were deposited during the Mesoproterozoic and that are structurally continuous with Paleoproterozoic sediments. The folded metasediments are intruded by the undeformed El Oso granite (1449 ± 14 Ma). Monazite records growth at ca. 1485, 1465 and 1415 Ma. The youngest monazite growth event may be due to other tectonic processes not related to deformation. The orogenic peak in the Four Peaks area may be recorded by 1485-1460 Ma monazite growth. By the time of intrusion of the El Oso granite, the rocks in the Four Peaks area

had been tectonically buried to 11-15 km depth. Three orogenic cycles of deposition, deformation and uplift are recorded in the Four Peaks area (Table 3).

5.6 Cross Section

Figure 22 is a new cross section of the Four Peaks syncline, based on constraints from Powicki (1996), Skotnicki (2000) and the present study. Several of its features are worth noting. It is apparent from the map patterns (Figure 2) that both the Four Peaks Quartzite and Lower Sedimentary Unit must thicken substantially through the fold, on the order of hundreds of meters. This could be accomplished through thinning of the southern overturned limb, thickening of the northern limb or changes in the depositional thickness of the units. If substantial thinning occurred in the southern limb, we expect more evidence of flattening or extensional strain than is found in the field or in thin section, such as tension gashes or mylonitic fabrics. It seems unlikely, and overly convenient, that major depositional thickening occurred just at the hinge of such a major structure, however it is conceivable that a depositional change localized the syncline.

The preferred model involves thickening of the northern limb during folding. Abundant meso-scale folds can be found on the northern limb (Figures 13 and 14), which could have accomplished this thickening. When drawing the cross section, minimal thickening of the sedimentary units was allowed and the fit to the map pattern and data was accomplished by 100-200 meter minor folds. This is rather conceptual, and the data could have been fit by numerous, much smaller folds. When the cross-section is drawn in this way, the thickness of the sedimentary section is less than 900 meters on the thickened limb and 600 meters on the thin limb. The Four Peaks Quartzite is only 200-250m thick.

CHAPTER 6
REGIONAL IMPLICATIONS

6.1 Tonto Basin area

The events recorded in the Four Peaks area correlate well with the most recent interpretations for the surrounding Tonto Basin area. As discussed above, the structures and stratigraphy in the Four Peaks area are very similar to the Hess Canyon Group in the Salt River Canyon. The Salt River Canyon section is located about 55 km directly east of the Four Peaks. The stratigraphic and structural interpretations at Four Peaks are thus, regionally applicable to at least the Tonto Basin area and possibly further.

Deformation in the Tonto Basin area and central Arizona has generally been associated with the ca. 1.65 Ga Mazatzal orogeny (Karlstrom and Bowring, 1988; Labrenze and Karlstrom, 1991; Doe and Karlstrom, 1991; Eisele and Isachsen, 2001). The timing of motion along the Slate Creek movement zone, ~50km north of Four Peaks, was previously constrained to have ceased by 1.65 Ga, the age of the Young granite (Labrenze and Karlstrom, 1991), which is broadly in agreement with the geochronologic results of the present study. The granites of Soldier camp have a very similar age to the Young granite, so it is possible they are part of the same intrusive event. However, deformation of the Slate Creek movement zone predates the Young granite and D_2 in the Four Peaks area post-dates and deforms the granites of Soldier Camp (forming S_{2x}).

It is uncertain whether or not the Slate Creek movement zone and the development of S_{2x} in the Four Peaks area are synchronous and related. Given the large uncertainties in age, it is possible that deformation in the Slate Creek movement zone

may be a regional extension of either D_1 (ca. 1675 Ma) or D_2 (1665-1655 Ma) in the Four Peaks area. Based on the orientation of S_1 (NE-striking) this is a better match to deformation in the Slate Creek movement zone for regional deformation. In any case, Paleoproterozoic deformation was probably regionally extensive and evidence from the Four Peaks area confirms that Mazatzal-age deformation did take place in the Tonto Basin area.

Given the magnitude of Mesoproterozoic deformation evident in the Four Peaks area, it is likely that D_3 is regionally extensive as well. Other major structures in the Tonto Basin may have to be reinterpreted. For example the fold and thrust belt of Barnhardt Canyon, further north in the Mazatzal Mountains (Doe and Karlstrom, 1991) may be primarily Mesoproterozoic. This is significant because the Barnhardt Canyon structures are what Wilson (1939) used to define the ‘Mazatzal Revolution’, for which the Mazatzal orogeny is named. This fold and thrust belt was originally interpreted to have deformed at 1.66-1.65 Ma at the same time as the Slate Creek movement zone (Karlstrom and Bowring, 1991). The type location of the Mazatzal orogeny may in fact record mostly Mesoproterozoic shortening.

The Pinal schist, about 100 km south of the Four Peaks, has recently been interpreted as a forearc subduction complex (Meijer, 2014). Meijer (2014) argued that this subduction complex experienced the subduction of a spreading ridge at ca. 1.65 Ga, after the collision of the Mazatzal Arc terrane. Other workers in the Pinal schist have interpreted sedimentation, volcanism, deformation and a subduction mélangé to have resulted from the 1.65 Ga Mazatzal orogeny (Swift and Force, 2001; Eisele and Isachsen, 2001). It is beyond the scope of this study to evaluate these conclusions. Although there

was significant Mesoproterozoic deformation and moderate Paleoproterozoic deformation in the Tonto Basin area, Paleoproterozoic (Mazatzal) tectonism may have been much more significant further south.

6.2 Mazatzal and Picuris Orogenies

The geologic history of the Four Peaks area can be divided into three distinct orogenic cycles, consisting of deposition, uplift and deformation. This idea of orogenic cycles is meant to be descriptive and highlight the observation that, in the Four Peaks area, the sequence of deposition, deformation and uplift occurs repeatedly in the geologic record. The first orogenic cycle recorded in the Four Peaks area occurred at ca. 1675 Ma and is incomplete, consisting of deformation and uplift (though the emplacement of the Buckhorn granodiorite could broadly be considered deposition). The second cycle extended from 1665-1520 Ma and exemplifies the Paleoproterozoic Mazatzal orogeny. The final cycle covered 1520-1330 Ma and includes the recently defined Picuris orogeny. These are discussed in more detail in the following paragraphs.

The first orogenic cycle in the Four Peaks area (ca. 1675 Ma) occurred between the Yavapai and Mazatzal orogenies as they are commonly defined. It is older than what is usually considered the timing of the Mazatzal orogeny (1660-1600 Ma) and post-dates what would be considered Yavapai orogeny deformation (1740-1680 Ma) (Whitmeyer and Karlstrom, 2007). It is possible that D₁ deformation might represent a continuum of deformation between the Yavapai and Mazatzal orogenies. Alternatively, it could be a late stage of the Yavapai or early phase of the Mazatzal Orogeny.

Orogenic Phase	Event at Four Peaks	Timing
Deposition	Apache Group	ca. 1330 Ma
Uplift	(Uplift)	1450-1330 Ma
Deformation	D3- Picuris Orogeny	1490-1450 Ma
Deposition	Yankee Joe System	1520-1490 Ma
Uplift	Unconformity	1650-1520 Ma
Deformation	D2- Mazatzal Orogeny	1665-1655 Ma
Deposition	Lower Quartzite to Four Peaks Quartzite	1665-1655 Ma
Uplift	(Uplift)	1675-1665 Ma
Deformation	D1- Early Phase Mazatzal	ca. 1675 Ma

Table 3- Orogenic cycles in the Four Peaks area. A summary of the timing of geologic and tectonic events at Four Peaks. Major interpreted orogenic cycles are highlighted in uniform color.

The second orogenic cycle in the Four Peaks area can be ascribed to the classical definition of the Mazatzal Orogeny (1660-1600 Ma). The lower sediments in the Four Peaks section are a true quartzite-rhyolite, Mazatzal sequence, deposited in the Mazatzal orogenic cycle. D₂, which produced steeply dipping fabrics in the granites of Soldier Camp and possibly bedding parallel fabrics, involved north-south directed shortening. No large scale structures have been recognized that are associated with this event in the Four Peaks area. The Slate Creek movement zone does contain major structures that probably formed during this time. These features may be characteristic of the Mazatzal orogeny in southwestern North America.

Deformation in the second cycle (D₂) in the Four Peaks area has a very similar age to deformation constrained in New Mexico. Bauer and Williams (1994) constrained deformation to 1664-1654 Ma, based on U-Pb dating of a cross-cutting granite in the Magdalena Mountains. Brown et al. (1999) dated the syn-tectonic Manzanita pluton at 1645 ± 16 Ma. Additionally, a similar timing of deformation has been interpreted in the Tonto Basin area. The Mazatzal orogenic cycle seems to be extensive across southwestern North America, though it is probably less significant in terms of shortening and metamorphism than previously thought.

The characteristics of the Four Peaks quartzite correspond well to other quartzites exposed in the Mazatzal province. The deposition of the Mazatzal system sediments and their subsequent deformation occurred over a very short time, ~10 Ma. Thus, the thick Four Peaks Quartzite was probably deposited essentially syntectonically. Jones et al. (2009) came to strikingly similar conclusions for the Ortega Quartzite in northern New Mexico. They suggested that the Ortega Quartzite was deposited in a short-lived,

syntectonic, basin at 1680-1670 Ma (Jones et al. 2009). Detrital zircon populations, depositional environment and duration of deposition for the Four Peaks and Ortega Quartzites are very similar.

Paleoproterozoic deformation occurred in the Four Peaks area ca. 1675-1655 Ma, and possibly on to ~1570 Ma. Early work by Karlstrom and Bowring (1988) suggested that the timing of the Mazatzal orogeny was 1695-1630 Ma, which would fit well with the timing of deformation in the Four Peaks area. In this part of Arizona there is no known evidence of Paleoproterozoic deformation after ~1650 Ma. 1680-1650 Ma is potentially a better interval for describing Mazatzal-age deformation in central Arizona (similar to the conclusions of Karlstrom and Bowring, 1991). The first two orogenic cycles recorded in the Four Peaks area should be considered two phases of the Mazatzal orogeny.

It is possible that S_{2y} in the Four Peaks area formed during the Mazatzal Orogeny and the second orogenic cycle in the Four Peaks area. Layer parallel fabrics can form via nappe-style deformation. It seems plausible that S_{2y} formed during an early stage of the Mazatzal orogeny and erosion may have removed higher-level thrust sheets or nappes. It is emphasized that there is no direct evidence to support this hypothesis. If there were significant folding in the Four Peaks area at 1.66-1.60 Ga (as has previously been interpreted) we should expect to see evidence of it (folds, thrust or foliations) in the sediments that existed at that time. It is possible that bedding parallel shear was part of progressive Mesoproterozoic deformation that formed the Four Peaks syncline and partitioned strain between the granites of Soldier Camp and the metasedimentary rocks. Again, the latter is the preferred model.

The final Proterozoic orogenic cycle in the Four Peaks area occurred in the Mesoproterozoic and can be associated with the Picuris orogeny, proposed by Daniel et al. (2013). It is clear that significant Mesoproterozoic deformation occurred in the Four Peaks area that had previously been thought Paleoproterozoic. Deformation in this time period (1490-1450 Ma) has been recognized across the Southwest (Grambling and Dallmeyer, 1993; Nyman et al. 1994; Amato et al. 2011). Not only is Mesoproterozoic deformation recognized in the Four Peaks area, it is related to sedimentary deposition and plutonism as well. There is evidence in the Four Peaks area and across the Tonto Basin that the Mesoproterozoic was a time of intense deformation and orogenesis.

The style and intensity of Paleoproterozoic deformation in the Four Peaks area fits in well with the arc accretion model for the formation of the Mazatzal Province (Karlstrom and Bowring, 1988; Whitmeyer and Karlstrom, 2007). 1665-1655 Ma deformation may have resulted from the docking of a small arc terrane with only minor deformation. If this model is correct, we would predict that small terrane blocks and shear zones in between them would record a range of ages over the progressive accretion of arcs. Thus, slightly different constraints on the timing of deformation over the whole Mazatzal province should be expected. The more gentle accretion of island or continental arcs might have resulted in only subtle deformation (i.e. S_{2x} foliations) and no large folds or thrusts.

A significant collisional event or large roof thrust (Meijer, 2014) are attractive ways to explain Mesoproterozoic tectonism in central Arizona. Either of these scenarios could account for the significant shortening that occurred. A large obduction event, as described by Meijer (2014) would fit in with a model of the Four Peaks syncline as a

large drag fold beneath a roof thrust. However, this does not fit as well with the fold and thrust belt of Barnhardt canyon which probably formed close to the surface and is not a drag structure. The Four Peaks area could be considered a hinterland feature of a Mesoproterozoic mountain belt, where significant burial took place, behind the foreland fold-thrust system of Barnhardt canyon. This is similar to previous interpretations except for the Mesoproterozoic timing. It is possible that changes in the slab dynamics of an outboard subductions zone could have produced the observed crustal shortening, but more work is need to make meaningful interpretations along that line.

CHAPTER 7

CONCLUSIONS

There is evidence of deformation and sedimentary deposition from the Paleoproterozoic to Mesoproterozoic in the Four Peaks area. Three fabric forming episodes of deformation are recognizable: D₁ at ca. 1675 Ma, D₂ from 1665-1655 Ma, and D₃ 1490-1450 Ma. Two major depositional systems are distinguishable in the Four Peaks section based on cross-cutting igneous rocks and detrital zircon dates. The Lower Quartzite, Lower Sedimentary Unit and Four Peaks Quartzite were deposited 1665-1655 Ma and are member of the Mazatzal Basinal System (1660-1630 Ma) (Doe, 2014). The Upper Sedimentary unit was deposited 1520-1490 Ma and is a member of the Yankee Joe Basinal System (Doe, 2014).

The major structures, including the Four Peaks syncline, formed during the Mesoproterozoic and are consistent with the timing of the Picuris orogeny proposed by Daniel et al. (2013). There is deposition, deformation and uplift associated with the early part of the accepted timing of the Mazatzal orogeny (1660-1600 Ma) recorded in the Four Peaks area, but it is much less significant in terms of crustal shortening than Mesoproterozoic orogenesis. Based on the timing of deformation in Four Peaks area, it appears the Mazatzal orogeny occurred 1.68-1.65 Ga in central Arizona. Progressive terrane accretion during the Paleoproterozoic with more minor deformation, is the preferred tectonic model for the Four Peaks area during that time. Subsequent Mesoproterozoic deformation may have involved a more significant continental collision.

APPENDIX A

REMAINING WORK IN THE FOUR PEAKS AREA

A.1 Field Relationships

Several questions about important field relationships remain in the Four Peaks area. Mostly these stem from not having spent enough time in a particular area or not having directly observed a particular contact relationship. The most important of these are as follows. 1) The contact between the Buckhorn granodiorite and the Lower Quartzite. Based on the model presented in this thesis, this is hypothesized to be a depositional contact but this has been untested. 2) The contact between the granodiorite and the Four Peaks rhyolite. This also is expected to be a depositional contact, however it has not been firmly established as such. Also, is the Four Peaks rhyolite a metatuff or pyroclastic deposit? 3) Contact between the granites of Soldier camp and the Lower Quartzite should also probably be more closely examine. 4) There are two visibly indistinguishable megacrystic granites in the Four Peaks area. Work could be done to distinguish these and firm up the field relationship (dashed on Figure 2). 5) The contact between the Four Peaks Quartzite and the Upper Sedimentary Unit was never directly observed. Since it is such an important contact for the history of this area, future effort should be made to find an exposure of it. In general, the Southwestern part of the area, where the metasedimentary rocks taper to a few hundred meters wide, is very important for foliations and contact relationships and has been understudied during this research effort and those of Skotnicki (2000) and Powicki (1996). In general, the map by Skotnicki (2000) is an excellent resource.

A.2 Future Work

There are several goals that future work in the Four Peaks area could be directed toward. 1) The granites of Soldier Camp seem much more complex than has previously been recognized. At least three different phases of granite in the western region were documented during field work of this study, which have varying grain sizes and degrees of foliation development. Much more work could be done on the geochemistry of the granites in the Four Peaks area and the Tonto Basin area in general. 2) More work could be done on foliations and lineations in the Four Peaks rhyolite and Buckhorn granodiorite. Both of these units have complex composite foliations, and careful work using stretching lineations could lead to a better knowledge of the strain orientations for the various phases of deformation. 3) This thesis hypothesizes that the bedding parallel fabrics in the lower sediments were produced by strain partitioning against the granites of Soldier Camp, which didn't deform significantly during the high strain event in the Mesoproterozoic. This idea could be further tested. 4) There is probably a Paleoproterozoic metamorphic signature at Four Peaks and additional work could probably show that it is discernible.

APPENDIX B

ZIRCON GEOCHRONOLOGY

B.1 Zircon Age Data Plots

Below are shown the age histograms from each sample in that study from which zircons were dated. Plots were made in the Isoplot 4.1 macro for Microsoft Excel (Ludwig, 2008). Data for the K13- series samples and sample C13-067b can be retrieved on the Arizona Laserchron Center website under “Current Projects” in the Karlstrom, March, 2014 run.

Figure 23- Sample C13-029a- Four Peaks Quartzite. (There is one ~3500 Ma grain out of view)

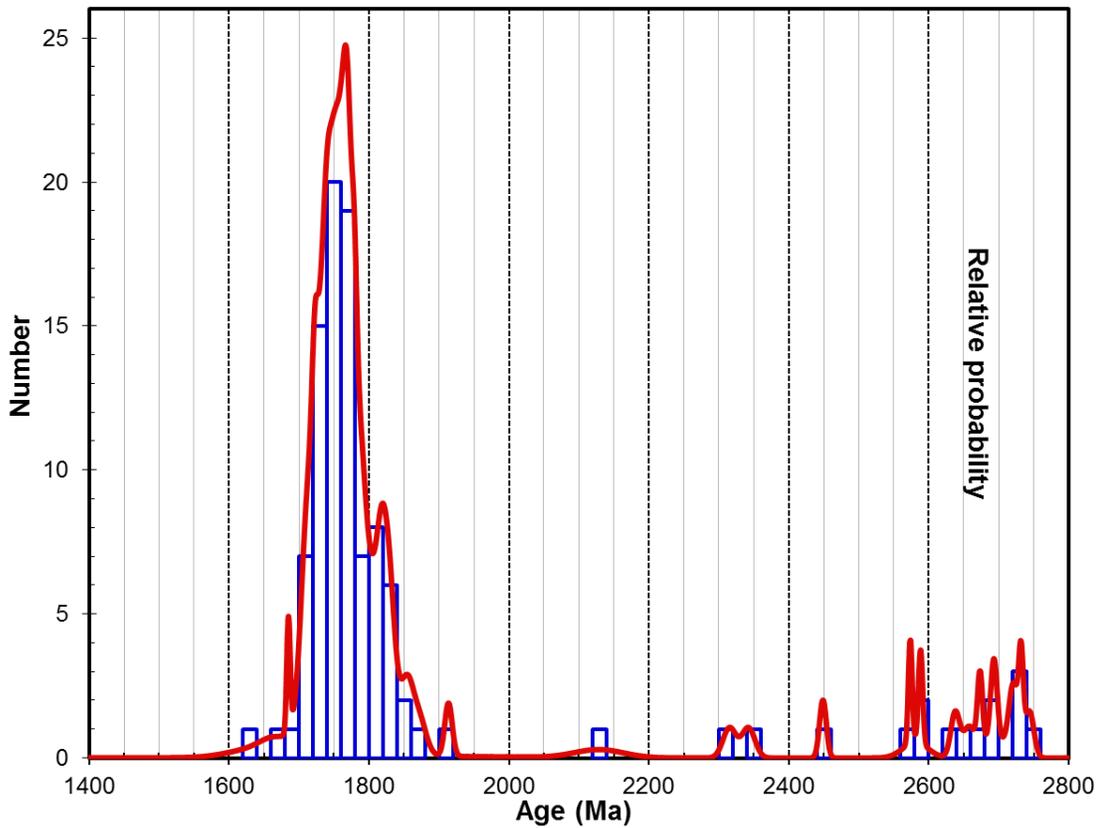


Figure 24- Sample 09162013-1- Upper Sedimentary Unit. (Doe, 2014)

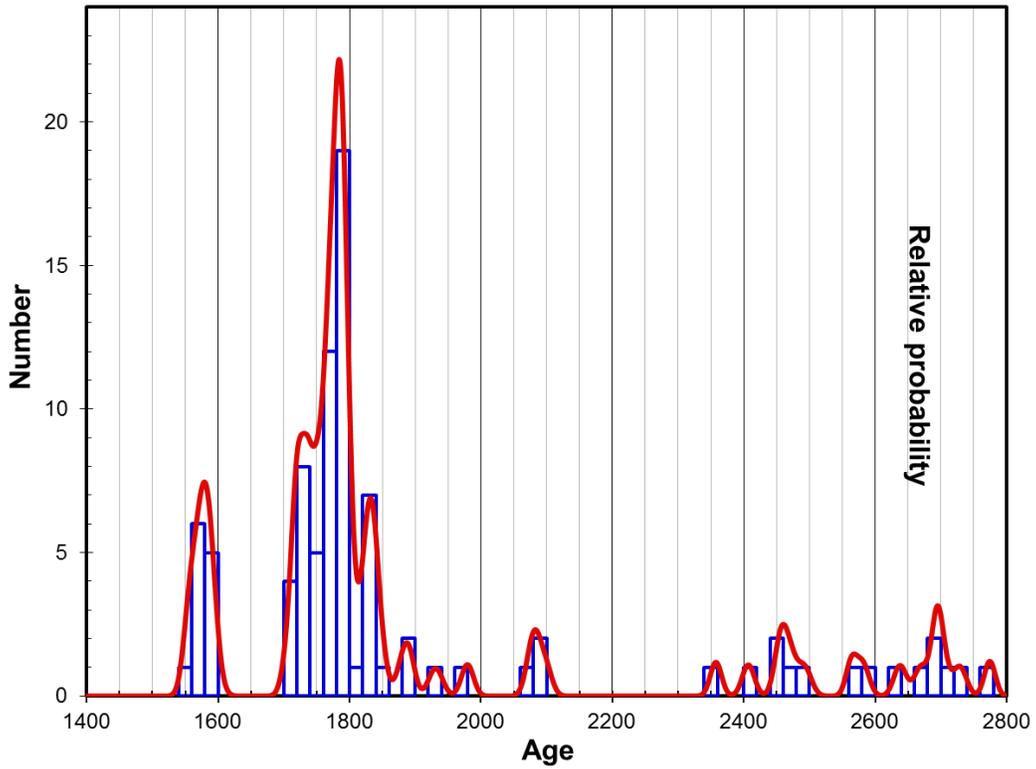


Figure 25- Sample C13-067b- Young Granite

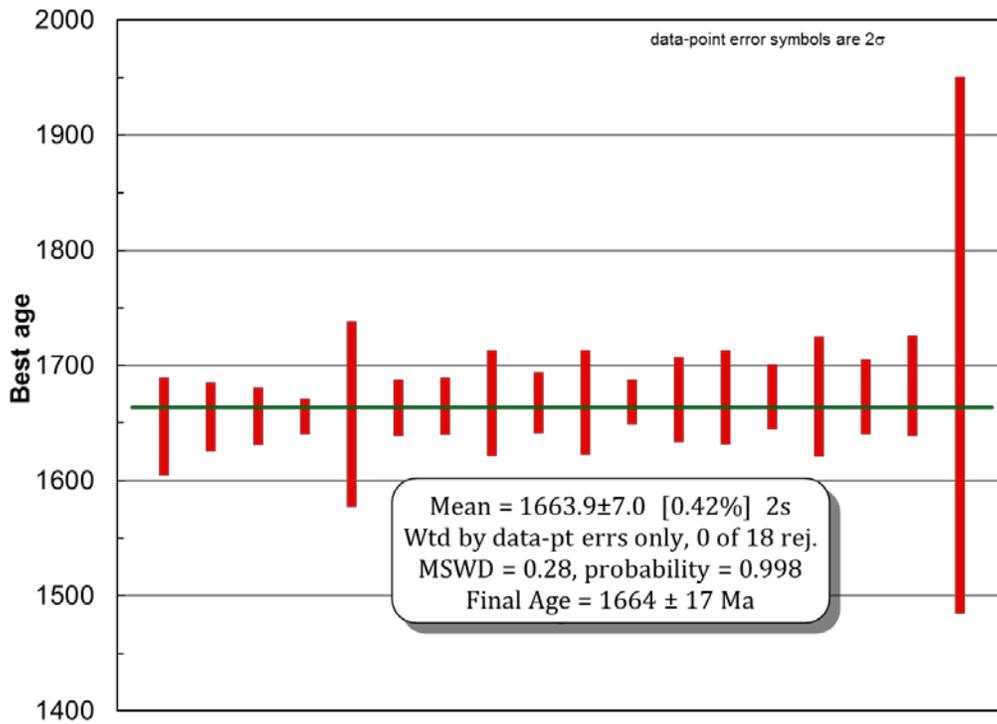


Figure 26- Sample C13-073- El Oso granite

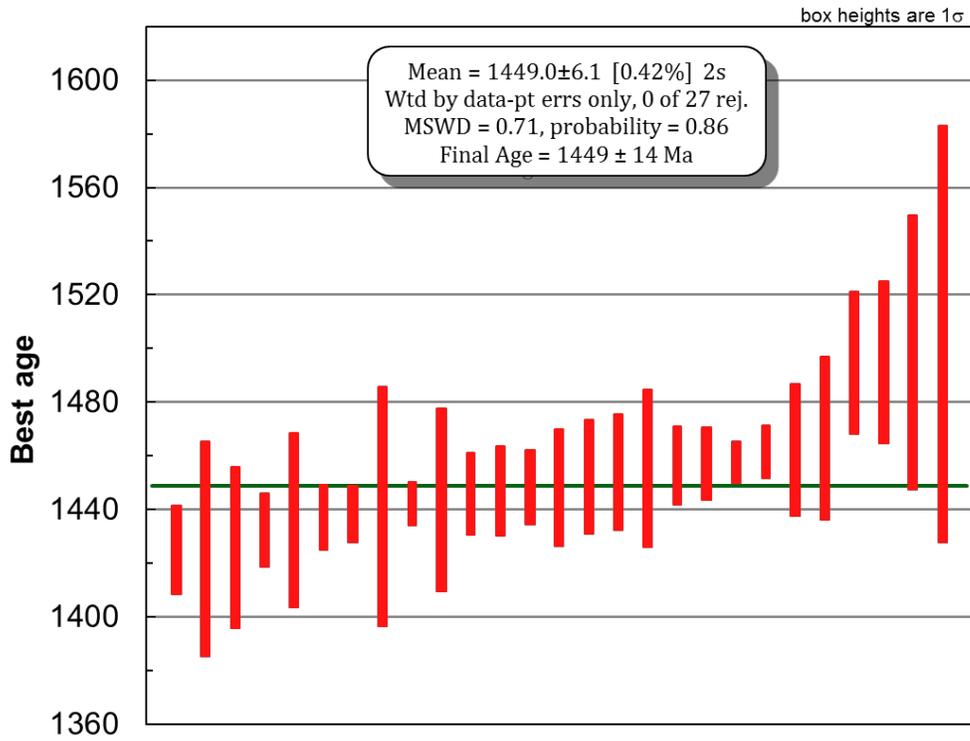


Figure 27- Sample C13-082b- Four Peaks rhyolite

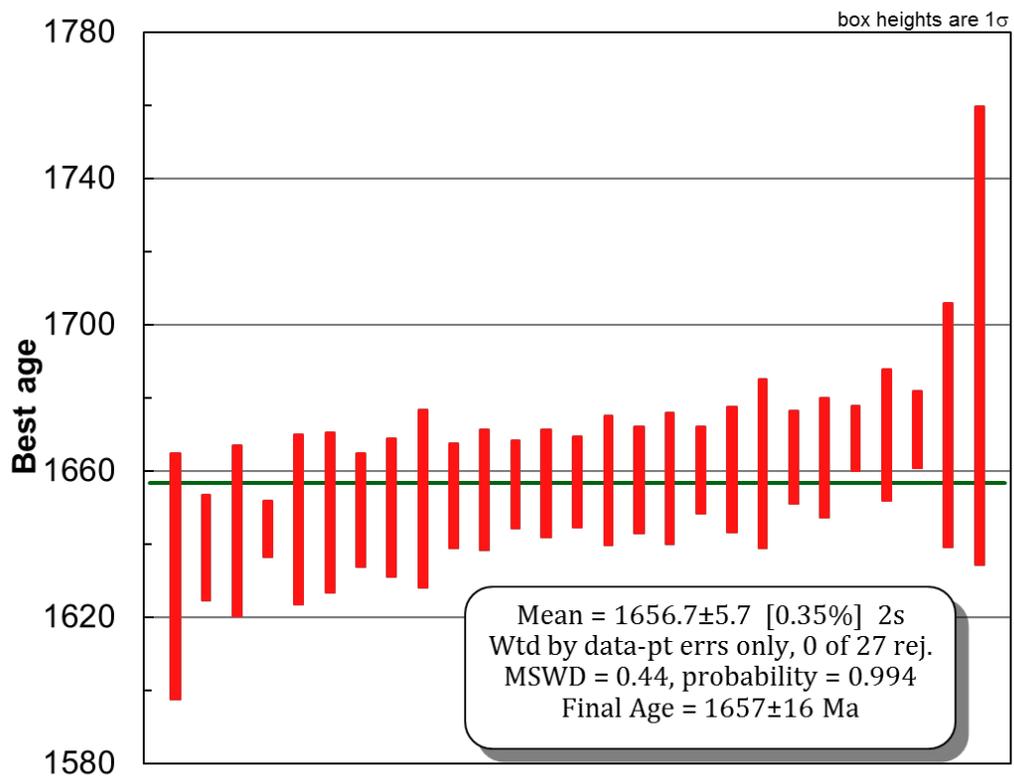


Figure 28- Sample K13-4PKS-3- Rhyolitic Dike in Buckhorn granodiorite. (collected by Karlstrom, Powicki, Doe, 2014)

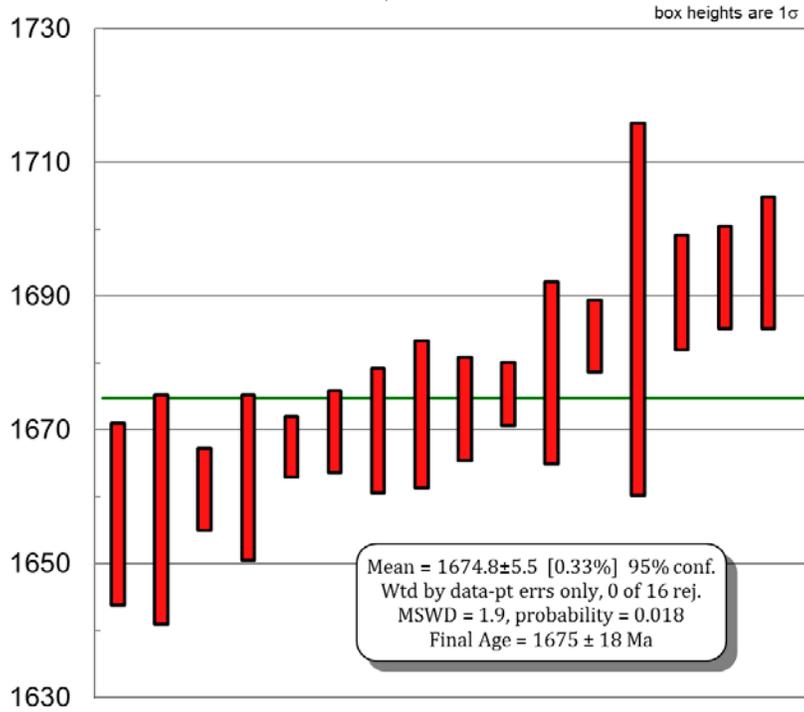


Figure 29- Sample K13-4PKS-4- Buckhorn granodiorite. (collected by Karlstrom, Powicki, Doe, 2014)

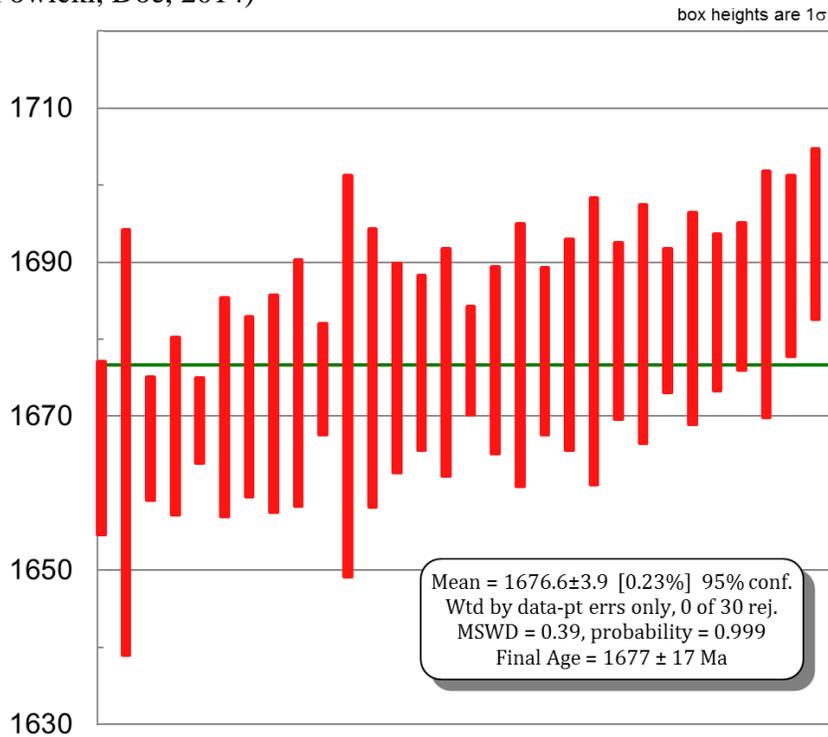


Figure 30- Sample K13-4PKS-5- Megacrystic granite. (collected by Karlstrom, Powicki, Doe, 2014)

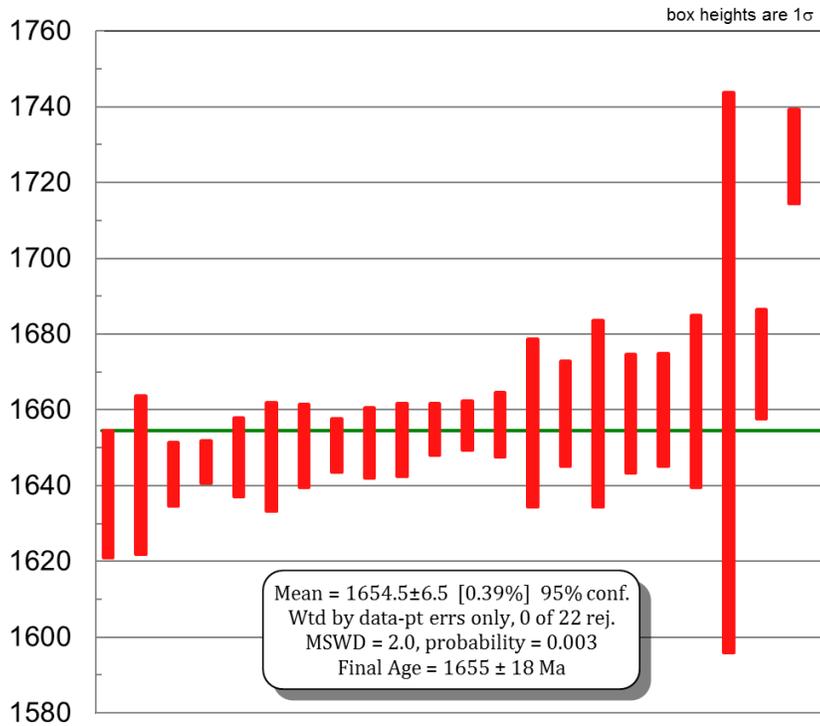


Figure 31- Sample K13-FPKS-14- Biotite, foliated granite of Soldier Camp. (collected by Karlstrom 2013)

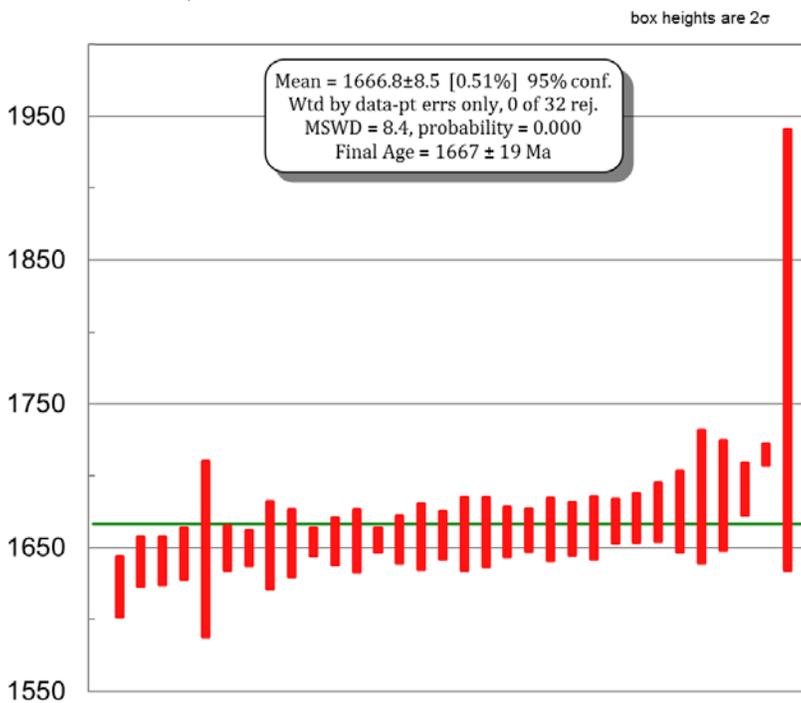
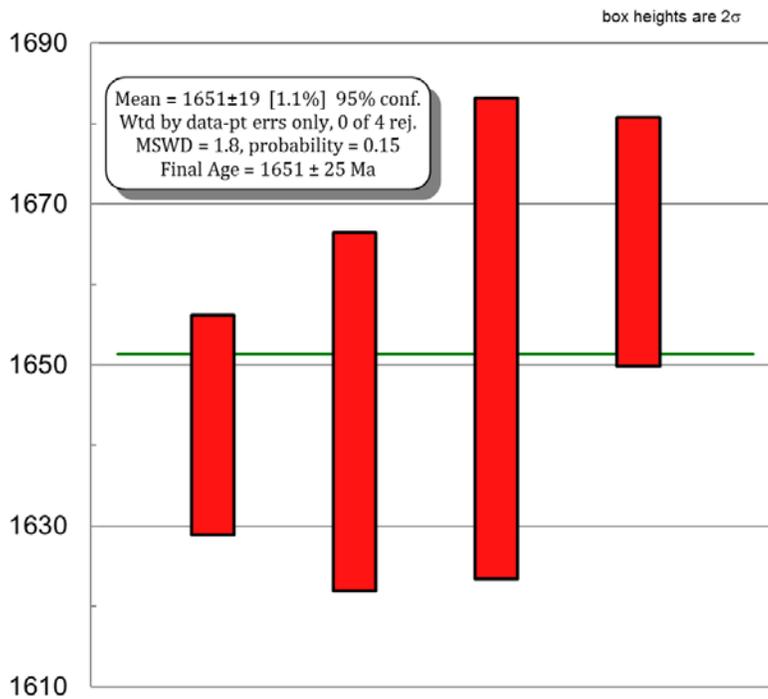
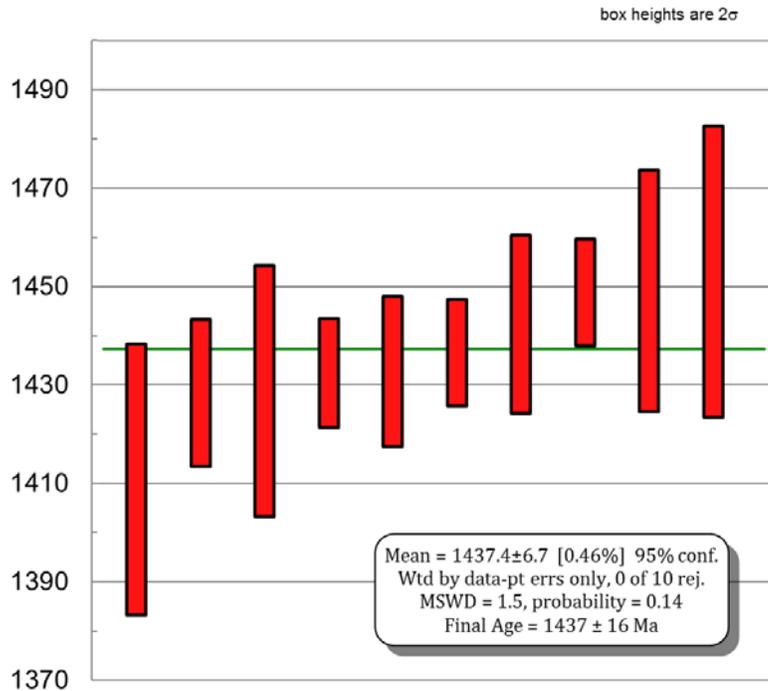


Figure 32- Sample K13-FPKS-15- Musc. granite, Paleo- and Mesoproterozoic grains.
 (collected by Karlstrom, 2013)



APPENDIX C

TABLE OF MONAZITE DATA

Monazite Domain	Age (Ma)	1-SD	MSWD	Pts Used
C13-012 m2 hi Th	1484	3.5	0.8	All
C13-012 m2 lw Th	1490	5.1	0.6	All
C13-012 m1 lw Th sect	1481	4	0.5	All
C13-012 m1 hi Th sect	1510	4.4	1.5	1,2,3,4
C13-012 m4 hi Th core	1487	3.6	2.1	All
C13-012_m5lowall	1483	5.2	1.6	All
C13-012_m14 hi Th core	1480	3.7	1.2	all
C13-012_m14_lwYrim	1465	3.9	0.7	all
C13-012_m8_core	1480	3.6	2.6	all
C13-012_m11	1468	3.7	1.2	all
C13-012_m9_hi Th	1487	4	4.1	all
C13-012_m9_lw_Th	1493	5.2	2.2	1,4,5
C13-012_m15 core	1480	4.6	1.2	all
C13-012_m15 rim	1470	4	0.5	all
C13-011-1_m2	1457	5.2	0.4	all
C13-011-1_m7	1454	6.4	0.5	all
C13-011-1_m7rim	1459	6.7	0.1	all
C13-056a-1_m4	1410	2.7	1.8	1,3,4,5,6
C13-056a-1_m4light	1416	2.2	1.8	all
C13-056a-1_m8	1418	4.6	1	1,3,4
C13-056a-1_m8light	1386	3.8	1.2	1,2,3
C13-056a-1_m3	1458	3.2	1.3	all

Table 4- Monazite age data. Different colors highlight the three age-groups and weighted means of these populations are given 'Monazite Geochronology'.

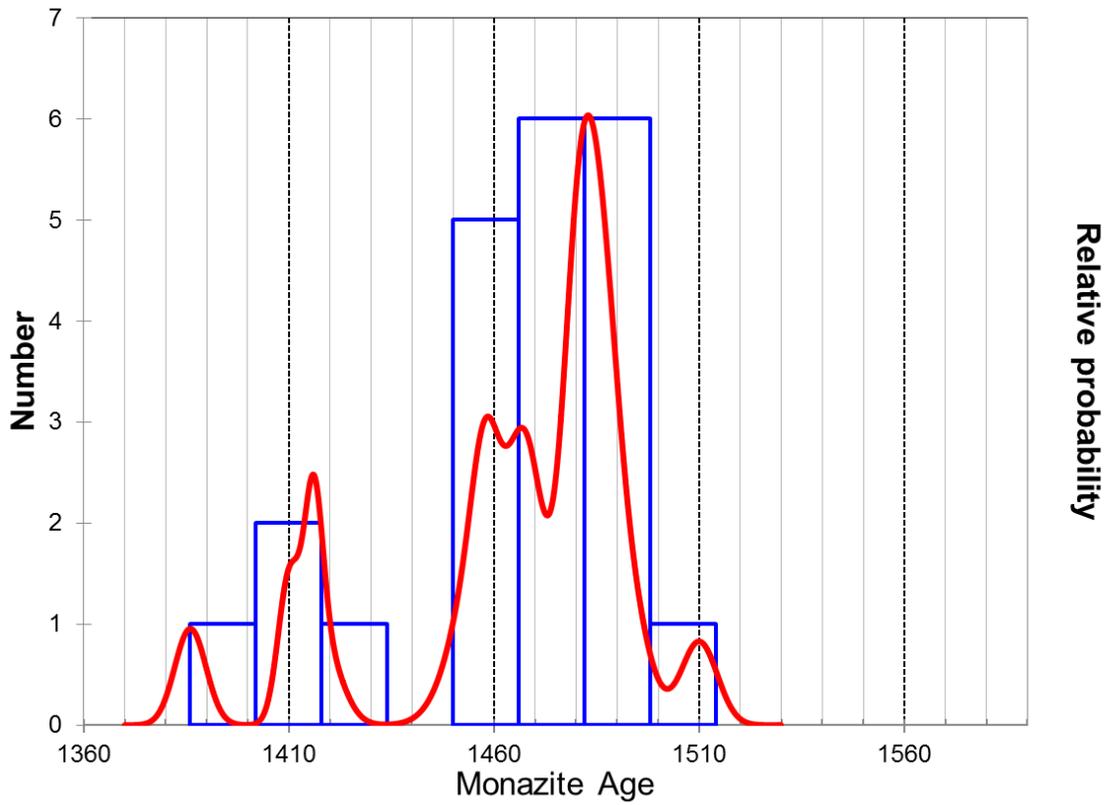


Figure 33- Probability density plot for monazite ages. Prominent peaks are 1415, 1460-1470, 1485 Ma. N=22 monazite. Plot made using Isoplot 4.1 (Ludwig, 2008).

APPENDIX D
SAMPLE LOCATION DATA

D.1 Table of Locations and related information

Below is a table of the locations of samples that were collected by the author and used in this thesis. These are UTM coordinates in NAD83 coordinate system. The author or Michael Williams at UMass, Amherst can be contacted if other samples, thin sections, maps or field notes are desired.

Sample #	Location	Easting	Northing	Rock Unit
C13-011	Amethyst Trail	469701	3728713	Migm., Lower Sed. Unit
C13-012	Amethyst Trail	469711	3728552	Deformed Migmatite, LSU
C13-029a	Browns Trail	469674	3724354	Upper Qtzt, lowest part
C13-035	Four Peaks Trail	471376	3726583	Lower Sedimentary Unit
C13-056a	Above El Oso Rd.	467745	3729464	Lw Qtzt xenolith in El Oso
C13-067b	Labrenze, 91 map area	501728	3779024	Young Granite
C13-073	Lone Pine TH	468720	3729545	El Oso Granite
C13-082b	South of Soldier Camp	467242	3723969	Four Peaks Rhyolite

Table 5- Sample location data

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