

**ELECTRON MICROPROBE IN SITU MONAZITE
DATING OF THE SLIDE LAKE SHEAR ZONE**

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ABSTRACT

The Colorado mineral belt (CMB) shear zone system records Proterozoic deformation episodes documenting the progressive tectonic accretion of Laurentia. Regional fold formation (D_1 & D_2) is coeval with the ca. 1700 – 1600 Ma Yavapai and Mazatzal orogenies, while Mesoproterozoic sub-vertical shear zones (D_3 & D_4) are a response to 1450 – 1300 Ma intracontinental deformation. The Slide Lake shear zone (SLSZ) is a sub-horizontal shear zone located in the Northern Sawatch Range, central Colorado. Aside from its orientation, the SLSZ records similar deformational structures to other shear zones in the CMB, but there is no timing constraint to test this relationship. Monazite is used as a geochronometer for poly-deformed metamorphic assemblages that record phases of growth through compositional zoning related to deformation and fluid-alteration. This thesis implements microstructural observations, electron microprobe in-situ monazite U-Th-Pb dating, and trace element analysis to place a timing constraint on SLSZ activity. Monazite dates from this research dominantly range from 1716 – 1580 Ma and 1538 – 1413 Ma, the latter of which roughly coincides with dates from the CMB shear zones. Monazite domain-age relationships in some grains suggest that U-Th-Pb monazite system was incompletely reset, commonly leading to younger inner-cores and older outer-cores. Core domains from HS09-42a record older dates (avg: 1700 ± 6.9 Ma) than is expected from a mylonitic sample, which may imply that monazite grains from Paleoproterozoic deformation (D_1 & D_2) were not reset by fluid alteration during shear zone activity (D_3 & D_4). The ranges of monazite sample dates shows a progression of younger average ages in samples with more advanced grain-size reduction (HS09-36: 1640 ± 23 Ma $\rightarrow$ HS09-35: 1502 ± 39 Ma $\rightarrow$ SL08-07: 1421 ± 7.6 Ma), paralleling the structural evolution of the CMB shear zones. Low-Y domains from HS09-35 (1423 and 1420 Ma) and SL08-07 (avg: 1421 ± 7.6 Ma) support fluid-alteration in the shear zone at ~ 1421 Ma, possibly corresponding with Mesoproterozoic deformation (D_3 &

D₄) in the CMB. Monazite dates from mylonitic samples in the SLSZ are coeval with ages of the neighboring Homestake shear zone (HSZ), suggesting that the shear zones were active at similar times.

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CHAPTER 1:

INTRODUCTION

Monazite geochronology is popular for dating poly-metamorphosed assemblages (Williams et al., 1999; Shaw et al., 2001; Williams et al., 2006). Electron microprobe (EMP) *in situ* monazite U-Th-total Pb dating can potentially allow the user to relate metamorphic microstructures to monazite genesis, providing the framework for dating reactions and deformation conditions (Williams et al., 2017). Due to its wide stability range and incorporation of a number of trace and major elements, monazite is appropriate for studying silicate metamorphic reactions that operate during deformation events (Williams et al., 2006). Monazite stability ranges from granulite ($T > 700^{\circ}\text{C}$) through lower greenschist facies ($T = 300 - 450^{\circ}\text{C}$) conditions, bridging the gap between higher (e.g., U/Pb, zircon; $T > 900^{\circ}\text{C}$; Lee et al., 1997) and lower (e.g., K-Ar, muscovite; $T = 300 - 400^{\circ}\text{C}$; Jäger, 1979) closure temperature geochronometers. In some examples of mylonitic shear zones monazite acts as a rigid grain, dissolving and reprecipitating as metamorphism persists (Mahan et al., 2006; Sindern et al., 2012; Wawrenitz et al., 2012). My thesis focuses on using monazite as an indicator of shear zone activity.

The Colorado mineral belt (CMB) contains a complex system of poly-deformed Proterozoic rocks that formed during the multistage accretion of Laurentia (Figure 1) (Tweto and Sims, 1963; Karlstrom and Humphreys, 1998; Shaw et al., 2001; McCoy et al., 2005; Shaw and Allen, 2007). These rocks record the tectonic evolution of the western Laurentian craton into successively narrower zones of deformation, from regional scale folding, to localized northeast-striking shear zones that represent an intracratonic response to mid-crustal shortening (Bickford

et al., 1989; Bowring and Karlstrom, 1990; Shaw and Karlstrom, 1999; Shaw et al., 2001; Jessup et al., 2005; McCoy et al., 2005; Shaw et al., 2005; Jessup et al., 2006; Allen and Shaw, 2011).

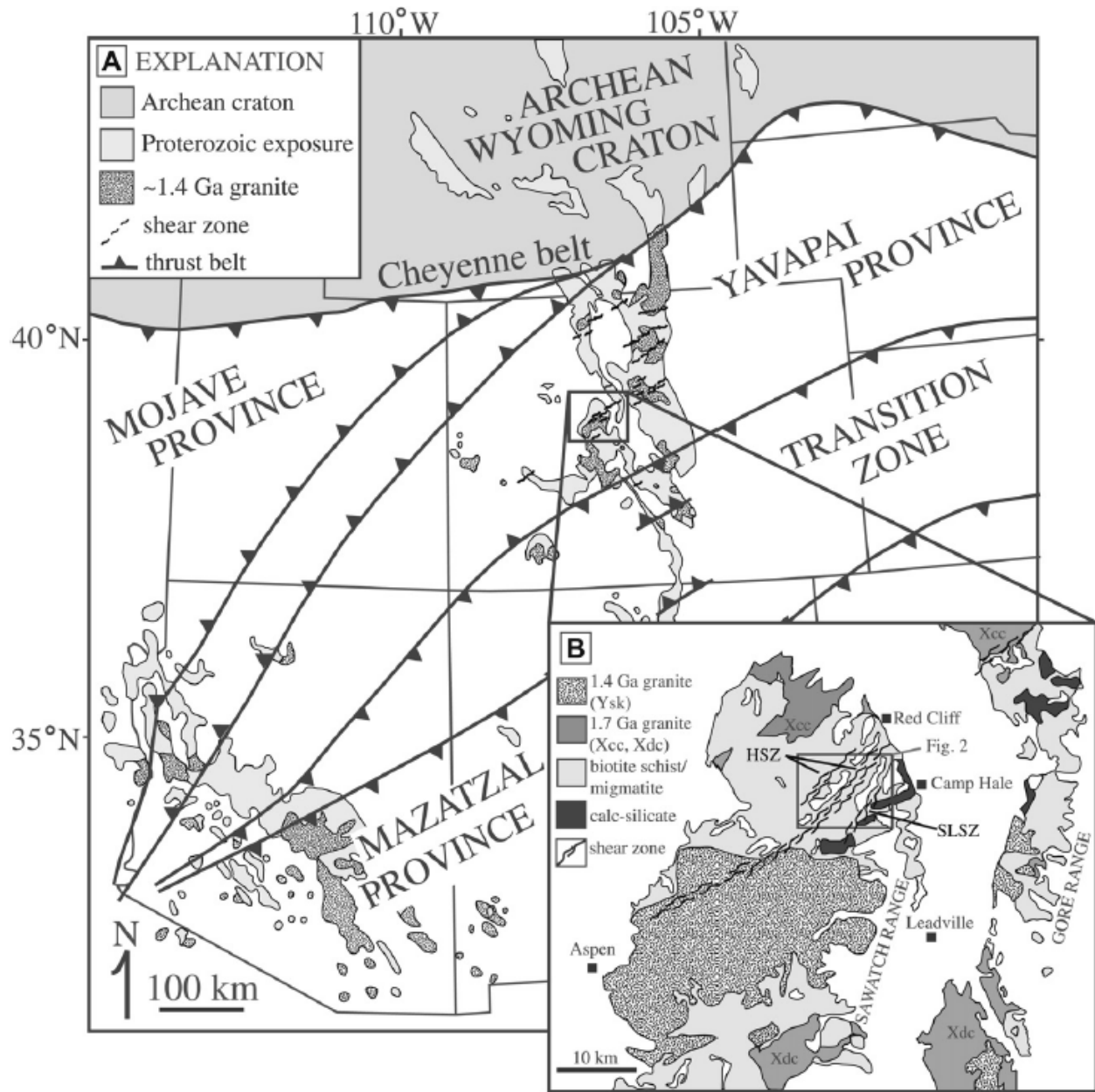
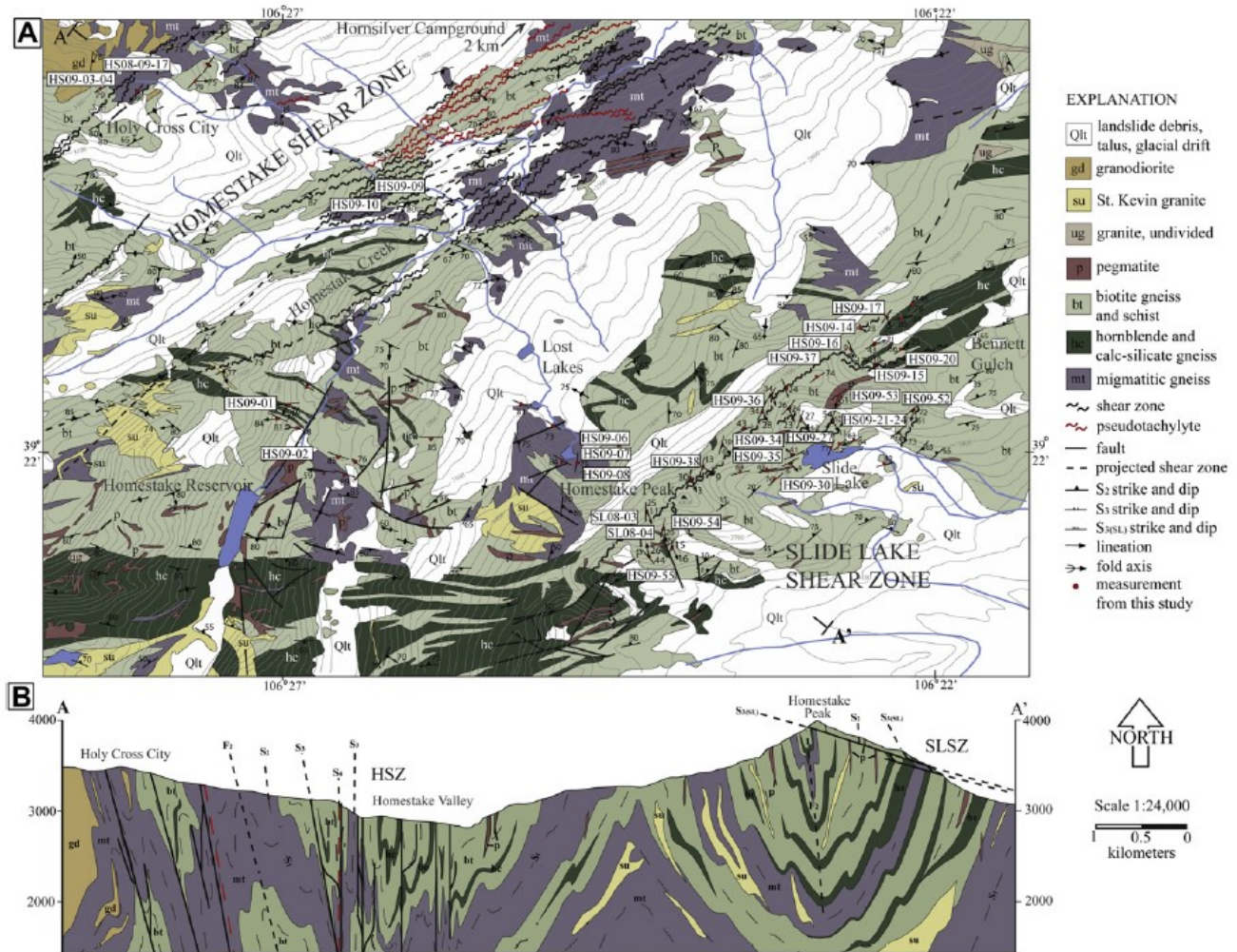


Figure 1: Regional tectonic map of Proterozoic terranes with shear zones. A.) Regional tectonic map of Proterozoic terranes in the western United States. B.) Inset geologic map of the northern Sawatch range with the location of Figure 2. From Lee et al. (2012).

Application of *in situ* monazite dating to the sub-vertical Homestake shear zone (HSZ) (Figure 2), located in the Northern Sawatch Range (Figure 1), related monazite growth to fabric development and deformation episodes (Shaw et al., 2001). The same technique was implemented with three other shear zones in the CMB (Gore Range, St. Louis Lake, and Idaho-Springs Ralston shear zones), resulting in recognition of four deformation events in the Proterozoic core of Colorado. The oldest monazite dates in the CMB are linked to Yavapai tectonism (~1700 Ma; D₁), followed by Mazatzal tectonism (~1650 – 1600 Ma; D₂), each involving regional high temperature metamorphism, open to isoclinal folding, and plutonism. Proterozoic deformation resumed around ~1450 – 1370 Ma (D₃ & D₄) with rampant magmatism and shear zone development along Paleoproterozoic high-strain zones as a response to deformation along the former southern margin of Laurentia (Shaw et al., 2001). More recent studies from metasedimentary units in the Picuris Mountains of northern New Mexico, detailing sedimentation and crustal thickening during the tectonic event termed the Picuris orogeny (1500 – 1400 Ma; Daniel et al., 2013; Aronoff, 2016), may serve as a mechanism for shear zone activity in central Colorado, far inboard from the former active margin in northern New Mexico.

The Slide Lake shear zone (SLSZ) is a southeast-dipping sub-horizontal mylonite to ultramylonite zone located 4 km southwest of the HSZ (Figure 2). Lee et al. (2012) performed the first kinematic analysis of the SLSZ, using the HSZ as a reference. The shear zones record similar metamorphic signatures (amphibolite to greenschist facies), kinematic shear sense (top-to-the-southeast and top-to-the-northwest shear sense), and deformation textures; this evidence suggests that the shear zones were active at around the same time and at the same depth in the crust. A timing constraint for the activity of the SLSZ will give insight into how neighboring sub-vertical and sub-horizontal shear zones work to accommodate strain in the mid-crust during tectonic

events. Additionally, advancements of the *in situ* monazite dating technique (Williams et al., 2006; Williams et al., 2017) since the original application (Shaw et al., 2001; McCoy et al., 2005) presents an excellent opportunity to revisit the CMB shear zone system with a refined methodology.



This study combines *in situ* monazite dating with new field and microstructural observations, and aims to 1) re-examine the timing of the CMB shear zones, 2) better understand the link between monazite microstructures and strain, and 3) place the first ever timing constraint on the activity of the SLSZ.

CHAPTER 2:

BACKGROUND

Tectonic convergence adds newer terranes onto preexisting lithosphere, as the continental interior grows outward with progressively younger crust. Upon assembly, these terranes are subjected to crustal shortening, extension, and transpression as blocks of crust with varying rheological properties move relative to one another (Molnar, 1988; Bowring and Karlstrom, 1990). The resulting structures are weakened upon repeated activation, producing lasting tectonic discontinuities that persist into an intracontinental setting (Burchfiel et al., 1989). Continued shortening along these tectonic boundaries results in concentrated strain, forming penetrative structures where stress is localized into shear zones (Sibson, 1977). At mid to lower crustal depths these structures are represented by ductile shear zones, which transition upward into brittle faults (Passchier and Trouw, 2005). The recognition and study of these shear zones helps to better understand how deformation is accommodated in the middle-crust during convergence.

Shear zones that are recorded by Proterozoic rocks in the southwestern United States have been thoroughly researched, and are believed to correspond to the reactivation of structures formed during 1800 to 1600 Ma convergent events (Tweto and Sims, 1963; Bowring and Karlstrom, 1990; Karlstrom and Humphreys, 1998; Shaw et al., 2001; McCoy et al., 2005). These shear zones cross-cut Proterozoic crust that extends from the Cheyenne belt suture (Karlstrom and Houston, 1984) southwards into Colorado and New Mexico, constituting juvenile lithosphere and volcanic arcs that accreted to the Wyoming craton in a series of northwest-directed shortening events (Whitmeyer and Karlstrom, 2007). Sub-vertical shear zones in the CMB specifically record the deformation associated with mylonitic shearing (~1400 Ma) chronologically and spatially related to localized pluton emplacement (Shaw et al., 2001; McCoy

et al., 2005). The presence of sub-horizontal shear zones in the CMB raises the question as to whether these are linked to the steeply dipping shear zones, or whether they correspond to a different intracontinental mechanism related to crustal shortening or extension (Lee et al., 2012).

2.1. Geologic Setting

The collision of the Archean cratons during the Trans-Hudson orogeny (1900 – 1800 Ma) provided the tectonic foundation for the subsequent allochthonous terrane accretion that would persist throughout the Proterozoic (Hoffman, 1988; Ross and Villeneuve, 2003; Whitmeyer and Karlstrom, 2007). Following assembly of the Laurentian core, juvenile island arcs accreted onto the southern margin of the Archean craton (1800 – 1700 Ma), making up the Yavapai province (Whitmeyer and Karlstrom, 2007). A series of northeast-trending subduction zones delivered arc material with fragments of older crust (Hill and Bickford, 2001), culminating in the Yavapai orogeny 1710 – 1680 Ma (Whitmeyer and Karlstrom, 2007). The Yavapai province extends from Arizona and New Mexico to the Cheyenne belt suture in northern Colorado (Bowring and Karlstrom, 1990; Karlstrom and Bowring, 1993; Karlstrom and Humphreys, 1998).

The Mazatzal province consists of 1700 – 1600 Ma volcanic-arc material that formed on southern Laurentia following the Yavapai orogeny (Karlstrom and Bowring, 1988; Karlstrom and Bowring, 1993; Whitmeyer and Karlstrom, 2007). 1680 – 1650 Ma plutons range from the Cheyenne belt to the Mojave province (Premo and van Schmus, 1989), recording magmatism over an extensive area of southern Laurentia during the construction of the Mazatzal province (Whitmeyer and Karlstrom, 2007). The Mazatzal orogeny (1650 – 1600 Ma) comprised the metamorphism, thrusting, and shortening of the Mazatzal crust that accreted following the Yavapai orogeny (Whitmeyer and Karlstrom, 2007).

Mesoproterozoic tectonism in the Yavapai province (Tweto and Sims, 1963; McCoy et al., 2005) is interpreted to be a response to far afield tectonic forces in southern Laurentia coeval with the assembly of the Granite-Rhyolite province (1500 – 1300 Ma) (Bickford and Van Schmus, 1985; Lidiak et al., 1966) as part of A-Type intracratonic magmatism (Whitmeyer and Karlstrom, 2007). Evidence for this Mesoproterozoic deformation event comes from widespread shear zone development and plutonism (Bowring and Karlstrom, 1990). Originally thought to be anorogenic (Anderson, 1983; Hoffman, 1989; Frost et al., 2001), many of these granitic intrusions are locally associated with mylonitic shear zones (McCoy et al., 2005). This correlation may be caused by the relationship between magmatism and thermally weakened crust, where reactivated tectonic fabrics assist pluton emplacement. For example, shear zones in the CMB record 1450 – 1300 Ma high-strain deformation, coeval with adjacent plutonism (McCoy et al., 2005).

More recent studies have alternatively suggested that the 1500 – 1300 Ma deformation event is related to the final accretion of the Mazatzal province (Aronoff et al., 2016; Daniel et al., 2013; Jones et al., 2015) after a period of tectonic quiescence following the Yavapai orogeny. Detrital zircon grains (1490 – 1450 Ma) deposited in the Trampas/Picuris basin of northern New Mexico, which preceded regional Al_2SiO_5 triple point metamorphism and 1460 – 1400 Ma amphibolite facies metamorphism, detail sedimentation and crustal thickening during the contractional Picuris orogeny (Daniel et al., 2013; Jones et al., 2015; Aronoff et al., 2016).

2.2. The Colorado mineral belt shear zone system

The CMB shear zone system consists of northeast striking ($028^\circ - 090^\circ$; McCoy et al., 2005) mylonite and ultramylonite zones that record the Proterozoic deformation of Laurentia

(Tweto and Sims, 1963; Selverstone et al., 2000; Shaw et al., 2001; McCoy et al., 2005; Allen and Shaw, 2011; Lee et al., 2012). Each main shear zone is ~1 km wide, with individual mylonite zones and ultramylonite zones that are meter- to decimeter-scale, and millimeter- to centimeter-scale, respectively. These shear zones are mostly sub-vertical (dips range from 74° NW to 66° SE; McCoy et al., 2005), have steeply dipping mineral lineation's, and record dip-slip motion (McCoy et al., 2005; Lee et al., 2012). Individual shear zones may represent discontinuous branches of one shear zone splay that was offset by dextral faulting (McCoy et al., 2005). Shear zones are subparallel to high strain axial planar cleavage found in Paleoproterozoic folds (Shaw et al., 2001; McCoy et al., 2005).

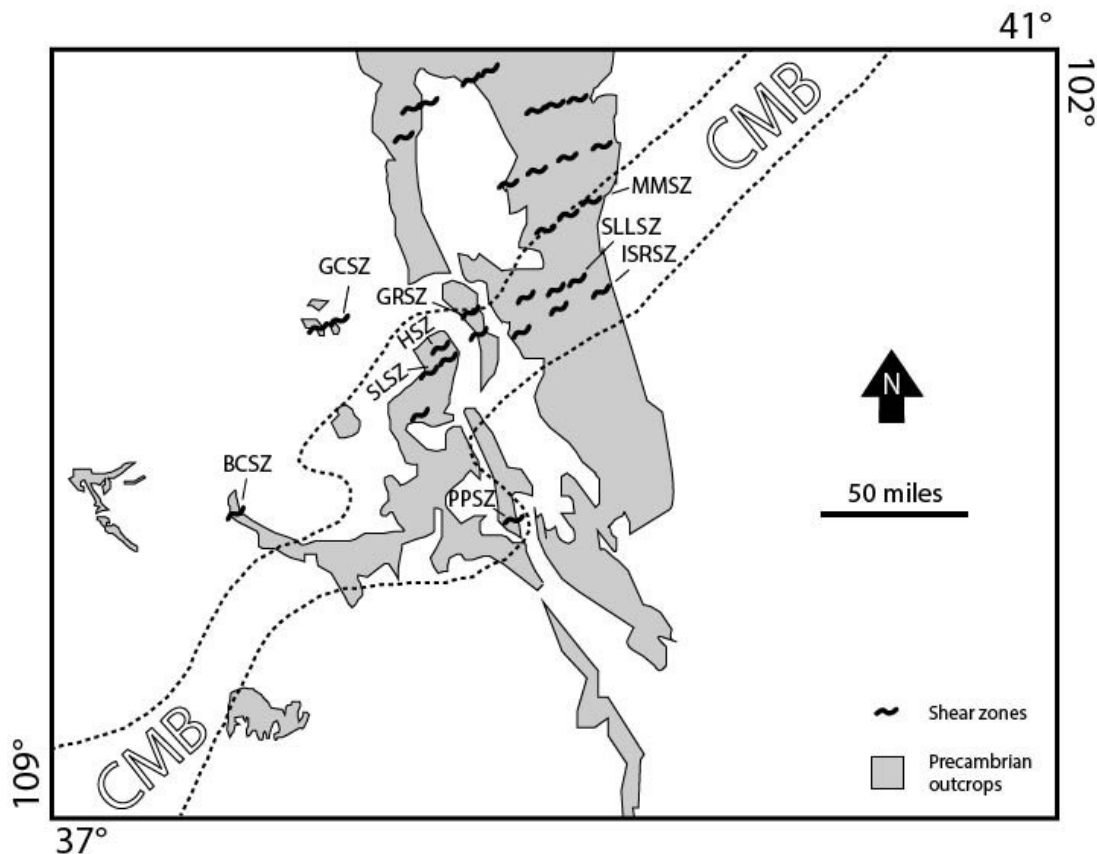


Figure 3: Geologic map of Colorado with highlighted Precambrian outcrops and shear zones in the Colorado mineral belt (CMB) (Clarey et al., 2004; Allen and Shaw, 2011). Shear zone locations from Allen and Shaw, 2011; Lee et al., 2012. BCSZ = Black Canyon, GCSZ = Grizzly Creek, SLSZ = Slide Lake, HSZ = Homestake, GRSZ = Gore Range, PPSZ = Poncha Pass, MMSZ = Moose Mountain, SLLSZ = St. Louis Lake, ISRSZ = Idaho Springs-Ralston.

Combining field relationships, geometry, and kinematics of different shear zone segments yields four distinct deformation events that record the evolution of the intracontinental Proterozoic core of Laurentia into progressively narrower zones of deformation (Figure 4) (Shaw et al., 2001; McCoy et al., 2005). D₁ is defined by regional S₁ sub-horizontal fabrics with isoclinal, recumbent F₁ folds with migmatites that were synchronous with high-grade metamorphism (McCoy et al., 2005). D₂ is recorded by the refolding of S₁ into F₂ folds with shallowly plunging fold axes (S₂), which are locally rotated into the S₂ sub-vertical high-strain zones. F₂ folds steepen with proximity to the high-strain domains, such that the F₂ fold axes parallel the sub-vertical mineral lineations, indicating that both the folds and high-strain zones were part of D₂ (McCoy et al., 2005). Zones of mylonitic deformation overprint older high-strain D₂ domains with sub-vertical S₂ fabrics, recording lower temperature microstructures with southeast-side-down displacement (Shaw et al., 2001). Ultramylonite formation (D₄) features grain-size reduction with a strong mineral lineation, lower deformation temperatures, and southeast-side-up shear sense with a minor dextral component.

Electron microprobe (EMP) *in situ* monazite dating applied to the sub-vertical Homestake shear zone (HSZ) related monazite growth to fabric development, deformation episodes, and metamorphism (Shaw et al., 2001; McCoy et al., 2005). Results from the HSZ indicated that the first phase of Paleoproterozoic deformation (D₁) is recognized by high-temperature, flow near the sillimanite stability field which generated partial melting and the formation of magmatic leucosomes and melanosomes, defining the subhorizontal S₁ at $>1708 \pm 6$ Ma (Shaw et al., 2001). This sub-horizontal flow progressed into northwest-southeast-shortening that transposed S₁ into a sub-vertical, northeast striking shear zone S₂ with steeply plunging mineral lineation at 1637 ± 13 Ma (Shaw et al., 2001). Mesoproterozoic deformation is

characterized by localized, moderate temperature shear zone development that overprinted steep S_2 fabrics with mylonitic foliation (1450 – 1370 Ma). A weighed average of 1372 ± 19 Ma was interpreted to represent the age of D_3 top-down-to-the-southeast shear sense. The final phase of Proterozoic deformation overprinted earlier fabrics with straight, narrow shear splays of ultramylonite, recording top-up-to-the-northwest shear sense at 1375 ± 14 Ma (Shaw et al., 2001). The timing of structure formation in the HSZ field area inferred from Shaw et al. (2001) overlaps with the emplacement of the neighboring Cross Creek (~ 1675 Ma [Rb-Sr]; Tweto and Lovering, 1977) and the St. Kevin Batholiths (1396 ± 40 Ma [U-Th-Pb zircon]; Doe and Pearson, 1969); hornblende and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ data from a transect across the HSZ range from 1650 to 1400 Ma (Shaw et al., 2005).

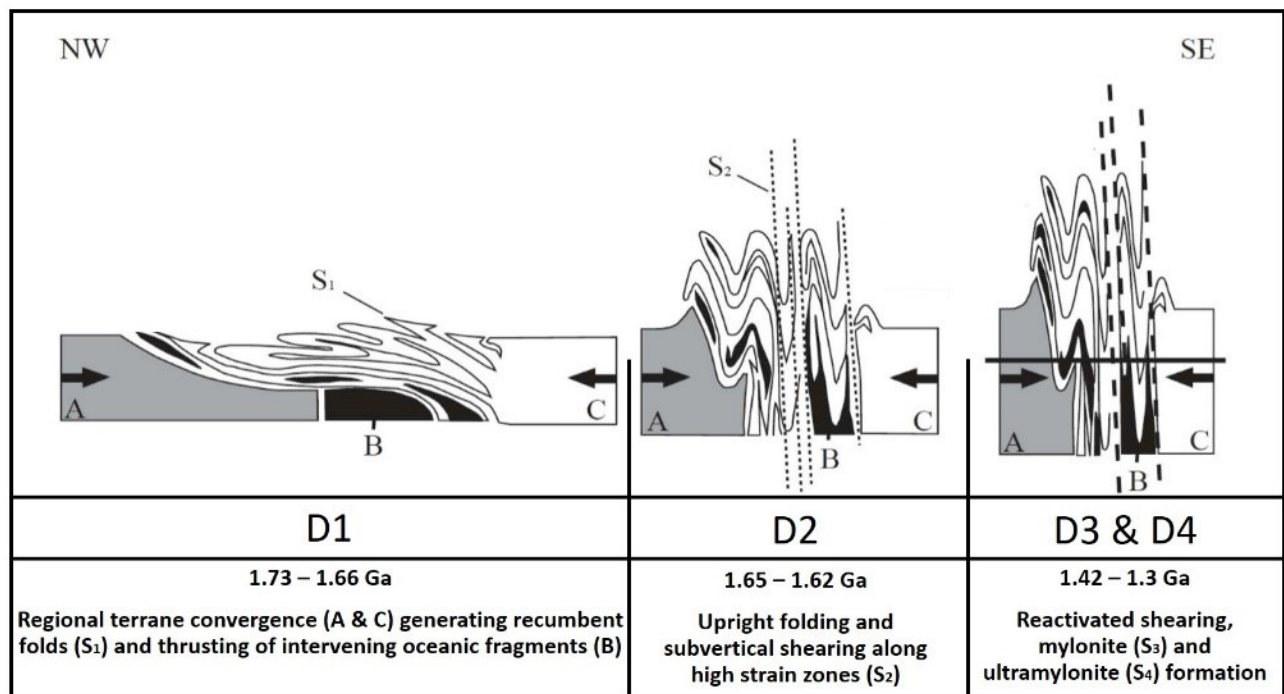


Figure 4: Model assembly for Proterozoic terrane accretion and the resulting structures. Modified from McCoy et al. (2005).

In situ monazite dating was applied to three other sub-vertical shear zones in the CMB, roughly on strike with the HSZ: Gore Range shear zone (GRSZ), Idaho-Springs Ralston shear zone (ISRSZ), and St. Louis Lake shear zone (SLLSZ) (Figure 5) (McCoy et al., 2005). Monazite ages from the three shear zone segments cluster at around ~1700 – 1600 Ma, and 1450 – 1300 Ma, with little activity recorded between the major events. In relation to structural fabrics and regional tectonic events, this research infers monazite growth in the CMB approximately parallels with Yavapai (D₁: 1700 Ma) and Mazatzal (D₂: 1650 Ma) orogenesis followed by Mesoproterozoic shear zone activity associated with intracontinental deformation during rampant plutonism (D₃ & D₄: 1450 – 1300 Ma) (McCoy et al., 2005). All told, these four Proterozoic deformation events recorded in the CMB have served as a crucial reference for continental assembly and subsequent intracontinental deformation of the Yavapai province.

2.3. The Slide Lake shear zone

Lee et al., (2012) completed the first detailed structural study of the Slide Lake shear zone (SLSZ). The SLSZ is located at the juncture between Lake and Eagle Counties, CO, adjacent to Homestake Peak (Figure 2). The shear zone is defined by mylonite, ultramylonite, and pseudotachylite zones that cut across a *mélange* of variably folded and partially melted metasedimentary rock, consisting of migmatite, schist, gneiss, amphibolite, and calc-silicate gneiss (Figure 2) (Lee et al., 2012). The northeast-trending shear zone is exposed southeast of Homestake Valley along the Homestake and Bennett ridgelines, and down into Slide Lake Cirque and Bennett Gulch (Figure 6). The three main splays of the SLSZ, as defined by Lee et al. (2012), include the Homestake Ridgeline, Bennett Ridgeline, and Slide Lake pavement.

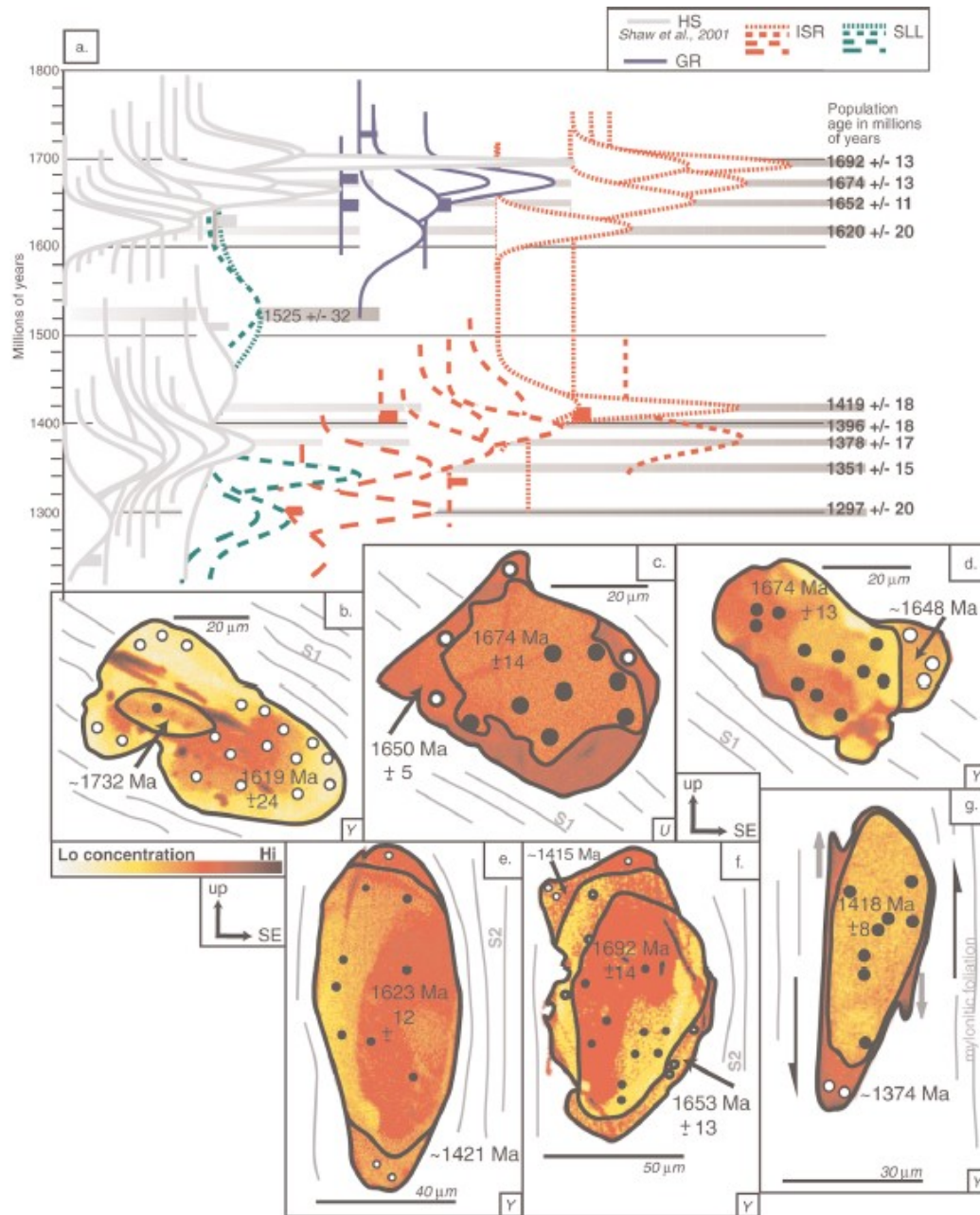


Figure 5: Electron microprobe monazite data from Colorado mineral belt shear zones. A.) Distribution curves of microprobe monazite dates based on 4–17 spot analyses from the Homestake (HS), Gore Range (GR), Idaho-Springs Ralston (ISR), and St. Louis Lake (SLL) shear zones. B – G.) Examples of electron microprobe X-ray maps demonstrating uranium (U) and yttrium (Y) zoning and average U-Th-Pb monazite dates. From McCoy et al. (2005).

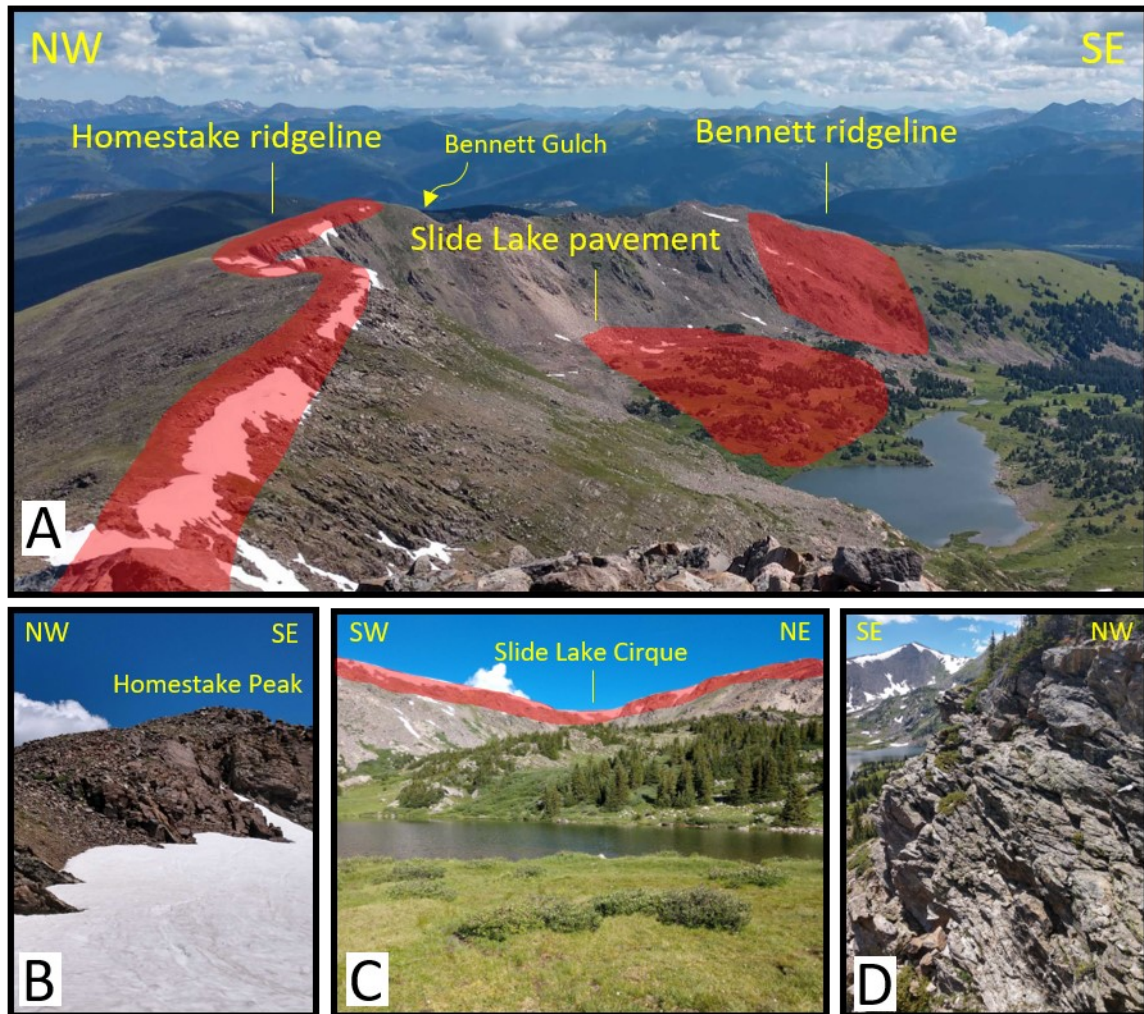


Figure 6: Geographic context of representative field features in Slide Lake. Overview of Slide Lake field area with reference to geographic markers A.) Picture taken from Homestake Peak showing the locations of the three main mylonite exposures (Homestake ridgeline, Slide Lake pavement, Bennett ridgeline). B.) View of mylonite splays just below Homestake Peak. C.) View of Slide Lake pavement and Slide Lake Cirque. D.) View of Homestake Peak from Slide Lake pavement.

Mesoscale framework

Lee et al. (2012) found the majority of the Proterozoic basement featured in the SLSZ field area consists of Paleoproterozoic biotite gneiss and migmatite (biotite [bt] + garnet [grt] + sillimanite [sil] + quartz [qtz] + feldspar [fsp] + muscovite [ms]), calc-silicate gneiss (hornblende [hbl] + calcite [cal] + qtz + chlorite [chl]), and granitoids (Figure 7). Lee et al., (2012) suggested Paleoproterozoic deformation events D₁ and D₂ are represented by high temperature metamorphism and open to isoclinal folding (Figure 7A & C). Leucosomes and melanosomes in

migmatite define S_1 sub-horizontal flow, corresponding to regional nappe formation (Figure 7B). This early fabric was displaced into moderately to steeply dipping S_2 gneissic fabric coeval with amphibolite facies metamorphism, with open to isoclinal F_2 folds.

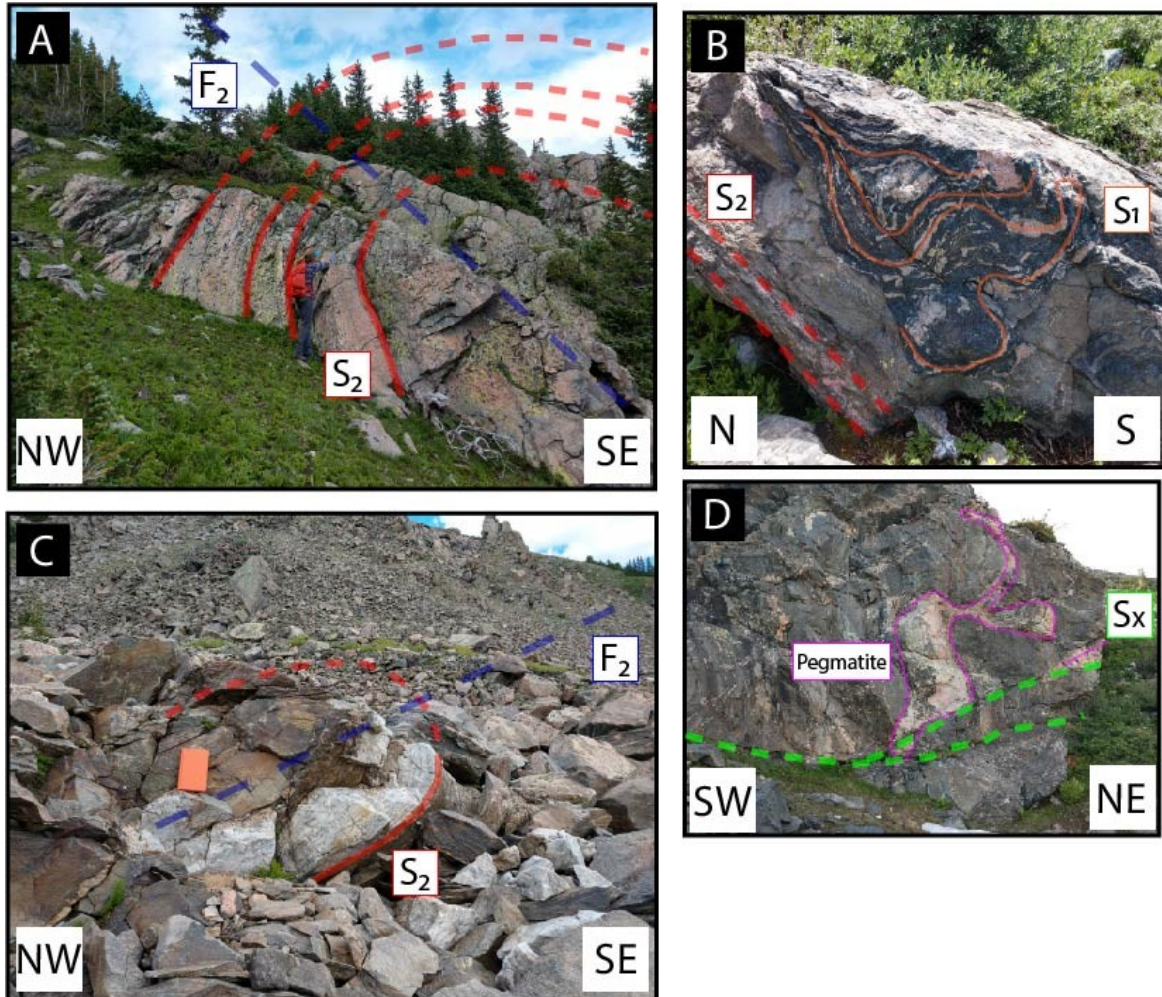


Figure 7: Paleoproterozoic structures from Slide Lake. A.) Open gneissic fold with SE-dipping axial plane. B.) S_1 migmatite fabric overprinted by S_2 gneissic foliation. C.) NW-dipping axial plane of F_2 fold. D.) Pegmatite intrusion adjacent to sub-horizontal mylonite zone (S_x).

Lee et al., (2012) proposed the higher strain Mesoproterozoic deformation events (D_x) are recorded by grain-size-reduced mylonite and ultramylonite zones that can in places truncate the older Paleoproterozoic fabric (Figure 8A). The greenschist facies mylonite zones (qtz+fld+bt $\pm$ chl+ms) dip gently to the northeast and southeast (Figure 8B, C, D), with north- and south-plunging stretching lineations. S_x is defined by the alignment of elongate micaceous layers and quartzose shear bands, with a larger proportion of mica in ultramylonite layers (Figure 8D). Asymmetric shear bands, rotated feldspar porphyroclasts, and S-C foliation are used to recognize top-to-the-southeast, and minor top-to-the-northwest, shear sense (e.g., Figure 8C). Exposures of mylonite zones are cm- to m- scale, while ultramylonite zones are usually 1 cm wide (Figure 8D).

The Slide Lake Pavement and Homestake ridgeline mylonite splays are characterized as dominantly east dipping and sub-horizontal (average: 007, 24°), with stretching lineation's plunging to the northwest and southeast (average: $L_{3(SL)} 9^\circ \rightarrow 165$) (Figure 9). The Bennett ridgeline mylonite is more moderately dipping to the southeast (average: 048, 60°), with southeast-plunging stretching lineations (average: $L_{3(SL)} 59^\circ \rightarrow 121$).

Microscale framework

Mylonitic rocks from the SLSZ (qtz+fsp+bt+ms $\pm$ cal) are dominantly characterized by a foliated matrix of grain-size reduced quartz and aligned mica grains (Lee et al 2012; Figure 10A). Quartz deformation textures show grain-boundary migration (GBM) (> 500°C) and grain-boundary area reduction (GBAR) textures (Lee et al., 2012; Figure 10F), sometimes pinned by phyllosilicates and restricted to narrow bands (Lee et al., 2012; Figure 10C). Feldspar porphyroclasts mostly exhibit microfracturing (< 450°C), with minor core and mantle structures

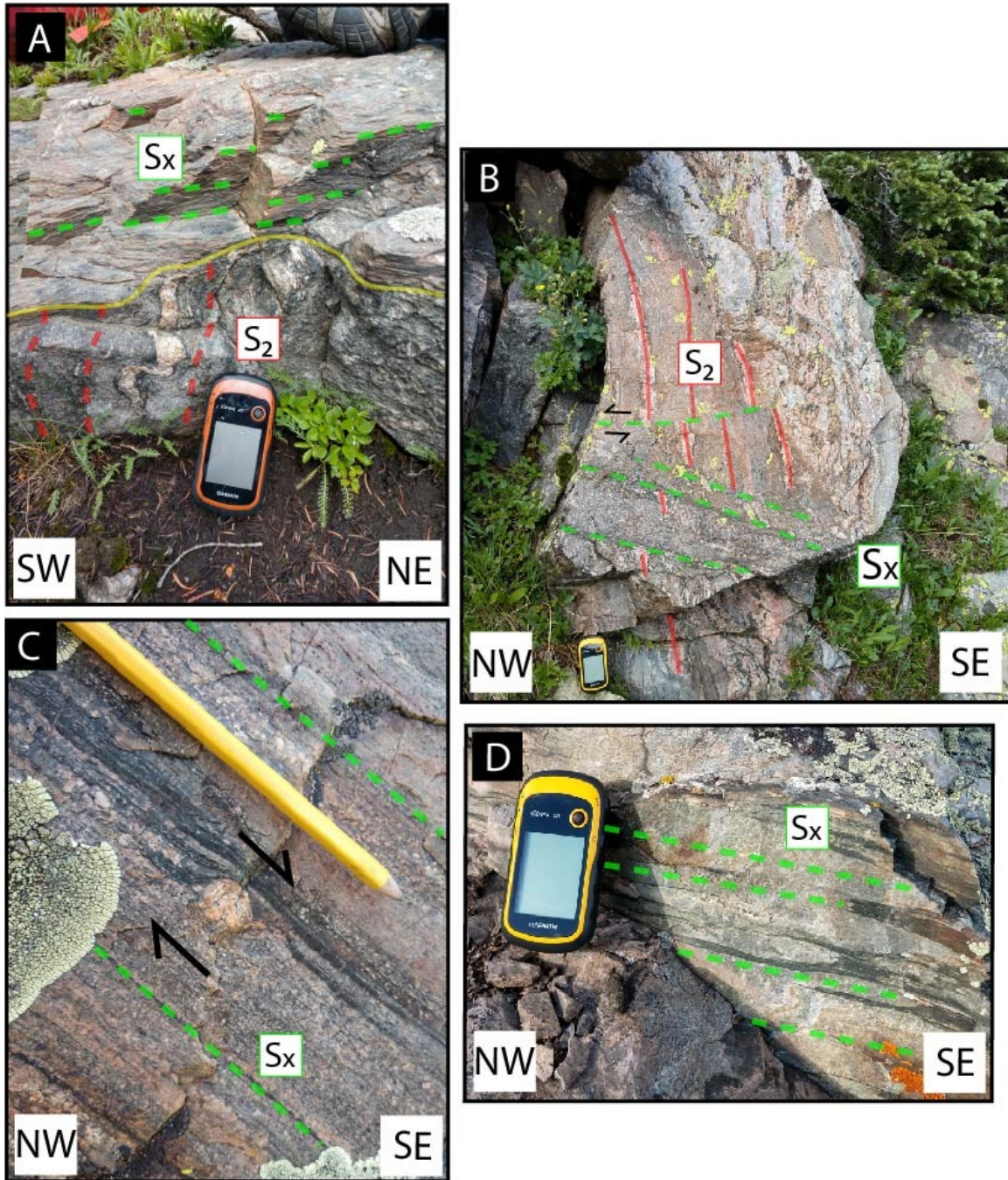


Figure 8: Mesoproterozoic structures from Slide Lake. A.) Gneissic fabric (S₂) crosscut by high strain mylonite zone (S_x). B.) S₂ fabric sheared by mylonitic high strain domain. C.) δ-clast showing t-SE shear sense in mylonite. D.) Sub-horizontal mylonite (light) and ultramylonite (dark) zone.

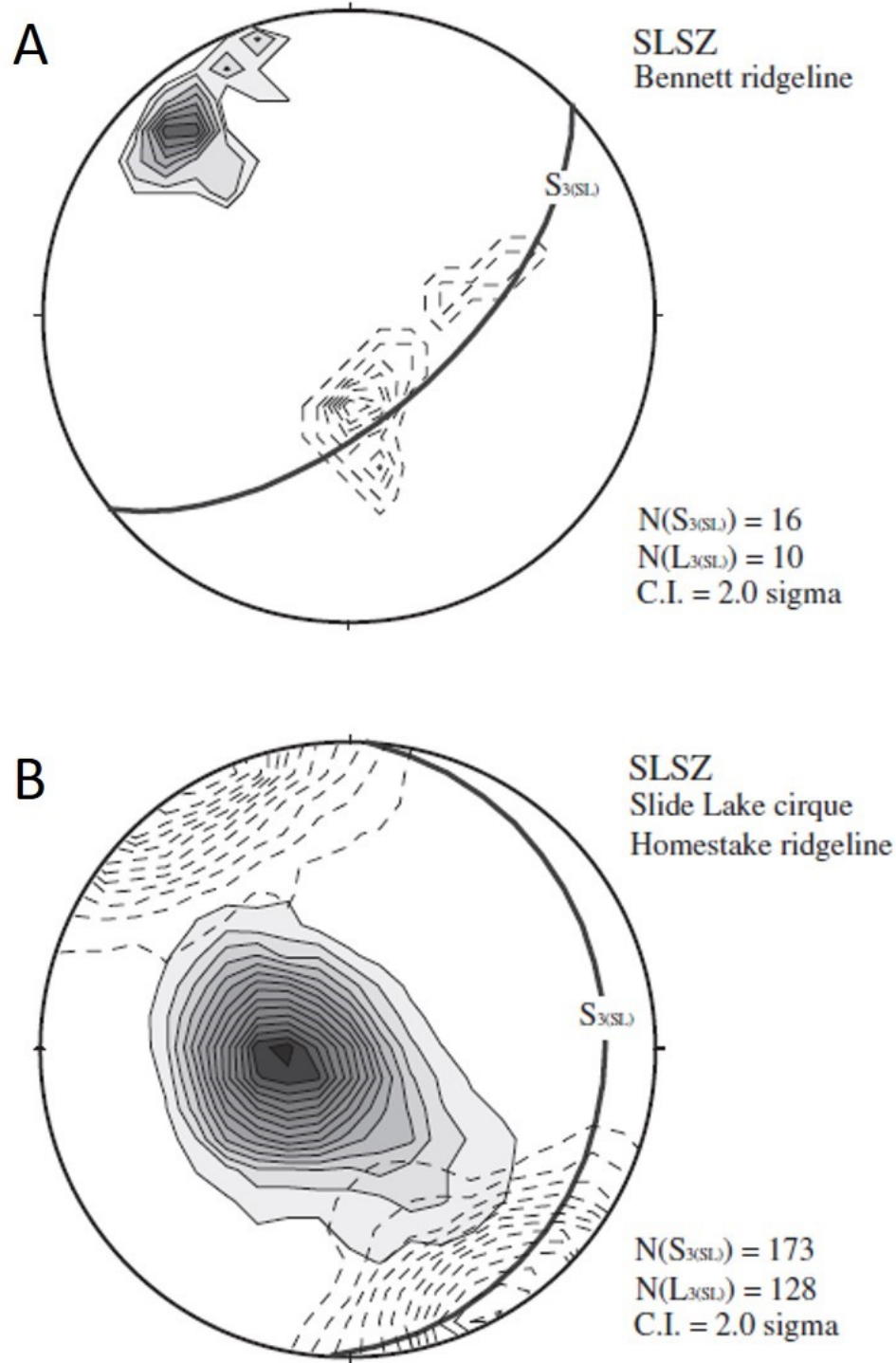


Figure 9: Lower hemisphere equal area stereograms demonstrating foliation and lineation measurements of mylonitic rocks from the Slide Lake field area. Black planes show the average mylonitic foliation plane, shaded contours represent poles to foliation, and dashed contours represent stretching lineations. (A) Bennett ridgeline splay, S_3 (048, 60°SE), $L_{3(SL)}$ (59°→ 121). (B) Slide Lake cirque and Homestake ridgeline splays, S_3 (007, 24°SE), $L_{3(SL)}$ (9°→ 165). From Lee et al. (2012).

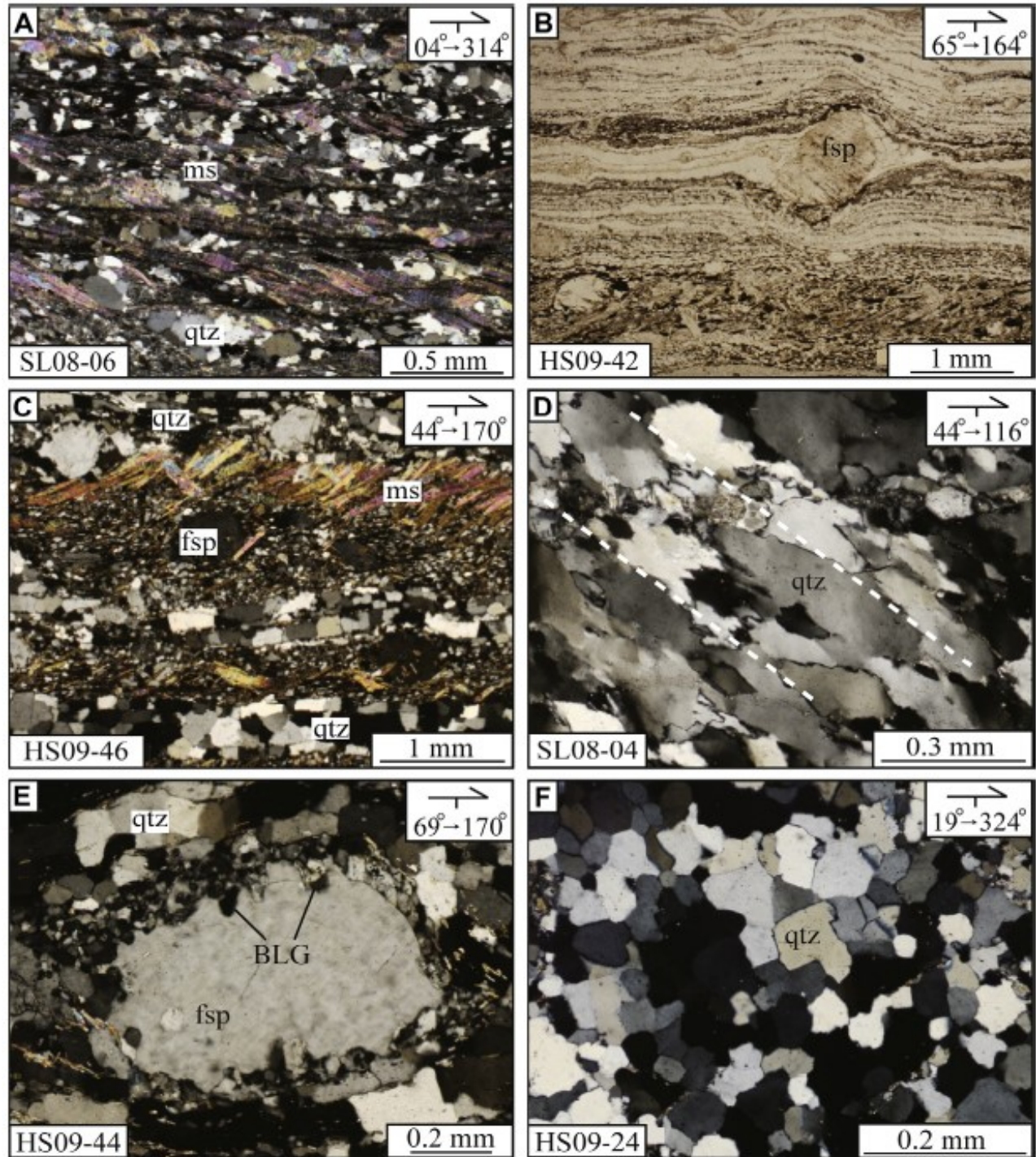


Figure 10: Examples of photomicrographs from SLSZ, from Lee et al. (2012). A.) Mylonite with S-C fabric recording top-to-the-southeast shear sense. (B) Rigid feldspar porphyroclasts showing top-to-the-southeast shear sense. C.) Mylonite with elongate grain-boundary migration (GBM) quartz domains pinned by phyllosilicates. D.) Oblique grain-shape fabric in quartz grains, showing top-to-the-northwest sense of shear. E.) Core and mantle feldspar structures surrounded by quartz grains. F.) Quartz grains exhibiting Grain Boundary Area Reduction (GBAR).

exhibiting bulging (BLG) recrystallization (450-600°C) (Lee et al., 2012; Figure 10E). Both top-to-the-northwest and top-to-the-southeast shear sense is exemplified by asymmetric tails on rigid porphyroclasts (Lee et al., 2012; Figure 10B), oblique grain-shape fabric (Lee et al., 2012; Figure 10D), and S-C fabric (Lee et al., 2012; Figure 10A).

Kinematic model

Figure 11 shows a block diagram that illustrates the kinematic relationship between the HSZ and SLSZ. Despite the lacking relative or absolute timing constraints between the HSZ and SLSZ, similarities in structural domains, shear sense, and microstructures suggest that the two shear zones were active at equivalent crustal levels (Lee et al., 2012).

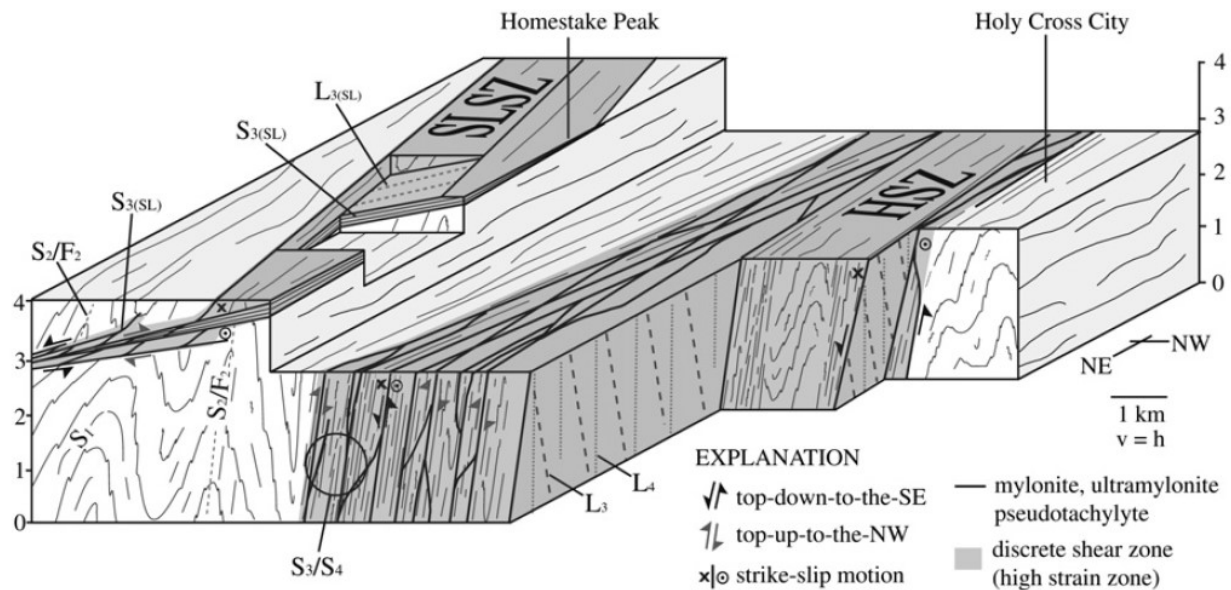


Figure 11: Kinematic diagram of the Slide Lake and Homestake shear zones viewed to the south. From Lee et al. (2012).

2.4. Introduction to Monazite

Electron Microprobe (EMP) dating of monazite has become popular for delimiting the timing of deformation in metamorphic assemblages (Suzuki and Adachi, 1991; Suzuki and Adachi, 1998; Montel et al., 2000; Terry et al., 2000; Simpson et al., 2000; Shaw et al., 2001; Williams and Jercinovic, 2002; Asami et al., 2002; Cheong et al., 2002; Pyle and Spear, 2003; Hibbard et al., 2003; Ticktyj et al., 2004; Foster et al., 2004; Goncalves et al., 2004; Mahan et al., 2006; Williams et al., 2006; Williams et al., 2017). Constraining the ages of deformation events involves choosing monazite crystals in relationship with structural fabric elements in a rock and obtaining EMP U-Th-Pb dates that can be tied to growth events (Williams et al., 1999). This technique is made possible by the high closure temperature of monazite ($> 900^{\circ}\text{C}$; Cherniak et al., 2004) and the slow diffusion of Pb in monazite (Crowley and Ghent, 1999; Cherniak et al., 2004). Metamorphic monazite typically displays compositional zoning corresponding to growth and dissolution events during deformation and metamorphism, creating a link between structural kinematics and geochronology (Williams et al., 2006). In some cases, these compositional domains can be related to the P-T path of a metamorphic assemblage (Williams et al., 2006). The small spatial resolution of the EMP ($< 5\ \mu\text{m}$) permits the user to examine several distinct compositional domains in a single monazite crystal (Williams et al., 2006). The goal of this method is to obtain geologically meaningful ages using *in situ* electron microprobe compositional mapping and chemical dating.

Monazite stability

The stability of monazite precipitating in metapelitic rocks along a prograde metamorphic path reportedly depends on bulk CaO, assuming moderate light rare-earth element (LREE)

concentrations: rocks deficient in CaO can precipitate monazite from low greenschist facies through granulite facies conditions (Overstreet, 1967; Spear and Pyle, 2002), whereas rocks with sufficient CaO concentrations see the replacement of monazite by allanite at ~ 450 °C until monazite reappears around the aluminosilicate-in isograd (e.g., Smith and Barreiro, 1990; Kingsbury et al., 1993; Wing et al., 2003; Kohn and Malloy, 2004; Fitzsimons et al., 2005; Rasmussen et al., 2006; Janots et al., 2006, 2008; Tomkins and Pattison, 2007; Corrie and Kohn, 2008; Spear, 2010). Monazite found in greenschist rocks are believed to be detrital relics, as it is unstable during diagenesis (Overstreet, 1967), and is mostly absent from samples in the chlorite + biotite zone (Kingsbury et al., 1993). Considerable growth of monazite is absent until the aluminosilicate-in isograd, above which monazite continues to grow with increasing metamorphic grade (Franz et al., 1996; Rubatto et al., 2001). In granulite facies conditions, monazite crystals are large and commonly have more complex compositional zoning, suggesting melt-assisted dissolution and reprecipitation (Rubatto et al., 2001).

Monazite stability additionally relies on the presence of additional P and REE-bearing phases (Spear and Pyle, 2002; Kohn and Malloy, 2004). Although monazite occurrence is often related to allanite breakdown, other studies have documented that major silicate phases have sufficient LREE and P concentrations to produce secondary monazite (e.g., Kohn and Malloy, 2004). Apatite $[\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})]$ and xenotime $[\text{YPO}_4]$ presence also control monazite stability, serving as a major sink for Y, P, and REE's (Spear and Pyle, 2002).). Like monazite, apatite and xenotime (if garnet is absent: Pyle and Spear, 1999) are stable across all metamorphic grades (Spear and Pyle, 2002). Monazite coexisting with xenotime has higher Y and heavy rare-earth element (HREE's) concentrations with increasing temperature, as these elements favorably partition into xenotime at lower grades (Pyle et al., 2001). Apatite often replaces monazite during

hydrothermal alteration where trace and REE's are removed from the host-monazite, sometimes resulting in discordant U-Pb ages (e.g., Lanzirotti and Hanson, 1996).

Monazite deformation

The U-Th-Pb monazite system operates according to fluid composition and intra-grain transport of elements during active deformation and metamorphism (Harlov and Hetherington, 2010; Seydoux-Guillaume et al., 2002). Metamorphic reactions release fluids that accelerate the resetting of the U-Th-Pb system in monazite, effectively producing datable monazite domains. Wawrenitz et al. (2012) describe two deformation mechanisms from which monazite recrystallizes: dislocation creep and dissolution-precipitation creep (DPC). The dissolution of major mineral phases (specifically feldspar and apatite) will produce an alkali-rich fluid that enhances DPC to dissolve older pre-deformative monazite, and precipitate younger syn-deformative monazite. Monazite solubility increases at grain boundaries normal to the principal compressive direction, and new grains exhibit shape elongation parallel to the principal extension axis. Rocks primarily deformed by dislocation creep involve intra-grain transport of U, Th, and Pb into anomalous patches within monazite grains, yielding too low or too high ages (Goncalves et al., 2005; Williams et al., 2011). Accordingly, rocks exhibiting DPC are more suitable for constraining the deformational history of a rock with in-situ monazite dating.

In ductile shear zones, syn-kinematic geochronometer minerals are typically present as small ($< 100 \mu\text{m}$) grains orientated parallel to the mylonitic fabric (Rolland et al., 2009). Shear zones localize fluid flow through grain-size reduction processes (Kerrick, 1986; McCaig et al., 1990; Barnes et al., 2004), affecting the porosity and permeability of rocks that can drive metasomatic reactions (e.g., Putnis and Austrheim, 2010). These reactions can alter U, Th, and /

or Pb in monazite, effectively resetting ages (Williams et al., 2011). As monazite is reset during metamorphic / fluid infiltration events, a record of these events can be preserved in monazite grains, with the youngest shear zone deformation preserved as rims (e.g., Mahan et al., 2006). Monazite susceptibility to these metamorphic fluids depends on its location in the rock, as when it is enclosed in a major phase (ex: porphyroclast), the monazite age should record the timing of entrapment (Ayers et al., 1999).

CHAPTER 3:

METHODS

This project combines field measurements, microstructural analysis, qualitative chemical mapping, and electron microprobe dating in an effort to generate ages for the timing of high-strain mylonite zones in the Slide Lake area as well as the tectonic conditions that were involved. Structural measurements and samples that were collected during the 2019 field season were added to the existing dataset of Lee (2011) and used to reinforce structural relationships. Lee (2011) created a detailed map, field context, samples, thin sections, detailed kinematics, lattice preferred orientation plots, qualitative estimates of deformation temperatures, and provided a tectonic framework for the SLSZ and HSZ (Lee, 2011; Lee et al., 2012). Lee (2011) identified monazite grains in some samples, by locating them on full thin section maps using a slide scanner. Previously collected mylonite samples (Lee, 2011; Lee et al., 2012) provided the framework for detailed microstructural analysis and monazite characterizations as part of my thesis. Correlation of monazite microstructures and geochemistry between grains allowed for the extrapolation of growth events through metamorphic reactions, leading to electron microprobe dating of monazite growth domains in relation to shear zone processes.

3.1. Field work and structural analysis

Field data and sample collection occurred during summer 2019 in the Slide Lake field area. Five days were based in Leadville, CO (with collaborator Joe Allen, Concord University, WV) as well as three days at the 10th Mountain Division hut near Slide Lake (with collaborator Colin Shaw, Montana State University). This excursion focused on meso-scale structural relationships between the different rock types based on the previous research. It also served as an

overview of the areas geology, including the HSZ. Representative structural measurements of foliations, lineations, contacts, and shear-sense indicators were recorded and plotted on equal-area stereonet. Four oriented rock samples were collected along foliation planes for thin section preparation.

3.2. Microscale analysis

Polished thin sections were developed for microstructural and electron microprobe analysis. After using petrography to evaluate all the thin sections to establish the most suitable for the project, rock billets sampled by Lee et al. (2012) were used to create polished thin sections in spring 2019. Field samples collected during the summer 2019 were cut into billets in fall 2019. They were cut so that they were oriented perpendicular to foliation and parallel to lineation, as the XZ view is the best way to show sense of shear. All billets were sent to Spectrum Petrographics Inc. for thin section preparation. Due to limitation with time and budget, only the thin sections prepared in spring 2019 were used for the investigation of monazite, and the newly collected samples were only used for microstructural data. Microscopic investigation of thin sections took place in the Department of Earth and Planetary Sciences at UTK using the petrographic microscope in the Structural and Tectonics laboratory and Phenom Pro SEM in the electron microprobe laboratory. The samples were first inspected for microstructural features including bulk mineralogy and deformation/metamorphic fabrics, followed by monazite identification at precise locations. The petrographic microscope served as a first step for monazite recognition, which was later confirmed using the SEM.

Deformation mechanisms were utilized as described in Passchier and Trouw (2005) for quartz (Hirth and Tullis, 1992; Stipp et al., 2002), and feldspar deformation textures (Pryer,

1993). During dynamic recrystallization, quartz deformation textures reflect distinct styles of intra-crystalline deformation according to temperature, strain rate, and fluid content. Dynamic recrystallization of quartz includes grain-boundary bulging (BLG, 280-400°C), sub-grain rotation recrystallization (SGR, 400-500 °C), and high temperature grain boundary migration (GBM, > 500°C). Grain boundary area reduction (GBAR) denotes static recrystallization of quartz, typically following a relatively high temperature deformation event (Stipp et al., 2002). Intracrystalline deformation of feldspar involves BLG occurring around 450-600°C, SGR and BLG above 600°C (Pryer, 1993). Onset of microfracturing occurs at < 450 °C.

Once a detailed understanding of monazite characteristics and abundance in samples was established, four samples were selected to undergo more detailed electron microprobe mapping that preceded in-situ monazite dating. These samples were selected on the basis that they contained a sufficient number of monazite grains (> 15) and had varying microstructural characteristics, including bulk mineralogy, quartz and feldspar deformation textures, and strain indicators.

3.3. *In situ* monazite dating

Initial electron microprobe mapping of full thin sections and monazite grains was conducted using the Cameca SX-100 electron microprobe at UTK to chemically characterize the full thin section and determine monazite abundance. Individual monazite grains were mapped in summer 2019 for Y, U, Th, and Ca, and thin sections were mapped in Winter 2019 – 2020 for Al (for a general overview of sample microstructures) and Ce (for the precise location of monazite grains). These maps served as a precursor to more detailed mapping and dating to be conducted at the University of Massachusetts, Amherst.

Electron microprobe mapping and U-Th-Pb dating was completed at the University of Massachusetts (Amherst) Department of Geosciences Electron Microprobe/SEM Facility during Spring 2020, according to the analytical protocol of Williams et al. (2017). Polished thin section samples were coated with a 30 nm film of carbon coat for analysis with the Cameca SX-100 Electron Microprobe. Full thin section electron microprobe maps of Mg and Ce were used to identify the distribution of monazite grains and their relationship to the surrounding microstructural fabric in each polished section. Approximately 16 - 18 monazite grains from each sample were mapped at higher resolution to distinguish compositional domains represented by qualitative compositional variation in Y, Th, U, and Ca. The grain maps were simultaneously processed to normalize the intensity of element abundances in each grain. The resulting maps were overlain with the full sample maps in Adobe Illustrator to relate monazite locations and compositional zoning between grains.

Selected monazite domains were analyzed using the Cameca SX-Ultrachron microprobe. Each domain is measured for U-Th-Pb for age calculation, concurrent with the analysis of trace (Ca and Y) and rare-earth-elements (REE). The heavy REE's (HREE) measured include Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb, the light REE's (LREE) measured were La, Ce, Pr, Nd, Sm. A consistency standard was analyzed before and after each dating session (Moacyr: 505 ± 2.3 Ma). The analytical error for each domain was reported as a 1-sigma standard deviation. Monazite ages (mean) and their associated errors (standard deviation) were plotted as normal distribution curves using MATLAB. The analytical methods for domain-specific U-Th-total Pb dating are included in Williams et al. (2006) and Williams et al. (2017).

CHAPTER 4:

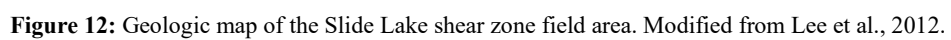
SAMPLE DESCRIPTIONS

Four samples previously collected by Lee et al. (2012) were selected for in situ monazite dating (HS09-36, HS09-35, HS09-42a, and SL08-07). Microstructural data from Lee et al. (2012) were used as a reference (Table 1) and expanded upon in this research. The samples were selected in order to evaluate the differences in monazite between samples of varying microstructural signatures. The chosen samples include a high-strained gneiss sample (HS09-36), two mylonites (HS09-35 and HS09-42a), and one ultramylonite (SL08-07). Figure 12 shows the locations of the samples used in this research: samples HS09-36 and HS09-35 are from Slide Lake Cirque along Homestake Ridgeline, SL08-07 is from Homestake Peak, and HS09-42a is from Bennett Ridgeline. Here we present full thin section scans, EMP maps, photomicrographs, and SEM backscatter images.

Table 1: SLSZ selected sample locations, structural, and microstructural data from Lee et al. (2012). Abbreviations: SLC, Slide Lake Cirque; BR, Bennett Ridgeline; HP, Homestake Peak; qtz my, quartz mylonite; c.s. my, calc-silicate mylonite; fsp my, feldspar mylonite; t-SE, top-down-to-the-southeast; t-NW, top-up to-the-northwest; q.d., quartz deformation textures, m.a., mineral assemblage.

Sample	Longitude	Latitude	Strike	Dip	Trend	Plunge	Rock type*	Shear sense*	Deformation Temperature (°C)	Temperature Indicator
HS09-36	39.37876	106.40499	139	28 NW	008	23	qtz my	t-NW	650 +	q.d. m.a.
HS09-35	39.37583	106.40716	102	22 NE	299	4	qtz my	t-SE	450 – 650	q.d. m.a.
HS09-42a	39.37498	106.39156	51	68 SE	164	65	qtz-fld my	t-SE	450 – 650	q.d. m.a.
SL08-07	39.36708	106.4171	330	21 NE	128	11	c.s. my	t-NW	400 - 500	m.a.

* Microstructural observations from Lee et al. (2012) were used as a guide, but different descriptions of rock types and shear sense were applied to the samples based on microstructural evidence from this research.



4.1. Microstructural framework

HS09-36

Sample HS09-36 is a high-strained gneiss (qtz+fsp+ms+bt) consisting of GBM quartz textures ($> 500\text{ }^{\circ}\text{C}$) and BLG feldspar ($450 - 600\text{ }^{\circ}\text{C}$) (Figure 13 & 14). An aluminum- rich layer bisects the sample consisting of syn-deformational muscovite and quartz (Figure 13). This layer, along with other small muscovite-rich layers, appears to crosscut the qtz+fsp+bt dominated fabric, likely corresponding to a later metamorphic / fluid infiltration event (Figure 14B). Asymmetry of quartz shear bands comprises an S-C fabric indicating top-to-the-southwest shear sense (Figure 14B).

HS09-35

Sample HS09-35 is a mylonite (qtz+ms+bt+fsp+sil) with a fabric of grain-size reduced quartz and aligned mica grains (Figure 15). Sillimanite is present as relict boudins and porphyroclasts (top-to-the-southeast shear sense), frequently rimmed by retrograde muscovite (Figure 14C). A large porphyroclast dominates the bottom of the samples, consisting of sillimanite surrounded by GBM quartz ($> 500\text{ }^{\circ}\text{C}$), which appears to have protected the sillimanite from retrograde metamorphic fluids (Figure 14E & 15). In the matrix, relict GBM quartz underwent grain-size reduction (Figure 14D). A finer-grained mylonitic fabric of grain-size reduced quartz and phyllosilicates is present outside of the clast, suggesting high-strain flow around the clast; a similar high-strain fabric occurs towards the top of the sample as one discontinuous layer (Figure 14E).

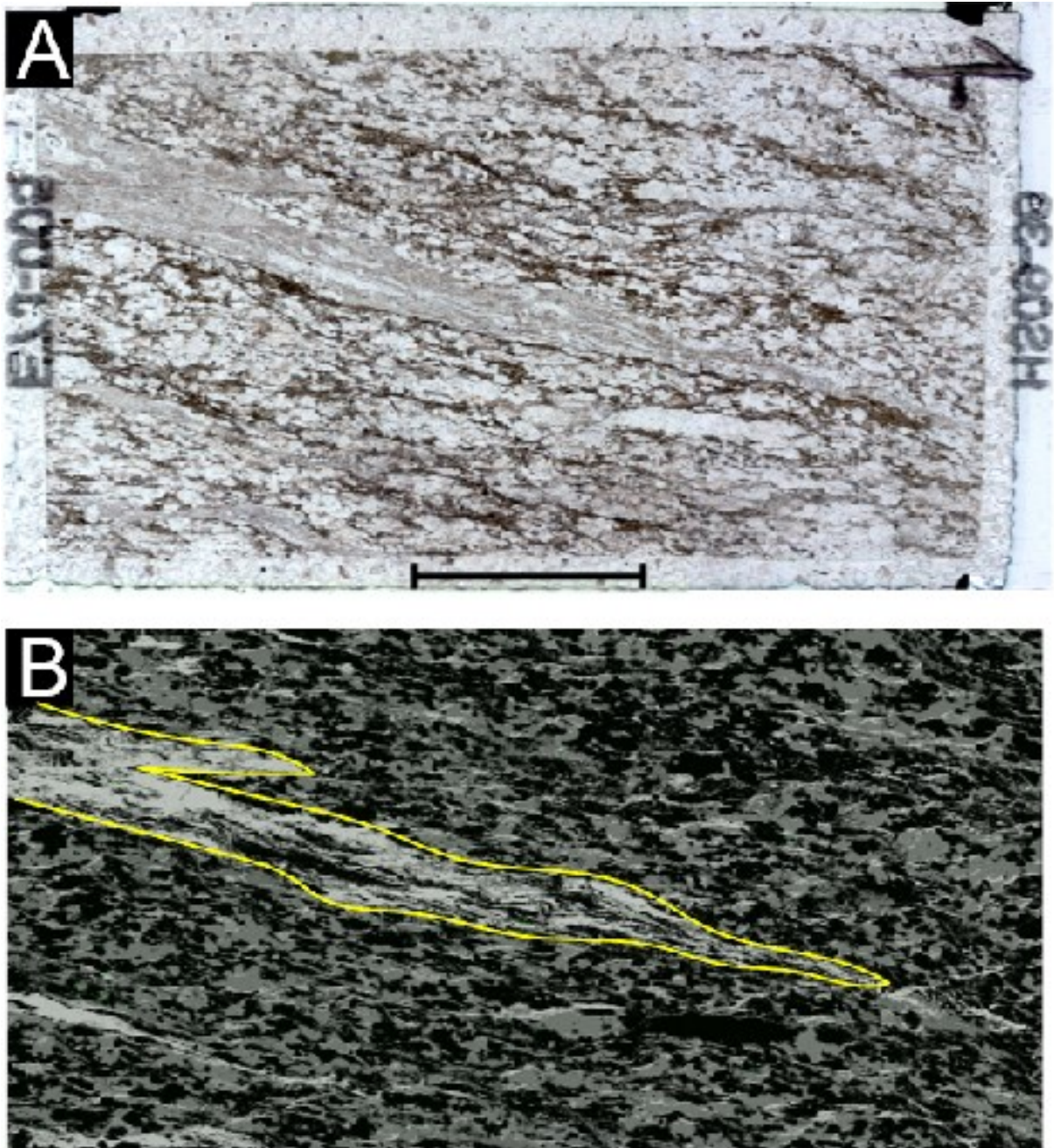


Figure 13: Full thin section view of sample HS09-36. A.) Full thin section scan. Scale is 1 cm. B.) Full thin section Al map. High aluminum layer outlined in yellow.

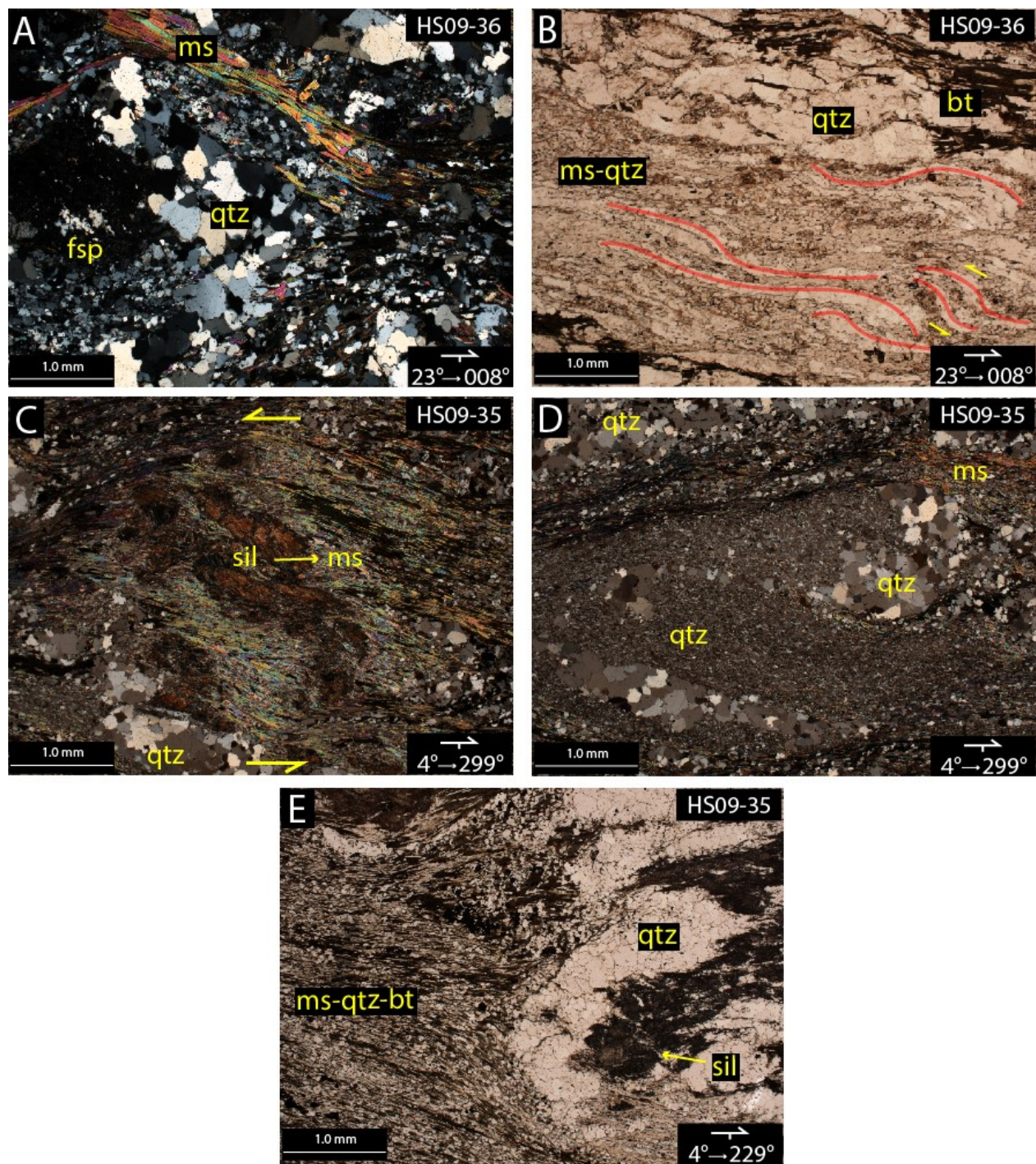


Figure 14: Photomicrographs of samples HS09-36 and HS09-35. A.) Recrystallized feldspar and GBM quartz clast pinned by phyllosilicate layer in sample HS09-36. B.) High aluminum layer in sample HS09-36. Note the asymmetry of quartz shear bands (red outlines). C.) Sillimanite to muscovite porphyroblast in HS09-35. D.) Grain-size reduced quartz surrounding relict GBM quartz textures. E.) High strained ms + qtz + by fabric flowing around qtz + sil clast.

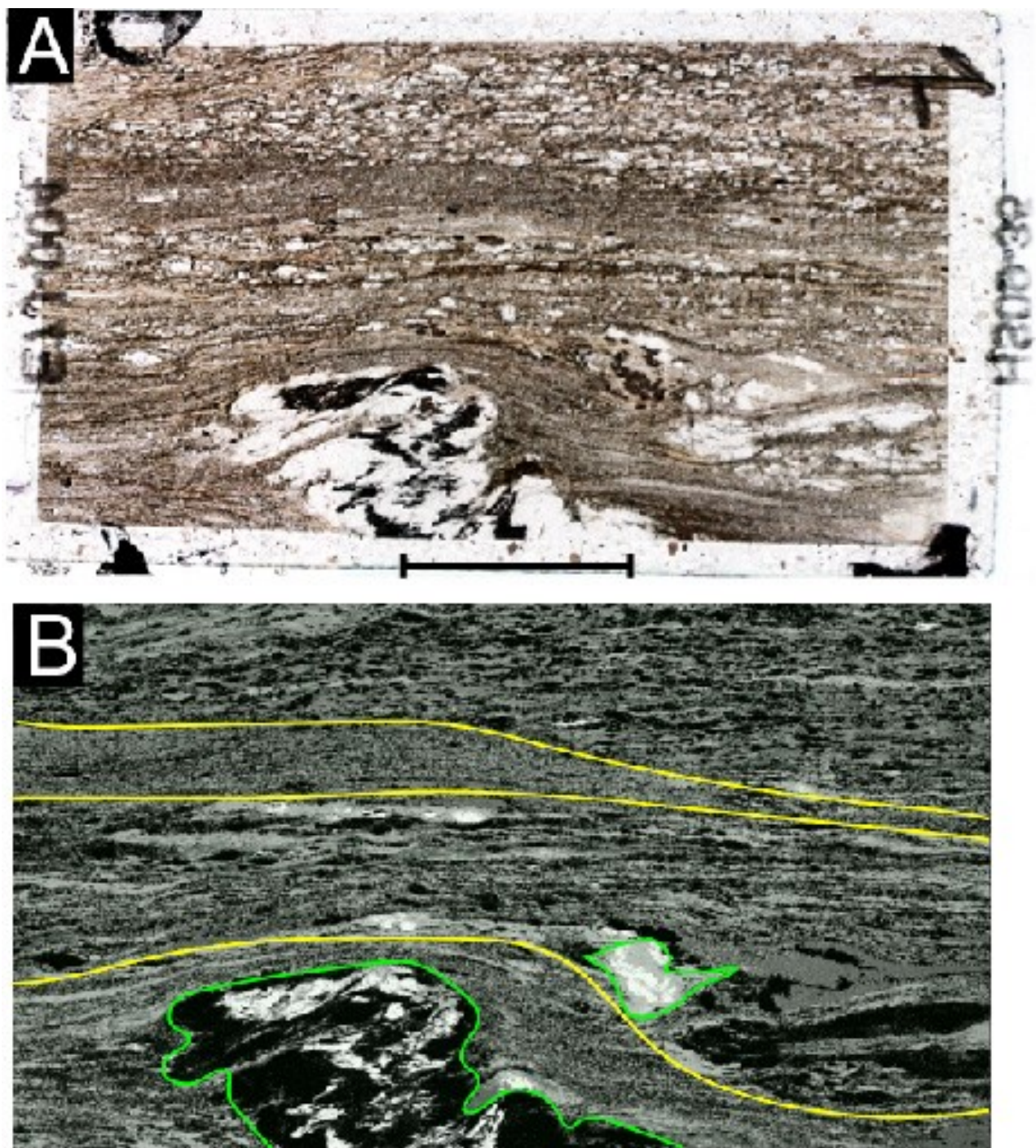


Figure 15: Full thin section view of sample HS09-35. A.) Full thin section scan. Scale is 1 cm. B.) Full thin section Al map. Finer-grained mylonitic fabric outlined in yellow. sil+qtz+ms clasts outlined in green.

HS09-42a

Sample HS09-42a is a quartzo-feldspathic mylonite (qtz+fsp+ms+bt) with GBM quartz ($> 500^{\circ}\text{C}$) flowing around feldspar porphyroclasts with brittle fracturing (Figure 16). Feldspar porphyroclasts with asymmetric tails reveal top-to-the-southeast shear sense (Figure 17A). Paralleling the mylonitic fabric of the sample is a mica-rich layer dominated by tabular muscovite and biotite grains, suggesting post-deformational crystallization (Figure 16 & 17). The alignment of phyllosilicates in this layer displays an S-C fabric exhibiting top-to-the-southeast shear sense (Figure 17B).

SL08-07

Sample SL08-07 is an ultramylonite (qtz+ms+bt+chl $\pm$ fsp) that exhibits a significantly grain-size reduced fabric of SGR quartz ($400^{\circ} - 500^{\circ}\text{C}$) and phyllosilicates with few relict high-temperature quartz porphyroclasts (showing top-to-the-southeast shear sense; Figure 17C). There is a subtle compositional banding of quartz- and mica-rich domains, the latter of which contains crenulations (Figure 17D).

4.2. Monazite

Occurrence

The preliminary qualitative investigation of monazite was conducted for confirmation and recognition of accessory phases. Grains were first investigated using petrography (Figure 19), which were later confirmed using the SEM (Figure 20). Monazite is typically $< 100\text{ }\mu\text{m}$ on its longest side, although some grains exceed $300\text{ }\mu\text{m}$.

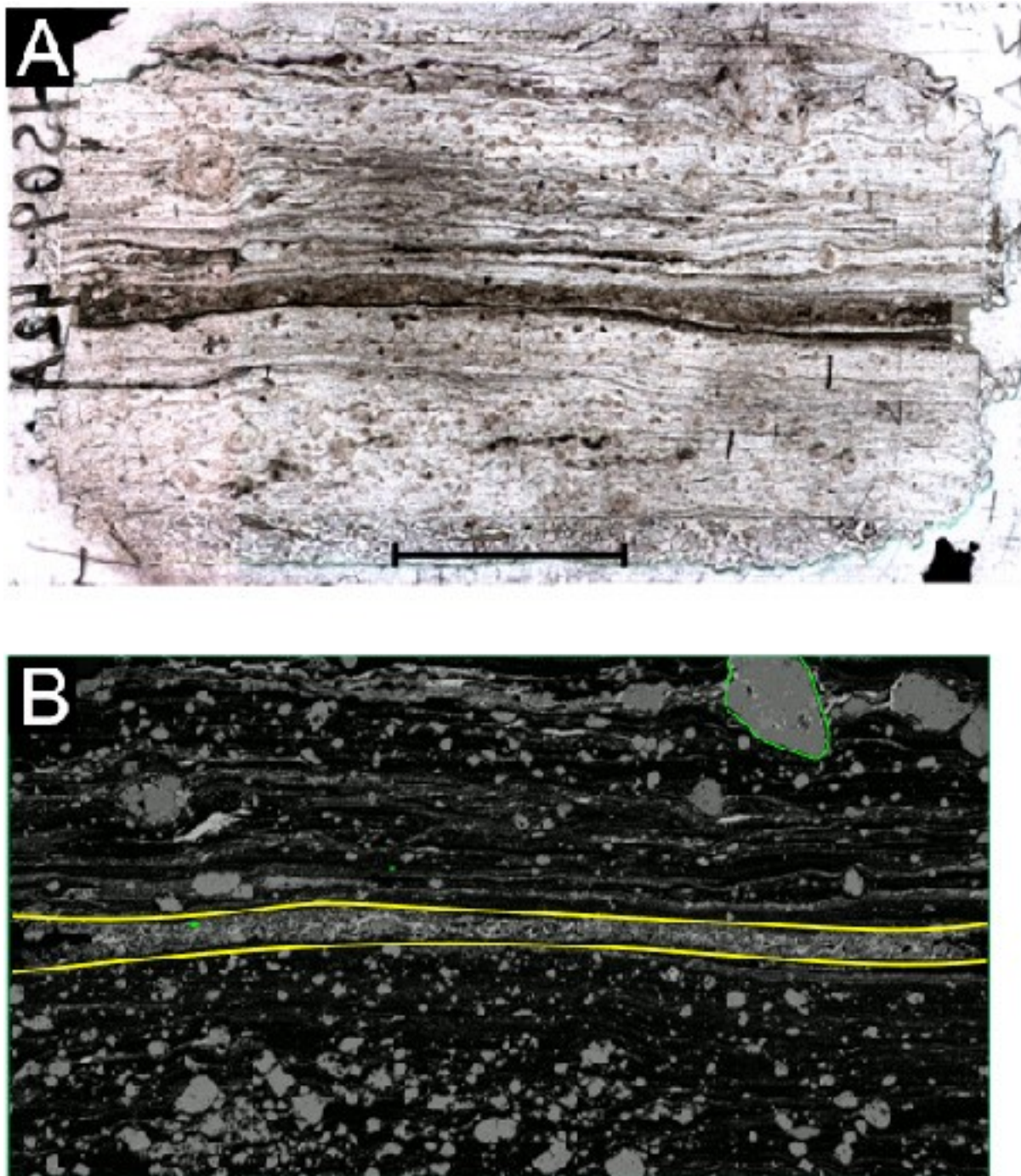


Figure 16: Full thin section view of sample HS09-42a. A.) Full thin section scan. Scale is 1 cm. B.) Full thin section Al map. Tabular phyllosilicate layer outlined in yellow. Example of feldspar porphyroblast outlined in green.

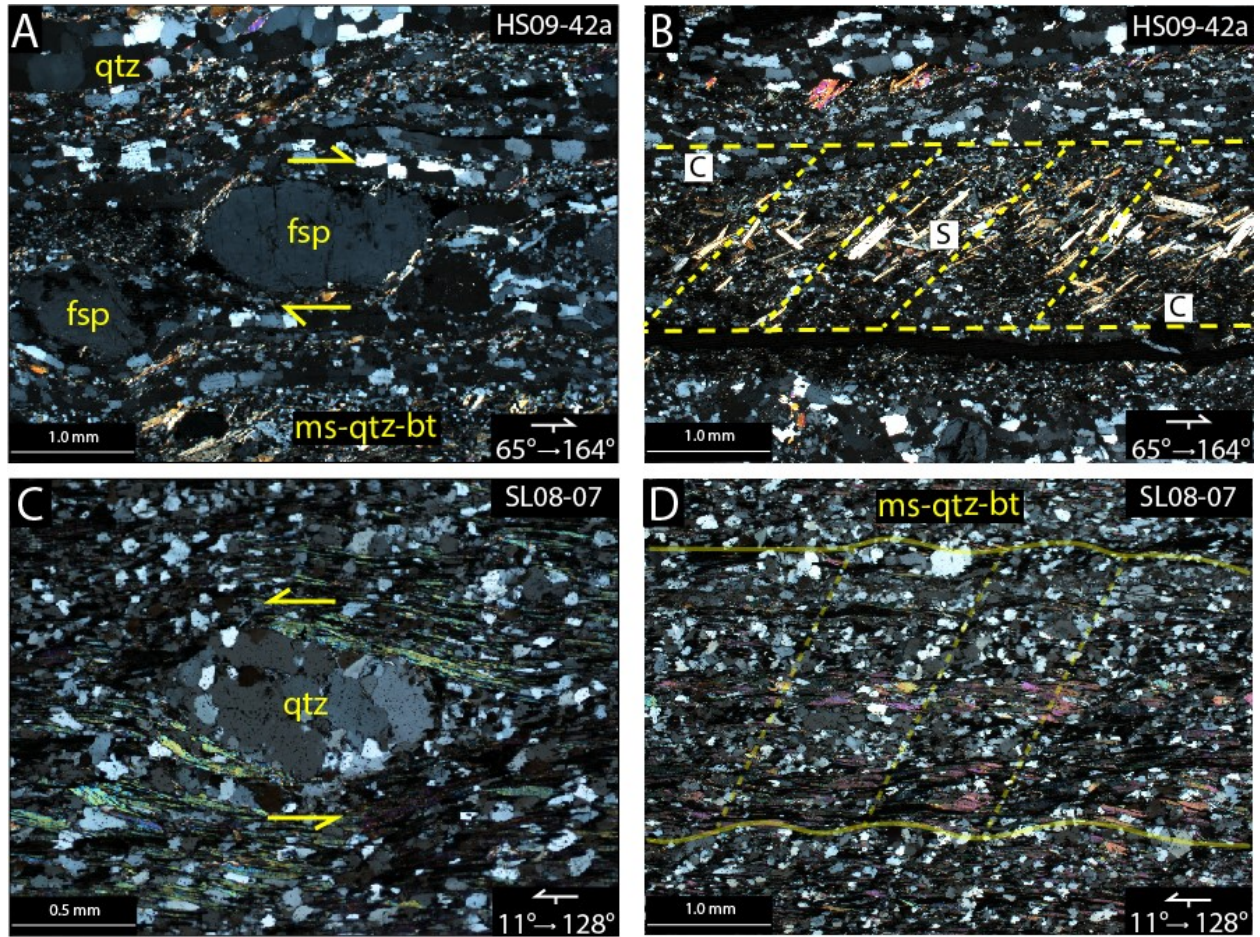


Figure 17: Photomicrographs of samples HS09-42a and SL08-07. A.) Feldspar porphyroblast showing top-to-the-southeast shear sense. B.) High phyllosilicate layer and S-C fabric. C.) GBM quartz porphyroblast showing top-to-the-southeast shear sense. D.) Crenulations in SL08-07.

Monazite occurs in a variety of microstructural settings, and in association with each of the major silicate phases present (Figure 20). Most grains are isolated from one another in the rock matrix (Figure 20A) but can also collect in grain clusters (Figure 20D) or be enclosed in feldspar or sillimanite porphyroclasts (Figure 19C & 20B). Generations of monazite growth are rare to see with optical petrography and SEM analysis (Figure 19D). Monazites long-axis are often oriented sub-parallel to the rocks foliation, especially when in a layer of paralleling

phyllosilicates (Figure 20C). Monazite crystals are rarely euhedral (Figure 19A), often appearing tabular and elongate (Figure 19B).

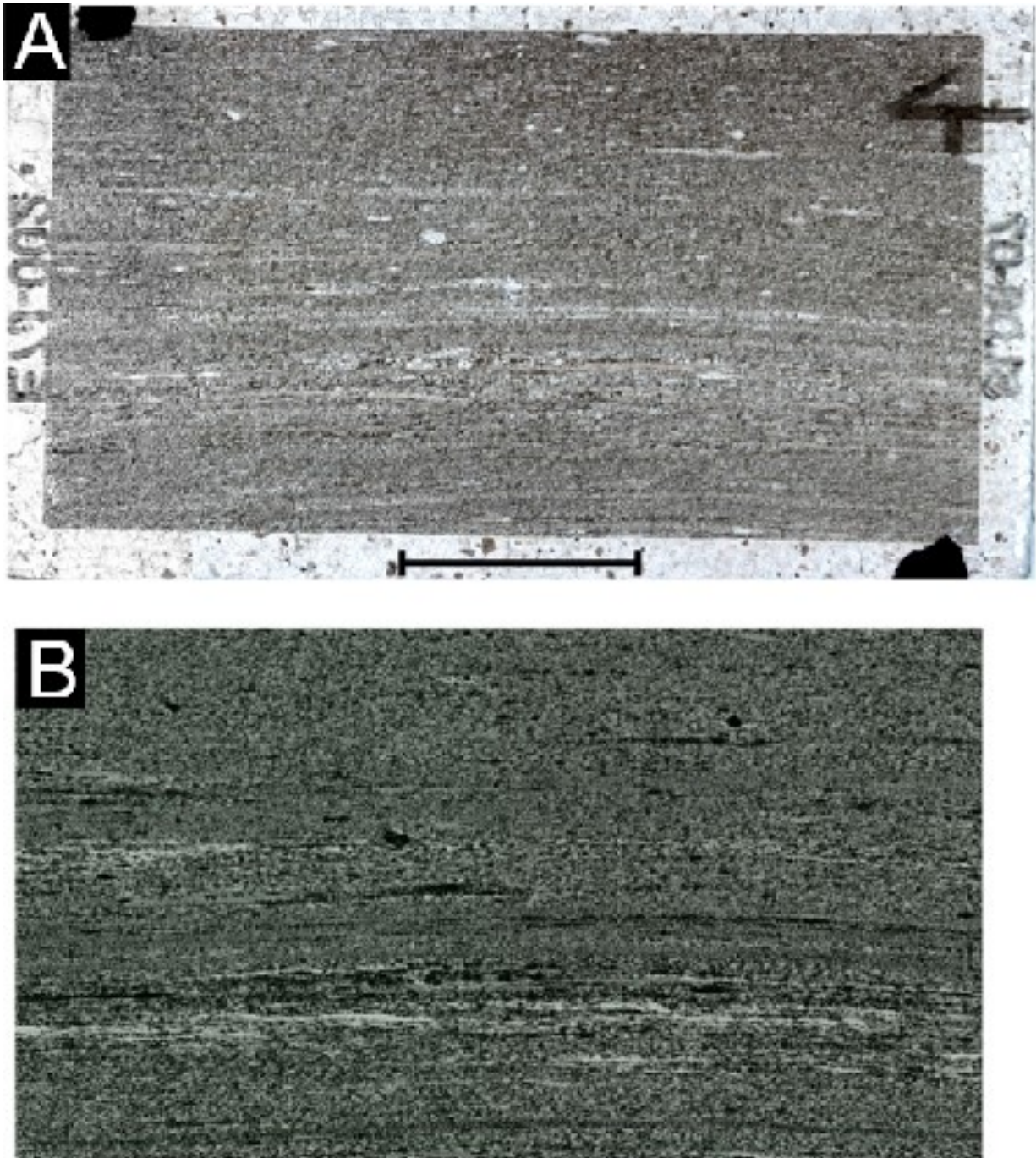


Figure 18: Full thin section view of sample SL08-07. A.) Full thin section scan. Scale is 1 cm. B.) Full thin section Al map.

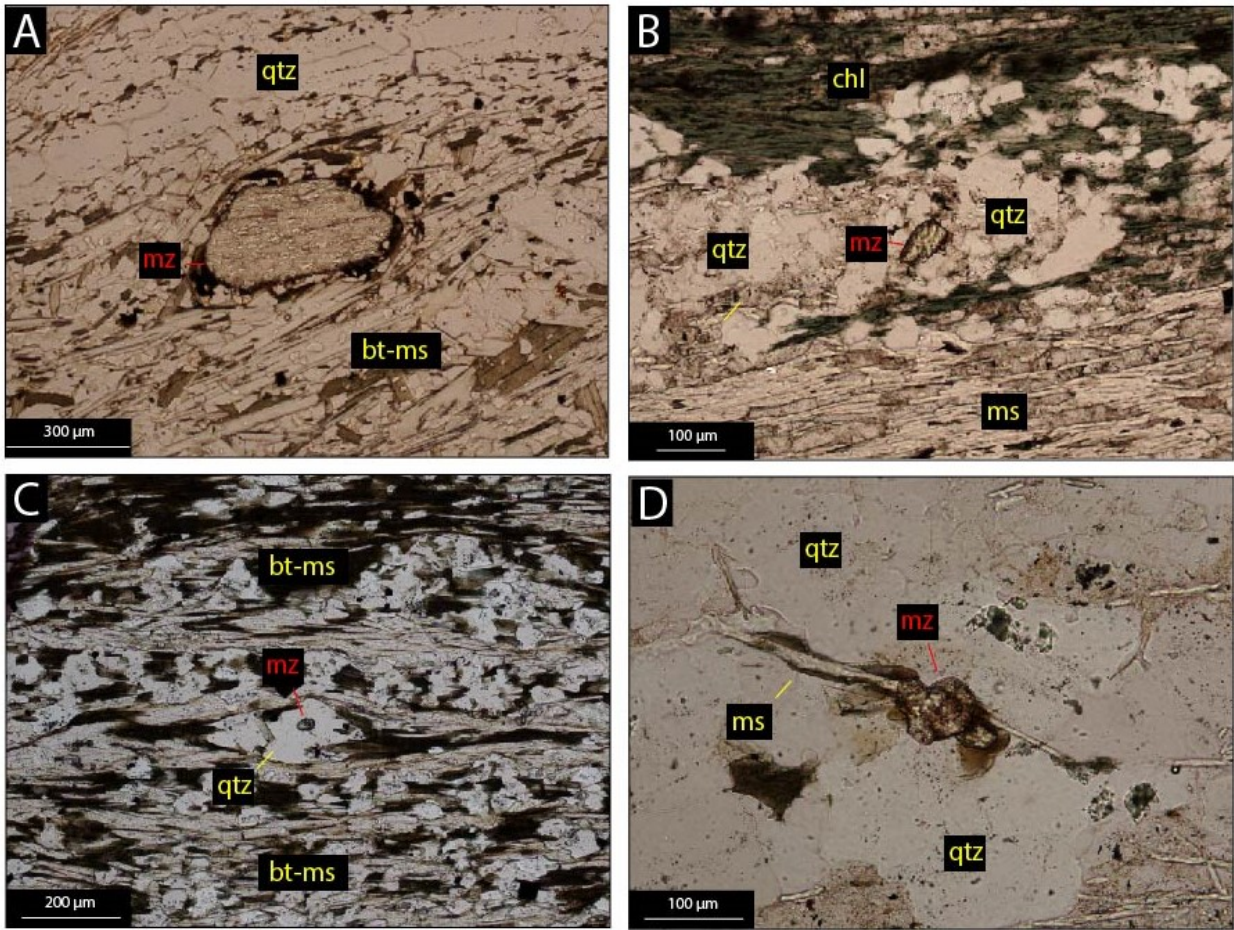


Figure 19: Photomicrographs of monazite grains. A.) Euhedral monazite crystal elongated sub-parallel to foliation. B.) Tabular monazite grain in quartz clast. C.) Monazite in quartz clast. D.) Monazite showing an apparent overgrowth.

HS09-36

Monazite from sample HS09-36 has a generally blocky appearance (Figure 21B) but appears more elongate in the high-aluminum layer (Figure 21A); other grains in this layer appear to have undergone brittle deformation (Figure 21C).

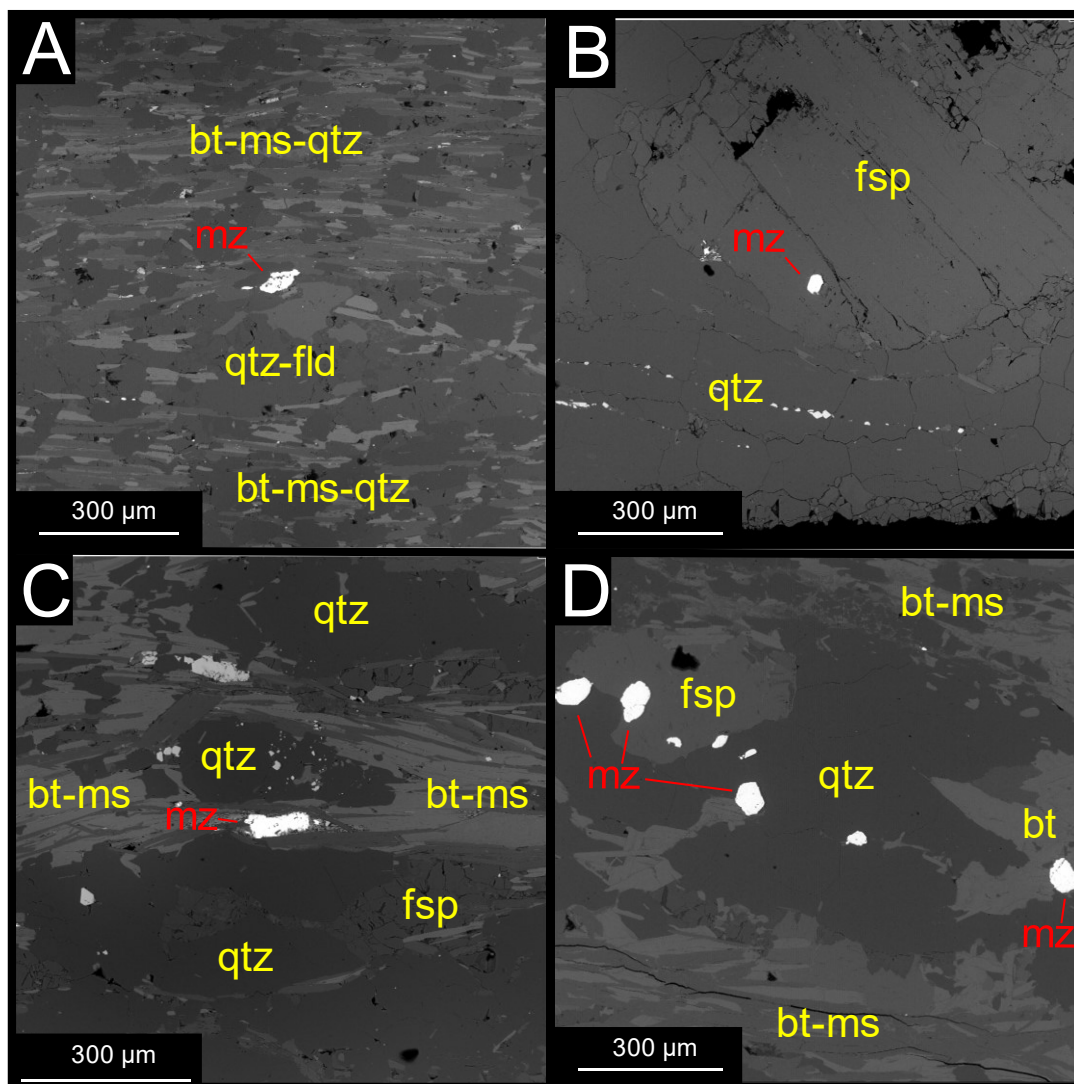


Figure 20: SEM backscatter images of common monazite occurrences. A.) Monazite oriented subparallel to high-strained fabric. B.) Monazite enclosed in feldspar porphyroclast. C.) Monazite pinned by paralleling phyllosilicates. D.) Cluster of monazite grains.

HS09-35

A majority of the monazite in sample HS09-35 parallels aligned phyllosilicates as interstitial grains (Figure 21F). Grains inside sillimanite-phyllosilicate assemblages have

irregular shapes (Figure 21E). A few grains are almost completely broken down and consumed by apatite (Figure 21D).

HS09-42a

Monazite grains from HS09-42a have a generally blocky shape, similar to HS09-36. Grains surrounded by phyllosilicates have irregular grain boundary morphology (Figure 22A & B), where they are more uniform where surrounded by quartz (Figure 22C).

SL08-07

Monazite grains in SL08-07 are the most unique in the sample set, with very few if any of the more equant grains from the other samples. Many of the grains are broken into small clusters where the grains appear to have undergone brittle deformation (Figure 22D). Grains sometimes have an interstitial appearance and look as though they crystallized interstitially between major silicate phases (Figure 22E). Similar to HS09-35, monazite frequently is observed breaking down to form apatite (Figure 22F).

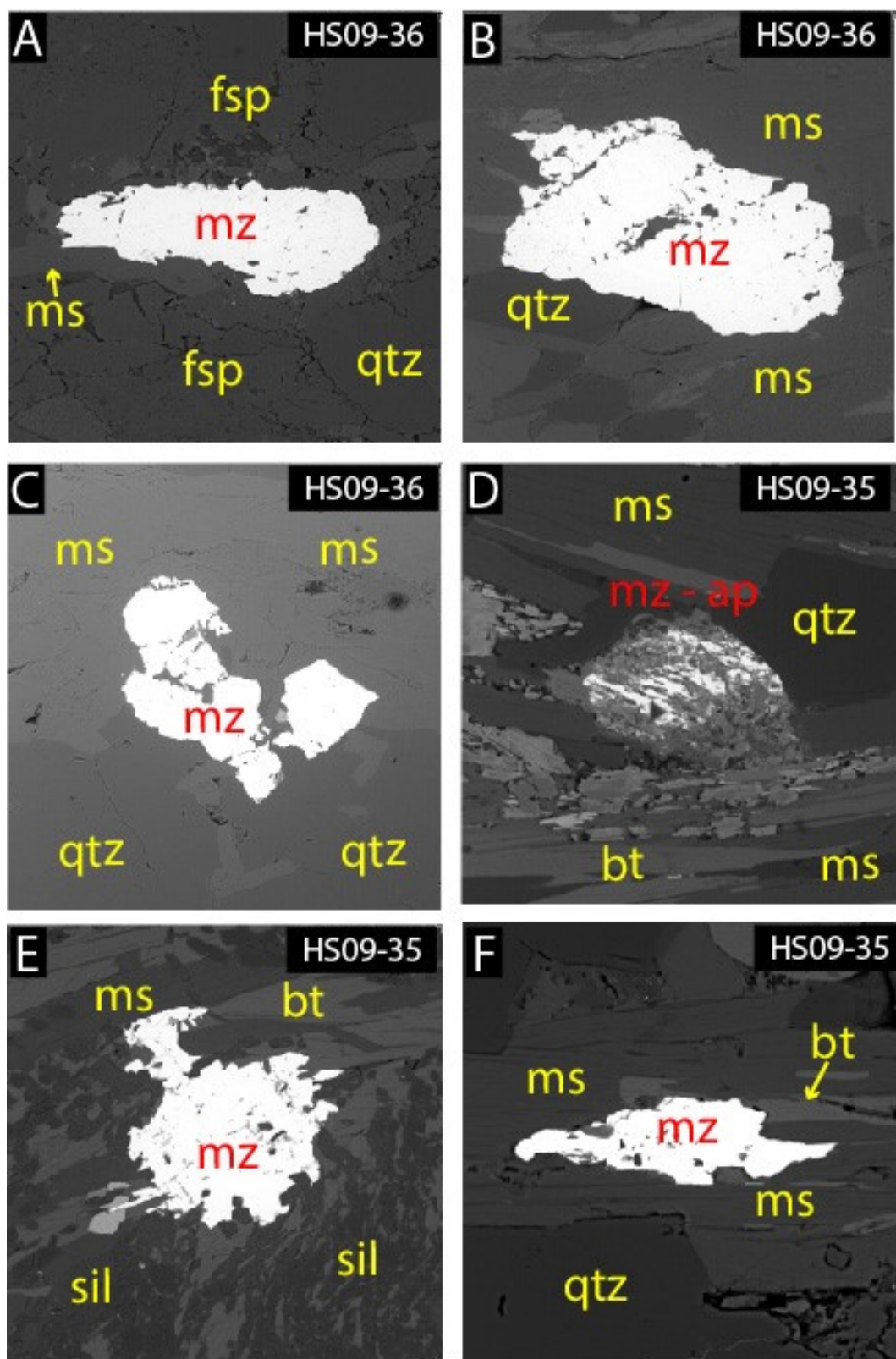


Figure 21: Examples of backscatter SEM images of monazite from samples HS09-36 and HS09-35.

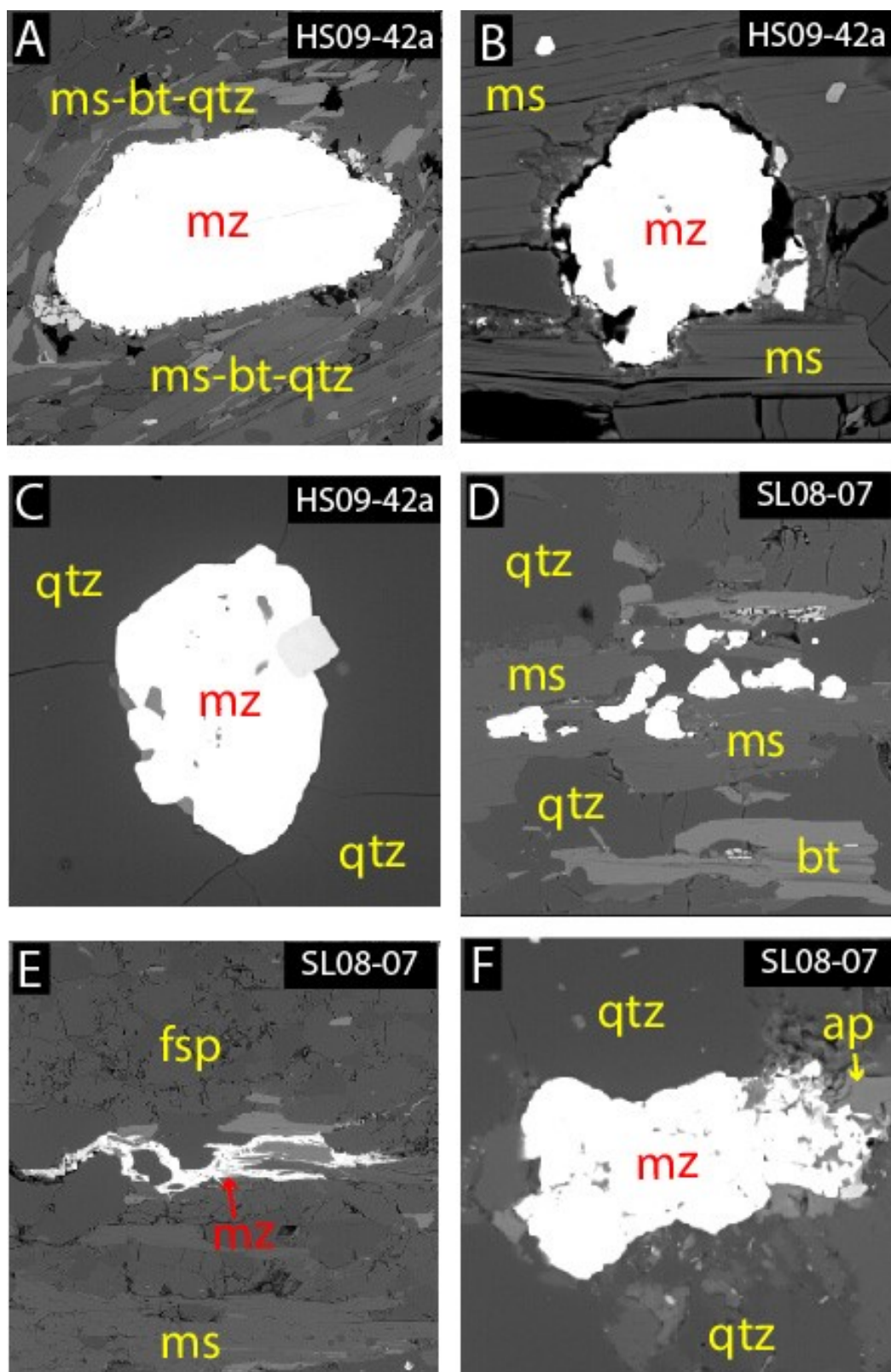


Figure 22: Examples of backscatter SEM images of monazite from samples HS09-42a and SL08-07.

CHAPTER 5:

MONAZITE ANALYSIS

This chapter focuses on the monazite results for the selected samples. Here is presented full thin section maps, grain maps, and monazite dates for the four selected samples.

5.1. Monazite age-composition relationships

A total of 68 monazite grain maps were created for the samples to investigate the unique compositional zoning of each. Y K α maps were primarily used to qualitatively reveal the compositional zoning relationships in each grain. Monazite domains will be described by core, outer core, rim, or main (single dominant domain). Based on qualitative assessment, grains commonly possess 3 domains (inner core, outer core, rim), with some having as many as 4 or 5. Rim domains often appear as discontinuous layers with varying thickness along the perimeter of a grain. Y concentration in rim domains is almost always lower than the inner and / or outer core domains. Grains with one main domain typically have the lowest relative Y concentrations in the sample. Anomalously high-Y spots on grains are xenotime inclusions.

U-Th-Pb ages were acquired from 42 domains across the four samples. Age error is reported as 1-sigma standard deviation. Monazite ages from this research span the Paleoproterozoic (> 1700 Ma) through the Mesoproterozoic (< 1400 Ma). The range of ages within samples is >100 Ma for each sample, and the 1-sigma age error for the samples ranges from 5 – 80.7 Ma. Inner cores normally record older dates than outer cores, although the reverse is seen as well. Few low-Y rim domains were dated due to the limited analysis space, but low-Y main domains always record younger monazite ages relative to the remainder of the sample.

Calculated ages, EMP maps, and elemental data will be considered for each individual sample below.

HS09-36

18 monazite grains from this sample were mapped, revealing three compositional domains distinguished by Y and Th concentrations: 1) low-Y / Th inner core domains, 2) medium to high-Y domains, and 3) low-Y rims (Figure 23). Up to three core domains are present

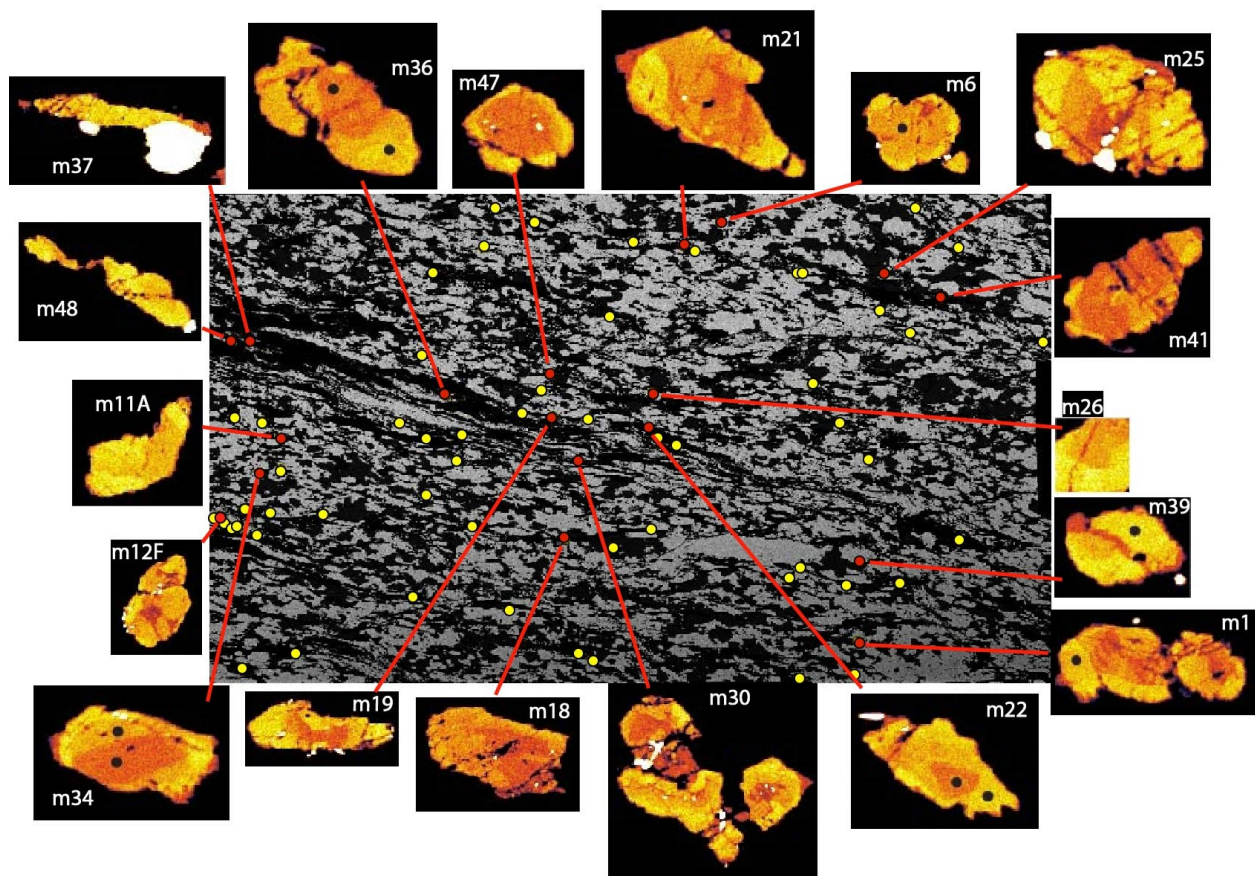


Figure 23: Full thin section Mg map of HS09-36 with monazite Y maps and grain locations. Black dots represent monazite analyses.

in each grain (e.g., Figure 24, m30), which generally increase in Y concentration from the inner to outer core (Figure 24). Group 1 low-Y / Th inner core domains are distinguished separately from the remainder of the core domains that may have comparable Y levels, because of their significantly lower Th concentrations (Figure 24). Some inner cores appear to contain a relict high-Th domain that is overprinted by a lower-Th domain (Figure 24: m22). High-Y outer core domains are the most common domain in each grain. The low-Y rims appear as disconnected lenses that are often attached to the edge of the grain on its longest side. HS09-36 is the only sample where a grain with a low-Y main domain was not identified.

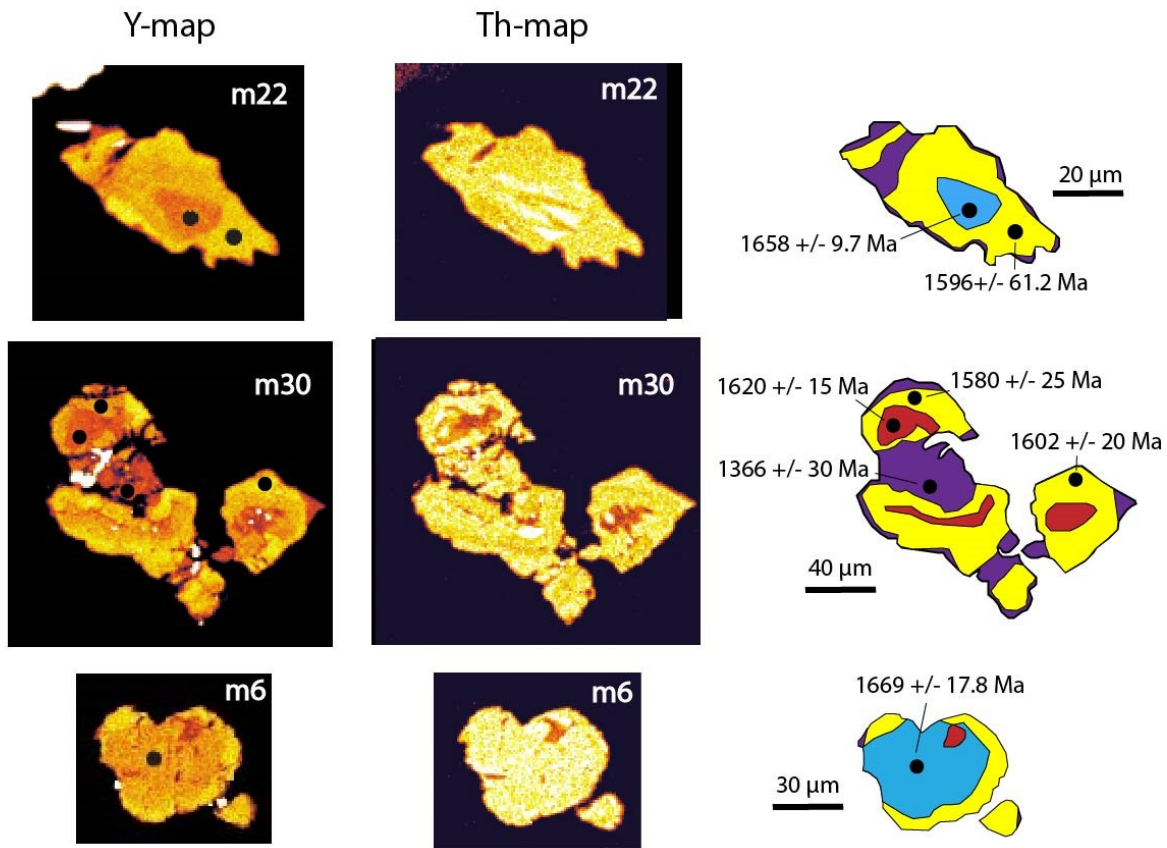


Figure 24: HS09-36, examples of interpreted monazite domains and respective ages with Y and Th compositional maps (m22, m30 and m6). Domain interpretation: Red = group 1, Blue = group 2a, Yellow = group 2b, Purple = group 3.

HS09-36 has the largest range in monazite ages (1680 to 1366 Ma) and age error (9.7 to 80.7 Ma) of the four samples (Figure 25). There is no obvious zoning-age relationship between the group 2 domains despite the wide range of ages, so they are plotted as separate populations into two older (2a: 1680 - 1620 Ma) and younger (2b: 1602 - 1539 Ma) sub-groups in Figure 24 and 25. The age error is the lowest for the older (2a) group of domains (9.7 to 26.6 Ma), relative to the younger (2b) domains (20 to 80.7 Ma). The only low-Y core domain dated in this sample is from m30 (1620 ± 15 Ma). The one low-Y rim dated (1366 ± 30 Ma) is much younger than the group 1 and 2 core domains dated. Grains m22, m30, m34, and m36 have group 2 outer core domains with increasing Y content from the interior to the exterior (Figure 24), but the dates acquired from those domains reveal an inconsistent relationship between core to rim ages and zoning; for example, m36 records an older outer core (1680 Ma) and a younger inner core (1627 Ma), and m22 records an older inner core (1658 Ma) and a younger outer core (1596 Ma).

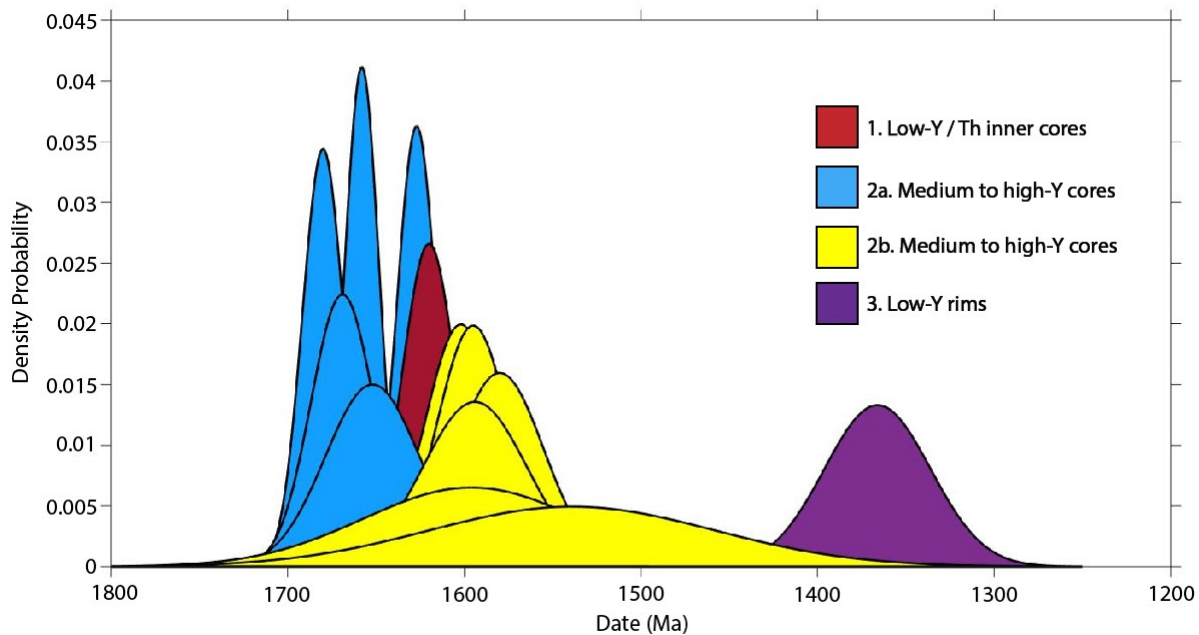


Figure 25: Normal distribution plot of monazite dates from HS09-36.

The age-composition relationship for monazite domains from HS09-36 show outer cores have higher Y concentrations than inner cores (Figure 26).

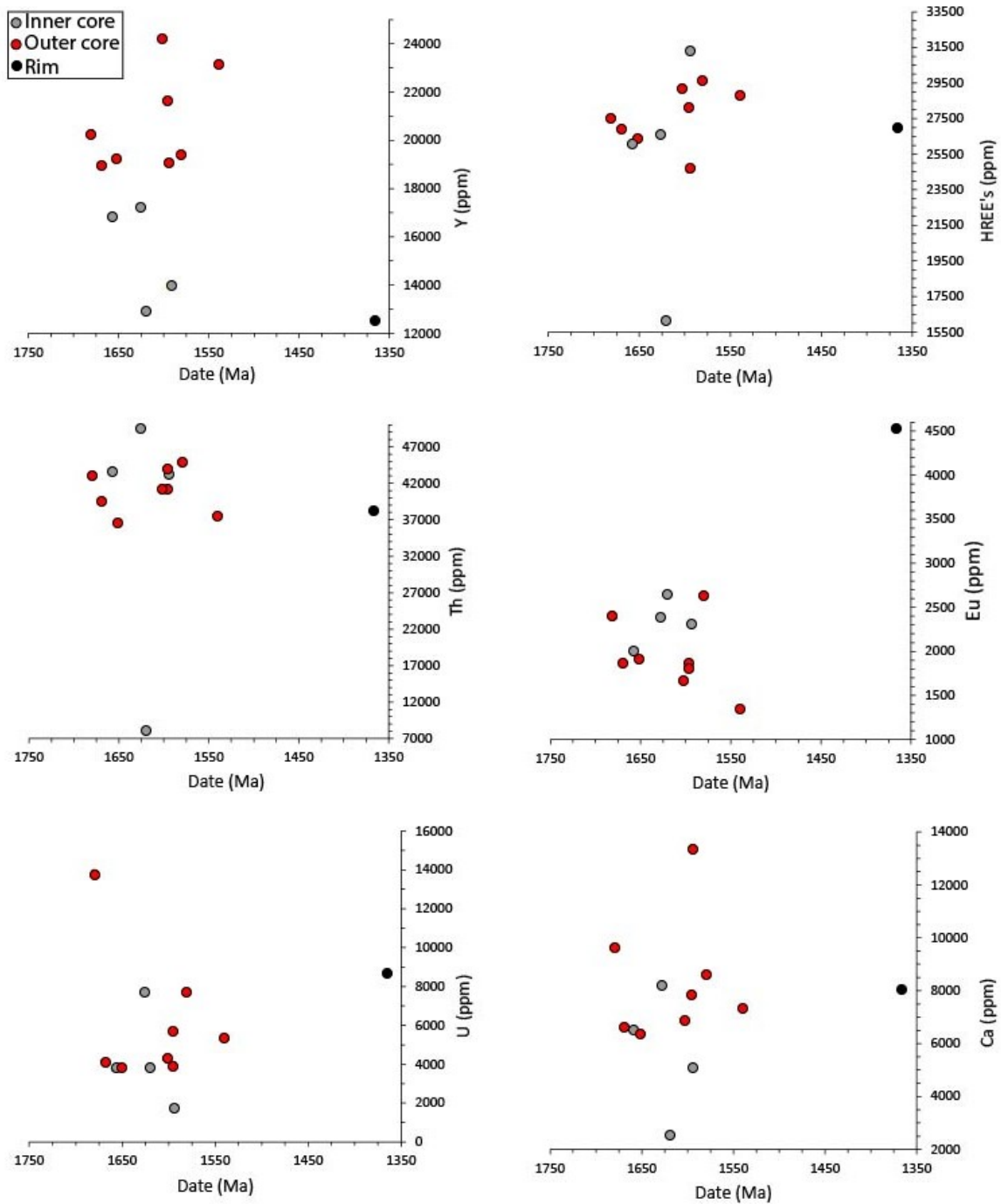


Figure 26: Age-composition relationships for monazite from HS09-36

18 of the 49 monazite grains in this sample were mapped, revealing three compositional domains: 1) low-Y inner core, 2) high-Y outer core, 3) low-Y main (Figure 27). Group 1 and 2 core domains make up nearly the entire grain where present. The low-Y rims form a thin layer along the perimeter of the grains, which may correlate with the low-Y main domains, although no rims were analyzed. (Figure 28: m2). Almost half of the grains mapped (8/18) contain one low-Y main domain (m3, 4, 8, 11, 12, 14, 15, 16, 17).

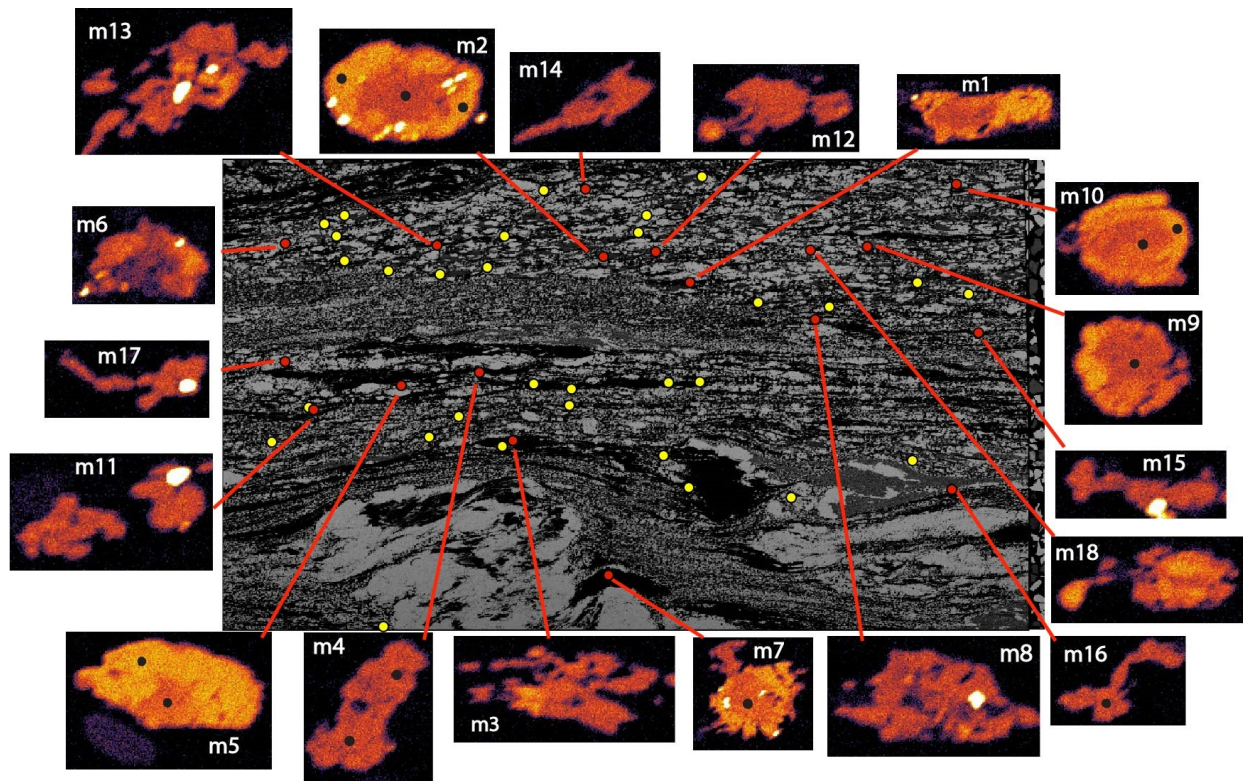


Figure 27: Full thin section Mg map of HS09-35 with monazite Y maps and grain locations.

10 of the 18 grains were used for dating (Figure 29). Monazite domain ages range from 1538 to 1420 Ma, with error < 40 Ma for each domain date. Core domains range from 1520 to 1438 Ma, and outer cores range from 1538 to 1481 Ma. Intragrain age relationships for grains m2, m5, and m10 reveal younger inner cores and older outer cores, similar to observations from HS09-36. The two low-Y main domains dated (m4 & m16) record the youngest dates and smallest age-errors in the sample (1420 ± 9 and 1423 ± 8).

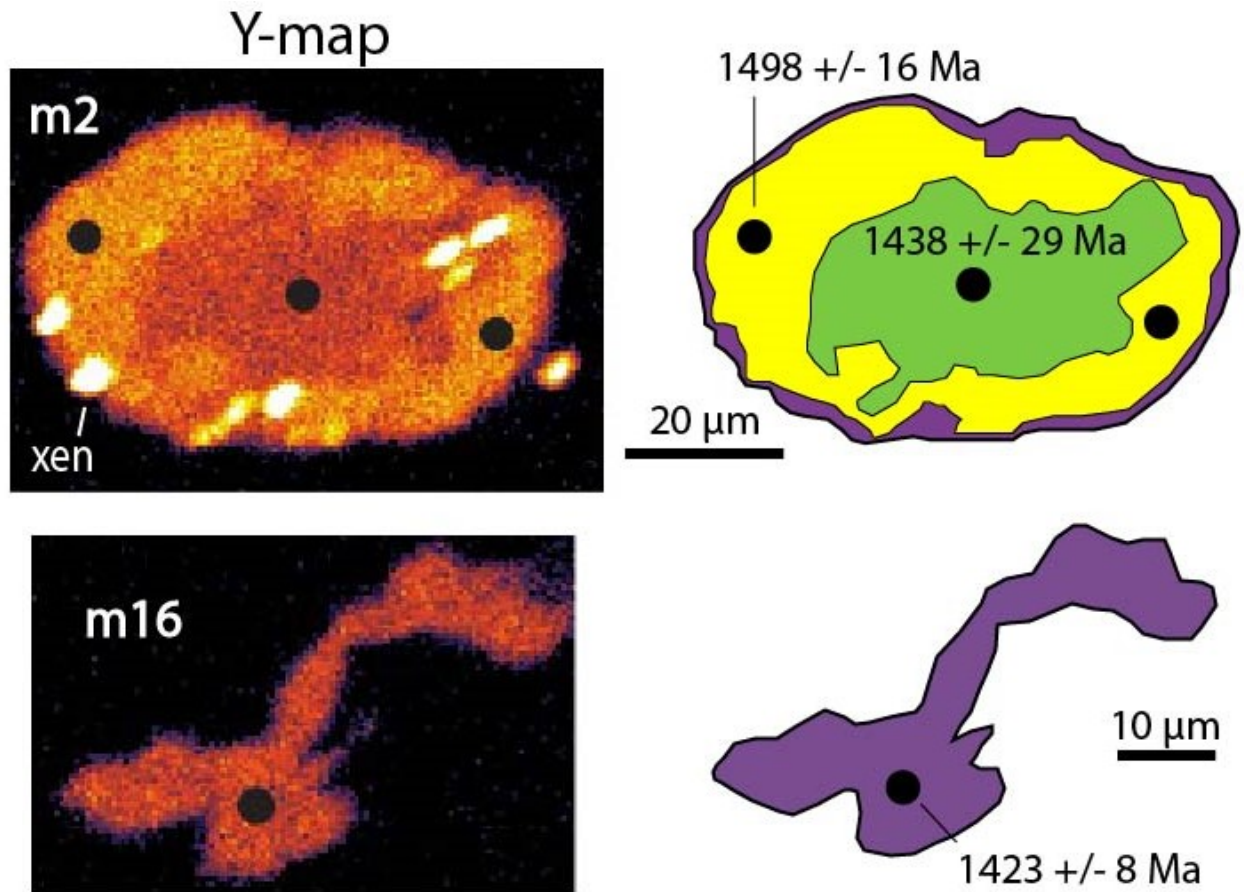


Figure 28: HS09-35, examples of interpreted monazite domains with simplified Y compositional monazite maps (m2 and m16). Domain interpretation: Green = group 1, Yellow = group 2, Purple = group 3. Note the high-Y xenotime inclusions on grain m2.

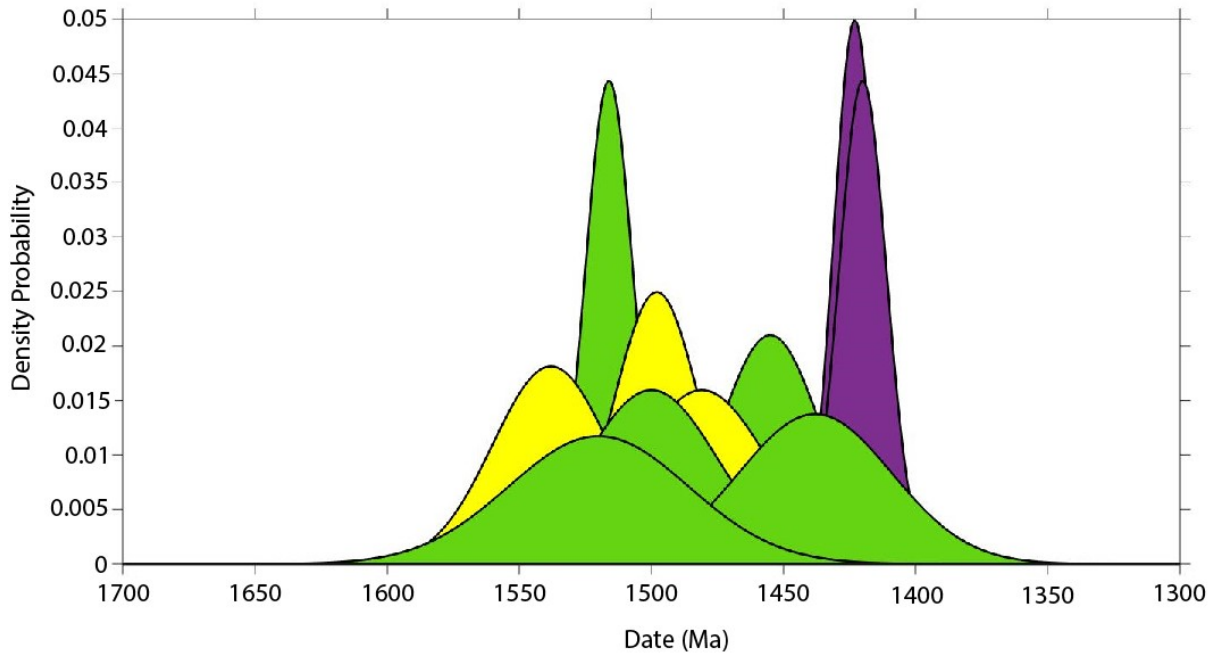


Figure 29: Normal distribution plot of monazite dates from HS09-35

Outer cores are enriched in Y, Th and HREE's relative to their inner core counterparts, yet are depleted in Eu (Figure 30). Main domains are more compositionally like inner cores than outer cores, and are depleted in Y, HREE's and U, and enriched in Th.

HS09-42a

16 of 27 monazite grains from HS09-42a were mapped, revealing three compositional domains: 1) low-Y / low Th cores, 2) medium to high Y cores and 3) low-Y rims. (Figure 31 and 32). Core domains can be described by relative differences in Y concentrations typically consisting of lower-Y inner cores and a higher-Y outer cores, although this relationship isn't representative of each grain. Grain m1 is an inclusion inside a feldspar porphyroclast and

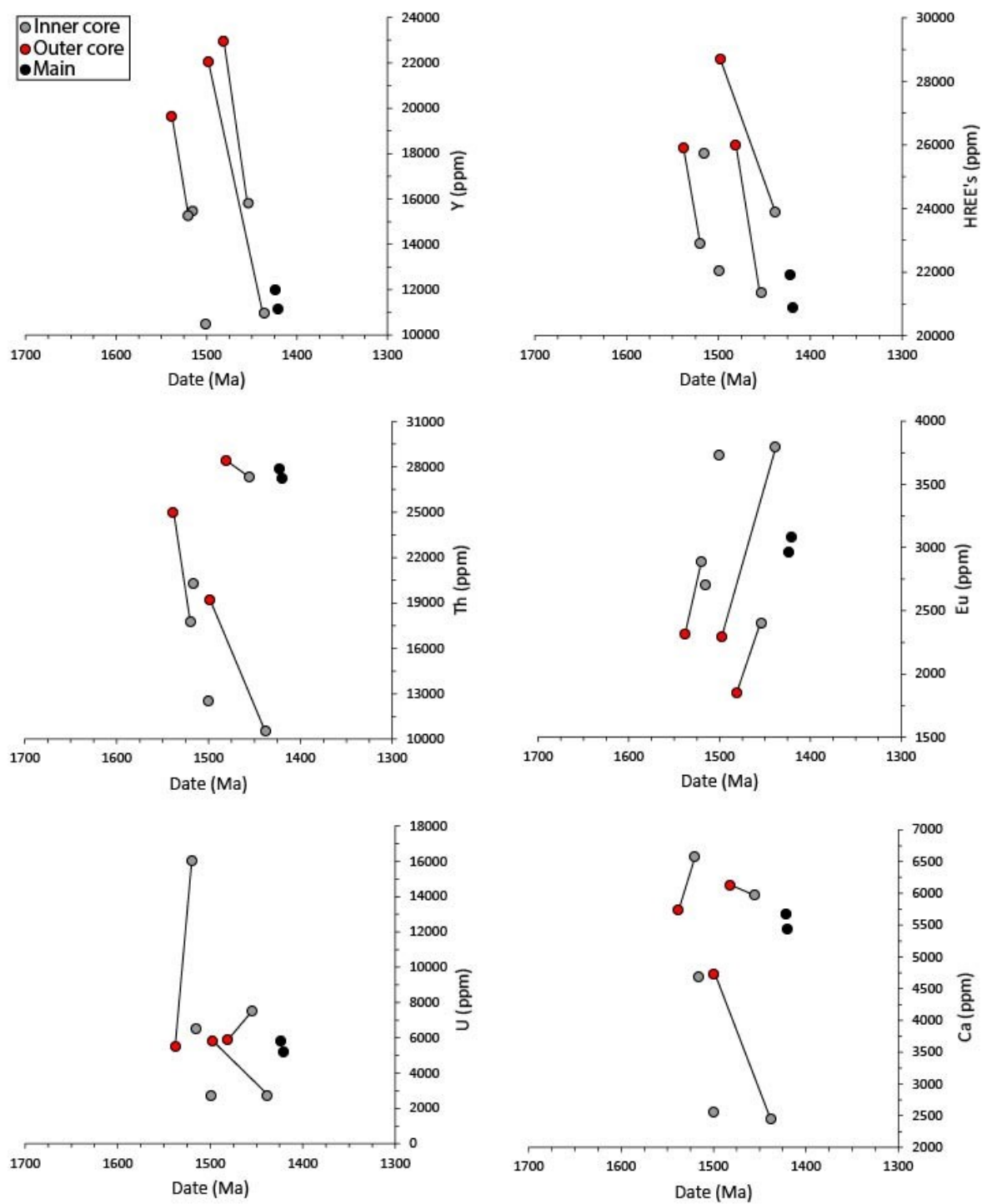


Figure 30: Age-composition relationships for monazite from HS09-35. Line connect domains in same grain.

therefore cannot be grouped as representative of the other matrix monazite and is grouped separately. The core of m18 has an anomalously low Th concentration relative to the remainder of the core domains in the sample (Figure 32). The low-Y rim domains are seen on almost every grain (ex: m11, m22), and are compositionally indistinguishable from the low-Y main domains (ex: m25, m27). The inner core of mC2 has a clearly similar morphology to the surrounding grain and exhibits sector zoning, which is not seen anywhere else in the monazite grains from this study.

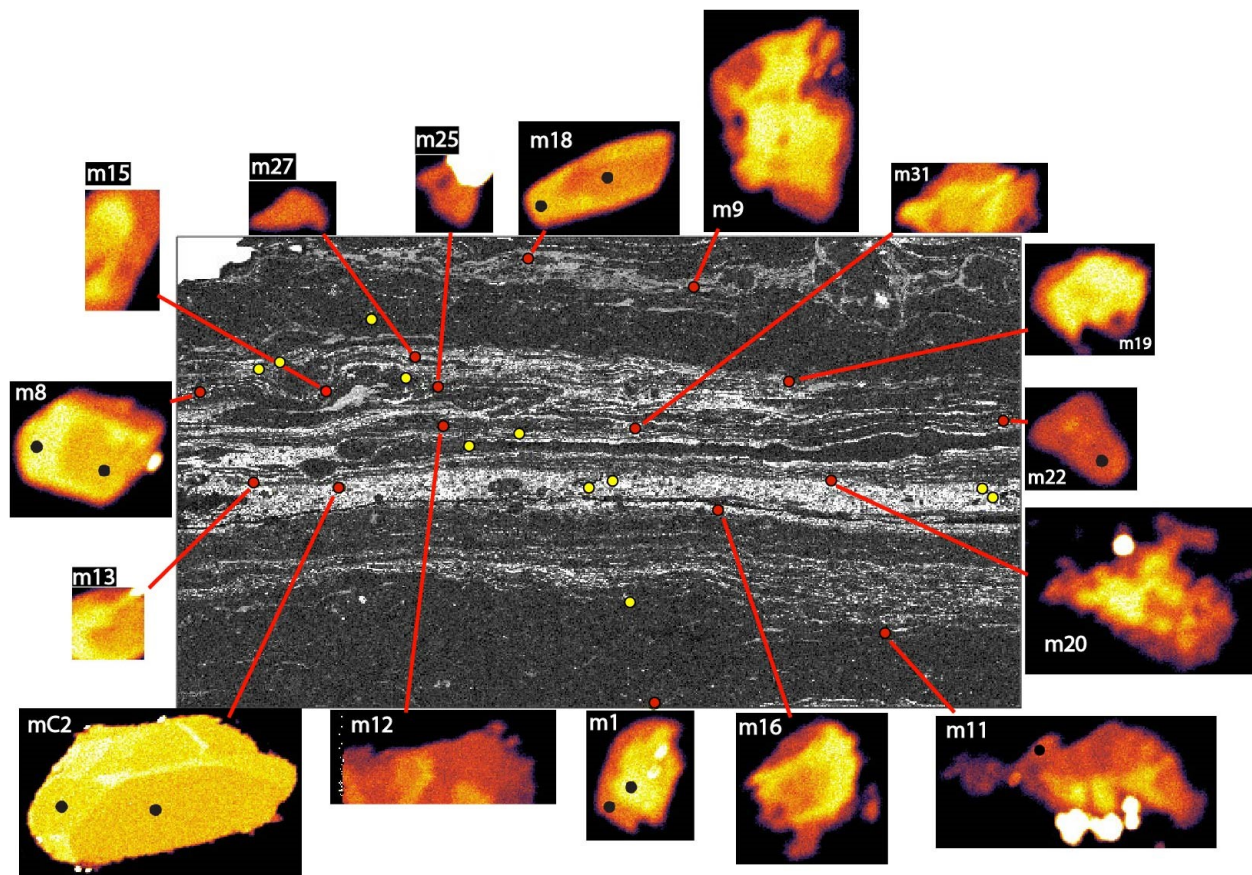


Figure 31: Full thin section Mg map of HS09-42a with monazite Y maps and grain locations. Black dots are monazite analyses.

HS09-42a has the smallest range in monazite ages from 1716 to 1604 Ma, with an age error range of 5 to 31.3 Ma (Figure 33). The four inner core to outer core pairs in this sample (m1, m8, m18, mC2) are delimited to a narrow time period (1716 to 1688 Ma) (Figure 33), and the two low-Y rims (m11 & m22) dates are younger and statistically indistinguishable (1615 and 1604 Ma, respectively). The two domains analyzed from the grain inside a feldspar porphyroclast (m1) are constrained to the same time period as the other group 1 and 2 core domains.

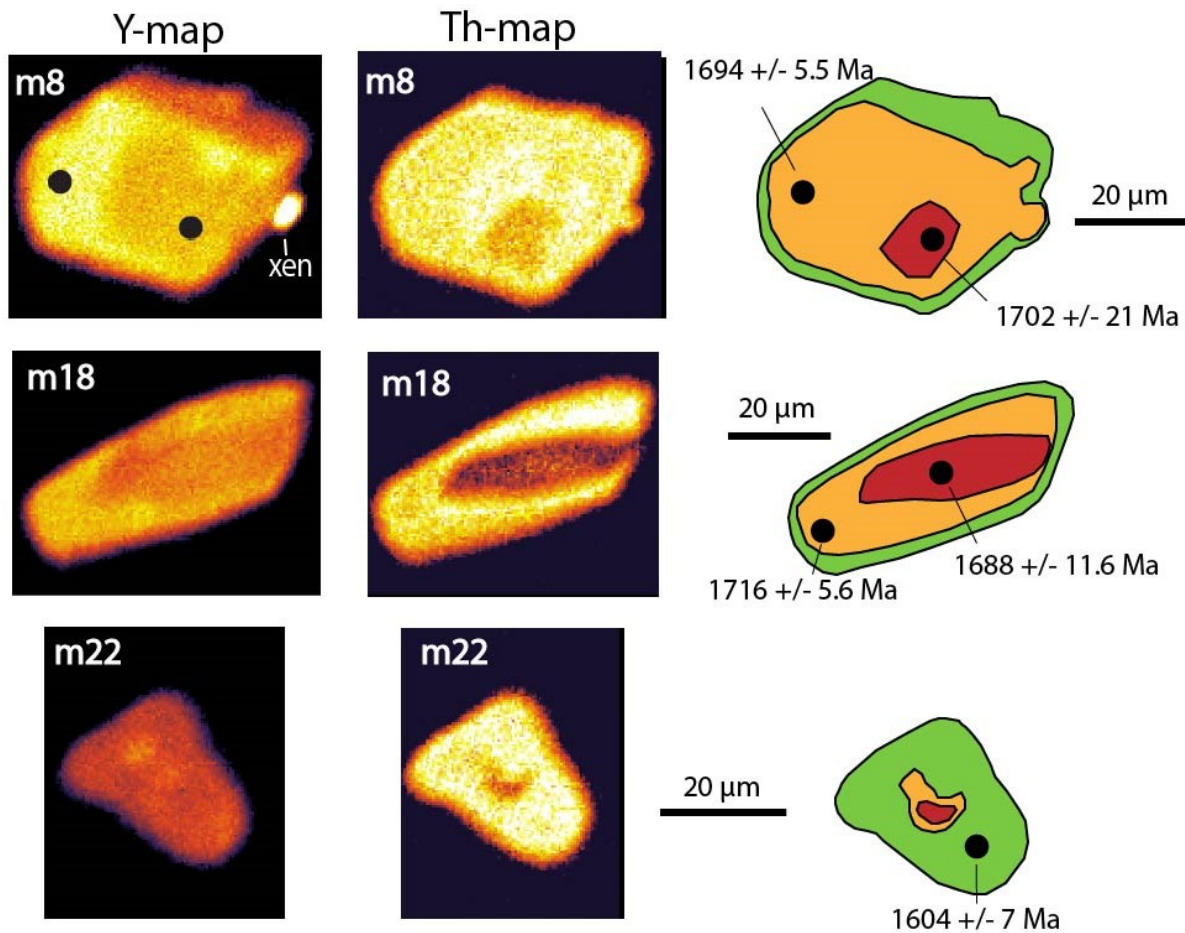


Figure 32: HS09-42a, examples of interpreted monazite domains with simplified Y compositional monazite maps (m8 and m22). Domain interpretation: Red = group 1, Orange = group 2, Green = group 3. Note the high-Y xenotime inclusion on grain m8. YPO₄

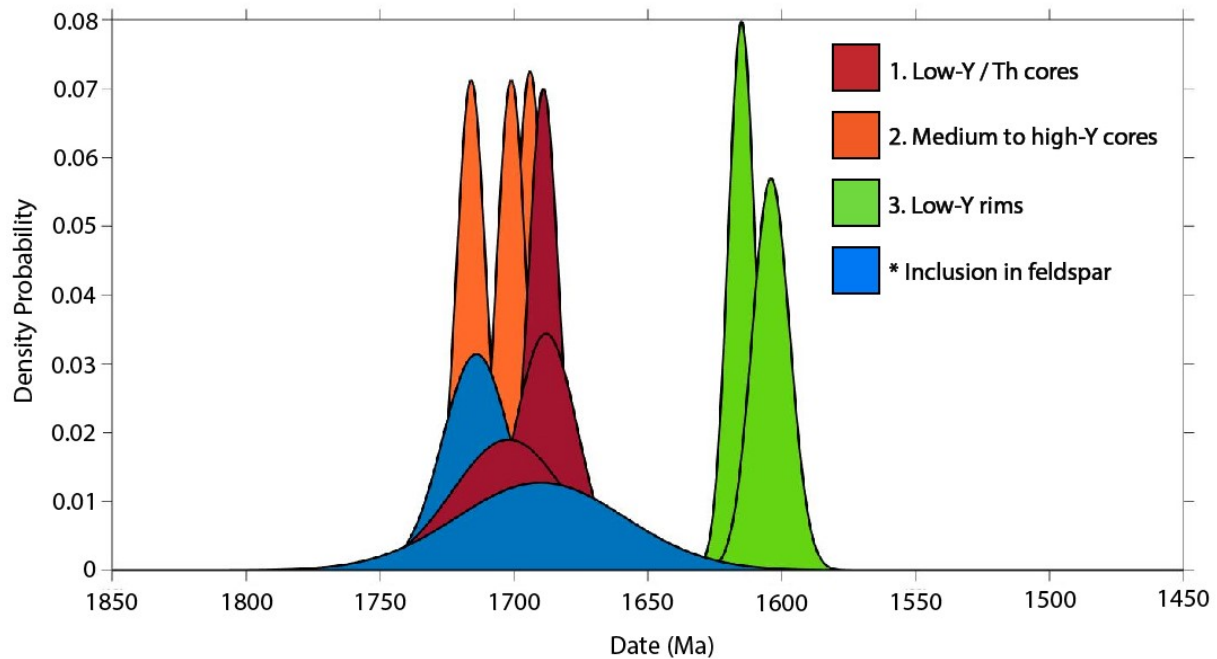


Figure 33: Normal distribution plot of monazite dates from HS09-42a.

There is no apparent compositional relationship separating the inner and outer core domains (Figure 34). The main/rim domains have a similar behavior to the main domains in HS09-35, in that they are depleted in Y, HREE's and U relative to the core domains (Figure 34).

SL08-07

16 of 24 monazite grains from sample SL08-07 were mapped, and only one compositional domain was recognized: 1) low-Y main (Figure 35 & 36). Grains m1 and m2 have an almost granular appearance to them created by relative differences in Y concentrations.

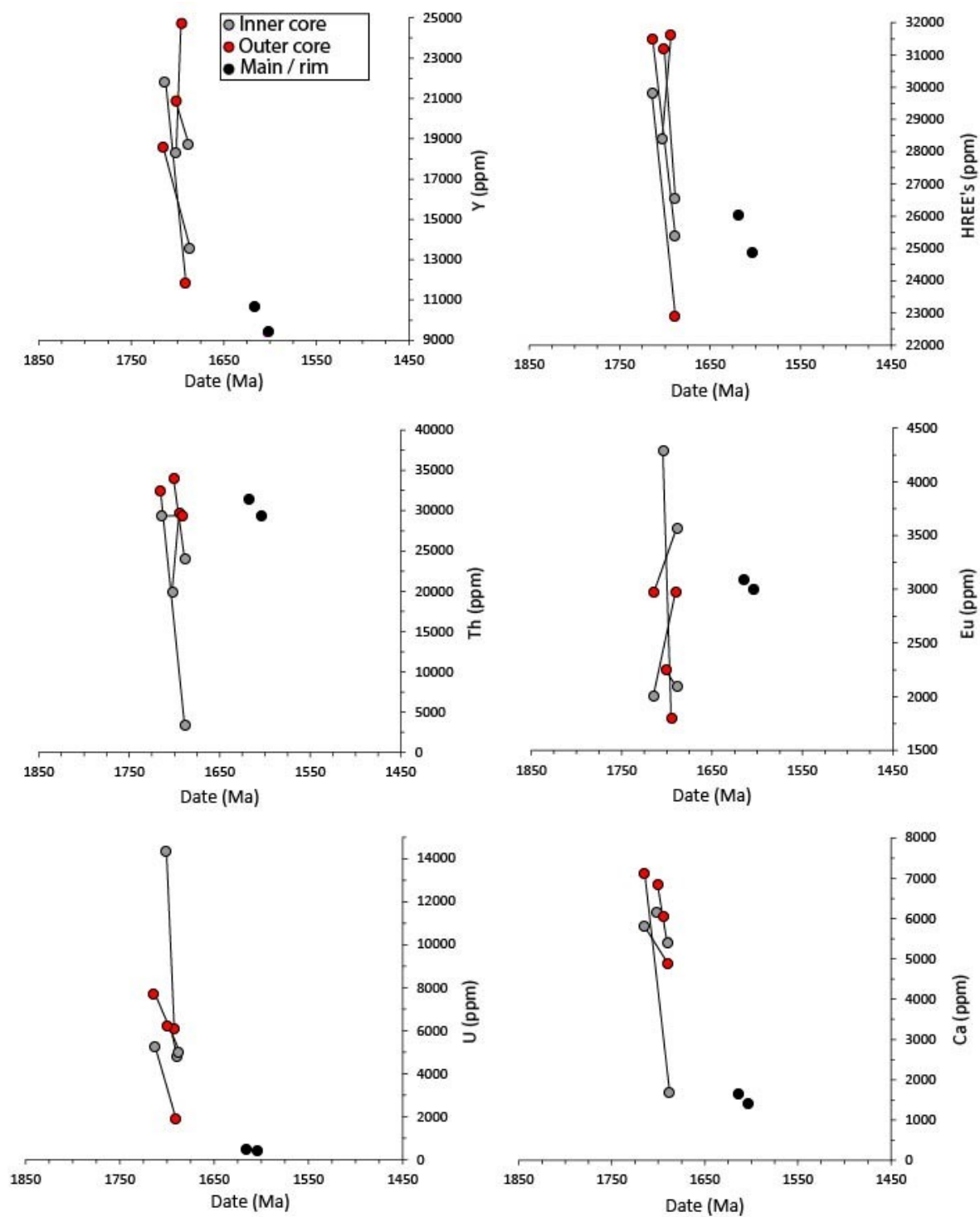


Figure 34: Age-composition relationships for monazite from HS09-42a. Line connects domains of the same grain

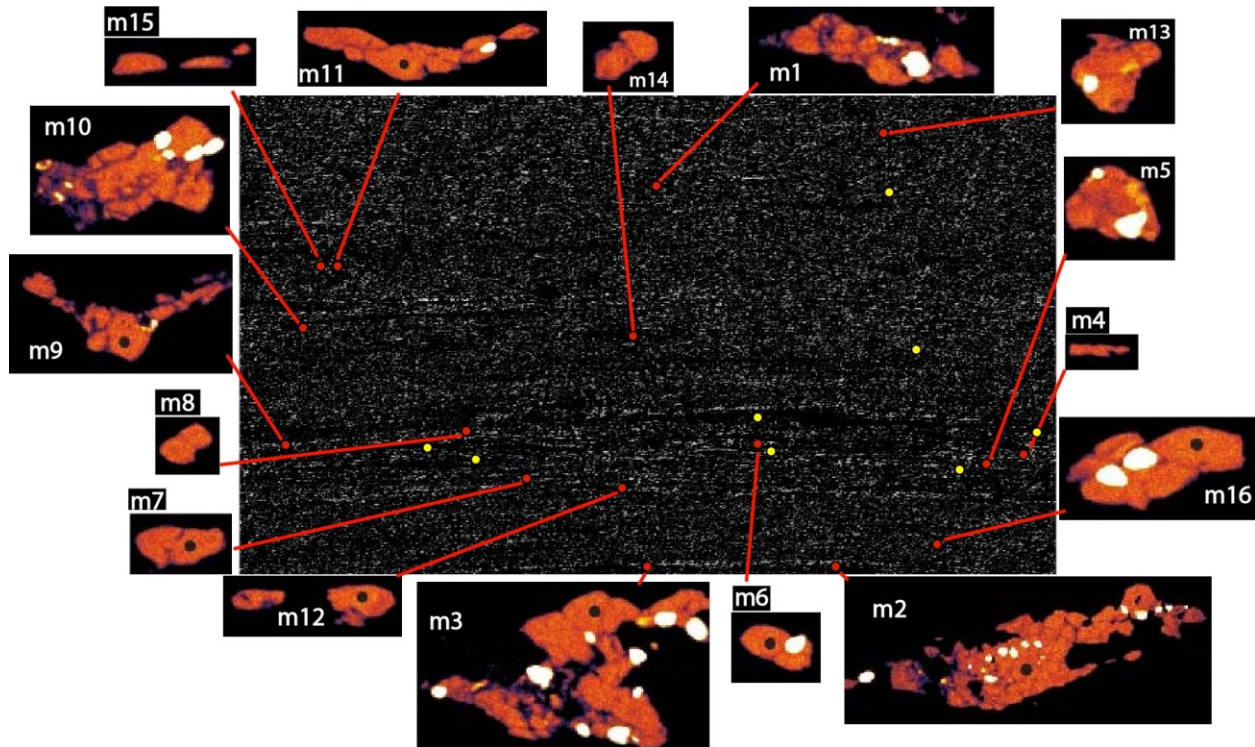


Figure 35: Full thin section Mg map of SL08-07 with monazite Y maps and grain locations.

9 monazite grains were analyzed in this sample, with a majority of the dates ranging from 1439 to 1413 Ma, and one anomalous date at 1310 Ma for grain m7 (Figure 37). The low-Y main domains were further separated into subgroups based on this age gap (Figure 37), between the grouping of 8 dates at 1421 Ma (1a), and grain m7 at 1310 Ma (1b). Group 1a records significantly lower age error values (5.8 to 13.3 Ma) relative to grain m7 (37.8 Ma).

The main monazite domains >1400 Ma have no obvious compositional pattern, but the one 1310 Ma monazite is depleted in the trace and REE's relative to the other monazite dates (Figure 38).

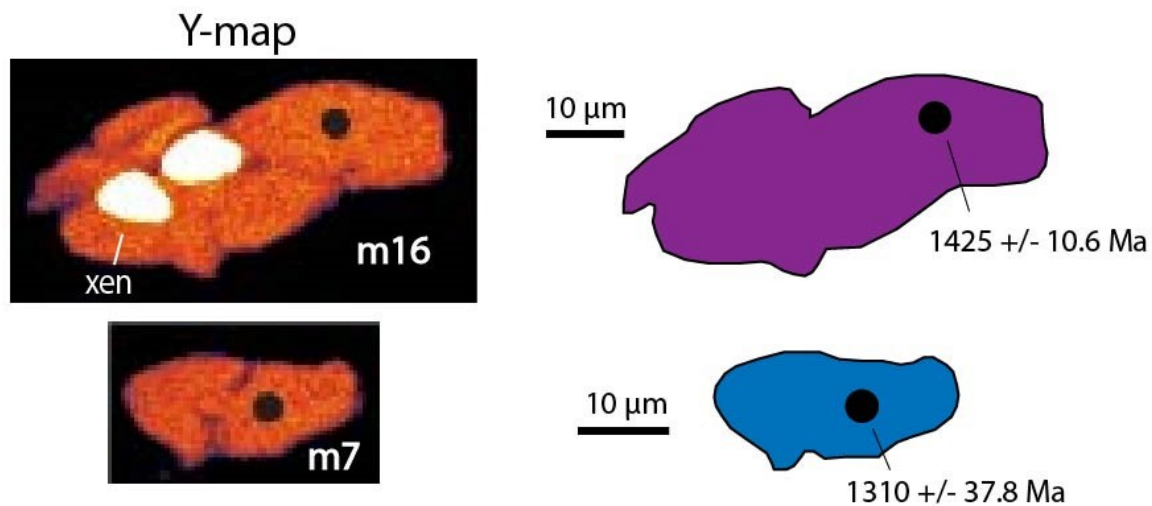


Figure 36: SL08-07, examples of interpreted monazite domains with simplified Y compositional monazite maps from sample SL08-07 (m16 and m7). Note the xenotime inclusions in grain m16.

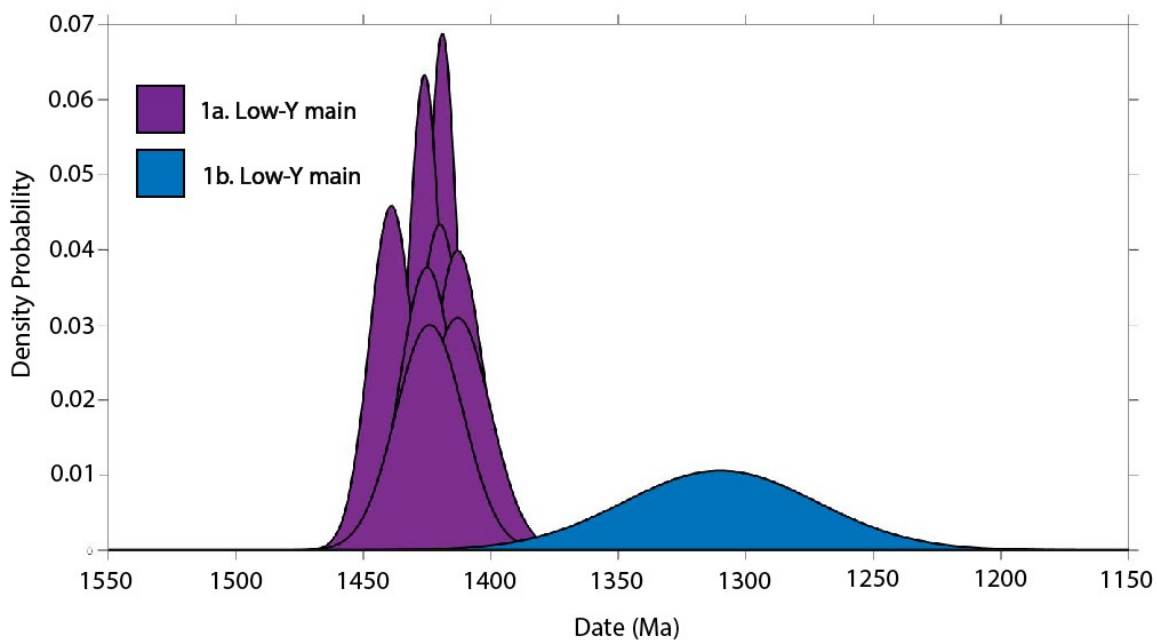


Figure 37: Normal distribution plot of monazite dates from SL08-07.

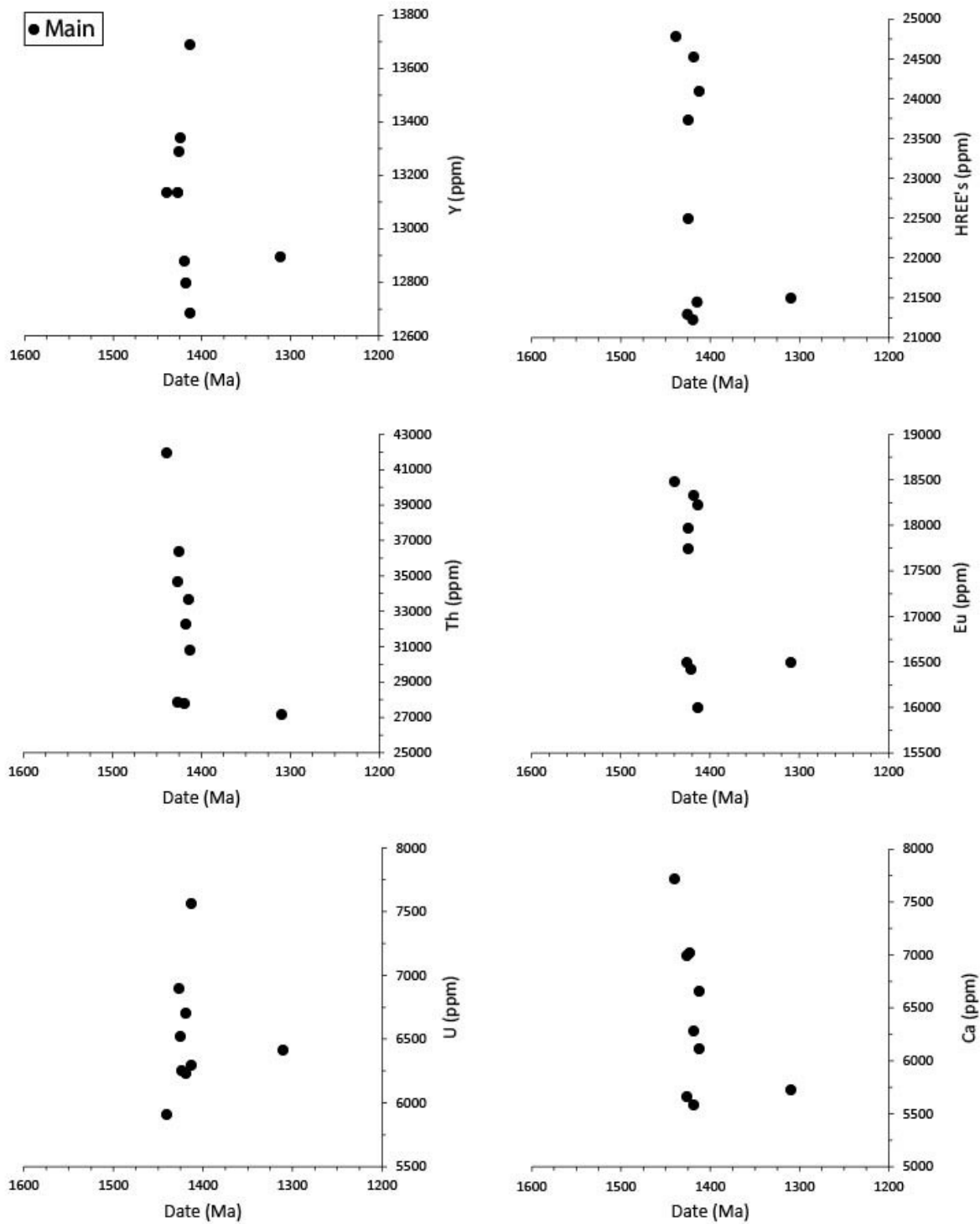


Figure 38: Age-composition relationships for monazite from SL08-07.

5.2. Sample comparisons

Monazite dates span the Paleoproterozoic through the Mesoproterozoic, with large groupings of dates from 1700 to 1600 Ma, and 1550 to 1400 Ma (Figure 39). The highest confidence in dates occurs at ~1700 and 1600 Ma with sample HS09-42a, and at ~1400 Ma with samples HS09-35 and SL08-07. The lowest confidence in dates is shown in a majority of the grains from samples HS09-36 and HS09-35, as well as the 1310 Ma date for SL08-07.

In general, Y and HREE concentration decrease with age, while Eu concentrations increase (Figure 40). Ca, Th, and U concentrations are comparable across the sample suite. The trend for HREE's is stronger than that recognized for Eu and Y. SL08-07 has the smallest range in trace and REE concentrations relative to the other samples.

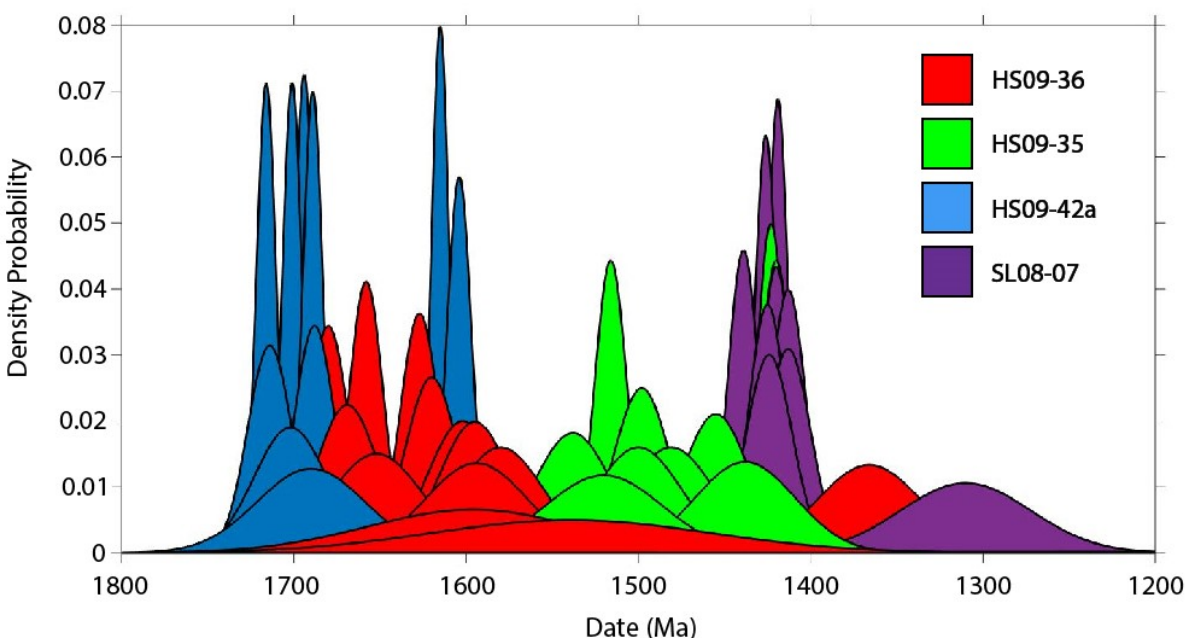


Figure 39: Normal distribution of monazite ages from the four selected samples.

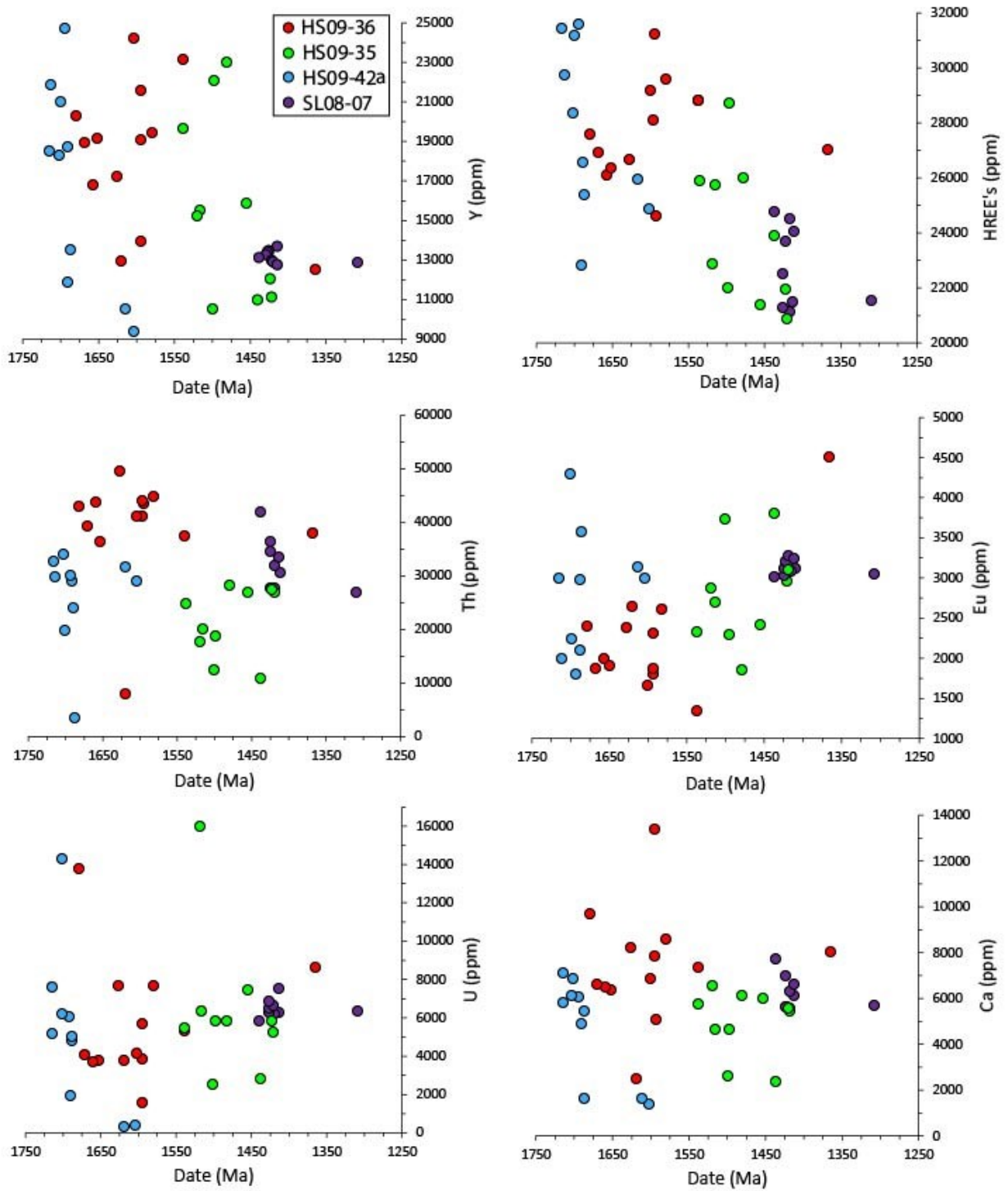


Figure 40: Age vs. composition plots for the monazite domains measured in this study.

CHAPTER 6:

DISCUSSION

Shear zone activity in the CMB is attributed to intracontinental deformation, likely as a response to tectonism on the southern margin of Laurentia ca. 1400 Ma (McCoy et al., 2005). The shear zones formed from reactivated Paleoproterozoic sub-vertical high-strain zones that formed during the Yavapai and Mazatzal orogenies and associated magmatic events. It is unknown as to whether sub-horizontal shear zones in the CMB were part of the same system of reactivated structural fabrics, or if they correspond to a separate mechanism of deformation during intracontinental reshuffling (Lee et al., 2012). This discussion serves to apply the structural relationships in the SLSZ established by Lee et al. (2012) to monazite systematics, to accurately determine the timing of shear zone activity. Shear zone tectonites were specifically targeted in this research to examine monazite domains of rocks that were subject to ductile shearing and grain-size reduction. Four samples with varying microstructural characteristics were chosen to systematically parse the differences in monazite domain types and dates between mylonitic samples (HS09-35, HS09-42a, SL08-07), and the high-strained gneissic protoliths from which they originated (HS09-36).

6.1. General age trends

Monazite ages from this study can be divided into two main groups: 1) Paleoproterozoic (1700 – 1600 Ma), and 2) Mesoproterozoic (1550 – 1400 Ma). Table 2 provides weighted averages for the monazite dates from the sample suite. Sample HS09-36 records monazite dates from 1680 – 1580 Ma, with an anomalous rim date at 1366 Ma; monazite core dates from this

high-strained gneissic sample correlate with timing of the D₂ deformation event (Table 2) (Shaw et al., 2001; McCoy et al., 2005). The youngest dates of the monazite sample suite almost entirely come from samples SL08-07 (avg: 1421 ± 7.6 Ma) and HS09-35 (avg: 1502 ± 39 Ma), which implies that mylonitic deformation completely reset the earlier deformation events recorded in monazite. These samples were likely reset by fluid-related alteration between 1550 and 1400 Ma, with a high probability at ~ 1421 Ma, exemplified by the cluster of low-Y main dates from SL08-07 (avg: 1421 ± 7.6 Ma), and the two low-Y main dates from HS09-35 (1423 and 1420 Ma). Core domains in sample HS09-35 are older than that recorded in other CMB shear zones, implying that shear zone activity may have occurred earlier than previously reported (Shaw et al., 2001; McCoy et al., 2005); however, due to the higher error in HS09-35 core domains, and relatively similar dates to Mesoproterozoic mylonitic deformation, they are inferred to be related to the D₃/D₄ deformation in the CMB. Monazite ages from sample HS09-42a (avg: 1700 ± 6.9 Ma), do not coincide with these other mylonitic samples, implying that the monazite grains were not reset during Mesoproterozoic deformation. Instead, these ages are the oldest recorded in the sample suite and are coeval with the oldest monazite ages in the CMB shear zone system (McCoy et al., 2005).

In concert with the timing of the CMB deformation events, monazite dates from this research are roughly consistent with regional tectonic events in southern Laurentia, including the Yavapai orogeny (1710 – 1680 Ma; Whitmeyer and Karlstrom, 2007), the Mazatzal orogeny (1650 – 1600 Ma; Whitmeyer and Karlstrom, 2007) and the Picuris orogeny (1500 – 1400 Ma; Daniel et al., 2013). Average core monazite dates from HS09-42a and HS09-36 coincide with the timing of Yavapai and Mazatzal orogenesis, respectively, while dates from samples HS09-35 and

SL08-07 are largely compatible with the timing of the Picuris orogeny, in addition to protracted Mesoproterozoic tectonism in Laurentia (1500 – 1300 Ma; Whitmeyer and Karlstrom, 2007). .

Table 2: Weighted averages of monazite ages from the four selected samples, and interpreted deformation event. Averages from HS09-36, HS09-35, and HS09-42a only include core domains, and exclude low-Y rim and main domains. Exclusions include: HS09-36, m30-4; HS09-35, m4 and m16; HS09-42a, m11 and m22; SL08-07, m7. CMB deformation events from Shaw et al. (2001) and McCoy et al. (2005).

Sample	Weighted average age (Ma)	Inferred CMB deformation event
HS09-36	1640 ± 23	D ₂ : 1670 – 1620 Ma
HS09-35	1502 ± 39	D ₃ /D ₄ : 1450 – 1300 Ma
HS09-42a	1700 ± 6.9	D ₁ : 1730 – 1690 Ma
SL08-07	1421 ± 7.6	D ₃ /D ₄ : 1450 – 1300 Ma

6.2. Microstructural significance of monazite dates

Samples HS09-36, HS09-35, and SL08-07 exhibit a progression of grain-size reduction and shear strain in the more mica-rich rocks from this study (Figure 41). Weighted averages of monazite ages are older in the sample with larger grain sizes and little evidence for shearing (HS09-36: 1640 ± 23 Ma), and younger in the samples with smaller grain size and higher mylonitic strain (HS09-35: 1502 ± 39 Ma) (SL08-07: 1421 ± 7.6 Ma). These ages and microstructural characteristics support the model of increasingly higher-strained deformation in the CMB over time (Shaw et al., 2001; McCoy et al., 2005). There is some indication that HS09-36 was active at around the same time as the higher-strain mylonitic samples, indicated by the one low-Y rim analyzed on grain m30 (1366 Ma). The lack of > 1600 Ma monazite ages of samples HS09-35 and SL08-07 implies that with increasing strain, grain-size reduction and possible fluid-interaction, younger monazite grains form at the expense and complete resetting of

Grain-size reduction



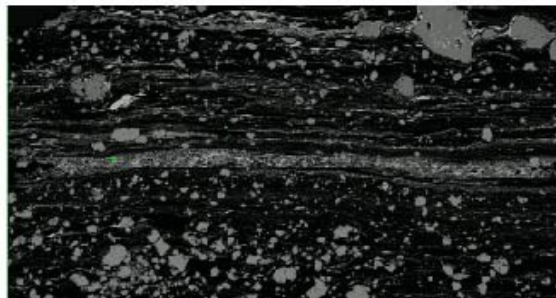
HS09-36:
 1640 ± 23 Ma
Mz count: 73



HS09-35:
 1502 ± 39 Ma
Mz count: 49



SL08-07:
 1421 ± 7.6 Ma
Mz count: 24



HS09-42a:
 1700 ± 6.9 Ma
Mz count: 27

Figure 41: Sample comparison of microstructures with average monazite dates. Full thin section Al X-ray maps showing qualitative relationship between grain size reduction, average monazite dates (Table 2), and monazite count.

inherited monazite. This progression of dates is also reflected by decreasing monazite abundance for each sample (HS09-36: $n = 73$, HS09-35: $n = 49$, SL08-07: $n = 24$), possibly reflecting a decline in monazite stability in the greenschist-facies mylonites (Kingsbury et al., 1993).

Monazite dates from sample HS09-42a were the only ones that did not coincide with previous findings from the CMB shear zone system. Despite having clear evidence for mylonitic deformation, indicated by rotated feldspar porphyroclasts, the monazite dates from this sample (1716– 1604 Ma) are much older than the dates from the two other mylonite samples (1538 – 1413 Ma). One possible reason for this is the lower permeability in quartzose samples (Morrow et al., 1984), inhibiting the flow of metamorphic fluids necessary to dissolve and reprecipitate monazite. Sample HS09-42a was the only one which preserved pre-deformative feldspar, suggesting that dissolution-precipitation creep (DPC) was not the dominant deformation mechanism in the rock, which explains the preservation of ~1700 Ma monazite grains (Wawrenitz et al., 2012). The lack of alkali-rich fluids generated from the breakdown of feldspar inhibits the reactivity of monazite grains, regardless of strain or temperature conditions (Wawrentiz et al., 2012). Another possibility is that the sample was dry during shear zone deformation, which is independent from the breakdown of feldspar or other alkaline phases.

A majority of the dates from this HS09-42a (avg: 1700 ± 6.9 Ma) are coeval with the early Paleoproterozoic deformation (D_1) which was characterized by melt-present regional folding (Shaw et al, 2001). The sector compositional zoning found in grain mC2 (1701 and 1689 Ma) is characteristic of igneous monazite crystallization due to the differential uptake of REE's onto crystal faces (Cressey et al., 1999). The next grouping of monazite dates in this sample were from the two low-Y rims domains dated at 1615 and 1604 Ma, representing the youngest dates from this sample. This evidence potentially suggests that monazite from this sample are inherited

igneous grains that crystallized during the D₁ event, were reset at ~1610 Ma, but were not recrystallized during Mesoproterozoic shearing (1550 – 1400 Ma). Monazite ages from this sample are therefore not representative of mylonitization in the steeply dipping Bennett ridgeline splay.

6.3. Core to rim relationships

A common phenomenon in each of the samples exhibiting core-rim zonation (excluding SL08-07) is inconsistent age relationships between inner and outer cores, where inner cores were younger than their respective outer core. Inner cores were often characterized by low Y and Th, the latter of which may be an indicator of fluid-related alteration of U, Th, and/or Pb, distorting the actual age of the monazite (Goncalves et al., 2005; Williams et al., 2011). The incomplete removal of U-Th-Pb during alteration results in misinterpreted dates, and the variability and ambiguity of these occurrences must be considered when applying monazite dates to ages of geologic activity. Age disparity between older outer cores and younger inner cores ranged from 1 Ma (HS09-36: m34) to 60 Ma (HS09-35: m2). Th-maps commonly reveal enigmatic zonation, possibly related to the removal of Th through coupled dissolution – reprecipitation processes. Possible causes for these observations include: fluid-related pseudomorphic replacements of monazite during metasomatism (Harlov and Hetherington, 2010), or grain-scale porosity and permeability permitting metamorphic fluid infiltration (Putnis and Austrheim, 2010). Another consideration is the influence of cut effects when making the thin section, limiting the view of the monazite grains to two dimensions and potentially obscuring the interpretation of core and rim domains.

These domain inconsistencies make it difficult to interpret the geologic significance of the core domains. However, despite the variability in monazite core dates, weighted averages can be used to generalize age range of core domains in each sample (Table 2).

6.4. Trace element trends

The sample-composition comparisons show decreasing Y and HREE concentration over time, with increasing Eu concentration. This observation could represent an increasing favor of xenotime crystallization, which Y and HREE's favorably fractionate at lower-grade conditions (Spear and Pyle, 2002). As none of these samples are garnet- or allanite-bearing, monazite and xenotime alone control the balance of Y and HREE's in the sample (Spear and Pyle, 2002). These observations only provide a qualitative assessment of metamorphic grade and crystallization conditions, as xenotime was not analyzed in this research. The slight increase in Eu in the younger, Mesoproterozoic monazite dates from higher-strained samples (SL08-07 & HS09-35) relative to the older Paleoproterozoic monazite dates could be the result of increasing deformation and dissolution of feldspar grains at lower grades and higher strain rates, releasing Eu (Rubatto et al., 2006). Negative-Eu anomalies are common in metamorphic monazite grains as a result of fractionation into feldspar (Spear and Pyle, 2002), an effect that could lessen with increasing dissolution of feldspar.

6.5. Age of shear zone activity

Microstructural and geochemical data suggest that fluid-related alteration of monazite in mylonitic samples from the Homestake ridgeline (HS09-35 and SL08-07) occurred post-1550

Ma, with a high probability around 1421 Ma with dates from low-Y main domains. The lack of inherited monazite grains from these samples implies that this fluid alteration completely reset preexisting monazite grains, precipitating new grains that record this event. Monazite grains breaking down to form apatite also supports fluid-related alteration (Spear and Pyle, 2002). Core domains from HS09-35 (avg: 1502 ± 39 Ma) record incomplete alteration of monazite grains around 1500 Ma, with low-Y main domains recording secondary monazite precipitation (1423 and 1420 Ma). The same ~ 1421 Ma ages are reported in the low-Y main domains in sample SL08-07 (avg: 1421 ± 7.6 Ma); the low-Y domains in HS09-35 and SL08-07 are the only case where the same domain-monazite date relationship is present in two different samples. It is more difficult to attribute shear zone activity post-1400 Ma due to the lower abundance and the relatively higher error of monazite dates analyzed in this range (1366 ± 30 Ma and 1310 ± 37.8 Ma).

The similar orientation and kinematics between the Homestake ridgeline and Slide Lake pavement mylonite splays suggests that they are two parts of the same shear zone (Lee et al., 2012). However, it cannot be confirmed as to whether they were active at the same time, because of the lack of Slide Lake pavement monazite dates that could be compared to the two Homestake ridgeline mylonite samples analyzed in this research. Age of activity in the Bennett ridgeline splay is also inconclusive, due to the dry nature of sample HS09-42a and lacking syn-deformational reprecipitation of monazite in the Mesoproterozoic.

Monazite dates from the Homestake ridgeline mylonite samples are coincident with the timing of the Picuris orogeny (1500 – 1400 Ma) (Daniel et al., 2013). This relationship may imply that the activity of the SLSZ and other CMB shear zones formed during intracontinental deformation of the Yavapai province as a response to orogenesis on the southern margin of

Laurentia associated with the Picuris orogeny. These findings also align with the timing of the more traditional ~1400 Ma tectonic event in Laurentia associated with magmatism, deformation, and regional metamorphism inboard from the previous active plate margin (Whitmeyer and Karlstrom, 2007).

6.6. Relationship to Northern Sawatch range

Ages from the SLSZ correlate with other geochronologic constraints from the Northern Sawatch Range (Shaw et al., 2001; McCoy et al., 2005; Shaw et al., 2005). The Paleoproterozoic monazite ages from this research (1716 – 1580 Ma) generally overlap with the D₁ and D₂ events recorded in the neighboring HSZ area (1710 – 1630 Ma; Shaw et al., 2001) and the emplacement of the Cross Creek Batholith (ca. 1675 Ma [Rb-Sr]; Tweto and Lovering, 1977). Inferred shear zone activity from this research also overlaps with HSZ activity (1450 – 1370 Ma), as well as the emplacement of the neighboring St. Kevin Batholith (1396 ± 40 Ma [U-Th-Pb zircon]; Doe and Pearson, 1969). These findings reinforce the idea that elevated temperatures during ~1400 Ma plutonism in the CMB permitted the thermal weakening and reactivation of high-strain fabrics (McCoy et al., 2005).

The timing correlation reinforces coeval kinematic motion between the HSZ and SLSZ, like in the model proposed by Lee et al. (2012) involving the coupled top-to-the-southeast shear sense, top-to-the-northwest shear sense, and dextral shearing during regional transpression. Similar deformation temperatures (HSZ: 280 – 500 °C; SLSZ: 280 – 600 °C) as well as similar kinematic shear sense (top-to-the-southeast and top-to-the-northwest) between the HSZ and SLSZ recorded by Lee et al. (2012) is supported by corresponding monazite ages in the HSZ (1450 – 1370 Ma) reported by Shaw et al. (2001), and in the SLSZ reported in this study (1538 –

1413 Ma). The weighted average for top-to-the-southeast mylonite deformation (D_3) reported by Shaw et al. (2001) (1372 ± 19 Ma) is younger than the weighted averages recorded in the mylonites with similar top-to-the-southeast shear sense from this study (HS09-35: 1502 ± 39 Ma; SL08-07: 1421 ± 7.6 Ma), indicating that shear zone deformation in the SLSZ may have preceded that of the HSZ, but more data are needed to confirm this relationship and the potential strain compatibility between the shear zones. Consequently, although Lee et al. (2012) demonstrated the shear zones may be coeval based on orientation and kinematics, the weighted averages of monazite dates between the HSZ and SLSZ does not directly verify contemporaneous activity between the shear zones. However, the domain-specific dating scheme utilized in this research (Williams et al., 2017) differs from that used on the HSZ (Shaw et al., 2001), and as such the reanalysis of monazite grains from the HSZ with the refined dating technique used on the SLSZ would be more suitable for comparing the timing of activity between shear zones.

CHAPTER 7:

CONCLUSION

The SLSZ is a sub-horizontal mylonitic shear zone traceable from the Northern Sawatch range. As part of the CMB shear zone system, this shear zone serves as an important reference to how sub-vertical and sub-horizontal shear zones operate together during deformation events. Four previously collected samples from the Homestake and Bennett Ridgeline, each with varying microstructural characteristics, were chosen to investigate the monazite ages and geochemistry of the SLSZ. The three samples from the Homestake Ridgeline (HS09-36, HS09-35, and SL08-07) record successively younger monazite dates with more advanced grain-size reduction. Despite being a mylonitic sample, monazite grains cores from HS09-42a (Bennett Ridgeline) record older (avg: 1700 ± 6.9 Ma) dates that were not reset during shear zone deformation, likely due to the lack of dissolution-precipitation creep deformation in the sample, restricting the reactivity of fluids necessary to dissolve and reprecipitate monazite. Core domains from the high-strained gneissic sample (HS09-36, avg: 1640 ± 23 Ma) are coeval with the later Paleoproterozoic deformation event (D_2) and may correspond to high-strain zone formation documented around the CMB shear zone system, serving as the precursors to Mesoproterozoic mylonite formation. Monazite dates often record age inconsistencies from the inner core to outer cores, and instead reveal evidence for incomplete resetting where unbalanced removal of U, Th, or Pb results in distorted dates. Weighted means are better suited to evaluate the range in monazite dates from core domains, which was on the scale of 1 – 60 Ma separating younger inner cores from older outer cores. Monazite dates support that fluid-related alteration in the shear zone occurred around 1421 Ma, indicated by low-Y main monazite domains in grain-size-reduced mylonitic samples HS09-35 (1423 and 1420 Ma) and SL08-07 (avg: 1421 ± 7.6 Ma), as well as preserved monazite

– apatite reactions from these samples. Monazite core dates from HS09-35 (avg: 1502 ± 39 Ma) and low-Y main dates from SL08-07 (avg: 1421 ± 7.6 Ma) generally coincide with the activity of the HSZ (1450 Ma – 1370 Ma), suggesting that the two shear zones were active around the same time during the Mesoproterozoic. This supports previous models of coeval activity between the neighboring shear zones involving coupled top-to-the-northwest, top-to-the-southeast, and dextral motion. The results reinforce previous findings of the activity of the CMB shear zones (1450 – 1300 Ma), supporting the existence of a regional shear zone system in Colorado that records intracontinental processes during the Mesoproterozoic.

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APPENDIX I:
MONAZITE DATA

Table 3: Sample monazite analyses. Contact jeremyleierzapf@gmail.com or mjessup@utk.edu for full excel spreadsheet.

Analysis	Date	1-sigma error	Y	HREE's	Th	Eu	U	Ca
HS09-36								
Un 17 jl-HS09-36-m22-core	1658	9.7	16823	26057	43692	2000	3763	6502
Un 18 jl-HS09-36-m22-low-rt-rim	1596	61.2	21611	28119	41160	1873	5727	7838
Un 19 jl-HS09-36-m34-core	1594	29.4	13986	31280	43322	2307	1683	5077
Un 20 jl-HS09-36-m34-up-out-core	1595	20.1	19056	24631	43861	1800	3950	13385
Un 21 jl-HS09-36-m36-core	1627	11	17242	26629	49457	2387	7696	8190
Un 22 jl-HS09-36-m36-low-right-rim	1680	11.6	20280	27516	42945	2393	13839	9630
Un 23 jl-HS09-36-m39-up-right-core	1539	80.7	23132	28764	37575	1339	5338	7313
Un 24 jl-HS09-36-m6-core	1669	17.8	18945	26900	39344	1863	4127	6599
Un 25 jl-HS09-36-m1-left-side	1652	26.6	19200	26362	36381	1900	3827	6384
Un 66 JL-HS09-36-m30-1 inner core	1620	15	12935	16215	7908	2651	3873	2534
Un 67 JL-HS09-36-m30-2 outer core	1580	25	19435	29585	44869	2629	7730	8606
Un 68 JL-HS09-36-m30-3 outer core	1602	20	24207	29231	41196	1658	4266	6846
Un 69 JL-HS09-36-m30-4 rim	1366	30	12495	27018	38286	4519	8695	8026
HS09-35								
Un 5 jl-HS09-35-m2-core	1438	29	10975	23895	10488	3797	2790	2437
Un 6 jl-HS09-35-m2-left-rim	1498	16	22069	28705	19161	2289	5856	4719
Un 7 jl-HS09-35-m5-core	1455	19	15830	21344	27297	2407	7499	5967
Un 8 jl-HS09-35-m5-up-left	1481	25	23023	26022	28439	1857	5885	6129
Un 9 jl-HS09-35-m9-core	1500	25	10459	22054	12518	3728	2627	2557
Un 10 jl-HS09-35-m10-core	1520	34	15256	22906	17762	2892	16024	6566
Un 11 jl-HS09-35-m10-right-rim	1538	22	19609	25894	25011	2318	5517	5723
Un 12 jl-HS09-35-m7-core	1516	9	15485	25713	20236	2700	6460	4683
Un 13 jl-HS09-35-m4-all	1420	9	11144	20876	27223	3081	5289	5428
Un 14 jl-HS09-35-m16-all	1423	8	11979	21918	27864	2952	5884	5681

Table 3 Continued

HS09-42A

Un 29	jl-HS09-42A-mC2-Lower-core	1689	5.7	18721	26539	23975	2093	4963	5452
Un 30	jl-HS09-42A-mC2-Left-side	1701	5.6	21013	31174	33973	2248	6261	6824
Un 31	jl-HS09-42A-m8-right-core	1702	21	18320	28383	19899	4292	14346	6168
Un 32	jl-HS09-42A-m8-left-side	1694	5.5	24726	31607	29824	1807	6159	6047
Un 33	jl-HS09-42A-m1-core	1714	12.7	21824	29741	29628	2000	5240	5807
Un 34	jl-HS09-42A-m1-left-rim	1690	31.3	11897	22899	29363	2971	1913	4881
Un 35	jl-HS09-42A-m18-core	1688	11.6	13556	25381	3361	3561	5055	1697
Un 36	jl-HS09-42A-m18-left-rim	1716	5.6	18598	31465	32635	2983	7697	7111
Un 37	jl-HS09-42A-m22-low-right	1604	7	9336	24890	29257	2992	408	1419
Un 22	JL-42A-m11-rim	1615	5	10541	26064	31421	3093	491	1697

SL08-07

Un 41	JL-SL08-m3	1413	6	12682	24105	30744	3227	6296	6103
Un 42	JL-SL08-m11	1424	13.3	13340	23724	36363	3166	6263	7017
Un 43	JL-SL08-m9	1420	9.2	12876	21218	27749	3231	6689	5596
Un 44	JL-SL08-m2	1419	5.8	12791	24520	32253	3107	6234	6269
Un 45	JL-SL08-m6	1413	10	13690	21435	33678	3091	7566	6647
Un 46	JL-SL08-m7	1310	37.8	12897	21493	27131	3057	6420	5723
Un 47	JL-SL08-m16	1425	10.6	13288	22487	34710	3091	6519	6998
Un 48	JL-SL08-m12	1426	6.3	13131	21288	27870	3029	6899	5659
Un 49	JL-SL08-m10	1439	8.7	13135	24774	41949	3010	5906	7715

APPENDIX II:
MICROSTRUCTURAL OBSERVATIONS

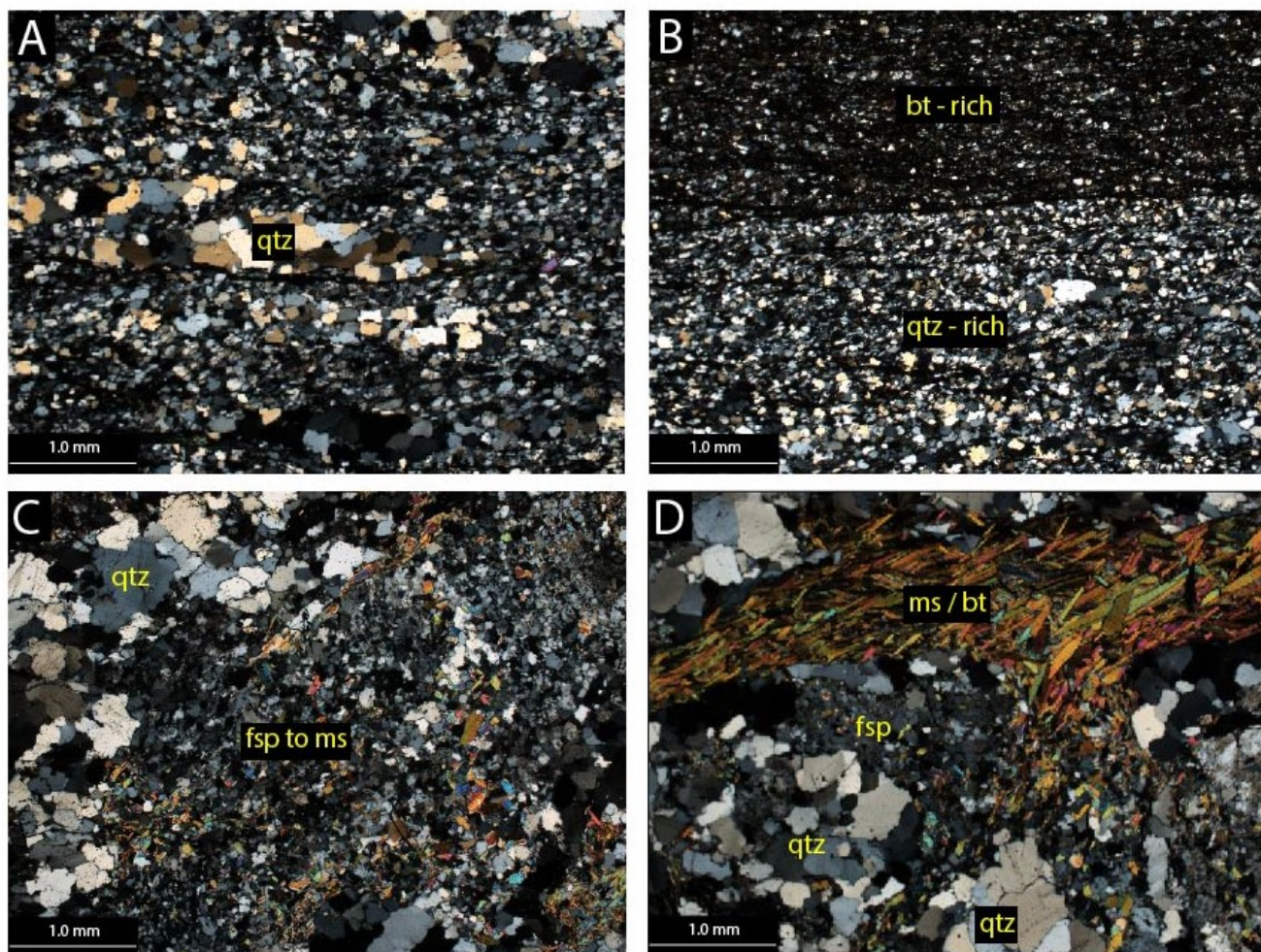


Figure 42: Photomicrographs from newly collected samples. A.) Relict GBM quartz textures surrounded by grain-size reduced quartz and phyllosilicates. B.) Compositional banding between a quartz and biotite rich layer. C.) Recrystallized feldspar altering to muscovite. D.) Phyllosilicate layer flowing around more rigid quartz and feldspar.

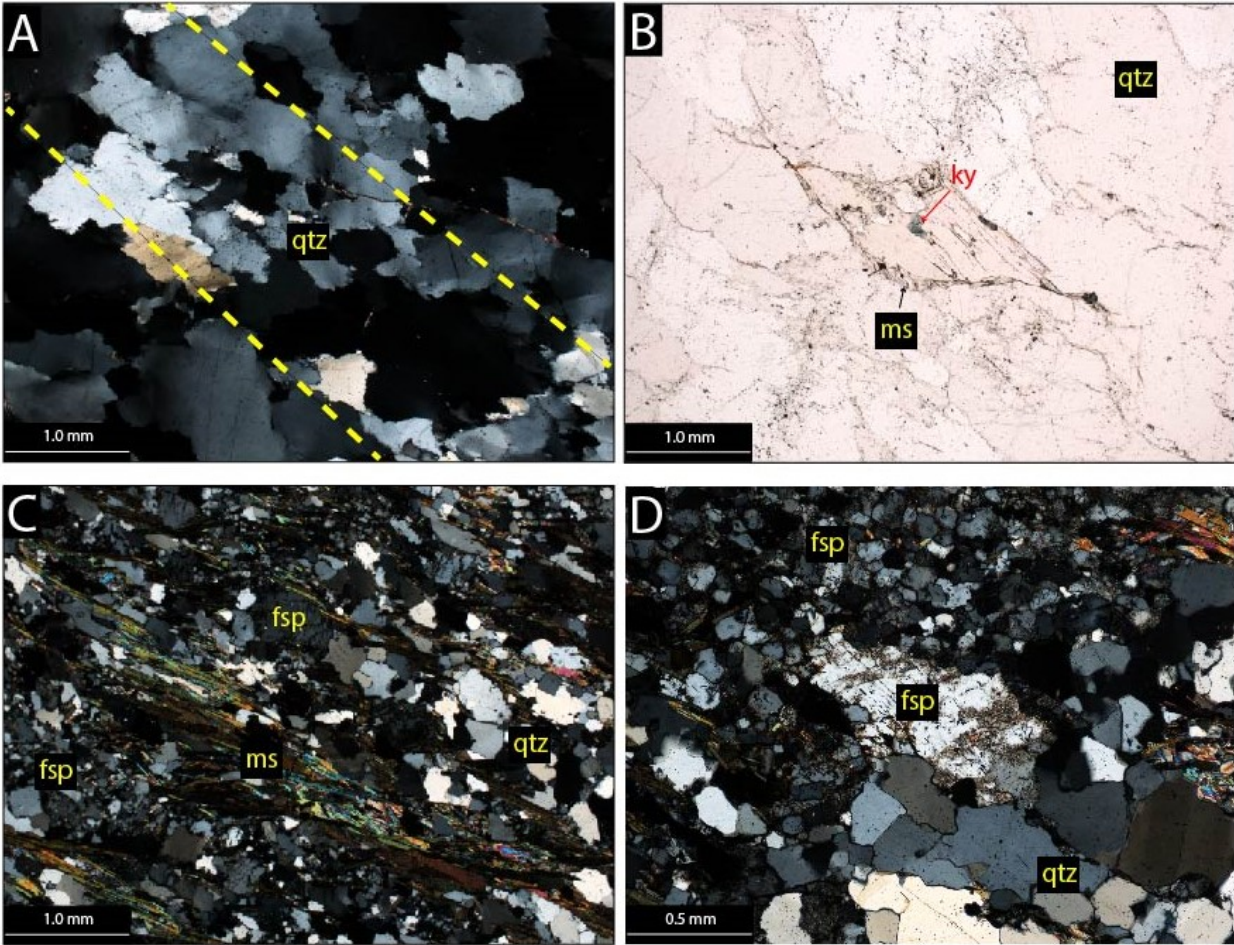


Figure 43: Photomicrographs from newly collected samples. A.) GBM quartz with elongated grain shape. B.) Muscovite pseudomorph enclosing relict kyanite. C.) Foliation defined by alternating layers of GBM quartz and recrystallized feldspar, and paralleling phyllosilicates. D.) Relict feldspar grain surrounded by recrystallized BLG feldspar grains and GBM quartz.

APPENDIX III:
FIELD OBSERVATIONS

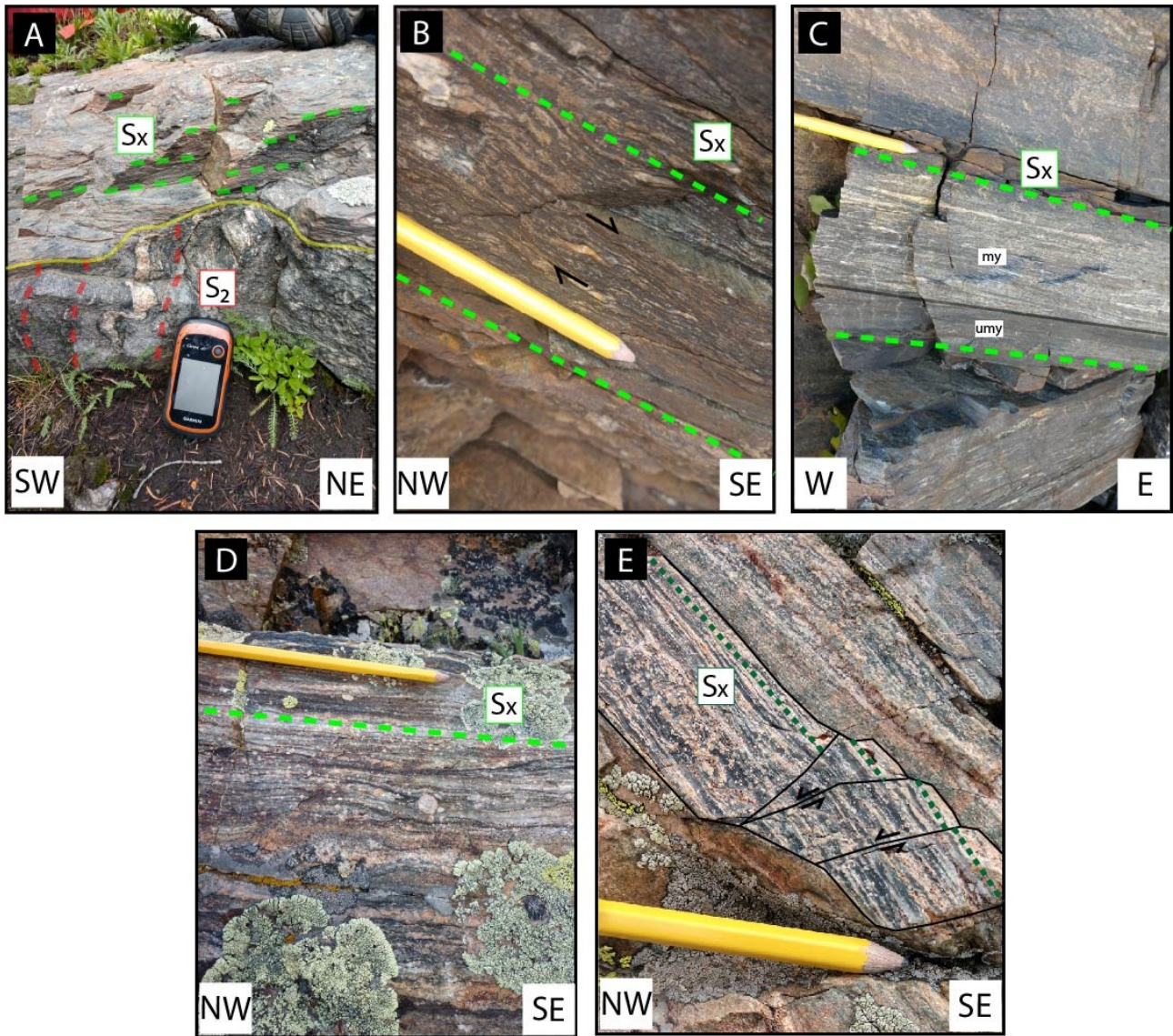


Figure 44: Additional field observations A.) Sub-horizontal high-strain mylonite cross-cutting gneissic leucosome fold. B.) Asymmetric quartz shear band showing t-SE shear sense. C.) Mylonite and ultramylonite from Homestake Peak. D.) Feldspar porphyroclasts in mylonite from Bennett ridgeline. E.) t-NW fracturing in mylonite from Bennett ridgeline.

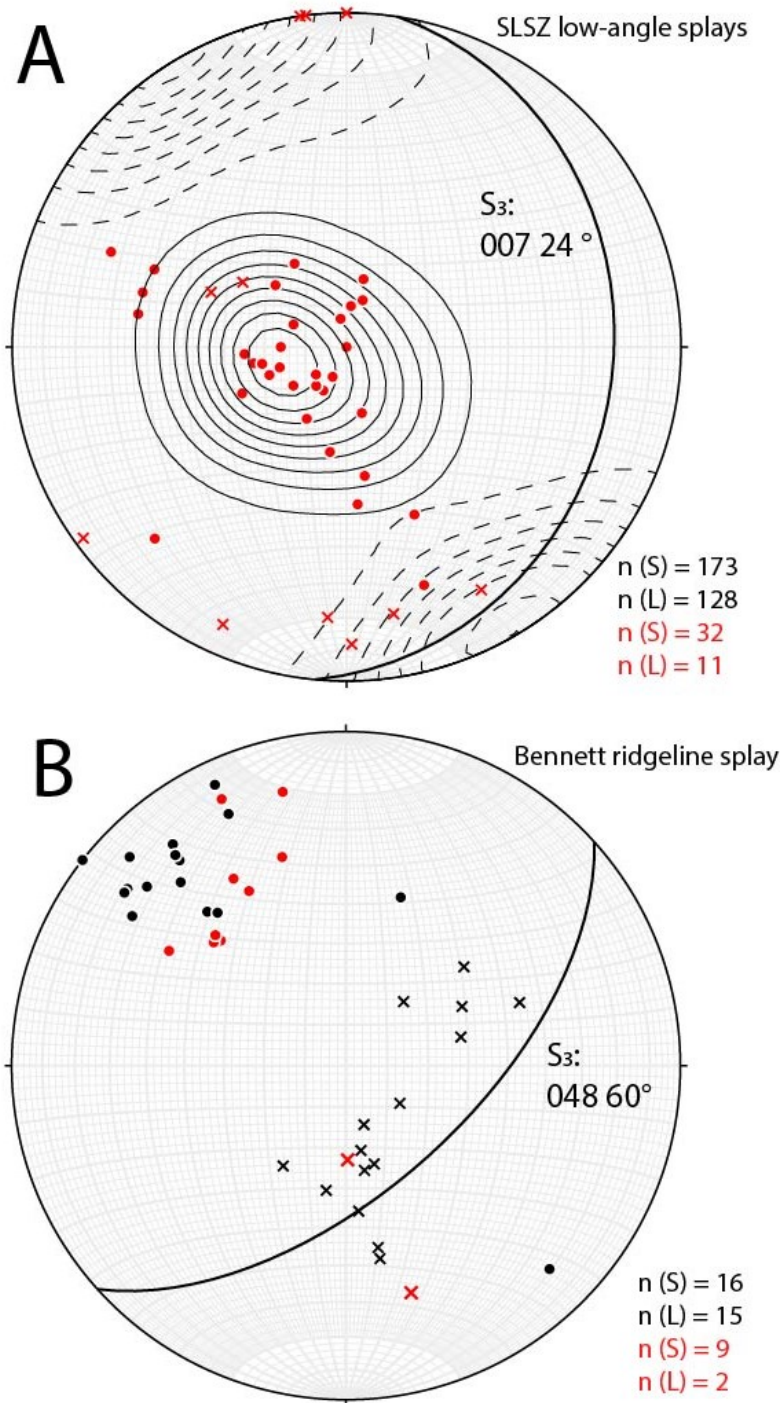


Figure 45: Lower hemisphere equal area stereonet showing foliations and lineations from mylonite splays. Circles are poles to mylonite foliation, and crosses are mineral lineations. Average mylonite foliation (great-circles in black) plotted from Lee et al., 2012. Red markers are from this study, black are from Lee et al., 2012 as a reference. A.) Homestake Ridgeline (Homestake Peak, Slide Lake Cirque, and Slide Lake Pavement). Black contours are from Lee et al., 2012; solid contours are mylonite foliation poles, and dashed contours are mineral lineations. Actual values of Lee et al. 2012 data not included but depicted with contours B.) Bennett Ridgeline mylonite splays. Contact jeremyleierzapf@gmail.com or mjessup@utk.edu for full excel spreadsheet of structural data.

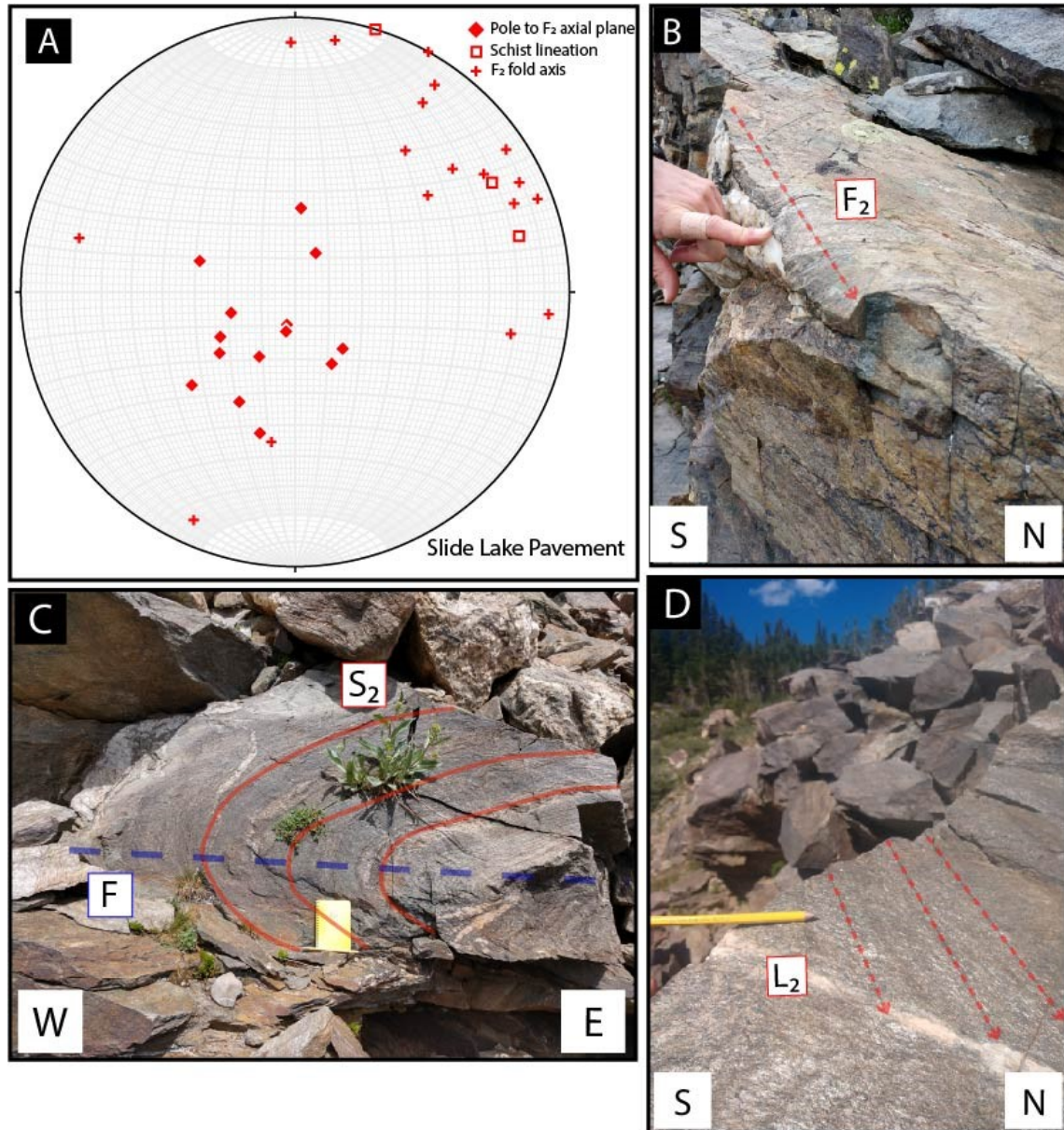


Figure 46: D₂ structures from Slide Lake Pavement. A.) Equal area stereonet showing poles to axial planes (n=14), fold axes (n=18), and crenulation lineations (n=3). B.) F₂ fold axis. C.) Sub-horizontal D₂axial plane. D.) Crenulated schist lineation. Contact jeremyleierzapf@gmail.com or mjessup@utk.edu for full excel spreadsheet of structural data.

VITA

Jeremy Roy Leierzapf was born in Columbia, Maryland, in September 1996 to Susan Elizabeth Barna and Roy Jerome Leierzapf. He attended Long Reach High School and graduated in 2014. He then attended Towson University and received a Bachelor's of Science in "Geology" in 2018. Jeremy spent the summer of 2018 taking part in the University of St. Andrews Geology Field Camp in Scotland. He started school at the University of Tennessee, Knoxville in fall of 2018, where he taught undergraduate introductory and structural geology lab courses.