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Movement History of the Pasayten Fault Zone: Insights into Large-Scale Transport Across the North American Continental Margin

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MOVEMENT HISTORY OF THE PASAYTEN FAULT ZONE, SOUTHERN BRITISH COLUMBIA: INSIGHTS INTO LARGE-SCALE TRANSPORT ACROSS THE NORTH AMERICAN CONTINENTAL MARGIN

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ABSTRACT

MOVEMENT HISTORY OF THE PASAYTEN FAULT ZONE, SOUTHERN BRITISH COLUMBIA: INSIGHTS INTO LARGE-SCALE TRANSPORT ACROSS THE NORTH AMERICAN CONTINENTAL MARGIN

by John D. Lee

Controversial paleomagnetic data implies that at 90 Ma much of the Coast Mountains and Insular superterrane were 1200-3000 km to the south. The eastern boundary of these allochthonous rocks is near the Pasayten fault in southern British Columbia. This study covered an ~40 km segment of the fault, and the Eagle Plutonic Complex and Eagle shear zone to the east. In the 157-123 Ma Eagle tonalite, NE-vergent reverse shear zones involve rafts of the host Nicola Group; overall, the Eagle shear zone has flattening fabrics. Plutonic screens in the tonalite yielded a U-Pb zircon age of 207.9±2.1 Ma, implying rocks related to the Triassic Mount Lytton Complex extend ~100 km SE into the tonalite. Greenschist-grade mylonites of the ~110 Ma Fallslake Plutonic Suite of the Eagle Plutonic Complex formed in the Pasayten fault zone. Kinematic indicators, including quartz fabrics from Electron Backscatter Diffraction, record sinistral slip with a west-side-down normal component. Cooling ages indicate motion at ~110-104 Ma, which is some of the youngest documented sinistral shear in the northern Cordillera. West of the Pasayten fault, detrital zircon ages from Eocene clastic rocks have a major peak at 93 Ma, which does not match Eocene basins east of the fault or adjacent Cretaceous strata of the Methow basin. Brittle slip with a presumed normal component occurred after the sinistral shear, but no dextral slip is recognized, casting serious doubt that the Pasayten fault is a major structure in the Baja BC hypothesis.

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INTRODUCTION

The Canadian Cordillera can be broadly divided into two superterranes, the Insular and the Intermontane (Monger et al., 1972) (Figure 1). The superterranes are separated by the Carboniferous to Cretaceous Coast belt, comprising oceanic and arc assemblages (Journeay and Friedman, 1993). In southwestern British Columbia and northern Washington, the western margin of the Intermontane superterrane is in contact with the southern Coast belt across the ≥250-km-long, northwest-striking, steeply dipping Pasayten fault. This fault is marked by distinct changes in crustal magnetism and conductivity (Bustin et al. 2013). East of the Pasayten fault gravity values are higher and conductivity is lower than to the west of the fault (Cook et al. 1995; Jones and Gough, 1995).

The Coast Mountains and deformed flanking terranes have been called the Coast-Cascade orogen (Monger and Brown, 2014). Broad agreement for the timing of events in the Coast Cascade orogen exists from Early-Middle Jurassic accretion of the Intermontane superterrane to North America to the present (e.g., Monger et al., 1982; Gehrels et al., 2009). However, understanding the spatial and temporal relationships of the Coast and Insular belts relative to North America during the Middle Jurassic through mid-Cretaceous is hindered by conflicting paleomagnetic and geologic data (e.g., Cowan et al., 1997). Monger et al. (1982) posited that the Coast belt formed during mid-Cretaceous accretion of the Insular superterrane to North America, after Middle Jurassic accretion of the Intermontane superterrane. Rubin et al. (1990) outlined evidence for a single east-dipping subduction zone where plate velocity changes during subductioninduced compression forming the Coast belt. Early models have largely been superseded by the model of Monger et al. (1994) wherein ~800 km of Late Jurassic-Early Cretaceous sinistral translation oblique to the convergent plate boundary separated previously contiguous magmatic arc segments. As a result, part of the central Coast belt was transported southward and westward outboard of the southern Coast belt (Monger et al., 1994). In this model, convergence changed from sinistral to dextral transpression during the mid-Cretaceous (~105-85 Ma) (Monger et al., 1994; Umhoefer and Schiarizza, 1996; Chardon et al., 1999; Evenchick et al., 2007; Nelson et al., 2012; Angen et al., 2014). In the early Eocene the tectonic regime changed again to transtension (Parrish et al., 1988; Miller and Bowring, 1990; Haugerud et al, 1991; Miller et al., 2016) and by the late Eocene the contemporary Cascade magmatic arc had formed (Misch, 1977; Tabor et al., 1984; Monger et al., 1994). From ~47-34 Ma the Coast belt was dextrally offset ~150 km along the N-S trending dextral Straight Creek-Fraser fault (Misch, 1977; Tabor et al., 1994; Monger and Brown, 2014).

Sinistral translation of the arc is recorded by clastic rocks of the Tyaughton-Methow basin of southern British Columbia and northern Washington. Detailed detrital zircon studies from this basin document an Early Cretaceous (~110 Ma) change from a fore-arc to an intra-arc depositional environment (Umhoefer et al., 2002; DeGraaff-Surpless et al., 2003). This change is evidenced by westerly derived arc detritus, signaling basin closure coincident with sinistral translation of the Coast belt (Monger et al., 1994; Umhoefer et al., 2002; DeGraff-Surpless et al., 2003; Gehrels et al., 2009).

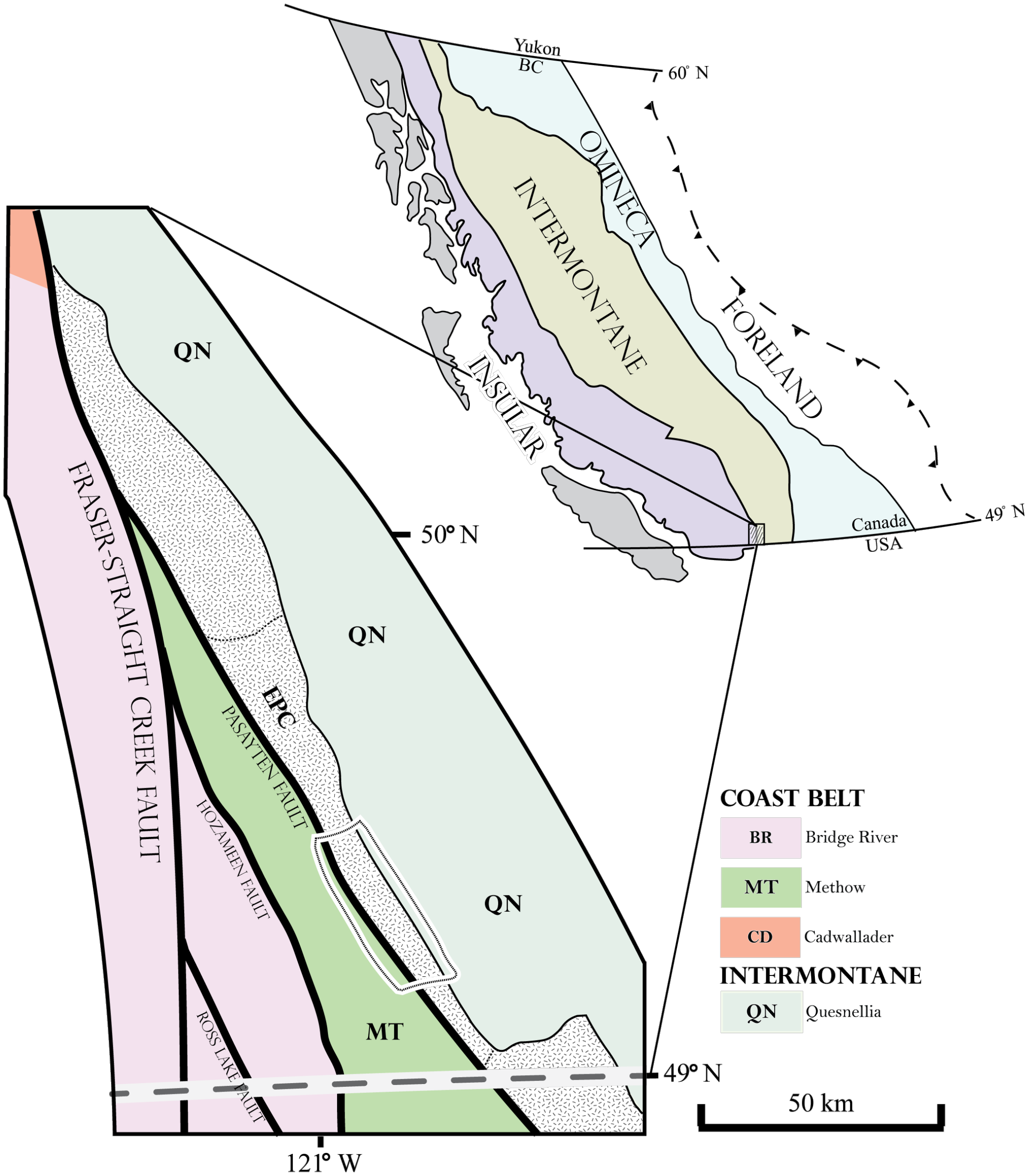


Figure 1. Simplified map of major faults and terranes near the study area. Hatched lines mark the extent of study area. EPC=Eagle Plutonic Complex. Modified from Journeay and Friedman (1993), and Monger (2015).

Paleomagnetic studies place much of the Coast Mountains and Insular superterrrane from north-central British Columbia to northern Washington near present day Baja California during the mid-Cretaceous (~90 Ma), leading to the Baja BC hypothesis (e.g., Beck et al., 1981; Irving et al., 1985; Umhoefer, 1987). This hypothesis requires very large (2000-3000 km) right-lateral strike-slip. The Pasayten fault is the closest mapped structure to the paleomagnetically defined boundary and is thought by many workers to be the main structure that accommodated translation of Baja BC (e.g., Wynne et al., 1995). Previous work, however, suggests that the Pasayten fault zone has experienced sinistral motion (Lawrence, 1978; Greig, 1992; Hurlow, 1993). Alternative paleomagnetic interpretations, incorporating an assessment of regional pluton tilting, stratigraphic relationships, and detrital zircon geochronology suggest significantly less dextral translation (Butler et al., 1989). Baja BC proponents contend that uniform tilting is unlikely, and that the widely distributed and consistent paleopoles make large-magnitude dextral translation a more probable explanation (Irving et al., 1985; Rees et al., 1985; Wynne et al., 1995). Resolution of this controversy relies in part on a more complete understanding of the Pasayten fault.

Pasayten Fault Zone

The Pasayten fault juxtaposes Jurassic-Cretaceous sedimentary and volcanic rocks of the Methow basin to the west with the Quesnel terrane (Figure 1) (Greig, 1992). A 1-4-km-wide belt of deformed Mesozoic plutonic rocks and amphibolite rafts parallels the length of the fault (Greig, 1992; Hurlow, 1993). Seismic lines across the fault are interpreted to show two listric east-dipping splays that merge at depth (Bustin et al., 2013).

The Pasayten fault was active periodically from at least the Early Cretaceous through the Paleocene according to previous workers (Lawrence, 1978; Greig, 1992; Hurlow, 1993). Several workers have argued for an early period of large ductile strike-slip and dip-slip, followed by later episodes of brittle dip-slip movement.

Coates (1974) noted evidence for ~10 km of vertical and lateral offsets from an investigation of a segment of the Pasayten fault just north of the Canada-U.S. border. Dip-slip was estimated by assuming that the basement rock of the Methow basin is the same as the Eagle Plutonic Complex and had been down-dropped the thickness of the Methow basin (Coates, 1974). However, Coates also recognized the lack of stratigraphic links across the fault making this estimate unreliable and later workers have shown that the Complex is not the basement to the basin (e.g., Ray, 1985; Monger, 1985).

Barksdale (1975) examined a segment of the Pasayten fault that stretched from the U.S.-Canada border southward for ~75 km along the western margin of the dominantly Cretaceous Okonagan Range batholith. Along this segment, a block of the Paleocene Pipestone Canyon Formation has been down-dropped on the southwest side of the fault (Barksdale, 1975), indicating offset continued into at least the Paleocene. Additionally, Barksdale confirmed the lack of stratigraphic links across the Pasayten fault noted by Coates.

Lawrence (1978) investigated a segment of the Pasayten fault in northern Washington where fabrics in trondhjemite rocks east of the fault indicated the Pasayten fault zone is a primarily strike-slip fault that experienced intermittent activity from at least the Early Cretaceous to the Paleocene. He concluded that the “strike slip motion...” is “pre-Cenozoic in age” and that “the lower limit on this activity is the Jurassic consolidation” of a trondhjemite. However, these age constraints were based on map relations of undated units reported by Barksdale (1975). McGroder (1989) noted that the western contact of the Jurassic trondhjemite is a fault.

Lawrence (1978) applied the Ramsay and Graham (1970) method to calculate displacement on ductile shear zones and determined a minimum strike-slip displacement of 2-4 km. This estimate excludes the inner 100 m of the mylonite zone due to faults that cross-cut the foliation (Lawrence, 1978), and including the entire width of the mylonite zone would likely have significantly increased the estimated ductile displacement. The upper age limit of fault motion is constrained by the overlapping Eocene Island Mountain volcanics and the Miocene Coquihalla Group (Figure 2) (Lawrence, 1978).

Greig (1992) examined structures along the Pasayten fault within the Eagle Plutonic Complex and integrated these structures with U-Pb, K-Ar, and Rb-Sr dating of the Complex and adjacent units (Figure 2) (Greig et al., 1992). The Eagle Plutonic Complex has yielded U-Pb zircon dates of 157 Ma to 123 Ma (Figure 2) (Greig, 1992). Mid-Cretaceous K-Ar and Rb-Sr dates are compatible with resetting during the emplacement of the Fallslake Plutonic Suite at approximately 110 Ma (Greig, 1992). Moreover, K-Ar dates of several stocks in the Coquihalla area (Figure 2) indicate widespread early Eocene (~55 Ma) magmatism (Greig, 1992).

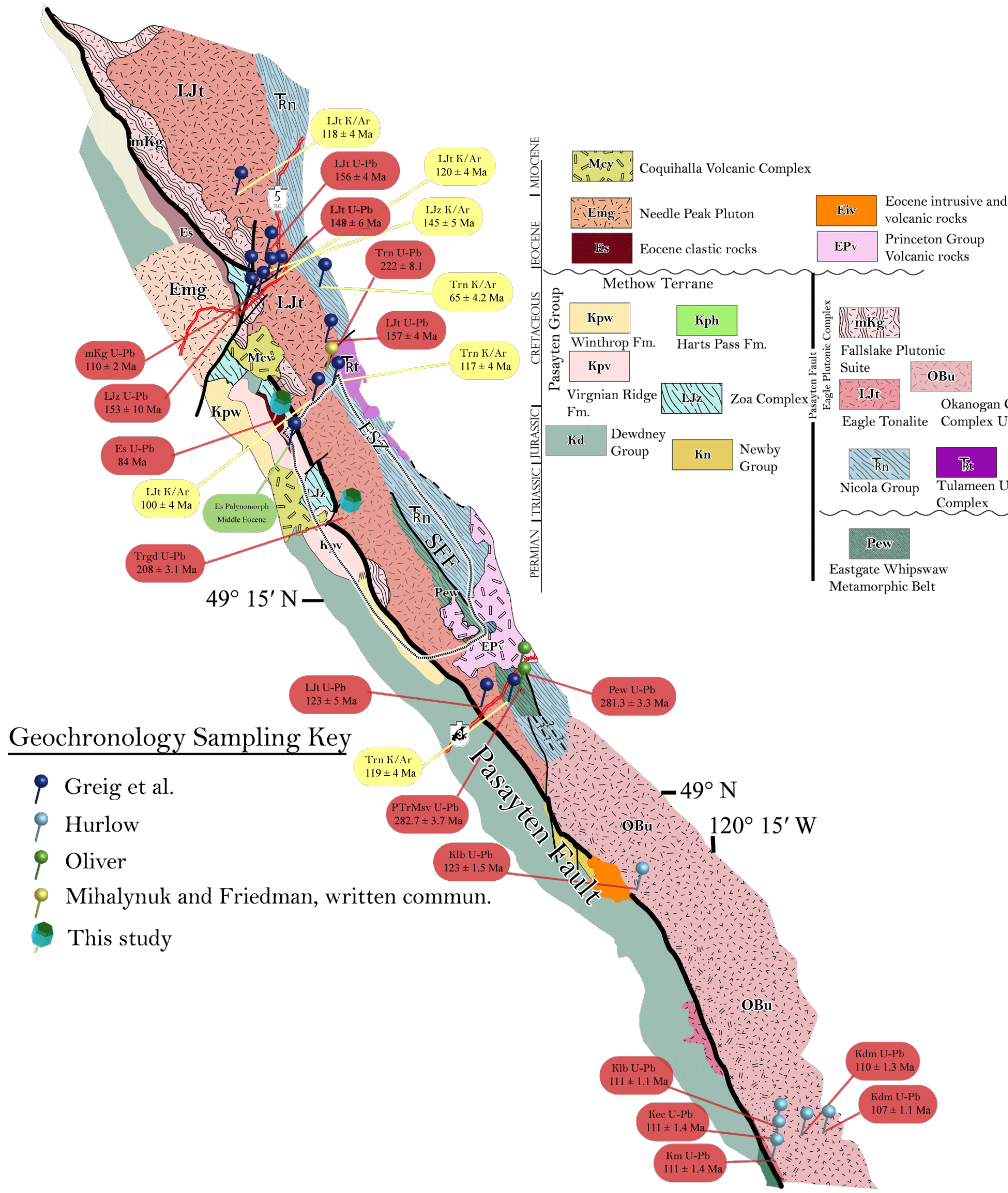


Figure 2. Geologic map of the Pasayten fault zone in southern British Columbia and northern Washington. Geochronology sampling locations are shown. Hatched lines mark the extent of the study area. ESZ=Eagle Shear Zone. SFF=Similkameen Falls fault. Modified from Monger (1989), Greig et al. (1992), Hurlow (1993), and Oliver (2008).

Mapping of the Pasayten fault zone and the geochronology work led Greig (1992) to define two episodes of deformation. Ductile contraction occurred from the Middle Jurassic to the middle Cretaceous. During this period the Eagle Plutonic Complex intruded and deformed the Nicola Group coincident with sinistral motion across the Pasayten fault. This episode was followed by a brittle middle-Eocene event (Greig, 1992).

Hurlow (1993) investigated the slip history of the Pasayten fault through a structural and geochronologic analysis of the Okanogan Range batholith in northern Washington. U-Pb dates from trondhjemitic plutonic rocks of the Okanogan Range batholith indicate a minimum crystallization age of 114-111 Ma (Figure 2) (Hurlow and Nelson, 1993). The parallel strike of the western margin of the batholith, the elongate geometry of the batholith, and the increase of magmatic foliation intensity towards the Pasayten fault suggest that the fault accommodated intrusion of magmas during a period of high-angle dip-slip according to Hurlow (1993). Hurlow also determined that ~20 km of left-lateral strike-slip motion occurred either due to oblique plate convergence or the southward contractional escape of the Methow basin using the method of Naruk (1986).

Research Objectives

Determining the Early Cretaceous to Paleogene (~90-50 Ma) slip history of the Pasayten fault zone has significant implications for understanding deformation in the Northwest Cordillera and evaluating the Baja BC hypothesis, respectively. If the Pasayten fault zone exhibits dextral slip between 90 Ma and 50 Ma important geologic support is provided for the Baja BC hypothesis. Alternatively, if the fault zone only records sinistral and/or dip slip during this time interval serious doubt is cast on the Baja BC hypothesis. Past work has focused on segments of the Pasayten fault located northwest (Greig et al., 1992; Greig, 1992), directly southeast (Budimirovic and Miller, 2017), and farther southeast (Lawrence, 1978; Hurlow, 1992) of the study area (Figure 3). The fault segment bounded by the Tulameen River to the north and the northern boundary of Manning Park to the south has only received limited study by mapping at a scale of 1:125,000 (Monger, 1989).

Rocks of the ~110.5 Ma (U-Pb zircon) Fallslake Plutonic Suite on the northeast side of the Pasayten fault (Figure 2) are inferred to cross-cut Late Jurassic fabrics in the Eagle Plutonic Complex (Greig, 1992). Foliations within the Fallslake rocks on the northeast side of the Pasayten fault exhibit a northwest strike, that is parallel to the fault and increases in intensity towards the fault (Greig, 1992). Examination of any cross-cutting relationships and fabrics in the two units will assist in refining the kinematic history of the Pasayten fault.

The eastern margin of the Eagle Complex juxtaposes Late Jurassic Eagle tonalite to the west with the Nicola Group and Eastgate-Whipsaw Metamorphic belt (EWm) to the east (Figure 2). Greig (1992) examined fabrics along part of this ~100-km-long contact and interpreted it as part of a northeast-directed, reverse-sense ductile shear zone, which he named the Eagle shear zone. Greig (1992) inferred a Late Jurassic age for the shear zone on the basis of strong parallel southwest-dipping foliations in the Eagle tonalite and Nicola Group and the higher metamorphic grade of the Nicola Group in the shear zone. The proximity of the Pasayten fault to the Eagle shear zone, and the presence of ductile fabrics next to both shear zones, leads to the question of whether there are overprinting relationships, which might provide further insights into the timing of deformation. Further evaluation of kinematic indicators and gradients in foliation intensity will also lead to a better understanding of the fabrics.

Middle Eocene clastic rocks mapped by Monger (1989) and Greig (1992) are thought to be the youngest rocks deformed by the Pasayten fault zone in British Columbia, and thus provide an important control on the upper limit of activity in the zone. The age of these rocks is derived from limited fossil identifications (Monger, 1989). U-Pb dating of detrital zircons obtained the Eocene clastic rocks in this study may provide the maximum deposition age and information on source regions.

Faults have been mapped near Vuich Creek, west of the Pasayten fault, and are shown to place the Eocene rocks on the Jurassic Zoa Complex (Figure 2) (Greig, 1992). Two mechanisms have been proposed for this arrangement by Greig (1992); either "upper plate-to-the-southwest normal faulting," or reverse faulting during east to northeast contraction. Thrust displacement is problematic in that the dominant tectonic regime during the Eocene is generally considered to be transtensional (e.g., Parrish et al., 1988; Haugerud et al., 1991; Eddy et al., 2016; Miller et al., 2016). If Eocene thrusting is confirmed, then this implies localized transpression along the Pasayten fault, perhaps in an unrecognized restraining bend.

Regional correlation of the Zoa Complex is uncertain. One U-Pb zircon date from north of the field area places a minimum crystallization age of ~153±10 Ma on intrusive rocks of the Zoa complex (Figure 2) (Greig et al., 1992). Metavolcanic inclusions in the intrusive rocks are not dated and previous workers have advanced three correlations for the Zoa Complex; the Nicola Group, Early Triassic Spider Peak Formation, and the Eagle Plutonic Complex (e.g., Ray, 1986; Monger, 1989; Greig, 1992). Rice (1947) mapped the Zoa Complex within the field area as part of the Nicola Group, noting the presence of pyroxene in each unit, and two geochemical analyses of Zoa Complex metavolcanic rocks indicate similarities with the Nicola Group (Greig, 1992). The Spider Peak Formation outcrops along the western boundary of the Methow basin (Ray, 1986). It consists of massive greenstone which is compositionally similar to metavolcanic rocks of the Zoa Complex (Ray, 1986). Monger (1989) included the Zoa Complex in the Eagle Plutonic Complex. The relationship of the Zoa Complex and Eagle Plutonic Complex is an important question, as the Zoa Complex and its deformation are localized near the Pasayten fault.

Methods

Field study consisted of a detailed geologic investigation and mapping at 1:40,000 of a segment of the Pasayten fault zone in southern British Columbia (Plate 1), which has only been mapped at 1:125,000 (Monger, 1989). The study area extends ~40 km along the Pasayten fault from the Tulameen River to the northeastern boundary of Manning Park (Figure 3). Access in the study area was facilitated by the construction of recent logging roads. Ridge and stream traverses were also undertaken in crucial areas. During an eight-week period of field work, orientations of lineations, foliations, and fold axes were measured in transects extending northeast from the Methow basin across the Pasayten fault and into the Eagle shear zone. Particular attention was given to the identification of kinematic indicators in the Pasayten fault zone and Eagle shear zone. Numerous oriented samples were collected for laboratory analysis, and several units were sampled for U-Pb dating and Electron Backscatter Diffraction Analysis (EBSD).

Forty thin sections oriented parallel to lineation and perpendicular to foliation were cut from selected samples and subsequently evaluated for microstructures. Sample selection criteria was based on the following: (1) representative specimens of each unit; (2) intriguing mesoscopic textures and structures; and (3) coverage of the study area. During analysis, emphasis was placed on kinematic indicators and deformation mechanisms to determine broad temperature ranges for deformation.

The dated samples were from an inclusion in the Eagle Plutonic Complex and Eocene clastic unit (Figure 2; Plate 1). The Eagle inclusion sample was collected ~200 m east of the Pasayten fault in the Granite Mountain area (Figs. 2 and 3). This location consisted of medium-grained Eagle tonalite with moderately developed foliation surrounding 1-2-m-thick, fine-grained weakly foliated bodies, which were sampled. Eocene clastic rocks were sampled for detrital zircons in the Railroad Creek area (Figure 3). U-Pb dates from this sample provide further insight into the age of the latest motion along the Pasayten fault. Results are compared to previous work and larger regional studies (Figure 2).

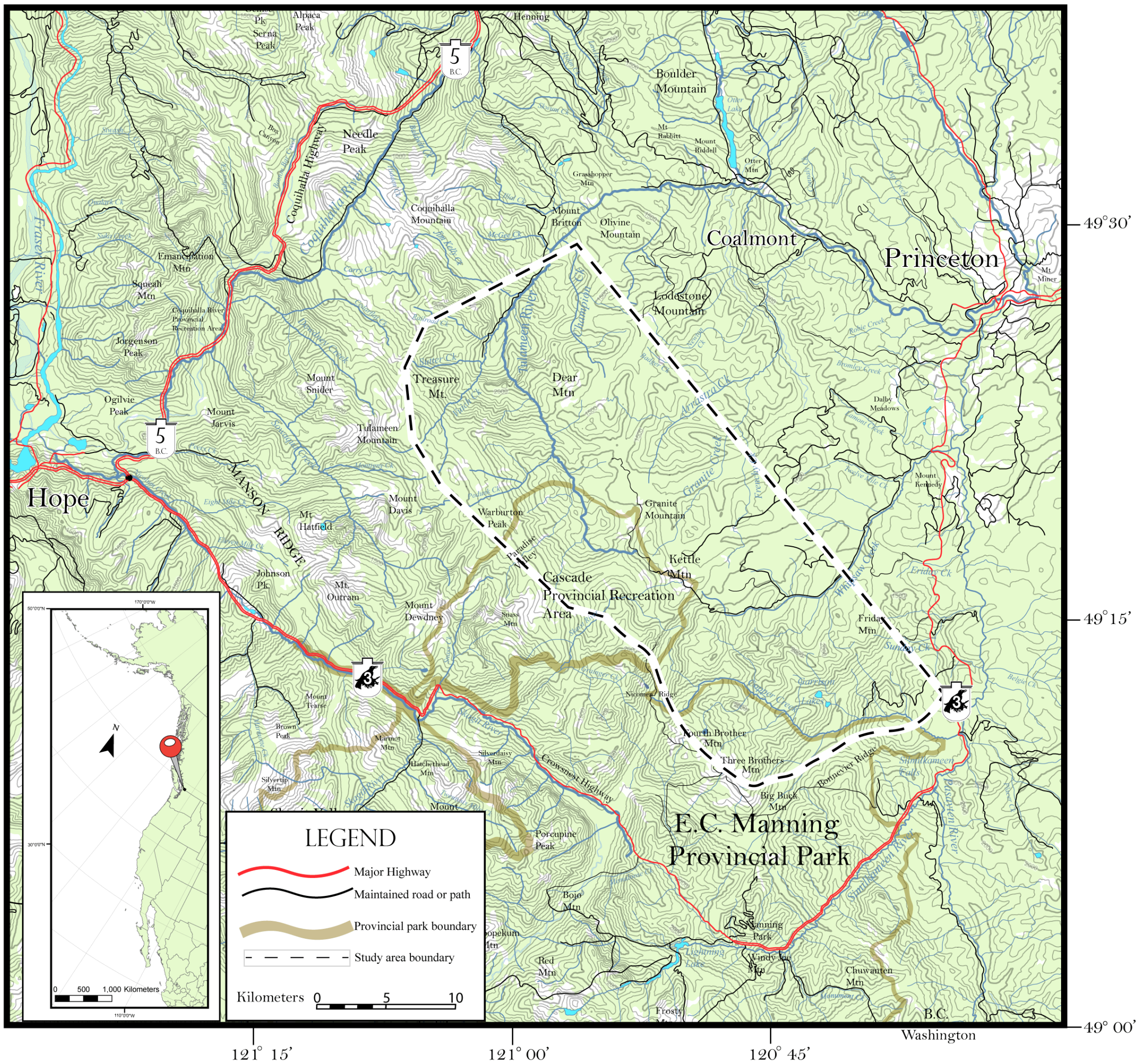


Figure 3. Index map of the study area. Dashed lines mark the extent of the field area. Contour interval=40 m. This map was created from metadata from the British Columbia Geological Survey.

Zircons were separated from the two samples at San Jose State University by milling rock fragments to ~0.420 mm and running the milled fragments through a Wilfley shaker table. The grains were then dried and passed through a Frantz magnetic separator set at 0.60 amperes and inclined 20°. The remaining grains were then separated using a methyl iodide solution. The zircons were mounted and imaged at the University of Nevada Reno using a Deben panchromatic cathodoluminescence detector and subsequently dated at Oregon State University using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS). The results were processed using methods described in Loewen and Kent (2012).

Two oriented thin sections from the Eagle Plutonic Complex were analyzed by EBSD to determine broad temperatures of deformation and infer motion in the Pasayten fault zone. The samples were prepared and analyzed for EBSD following the methods described by Mookerjee et al. (2016). Equal-area projections of the orientations of quartz grains in the samples were plotted using Mathematica scripts from Mookerjee and Nickleach (2011).

ROCK UNITS

In the study area, units west of the Pasayten fault are the Zoa Complex, Methow basin strata, and Eocene clastic rocks. Methow units include the Virginian Ridge Formation and Winthrop Formation of the Pasayten Group. East of the Pasayten fault are the Eagle Plutonic Complex, deformed Nicola Group rocks, and the Eastgate-Whipsaw metamorphic belt. Several ~500 m^2 bodies of the Miocene Coquihalla volcanic rocks and volcanic rocks of the Eocene Princeton Group occur in the study area, but only their extent and general lithology were investigated during this study.

Host Rocks to the Eagle Plutonic Complex

A 1-3-km-wide, NW-striking zone of upper-greenschist- to amphibolite-facies rock flanks the Eagle Plutonic Complex to the east (Plate 1). East-west transects across this zone show a progressive transition from moderately foliated greenschist-facies rocks with relict pyroxene to strongly foliated amphibolite-facies rocks near the Eagle Plutonic Complex. This zone extends from northwest of Highway 5 to southeast of Highway 3 (Figure 2). Monger (1989) and Greig et al. (1992) considered the zone to be correlative with Mortimer's (1987) westernmost calc-alkaline belt of the Upper Triassic Nicola Group.

Recent geochronologic work has refined the extent of the Nicola Group metamorphic belt (Massey et al., 2008; M. Mihalynuk and R. Friedman, written communication, 2018). Massey et al. (2008) reported an Early Permian (281.1±3.3 Ma) U-Pb zircon age for greenschist-facies, metavolcanic rock in the Whipsaw Creek area (Figure 2). The Permian age led Massey et al. (2008) to introduce the name Eastgate-Whipsaw metamorphic belt and separate it from the Nicola Group across the NW-striking Similkameen Falls fault (Figure 2) (Massey et al., 2008). Mihalynuk and Friedman (written communication, 2018) obtained a Late Triassic (~201 Ma U-Pb zircon) maximum deposition age from a greenschist-facies metasedimentary rock in the Champion Creek (Figure 3) area, thereby refining the southern extent of Nicola Group metamorphic rocks (Figure 2).

Eastgate-Whipsaw Metamorphic Belt (EWm belt)

The ~1-km-wide, NW-striking EWm belt extends southeast for ~20 km from the Arrastra Creek area to south of Highway 3 (Figure 2) (Massey et al., 2008). Quartzofeldspathic schist and marble of the EWm belt mapped by Massey et al. (2008) elsewhere are not seen in the study area. Within the study area, the EWm belt consists of poorly exposed, dark-green, epidote-plagioclase-actinolite schists. The schists contain ~1-2-mm-long plagioclase and actinolite porphyroblasts in a granoblastic matrix of ~40% actinolite, 20% epidote, 20% plagioclase, 10% chlorite, and ≤10% accessory and secondary phases. Accessory minerals include quartz, rutile, and opaques. Calcite and sericite variably replace plagioclase grains. Foliations are defined by strongly developed, mm-scale compositional layering and planar alignment of chlorite, actinolite, and, epidote. Compositional layers are distinguished by ~3-mm-thick mafic zones rich in actinolite porphyroblasts and felsic layers consisting primarily of granoblastic plagioclase. Foliations wrap the porphyroblasts. Lineations are defined by aligned, elongate porphyroblasts. More commonly, actinolite forms garbenscheifer texture, both along and locally across foliation planes. Sub-millimeter actinolite and epidote grains are generally euhedral. The high modes of mafic minerals and only sparse quartz make a basalt or andesite protolith likely.

Actinolite porphyroblasts have local asymmetric tails of plagioclase and chlorite. Porphyroblasts typically display zoning manifested by darker-green pleochroism in rims (Figure 4). Actinolite cores contain minor inclusions of euhedral epidote along cleavage planes. The epidote inclusions are likely a replacement product. Contacts between porphyroblasts and the matrix are generally sharp except where overgrown by local euhedral epidote (Figure 5).

Plagioclase porphyroblasts contain inclusions of variably aligned, highly elongate (10:1) ~100 μm-long rutile needles, ~100-μm-long actinolite grains, and anhedral epidote. Epidote inclusions are likely an alteration product given their shape. Contacts between plagioclase porphyroblasts and the matrix are obscured by euhedral actinolite overgrowths. The tails on plagioclase porphyroblasts consist of quartz and plagioclase grains overgrown by euhedral actinolite and epidote grains. Several tails are variably replaced by calcite.

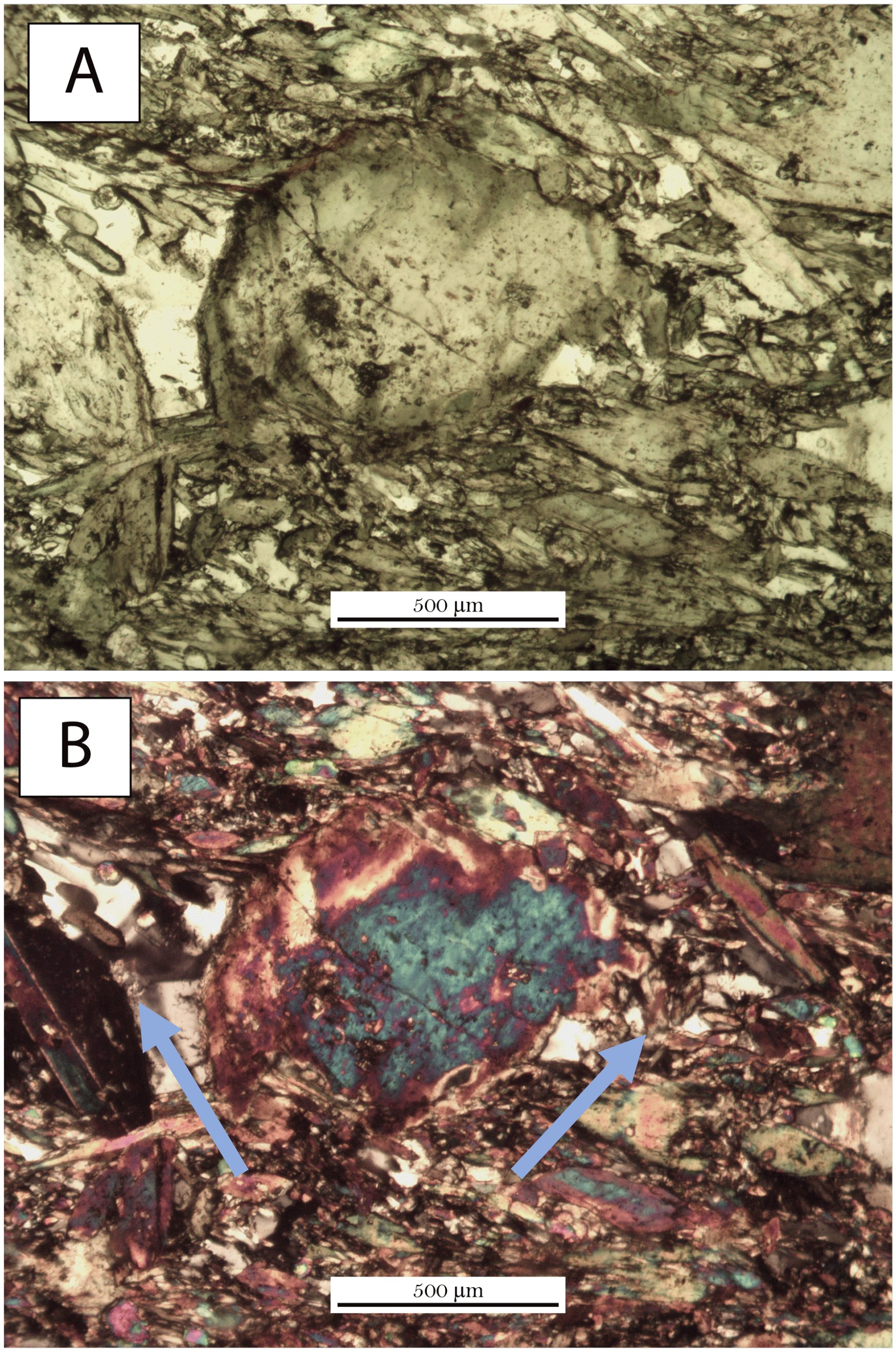


Figure 4. Concentric, compositionally zoned actinolite porphyroblast from the EWm belt. A) Plane-polarized light. B) Cross-polarized light. Arrows point to the plagioclase and quartz tails on the actinolite.

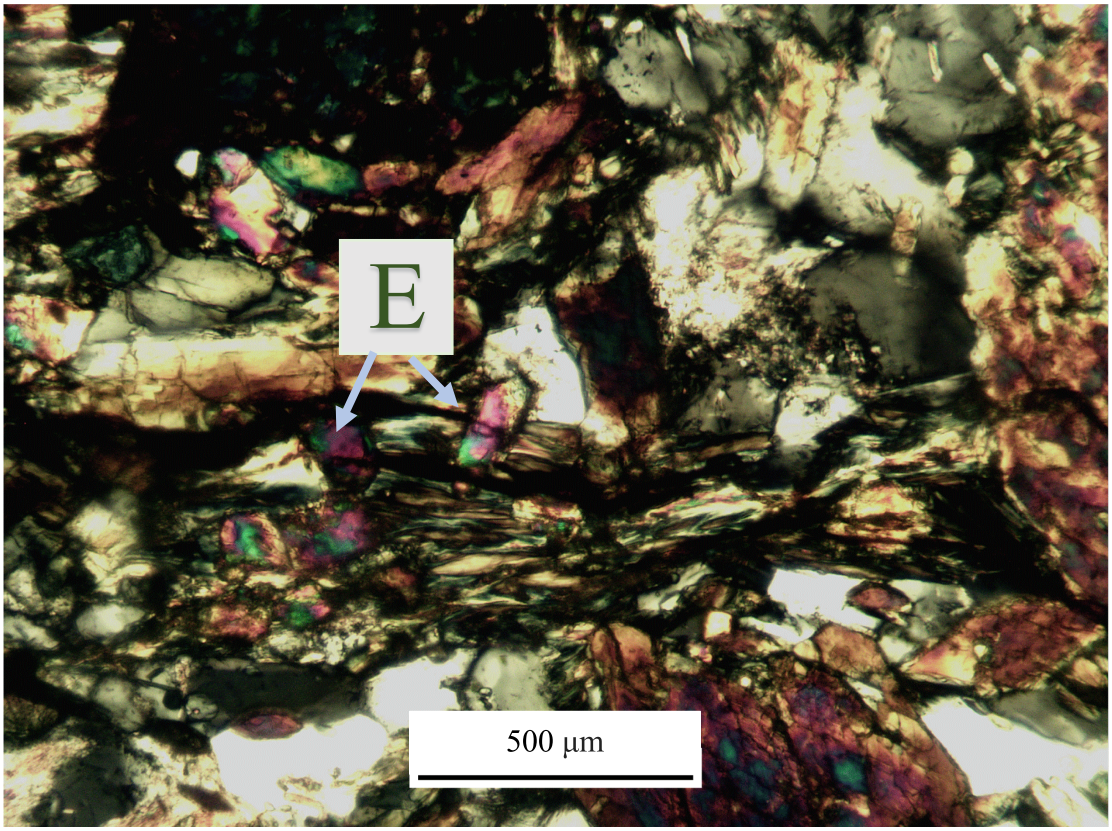


Figure 5. Euhedral epidote grain from EWm belt with sharp contacts against other phases. Arrows point to epidote grains. Cross-polarized light.

Nicola Group Metamorphic Belt

The Nicola Group forms an ~40-km-wide belt that extends northwest from the U.S.-Canada border past the 51st parallel (Preto, 1979). Preto (1979) separated the Nicola Group into three belts: (1) the western belt of felsic to intermediate calc-alkaline and pyroclastic rocks with common limestone lenses; (2) the central belt of mostly intermediate calc-alkaline volcanic and intrusive rocks; and (3) the eastern belt of mafic volcanic rocks and sedimentary rocks. Northeast of the study area the western belt interfingers with pyroclastic rocks of the central belt (Monger, 1989). Along the contact between the Nicola Group and Eagle Plutonic Complex, well-foliated amphibolite- to greenschist-facies rocks of the Nicola Group are interlayered with 1-3-m-wide bodies of foliated marble (Greig, 1992). These deformed rocks of the western belt comprise a small percentage of the Nicola Group, but make up the Nicola Group metamorphic belt of this study. Greig (1992) includes this belt and the eastern margin of the Eagle Plutonic Complex in the Eagle shear zone (Plate 1).

Within the study area, the Nicola Group metamorphic belt consists of epidote-amphibole schist, quartzo-feldspathic schist, and minor marble (Plate 1). Meter-scale rafts of the Nicola Group occur in the adjacent eastern part of the Eagle Plutonic Complex. East of the Nicola Group metamorphic zone are pyroxene-bearing volcaniclastic rocks, which were not investigated during this study. Outcrops of Nicola Group schist are mostly limited to drainages and roadcuts. Fresh epidote-amphibole schists are medium- to dark-green, whereas weathered surfaces are reddish-brown. Characteristic mm-scale, strongly to moderately developed foliations are defined by aligned amphiboles, chlorite, and rare biotite. Local strongly developed lineations are defined by aligned actinolite. Marble surfaces are pink or cream colored. The marbles have moderately developed foliation and compositional layering defined by 5-10-cm-wide zones rich in Fe-oxide minerals alternating with calcite.

Epidote-amphibole-schists are granoblastic and fine- to medium-grained. They consist of ~40% plagioclase, 30% amphibole, 10% quartz, 10% biotite, and ≤10% accessory and alteration minerals. Two-3-mm-long actinolite porphyroblasts occur in one thin section. Equilibrium phases include epidote, biotite, and chlorite. Alteration minerals include prehnite, epidote, and calcite. Compositional layering is strongly developed; dark layers contain abundant amphibole and light layers contain mostly granoblastic plagioclase. The compositional layers wrap local actinolite porphyroblasts. Intermediate to mafic volcanic rocks are likely protoliths given the mineral modes.

Nicola rafts in the Eagle Plutonic Complex are typically only exposed in roadcuts. Fresh exposures are dark with 1-5-cm-thick injected tonalite stringers, which are parallel to foliation. Minerals in the rafts are larger than in the Nicola Group rocks in the Eagle shear zone. Hornblende is locally compositionally zoned (Figure 6). Epidote grains are typically euhedral and some contain hornblende inclusions (Figure 7). Strongly developed foliations are defined by aligned biotite, hornblende, and compositional layers. The compositional layering is marked by ~3-mm-thick felsic and mafic layers of plagioclase and hornblende-biotite, respectively. Aligned hornblende grains define lineations (Figure 6). Some exposures with abundant biotite contain an S-C fabric. The S-surface is defined by biotite and hornblende, and the C-surface by biotite.

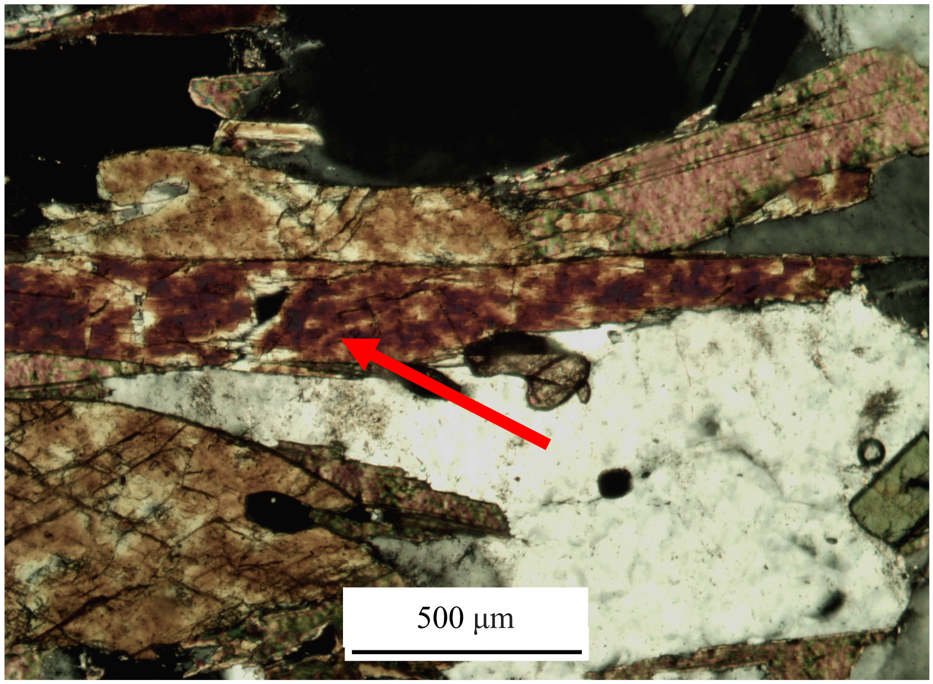


Figure 6. Photomicrograph of typical Nicola raft in cross-polarized light. Note the zoned hornblende grain and the adjacent euhedral sphene. The hornblende grain defines lineation in this sample. Arrow points to the zoned hornblende.

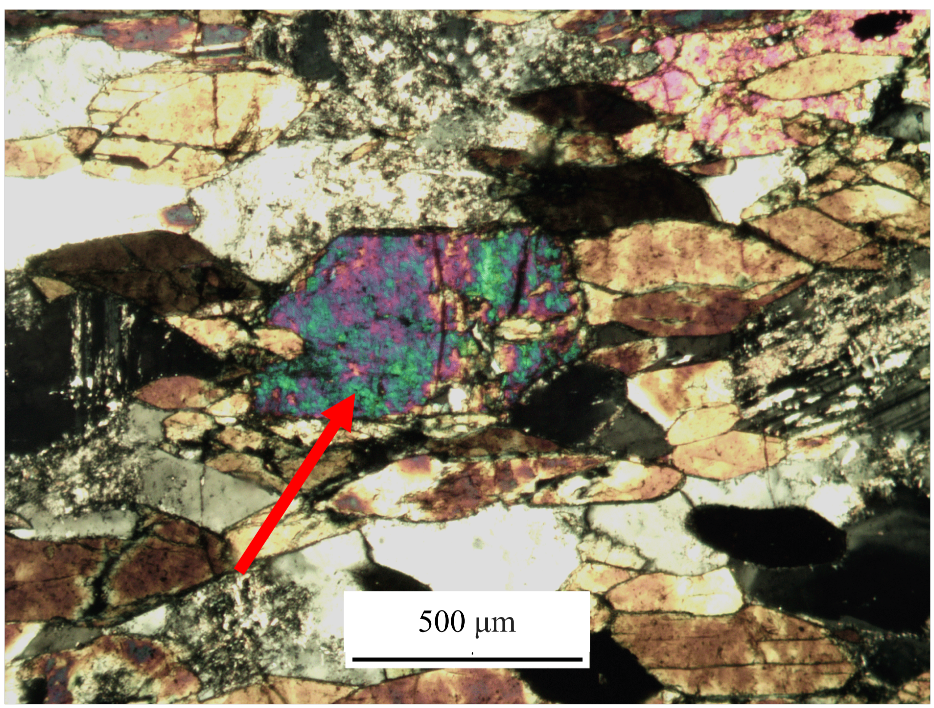


Figure 7. Euhedral epidote with hornblende inclusions in cross-polarized light. Arrow points to epidote.

Mount Lytton Complex

The southern margin of the Triassic (~250-208 Ma; U-Pb zircon) dioritic to tonalitic Mount Lytton Complex is intruded by the Eagle Plutonic Complex (Monger, 1989; Parrish and Monger, 1992). In the study area, Fallslake muscovite-biotite granodiorite on the western slope of Granite Mountain contains ~1-m-thick, fine-grained equigranular tonalite bodies with weak to no foliation (Plate 1). A sample of this fine-grained rock yielded a U-Pb zircon age of 208±10 Ma (see geochronology section). Herein the dated tonalite and nearby tonalite bodies are considered xenoliths of the Mount Lytton Complex due to similarity in lithology, texture, and ages. Descriptions of the Mount Lytton Complex (e.g., Parrish and Monger, 1992) better match the tonalite bodies than the Eagle Plutonic Complex (Greig, 1992).

The dated xenoliths of the Mount Lytton Complex consist of ~40-50% plagioclase, 30-40% quartz, <10% biotite, <5% muscovite, accessory rutile needles, and alteration products. Sericite partially to completely replaces plagioclase grains. Chlorite replacement of biotite is common. Opaque minerals fill fractures and border mica grains, and are commonly accompanied by thin margins of sericite. Weak foliation is defined by aligned biotite and subordinate muscovite. Muscovite grains have sharp contacts against other phases. Quartz grains show evidence for bulging recrystallization. Primary epidote is not present in the sample, in contrast to the Eagle tonalite.

Zoa Complex

The Zoa Complex comprises a discontinuous, ~1-km-wide belt of heterogeneous quartz diorite with massive dark green metavolcanic xenoliths and chlorite schists west of the Pasayten fault (Figure 2). Greig et al. (1992) reported a U-Pb zircon age of 153±10 Ma from the Zoa Complex ~12 km north of the study area (Figure 2). Metavolcanic and intrusive rocks of the Zoa Complex were first described by Camsell (1913) who considered them part of the Eagle Granodiorite. Monger (1989) included these rocks in the Eagle Plutonic Complex. Greig (1992) formally distinguished the Zoa Complex as a separate unit, based on the lack of intrusive relationships with adjacent rocks of the Eagle Plutonic Complex.

In the study area, the Zoa Complex is exposed in two heterogeneous bodies. The ~600 m^2 northern body is exposed in several roadcuts and outcrops near the confluence of Sutter Creek and the Tulameen River (Plate 1). The ~2 km^2 southern body is mostly covered, but several outcrops occur along the Hudson Bay Company Trail ~ 1 km NW of the confluence between Podunk Creek and the Tulameen River headwaters (Plate 1). Mylonitic Zoa Complex rocks occur locally within an ~500-m-wide zone extending from the Pasayten fault in the southern body.

Chlorite schists in the Zoa Complex are very fine-grained, medium-green, and poorly exposed. They occur as 1-8-cm-long deformed enclaves in Zoa quartz diorite. The enclaves have aspect ratios of 2:1 and consist of ~45% chlorite, 40% plagioclase, and 15% quartz. Sericite and calcite variably replace plagioclase grains and some of the chlorite likely replaced biotite. Quartz occurs as recrystallized elongate mosaics, which help define foliation along with chlorite. Mm-scale C-surfaces and S-surfaces defined by chlorite and quartz are recognized locally in thin section. The S-surfaces wrap around relict plagioclase grains that typically have undulose extinction and are microfractured.

Zoa quartz diorite forms light- to dark-green, moderately resistant exposures. Grain size in the quartz diorites ranges from fine to coarse. Typical modes are ~37% plagioclase, 25% quartz, 23% chlorite, 10% epidote, and 1% to 5% euhedral sphene. Additional minor phases include hornblende, biotite and opaques. Chlorite and subordinate biotite grains define weakly to moderately developed foliation that variably wraps 1-5-cm-long metavolcanic xenoliths. The chlorite commonly forms pseudomorphs of biotite. Elongate quartz aggregates define variably oriented, moderately developed lineations. Quartz in these aggregates records bulging and subgrain-rotation recrystallization. Plagioclase grains are typically heavily sericitized and saussuritized. Secondary epidote typically forms ~100 μm grains with sharp contacts against other phases.

Mylonites and ultramylonites of the Zoa Complex consist of plagioclase and quartz porphyroclasts in a matrix of sericite, chlorite, quartz, and epidote. Euhedral, ~1 mm sphene grains occur locally. Plagioclase porphyroclasts are variably fractured and typically have tails of chlorite and quartz (Figure 8). Quartz occurs in ~100-μm-wide recrystallized aggregates (Figure 9). Calcite and sericite variably replace feldspar grains. Foliation is defined by aligned chlorite and quartz, and local compositional layering. Compositional layers are distinguished by ~2-mm-thick lighter-colored zones of elongate quartz aggregates and chlorite, and darker zones of euhedral epidote and opaque phases. In one thin section, aligned epidote aggregates define a weak lineation. Locally, foliation and compositional layering are deformed into open folds with 20 cm wavelengths.

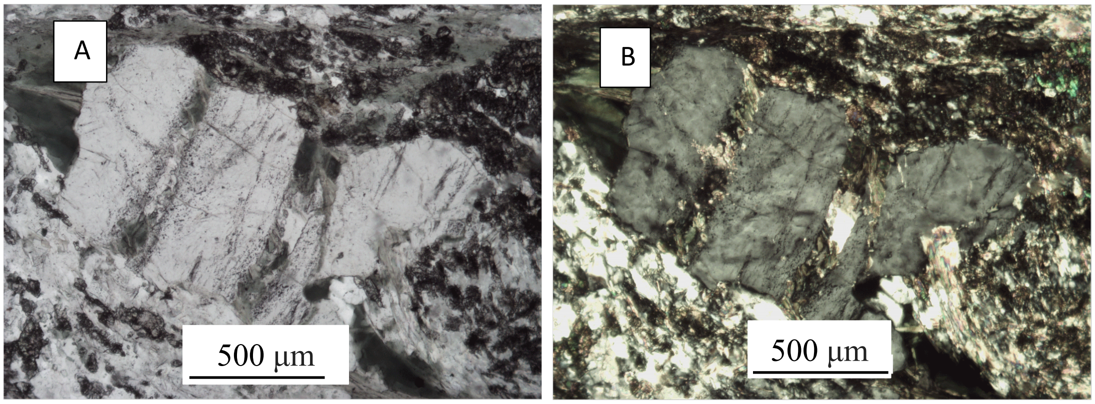


Figure 8. Fractured plagioclase porphyroclast with chlorite and quartz tails in Zoa Complex. A) Plane-polarized and B) Cross-polarized light. The anastomosing foliation is defined by chlorite, biotite, and quartz. Note that the foliations are perpendicular to fractures in the plagioclase porphyroclasts.

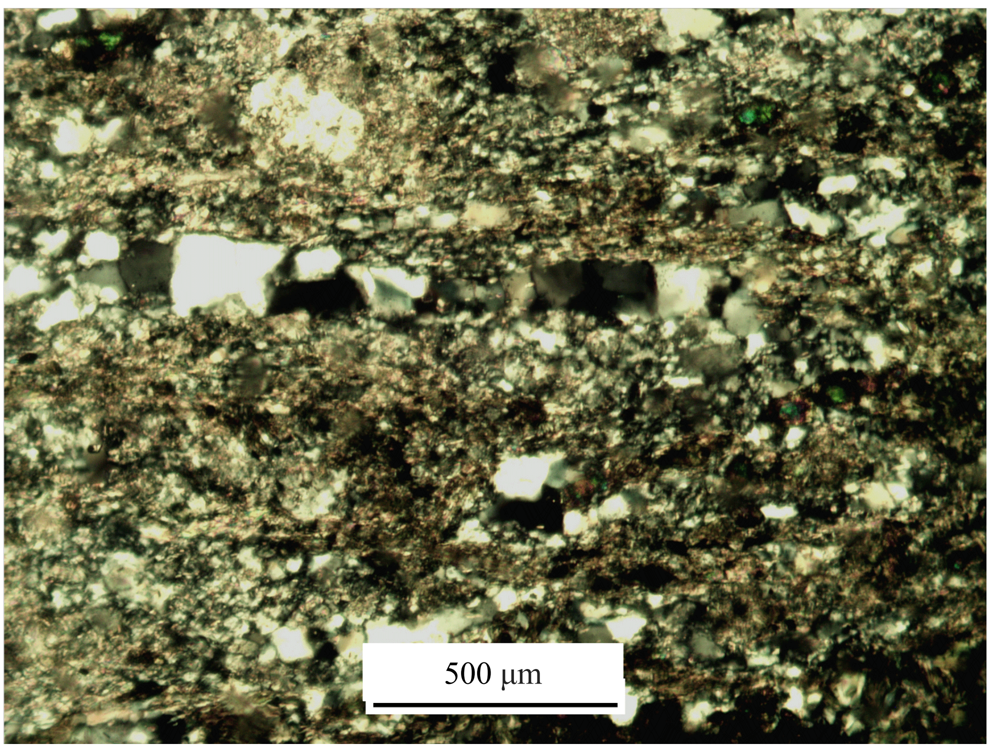


Figure 9. Recrystallized quartz in Zoa Complex mylonite. Cross-polarized light.

Eagle Plutonic Complex

Early workers included plutonic rocks of this study in the ~250-km-long, variably deformed Mesozoic Eagle Granodiorite (Rice, 1947; Anderson, 1984). Monger (1985) formally separated the Eagle Granodiorite into three bodies: 1) the Mount Lytton Complex, which is north of ~50˚N; 2) the Eagle Complex, which extends from ~50˚N to ~49˚N; and, 3) the Okanogan Crystalline Complex or Okanogan Range batholith, which is south of ~49˚N in northern Washington (Figure 2). Greig et al. (1992) renamed the Eagle Complex the Eagle Plutonic Complex and recognized three subdivisions: 1) the Eagle tonalite; 2) the Eagle Gneiss; and 3) the Fallslake Plutonic Suite. Due to the lack of mappable contacts between Eagle tonalite and gneiss, in this work rocks mapped as Eagle tonalite incorporate banded zones that match the description of Eagle gneiss. The Fallslake Plutonic Suite is mapped separately. Amphibolite-facies rafts that occur within a ~200-m-wide zone along the northeastern margin of the Eagle Plutonic Complex are herein differentiated. The rafts consist of recrystallized rocks of the Nicola Group and EWm belt.

Traverses across the width of the Eagle Plutonic Complex reveal consistent textural and structural trends. The Fallslake Plutonic Suite ranges from ~1-2.5 km in width and pinches out to the SE near Copper Creek (Plate 1). Mylonites and protomylonites of the Fallslake Plutonic Suite are concentrated in a ~500-m-wide zone next to the Pasayten fault. The Eagle tonalite is ~3.5-6 km in width. East of the Fallslake-Eagle tonalite contact, there is an ≤5-km-wide western zone, and an additional ≤1-km-wide eastern zone of Eagle tonalite. The western zone has only modest variation in texture and composition. The eastern zone is variably banded and intrudes and surrounds inclusions of the Nicola Group and EWm belt. Massive equigranular Fallslake bodies intrude the Eagle tonalite and western margin of the Nicola Group.

Eagle Tonalite

The 157-123 Ma (U-Pb, zircon) Eagle biotite-epidote tonalite forms the bulk of the Eagle Plutonic Complex (Figure 2) (Greig et al., 1992). A continuous, ~40-km-long segment of Eagle tonalite extending from Railroad Creek southeast to Copper Creek was studied during this work (Figure 2). Exposures were studied via a network of hiking trails, service roads, and stream and ridge traverses. Fresh surfaces are white with local mm- to cm-scale banding. Weathered surfaces are typically khaki and locally stained dark red. Enclaves are rare but where present are fine grained and have a higher color index than the tonalite.

The western zone was recognized in the Champion Creek transect and Arrastra Creek transect (Plate 1). Therein, the Eagle tonalite consists of meter-scale sheets with a predominantly medium-grained texture. These sheets are recognized by slight compositional and textural differences. Foliation in these sheets is moderately developed except near the Fallslake Plutonic Suite contact where the sheets are deformed into open folds that wrap intruding lobes of the Fallslake body. The lobes penetrate up to ~3 m into the Eagle tonalite.

The eastern zone of the Eagle tonalite is constructed of numerous cm- to meter-scale sheets. Across sheet contacts, grain size ranges from fine- to medium-grained and banding is variably developed. Near the eastern margin of the Eagle tonalite the banding becomes better developed. The color index of individual sheets varies from 2 to as much as 15, due to fluctuations in abundance of biotite, hornblende, and epidote. Accessory phases, including garnet and sphene, also vary from 0% to 5% across sheet contacts. Foliations within individual sheets and across sheet contacts are variably developed, spaced, and deformed, and in adjacent sheets may be misoriented by up to 15˚. In some sheets the foliations have been deformed into open folds with wavelengths of 10 to 50 cm.

Eagle tonalite and granodiorite are predominantly equigranular-hypidiomorphic and consists of approximately 30-45% plagioclase, 10-15% potassium feldspar, 20-35% quartz, 5% biotite, 2% hornblende and 2% epidote. Primary and secondary epidote are both present. Weakly to moderately developed foliation is defined by aligned biotite and elongate quartz. The foliations are presumed to be solid-state due to the alignment of quartz.

Banded zones in the tonalite consist of 2 mm-10-cm-thick layers of alternating light and dark minerals. The dark layers contain ~10% biotite and ~5% epidote and light layers contain mostly quartz, plagioclase, and potassium feldspar. Quartz in the banded zones is elongate. Accessory phases in these zones are hornblende, sphene, garnet, zircon, apatite, and opaque phases. Alteration products include chlorite, epidote, and hematite. Inclusions of 200-μm-diameter, euhedral garnets occur in some biotite and plagioclase grains.

Plagioclase is subhedral. Grains are kinked and display deformation twins locally. Potassium feldspar is subhedral. Quartz is interstitial and has aspect ratios of 2:1 and up to 3:1 in banded zones. Solid-state deformation of quartz is indicated by grain bulging and subgrain rotation recrystallization. Biotite locally forms 2 cm by 2 cm "books". Partial to complete chloritization of biotite is widespread. Euhedral magmatic sphene occurs adjacent to unaltered biotite. Epidote forms up to 1-mm-long, euhedral grains in dark compositional layers. The grains have sharp contacts against most phases, but are intergrown with quartz and plagioclase (Figure 10). Several epidote grains contain dark red allanite cores (Figure 10). These textures imply that the epidote is magmatic (Zen and Hammarstrom, 1984; Zen, 1985), a conclusion also reached by Greig (1992). Slickensides are typically plated with secondary epidote. Hornblende is rare and where present is anhedral and smaller than biotite.

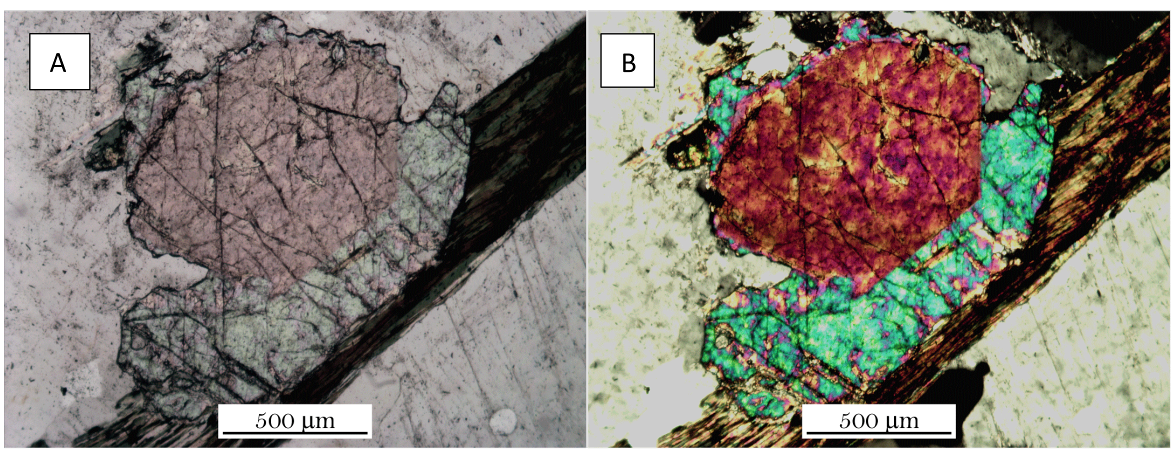


Figure 10. Zoned euhedral epidote. (A) Plane-polarized-light. (B) Cross-polarized-light.

Fallslake Plutonic Suite

The 110±2 Ma (U-Pb) Fallslake Plutonic Suite is the youngest member of the Eagle Plutonic Complex (Figure 1) (Greig et al., 1992). Typical Fallslake exposures consist of leucocratic granodiorite and tonalite (Greig et al., 1992). Discontinuous Fallslake bodies are reported from where the Eagle Plutonic Complex is truncated in the north by the Fraser-Straight Creek fault to Highway 3 (Figure 2) (Greig, 1992). The northeastern margin of the Fallslake Plutonic Suite forms a NW-striking intrusive contact with the Eagle tonalite. This contact zone consists of meter-scale dikes, sills, and local Fallslake intrusions that extend eastward up to 10 m into the Eagle tonalite. The main Fallslake body has yielded zircons of ~110 Ma with minor error, but zircons from the contact zone yield scattered ages (~147-100 Ma) that are attributed to inherited cores from the Eagle tonalite (Figure 2) (Greig et al., 1992). Unabraded zircons yield younger ages that match Fallslake ages to the west (Figure 2) (Greig et al., 1992).

In the study area, Fallslake rocks form a discontinuous, ~1-2.5-km-wide, NW-striking belt that extends southward from the northwest boundary of the mapping area until pinching out in the Copper Creek area (Plate 1). The Fallslake belt consists predominantly of homogeneous equigranular, fine- to medium-grained muscovite-biotite-granodiorite and muscovite-biotite-tonalite. In an ~200-m-wide zone near the Pasayten fault 10-cm- to 2-m-thick zones of Fallslake rocks are deformed into mylonites and protomylonites. Fallslake intrusions in the contact zone with the Eagle tonalite consist of equigranular muscovite-biotite granodiorite and tonalite. East of the contact zone, Fallslake-type intrusions have sharp contacts and ~2-mm-wide, fine-grained chilled zones against Eagle tonalite and Nicola Group metamorphic rocks.

Non-mylonitic rocks of the Fallslake Plutonic Suite consist of ~30% quartz and 40% plagioclase, with variable amounts of potassium feldspar (15-25%) and muscovite (2-

5%). Minor (~1%) phases include biotite, garnet and opaques. Secondary phases are chlorite and epidote. Muscovite and subordinate biotite define weak foliations. The color index ranges from 1-5 due to fluctuations in biotite modes. Quartz grains show local evidence for bulging recrystallization. Some plagioclase grains are normally zoned and myrmekitic texture occurs locally. Sericite and calcite variably replace plagioclase, and biotite is typically highly chloritized. Subhedral to euhedral garnet occurs as inclusions in, or adjacent to, muscovite grains. Sub-radial muscovite splays occur locally, commonly adjacent to the euhedral garnet (Figure 11). Undeformed quartz grains host muscovite splays (Figure 11).

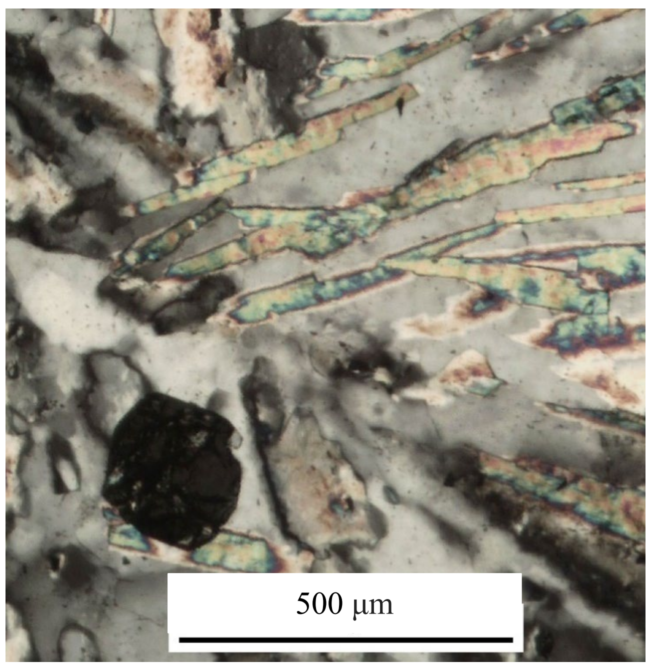


Figure 11. Photomicrograph of equigranular Fallslake granodiorite showing splayed muscovite and garnet. Cross-polarized light.

Near the contact with Eagle tonalite, the Fallslake Plutonic Suite has strongly developed, cm-scale compositional layering, which is progressively better developed approaching the Eagle tonalite. Light colored layers are rich in quartz and plagioclase, and dark layers consist of biotite and rare epidote, which replaces biotite.

Mylonitic rocks of the Fallslake Plutonic Suite consist of quartz (~45%), plagioclase (~30%), potassium feldspar (~15%) and muscovite (5-10%). Quartz forms elongate mosaics. Muscovite occurs as ~100-µm-wide trails and 2-4 mm lenticular "fish" with curved tips and 4:1 aspect ratios (Figure 12). Rare parallelogram-shaped fish are also present. Muscovite and elongate aggregates of quartz form a strong foliation. The foliation wraps plagioclase and potassium-feldspar porphyroclasts, which have tails of recrystallized quartz. Some plagioclase grains exhibit core and mantle structures. Lineation is defined by stretched quartz grains. Calcite and sericite partially to completely replace the porphyroclasts, some of which also have ~20-µm-wide epidote and chlorite rims. Fe-oxides and opaque minerals occur in 1-2-µm-wide zones parallel to muscovite trails.

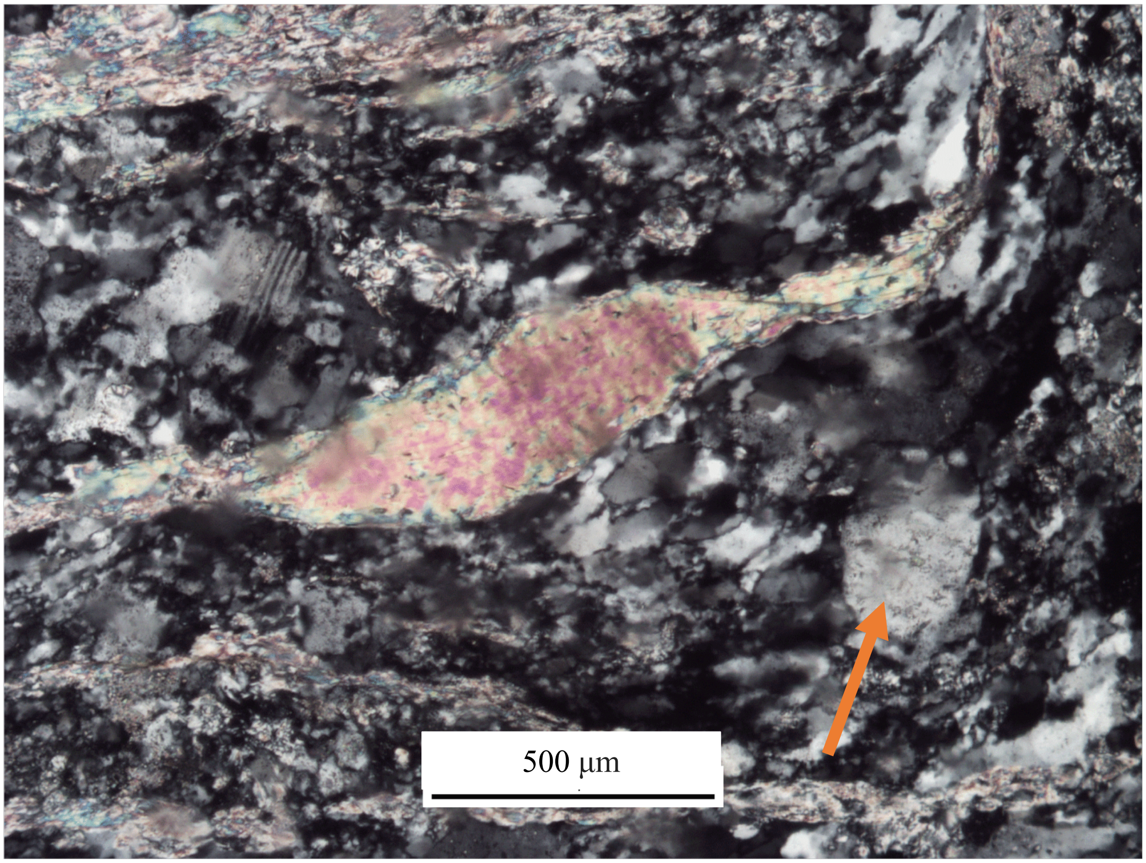


Figure 12. Photomicrograph of an asymmetric muscovite fish showing top-to-right motion in a Fallslake mylonite. Note the foliation defined by elongate recrystallized quartz aggregates, and feldspar porphyroclasts with core and mantle structures. Arrow points to porphyroclast. Cross-polarized light.

Methow Basin (Pasayten Group)

The Early Cretaceous Pasayten Group is ~2.4 km thick and consists of clastic rocks and volcanic flows (Coates, 1974; Barksdale, 1975; Trexler, 1985). Exposures extend along the Pasayten fault from near the Mount Lytton Complex in British Columbia, southward into north-central Washington (Barksdale, 1975; Monger, 1989). Coates (1970, 1974) and Barksdale (1975) defined two interfingering formations in the Pasayten

Group: 1) the west-derived Virginian Ridge Formation; and 2) the east-derived Winthrop Formation. In the study area, these Formations interfinger in the Skaist Mountain area (Plate 1). Barksdale (1975) also included dark red clastic rocks of the Midnight Peak Formation in the Pasayten Group. However, this Formation has only been described in Washington. The Pasayten Group in the study area is largely undeformed and only shows evidence for low temperature metamorphism, in contrast to units east of the Pasayten fault and the Zoa Complex. Clast assessments are based on qualitative observations.

Virginian Ridge Formation

The Virginian Ridge Formation consists of interbedded mudstone, siltstone, and sandstone, and local conglomerate (Barksdale, 1975; Trexler, 1985). Green-black siltstone is most common and local arkose beds occur in the upper part of the Formation (Barksdale, 1975). Standard QFL composition plots indicate either a continental block or magmatic arc provenance (Barksdale, 1975; Trexler, 1985).

In the study area, Virginian Ridge rocks crop out west of the Pasayten fault from the northern map boundary to the Hope Pass area (Figure 2). The Jurassic Zoa Complex and the overlying Miocene Coquihalla Volcanic Complex separate the Virginian Ridge Formation into two belts.

Lithologies in the study area include shale, siltstone, sandstone, and conglomerate. Resistant siltstone and local sandstone beds comprise ≥60% of outcrops. Siltstone beds are ~40 cm in thickness, with 5-10-cm-thick mudstone interbeds. Mudstone and siltstone beds weather to dark brown. Fresh surfaces are tan. Local fissile mudstone beds contain angular concretions ranging from ~1-2 cm in diameter. Local ≤0.5-m-thick, coarse-grained, poorly-sorted sandstone beds are interbedded with ~10-cm-thick mudstone beds.

Lenticular beds along the banks of Sutter Creek and Vuich Creek consist of ~80% siltstone and ~20% mudstone (Plate 1). Mudstone beds contain local 5-12-cm-thick nodules of medium-coarse sand, cemented in a calcite matrix. Subvertical ≤20-m-high cliffs that form the banks of Vuich Creek consist of green argillite (Plate 1). The argillite beds are 10-20 cm in thickness.

Conglomerate commonly forms ~20-cm-thick beds. Clasts are typically ≤6 cm in diameter and are supported by a coarse sand matrix. Locally, the long axes of larger (≥8 cm) clasts are aligned. Clasts range from sub-angular to sub-rounded. Sorting is typically poor except in Sutter Creek where well-rounded clasts are 5-10 cm in diameter (Plate 1).

Outcrop estimates of the conglomerate suggest it consists of ~70% mafic volcanic rock, ~20% felsic plutonic rock, and ~10% sedimentary rock. Mafic volcanic clasts are dark-green. Plutonic clasts commonly contain well-developed foliations and resemble rocks in the adjacent Eagle Plutonic Complex on the other side of the Pasayten fault. Sedimentary clasts are well-rounded and well-sorted lithic sandstone. Rare mudstone clasts occur locally.

An exposure along the northwestern bank of Vuich Creek near Treasure Mountain consists of conglomerate overlain by medium-coarse quartzofeldspathic sandstone. Angular tonalite clasts, which are ~5 cm in diameter make up ~70% of the conglomerate.

Some of these clasts resemble the Eagle Plutonic Complex. The remaining clasts include volcanic rock and mudstone. Overlying sandstone beds are ~2 cm in thickness.

Sandstones are poorly sorted and typically consist of ~75% feldspar, ~10% quartz, and ~5-15% lithic fragments. Minor (≤1%) components include muscovite, biotite, hornblende, zircon, opaques, and chlorite. Several clasts are altered to epidote, calcite, and sericite. Fibrous chlorite is common. Plutonic and volcanic clasts typically make up ~2% of the rock. Mafic clasts are basaltic.

Feldspar clasts are variably altered. Larger (400-900 µm in diameter) grains are typically mostly replaced by epidote and calcite. Smaller (≤200 µm in diameter) grains are subangular. Quartz clasts are angular to rounded and commonly ≤100 µm across.

Orthogneiss lithics are present in all sandstone samples and consist of equigranular plagioclase (50%), quartz (30%), potassium feldspar (~15%), and minor muscovite (≤1%). Several tonalite clasts contain ≤500-µm-long laths of muscovite that resemble those in the Fallslake Plutonic Suite. Trachytic clasts contain ≤400-µm in diameter, zoned plagioclase phenocrysts set in a matrix of alternating zones of fine- and very-fine plagioclase. Several ≥80-µm in diamater tonalitic clasts are also present. Strain in the tonalite clasts is indicated by bulging and subgrain-rotation-recrystallization of quartz.

Mudstone clasts larger than 200 µm comprise ≤10% of samples. Siltstone clasts include quartz, plagioclase, muscovite, and biotite.

Alteration in mudstone samples is common. A network of 1-5-µm-wide hematite veins cross-cuts and is locally concordant to bedding planes. Individual veins are discontinuous and undulating with 20-40-µm spacing. The centers contain local clusters of opaque minerals. Chlorite flanks some veins. Clasts adjacent to large hematite veins are replaced by epidote. Several ≤40-μm-wide calcite veins cut mudstones. Micro-folds of sericite are cut by hematite veins.

Winthrop Formation

The Winthrop Formation consists of quartzo-feldspathic sandstone that interfingers and partly overlies the Virginian Ridge Formation (Coates, 1974; Trexler, 1985). Coates (1974) and Barksdale (1975) suggested a fluvial depositional environment. Outcrops along the Pasayten fault are reported from Skaist Mountain southward from the study area (Coates, 1974; Monger, 1989) (Figure 2). The Formation continues farther northward from the study area, west of the Virginian Ridge Formation (Monger, 1989) (Figure 2). Detrital zircon work in the Winthrop Formation indicates a maximum deposition age of ~98 Ma, and cross-cutting 87 Ma dikes provide a minimum age limit (DeGraff-Surpless et al., 2003). These authors found the southern Canadian Cordillera to be the best source for the Winthrop Formation.

In the study area, the Winthrop Formation was only examined in four roadcuts which are within ~250 m of the Pasayten fault, near the headwaters of Copper Creek (Plate 1). Exposures consist of well-bedded, coarse-grained sandstone and mudstone beds in subequal quantities. Beds are typically 0.5 m to 1 m in thickness and are defined by alternating layers of coarse to fine sand. Weathered surfaces are khaki and fresh surfaces are pink. Clasts are sub-angular and moderately well sorted. One ~0.5-m-thick conglomerate bed contains felsic plutonic lithics, intermediate and mafic volcanic lithics, and metamorphic lithics.

A single thin-section was made from a medium-coarse sandstone. Grains include plagioclase (50%), quartz (35%), potassium feldspar (10%), biotite (≤ 2%), and chlorite (5%). Felsic plutonic clasts and mafic volcanic clasts make up ~5% of the sample. Grain size ranges from medium- to fine-grained sand. Quartz grains ≥ 400-µm-wide are sub-angular to angular. Grains ≤ 400-µm-wide are sub-rounded to sub-angular. Larger quartz clasts are partially fractured and the fractures are filled by sericite. Plagioclase rims and cores are variably replaced by sericite. Plutonic grains are sub-rounded. Several clasts contain quartz mosaics with evidence for bulging and subgrain-rotation recrystallization. Rare volcanic rock clasts have felty textures.

Eocene Clastic Rocks

Two NW-striking bodies of undeformed dark-red to purple clastic rocks occur west of the Pasayten fault north of the study area (Figure 2) (Cairnes, 1924; Monger, 1989; Greig et al., 1992). Cairnes (1924) assigned these rocks a Cretaceous age based on an assumed eastern intrusive contact with the Eagle Plutonic Complex. Monger (1985; 1989) refined the extent of the clastic rocks and further work by Greig (1992) suggested a middle Eocene age based on a palynomorph identification from Vuich Creek (Figure 2). Detrital zircon data collected during this work indicates a Late Cretaceous (~90 Ma) maximum deposition age.

A distinctive red sandstone forms an elongate, 500-m-wide, NW-trending body between the Zoa Complex and Virginian Ridge Formation near Railroad Creek (Plate 1). The body extends another ~1 km southeast of the Zoa body (Fig 2), and consists of interbedded red feldspathic arenite sandstone, grey mudstone, and grey siltstone. The sandstone plots in the dissected arc region on a QFL diagram.

The sandstone consists of poorly sorted and angular, fine to coarse grains, cemented in a Fe-oxide-rich matrix. Clasts are ~65% feldspar, 30% quartz, 10% plutonic fragments, and 3% other lithic fragments. Feldspar clasts are variably replaced by sericite.

Plutonic grains are ~3 mm by 2 mm. Quartz and feldspar grains dominate, and rare magmatic epidote grains also occur. The quartz grains have aspect ratios of 2:1 and display evidence for bulging recrystallization. Plagioclase grains in plutonic clasts contain sericite-filled veins that do not continue into the matrix.

Hornblende-Plagioclase Porphyry Dikes

Northeast-striking, 1-2-m-thick hornblende-plagioclase porphyry dikes intrude all the Mesozoic units in the study area. Exposures are light to dark green and are more resistant to weathering than host rocks. The dikes consist of 1-2-mm-long hornblende and plagioclase phenocrysts in a matrix of quartz, plagioclase, and hornblende. Common accessory phases include biotite and sphene. Elongate hornblende phenocrysts define weak foliations that are parallel to the dike contacts. Contacts are sharp with no apparent deflection of fabric in host rocks.

GEOCHRONOLOGY

Zircons were separated from a sample of fine-grained tonalite hosted by the Eagle tonalite and from an Eocene clastic rock (Plate 1). The xenolith in the Eagle tonalite was sampled in the Granite Mountain area (Plate 1). Individual zircons are typically ~150-μm-long, have aspect ratios of 3:1, and are euhedral. The zircons exhibit oscillatory zoning and do not show evidence for inherited cores or metamorphic rims. A total of 50 grains were picked and 49 were analyzed by inductively coupled plasma mass spectrometry. Twenty-nine of these grains were used to determine a weighted mean age of 207.9±2.1 Ma (Figure 13). Four grains were not used to calculate the age, as concordia plots imply that they suffered lead loss (Figure 13). The analyzed grains have a mean Th/U ratio of ~0.004, which is typical of igneous grains (e.g., Williams and Claesson, 1987).

The age of this xenolith is older than the Eagle Plutonic Complex (Figure 2). Triassic plutons are mapped ~20 km north of the study area in the Mount Lytton Complex, which is on strike with the Eagle Plutonic Complex (Figure 2) (Monger, 1985).
In addition, the Mount Lytton Complex is cross-cut by Jurassic plutons that yield ages similar to those of the Eagle tonalite (Figure 2) (Monger, 1985).

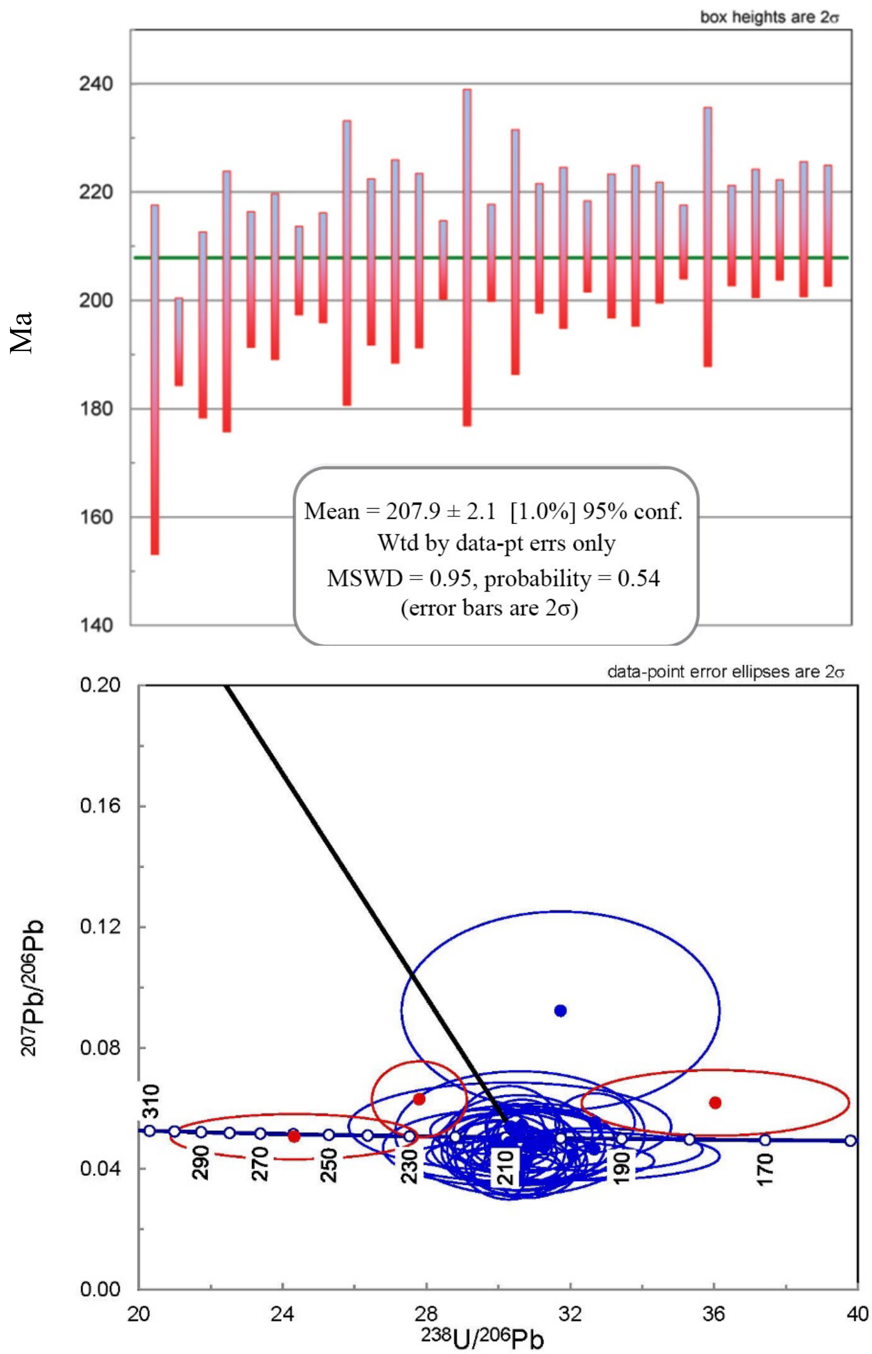


Figure 13. Plots of zircons from a xenolith hosted by the Eagle tonalite. A) Error bar graph for zircons from the xenolith. B) Concordia diagram of the zircons. Unused zircons are shown in red.

Eocene clastic rocks were sampled near Railroad Creek road, northwest of the Tulameen River (Figure 2). The sample contains abundant angular subhedral zircons with well-developed oscillatory zoning, from which 98 were dated. These zircons do not show evidence for inherited cores or metamorphic rims (Figure 14) and have a mean U/Th ratio of .095. The dated zircons range from the Late Triassic to the early Eocene. The youngest grain is 53±1 Ma (Figure 15). There is a major peak at 93 Ma and two broad peaks from 120 Ma to 150 Ma, and 200 Ma to 250 Ma (Figure 15). In between the broad peaks there is a gap at ~180 Ma (Figure 15). Following Dickinson and Gehrels (2009), a maximum depositional age of 86.2±1 Ma was calculated from the weighted mean of the three youngest grains with an overlap of 2σ. Notably, the calculated maximum deposition age is older than the palynmorph age reported by Greig (1992), but the single youngest grain of 53±1 Ma from this study is a close match.

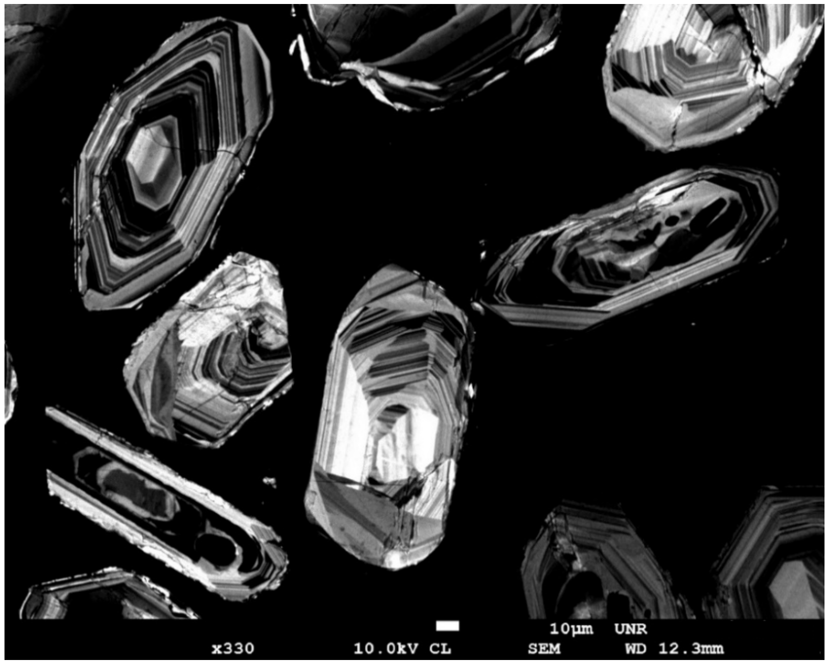


Figure 14. Cathodoluminescence image of representative zircons from the Eocene clastic rocks. Note the well-developed oscillatory zoning.

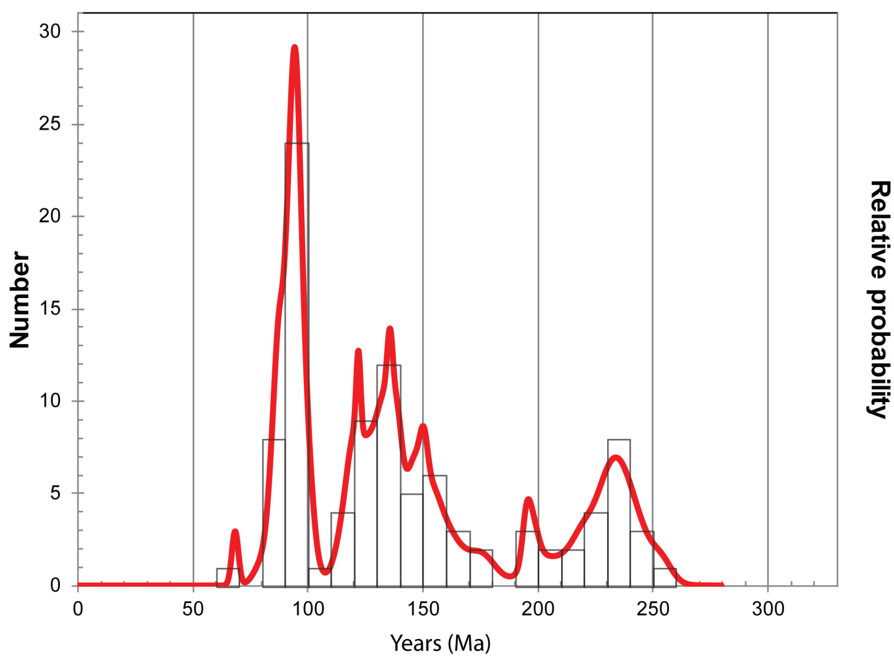


Figure 15. Age histogram and probability density distribution for the Eocene clastic rocks.

STRUCTURAL ANALYSIS

Structural measurements and descriptions were recorded at 290 stations in the study area (Plate 1). During field work, structural analysis focused on coverage of the study area and kinematic analysis of the Pasayten fault and Eagle shear zone. The Eagle Plutonic Complex comprises the bulk of the study area and thus received the most study.

Deformation attributed to motion along the Pasayten fault is evident in rocks on both sides of the fault, as best displayed by mylonites in the Fallslake Plutonic Suite and Zoa Complex. West of the Pasayten fault, foliations in the Zoa Complex increase in intensity approaching the fault, but some of them are not parallel to the fault (Plate 1). East of the Pasayten fault, the metamorphic and plutonic rocks have solid-state, NW-striking foliations (Plate 1). In the Eagle Plutonic Complex, changes in dip direction are common and occur with increasing frequency approaching the Pasayten fault and Eagle shear zone (Plate 1). Only subtle changes occur along strike (Plate 1). Foliations in the EWmb and Nicola Group have consistent NW strike and SW dip.

The trace of the Pasayten fault is offset by several NE-striking faults (Plate 1). Evidence for these faults was observed up to ~1 km east of the Pasayten fault.

Eastgate-Whipsaw Metamorphic Belt

The EWm belt is a NW-striking body with similar E-W structural and metamorphic gradients as the adjacent Nicola Group (Plate 1). Foliations in the EWm belt strike NW and typically dip moderately to steeply (26˚ to 77˚; average 52˚) SW (Figure 16; Plate 1) and become stronger to the west near the Eagle Plutonic Complex. The foliations have a maximum of 131˚, 61˚ SW. Most of the mineral stretching lineations plunge moderately to shallowly (19˚ to 39˚) NW and a few plunge 14˚ to 36˚ SE (Figure 16). Foliations in the EWm belt are typically better developed than lineations and are deformed into folds with cm-to-meter wavelengths and NW-trending hinge lines (Plate 1). Local NE (56˚ to 89˚)-dipping foliations occur on the limbs of such folds (Figure 16).

Nicola Group Metamorphic Belt

Foliations in Nicola Group rocks strike NW and dip moderately SW (Figure 17). The foliations steepen and become stronger near the Eagle tonalite. Foliations are typically much better developed than lineations except in several outcrops north of the Arrastra Creek area where there are L-tectonites (Plate 1). Lineations plunge gently to moderately SSW and SSE with one outlier plunging to the NW (Figure 17). Rafts of the Nicola Group in the Eagle tonalite have strong foliations that also strike NW and dip SW (Figure 17), and are parallel to foliations in the adjacent Eagle tonalite. The single measured fold axis plunges SW (Figure 17).

Eagle Shear Zone

Structures in the Eagle shear zone were examined in the Champion Creek area and along Tulameen Road (Plate 1). Nicola Group rocks there are deformed into kink folds and isoclinal folds with wavelengths of ~2 cm. Foliations are deflected in four ~50-cm-wide shear zones, which strike NW and dip moderately (~45˚) SW. The deflection in foliations is interpreted to record top-to-the-NE reverse slip. East of the Eagle shear zone, asymmetric fabrics were not observed. (Plate 1). Overall in the Eagle shear zone, the EWm belt and Nicola Group consistently strike NW and dip on average ~52˚ SW.

Thus, assuming that the Eagle shear zone is parallel to the eastern margin of the Eagle Plutonic Complex, the EWm belt and Nicola Group are structurally below the Complex.

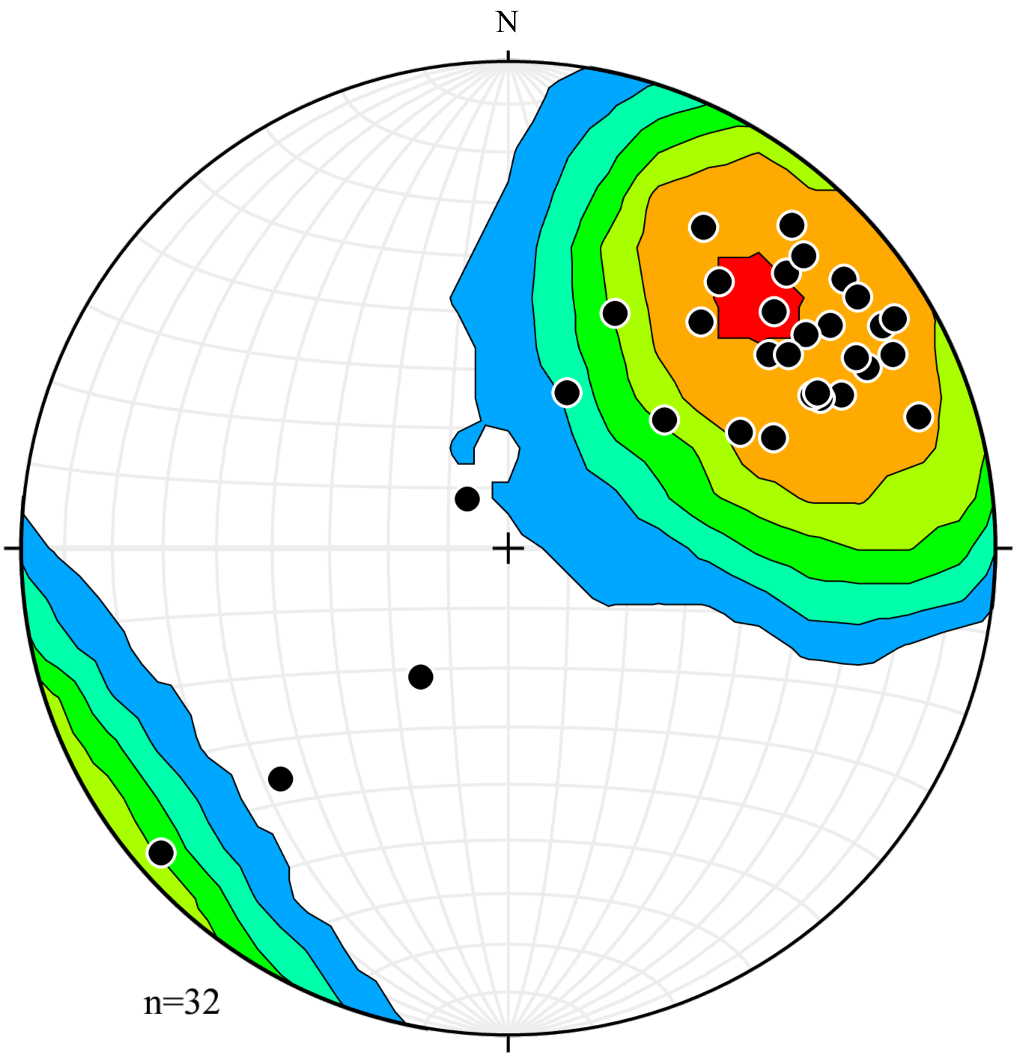


Figure 16. Poles to foliations in the EWm belt. Contour interval=2σ; after Kamb (1959).

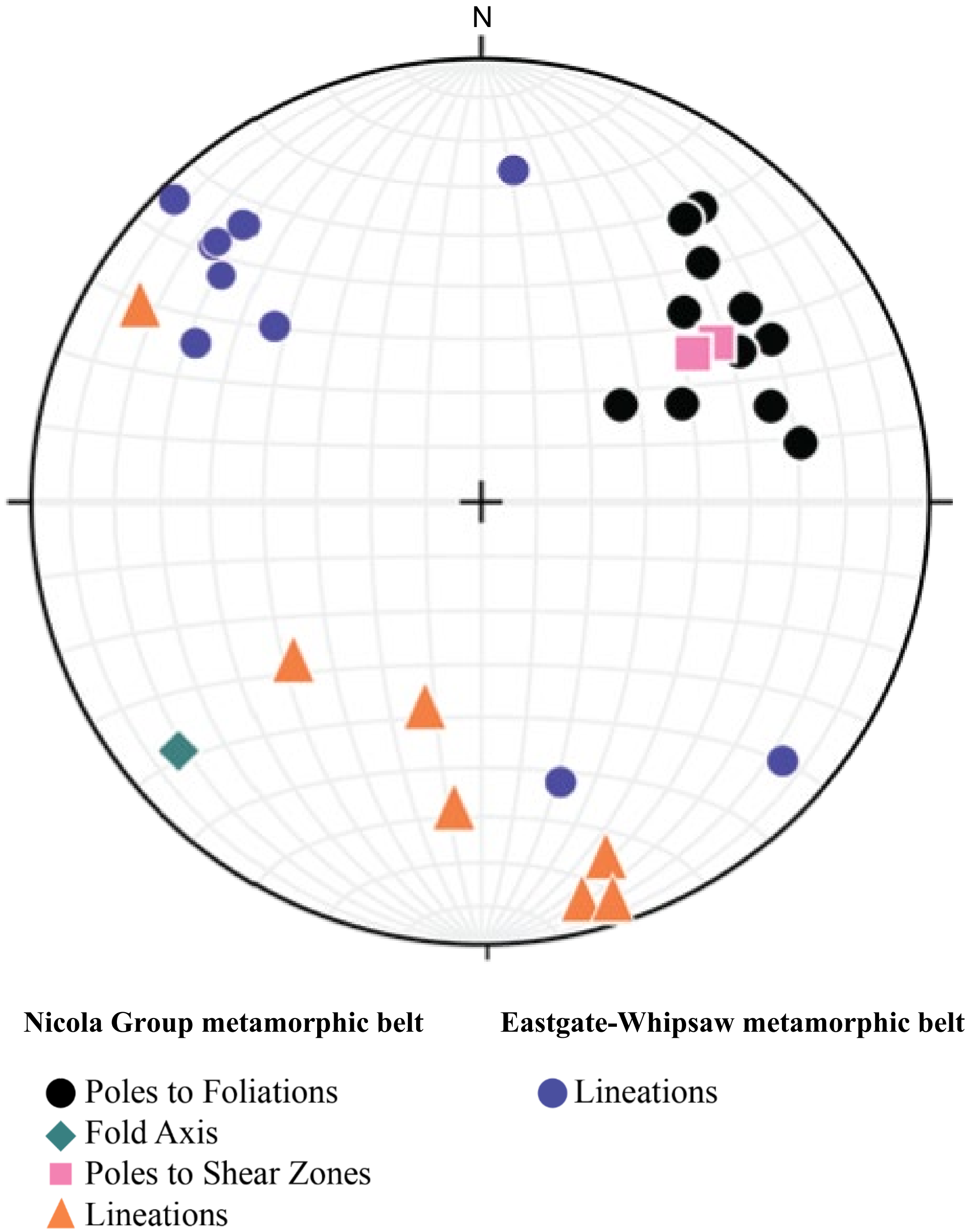


Figure 17. Poles to foliations and shear zones, lineations, and a fold axis from the Nicola Group metamorphic belt, and lineations in the Eastgate Whipsaw metamorphic belt.

Similkameen Falls Fault

The EWm belt is separated from the Nicola Group by the Similkameen Falls fault according to Massey et al. (2009) (Plate 1). In the study area, the orientation and intensity of foliations is similar on both sides of this fault and east-west gradients in deformation and metamorphism are continuous across the Similkameen Falls fault. Moreover, direct evidence for faulting near the fault, such as mylonites or cataclasites, were not observed.

Zoa Complex

The northern body of the Zoa Complex is in contact with the Fallslake Plutonic Suite across the Pasayten fault (Plate 1). Foliations in this body are defined by aligned chlorite and biotite, and strike variably NW, W, and SW (Figure 18). Dips range from 11˚ to 84˚ (Figure 18). Within ~200 m of the Pasayten fault the foliations are locally strong. Elsewhere in the northern body foliations vary in development (Figure 18) (Plate 1). Lineation was measured in a single outcrop that contained aligned epidote aggregates.

The southern body of the Zoa Complex displays an increase in deformation intensity from west to east. The rocks range from moderately foliated to ultramylonitic near the Pasayten fault. Foliations dip from 30˚ to 84˚ NE (Figure 18). Foliation is subvertical in ultramylonites near the Pasayten fault (Plate 1). The two measured stretching lineations plunge moderately SE and steeply ESE, respectively (Figure 18) (Plate 1). Foliations are typically better developed than lineations except in mylonites where they are subequal. An 8-10-m-thick zone of NW-striking mylonites is present in the southern Zoa body next to the Pasayten fault. Two samples of mylonitic greenschist from this shear zone were analyzed for kinematics (Plate 1). Foliation in one sample dips 60˚ NE, and lineations plunge ~30˚ SE indicating oblique slip. Asymmetric microcline porphyroclasts are interpreted to show dextral-normal shear (Figure 19). In contrast, rare calcite tails are interpreted to record sinistral-reverse shear (Figure 20). The second sample dips 84˚ to the NE and lineation plunges ~12˚ SE, as was determined by cutting oriented slabs. Shear bands in this sample indicate sinistral-reverse shear (Plate 1).

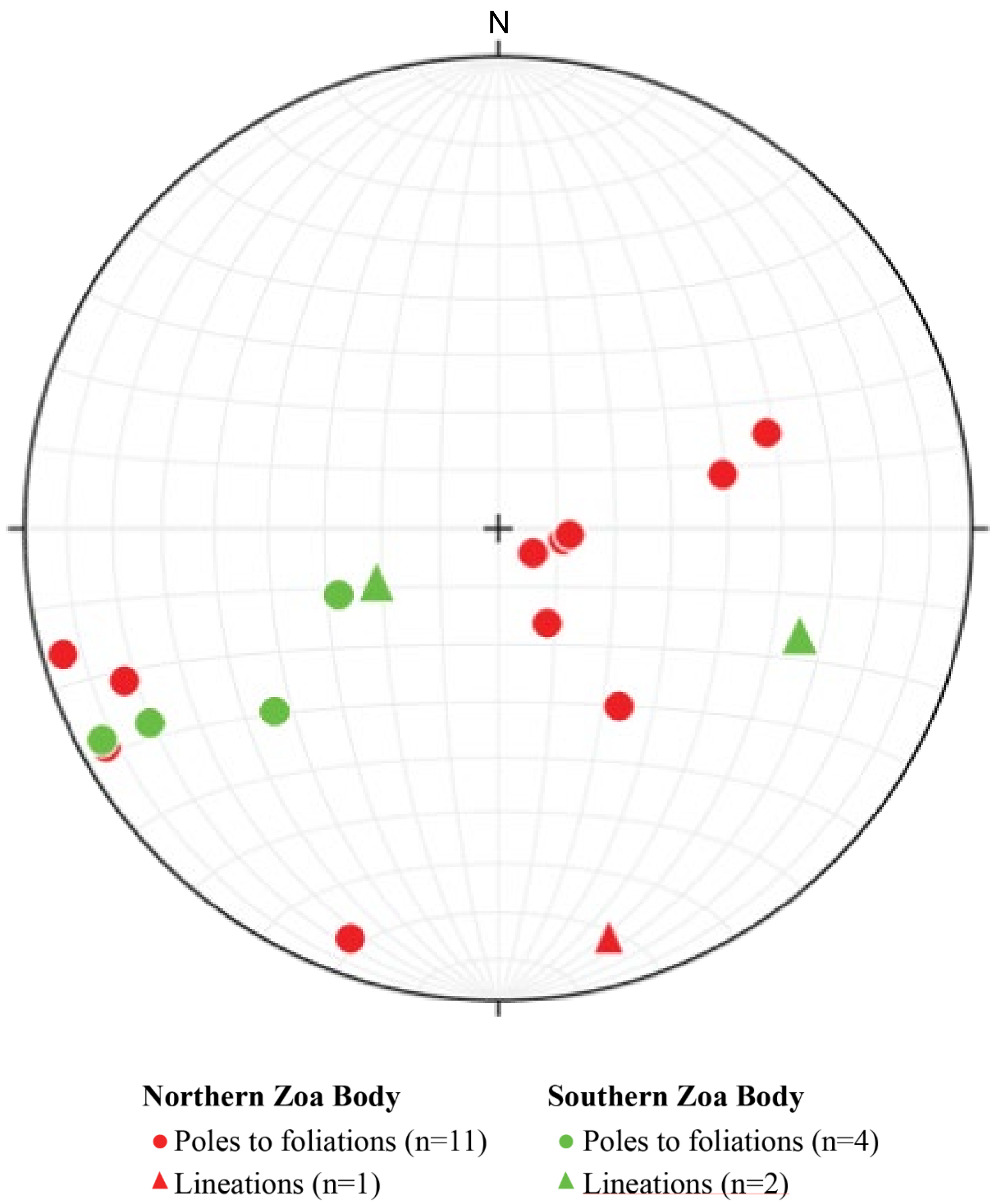


Figure 18. Stereographic projection of poles to foliations, and lineation from the northern and southern Zoa bodies.

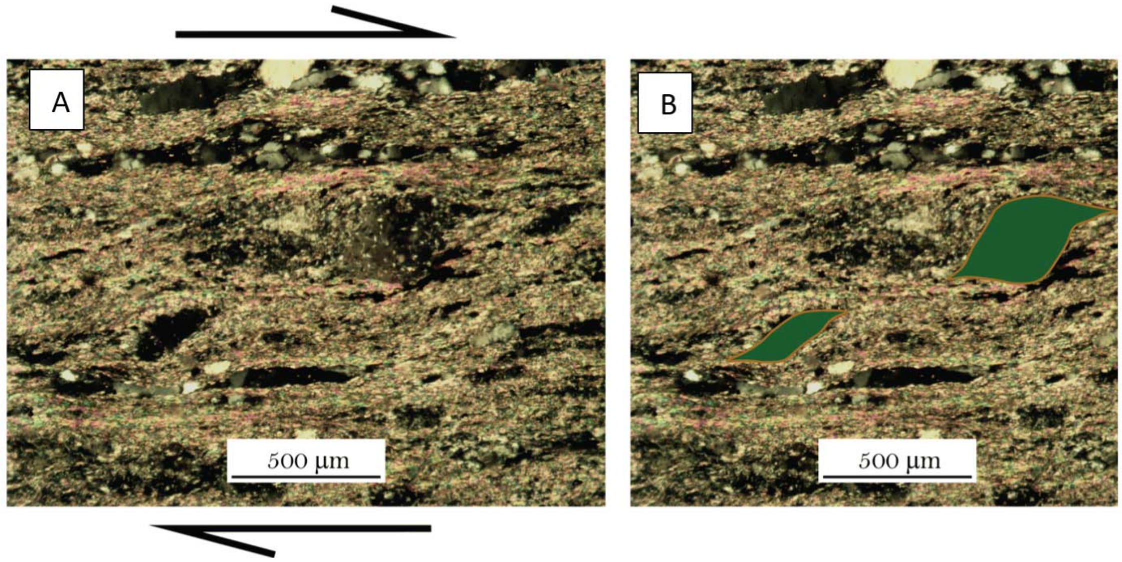


Figure 19. Microcline porphyroclasts in a mylonite from the Zoa Complex. (A) Half arrows indicate direction of non-coaxial shear. "B" outline emphasized.

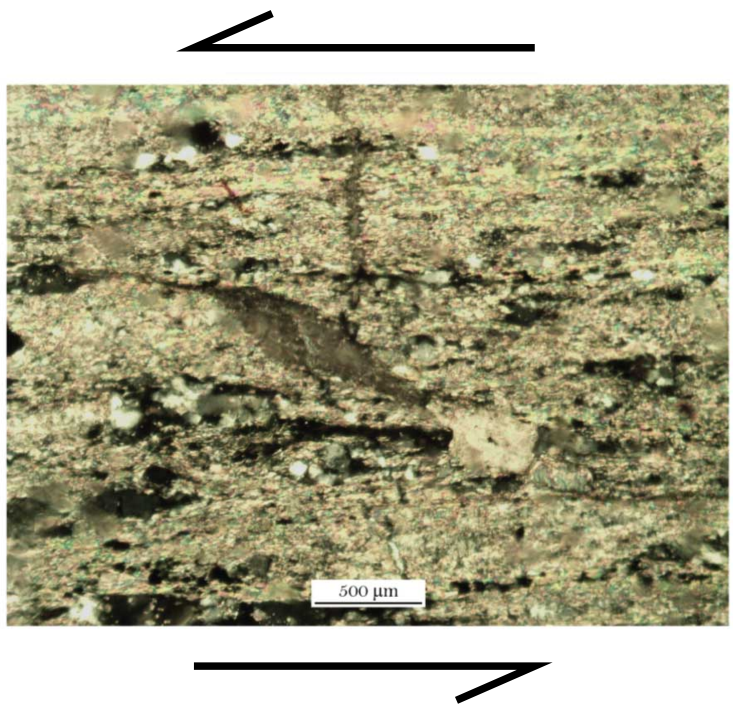


Figure 20. Mylonite from the Zoa Complex showing an asymmetric calcite grain. Note, this is the same sample as in Figure 19. Half arrows indicate direction of non-coaxial shear.

Eagle Plutonic Complex

The Eagle Plutonic Complex and Mount Lytton Complex form a highly elongate body (aspect ratio of 8:1) parallel to the trace of the Pasayten fault (Plate 1). U-Pb crystallization ages young from Triassic in the NW to mid-Cretaceous south of the study area (Figure 2).

Eagle Tonalite

Foliations in the Eagle tonalite dip mostly moderately to steeply NE and SW, and have a maximum of 146˚, 72˚ SW. The foliations are deformed into open macroscopic folds with axes that plunge moderately NW and SE (Figure 21; Plate 1). The folds have wavelengths of up to 150 m and extend through the study area. Subvertical foliations are present near the Pasayten fault and locally next to the Eagle shear zone (Figure 21) (Plate 1). Foliation is concordant to variably developed compositional layering.

Lineations in the Eagle tonalite typically plunge shallowly to moderately SE and NW, and have a maximum of 7˚, 143˚ (Figure 22). A small subpopulation also plunges moderately to steeply NE (Figure 22). The majority of lineations define a NW-striking and steeply NE-dipping great circle (Figure 22). Shallow to moderately plunging lineations are more common near the Eagle shear zone and Pasayten fault (Plate 1). The steeply plunging lineations are concentrated in the middle of the Eagle tonalite body (Plate 1).

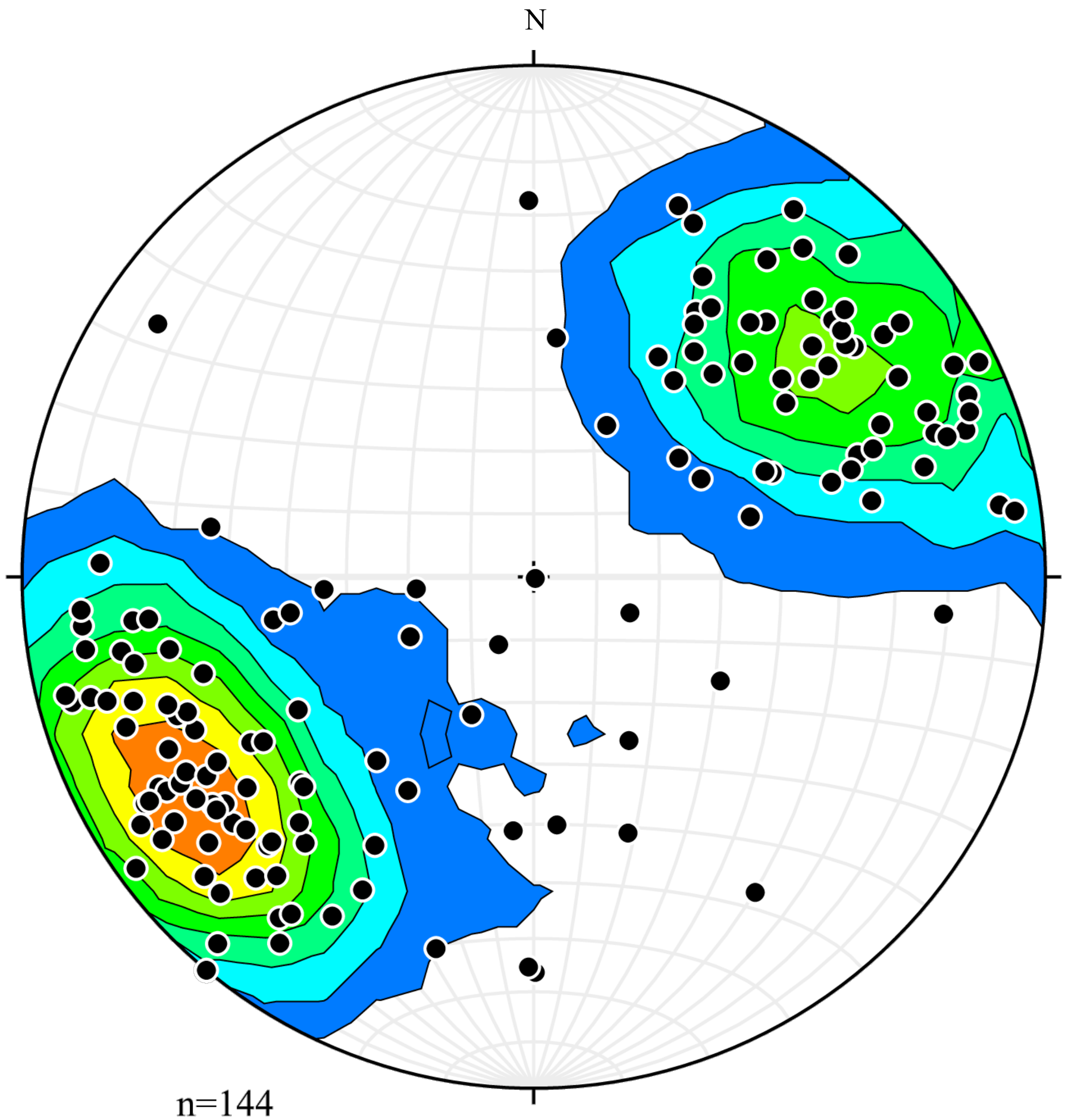


Figure 21. Poles to foliations in the Eagle tonalite. Kamb (1959) contour interval of 2σ.

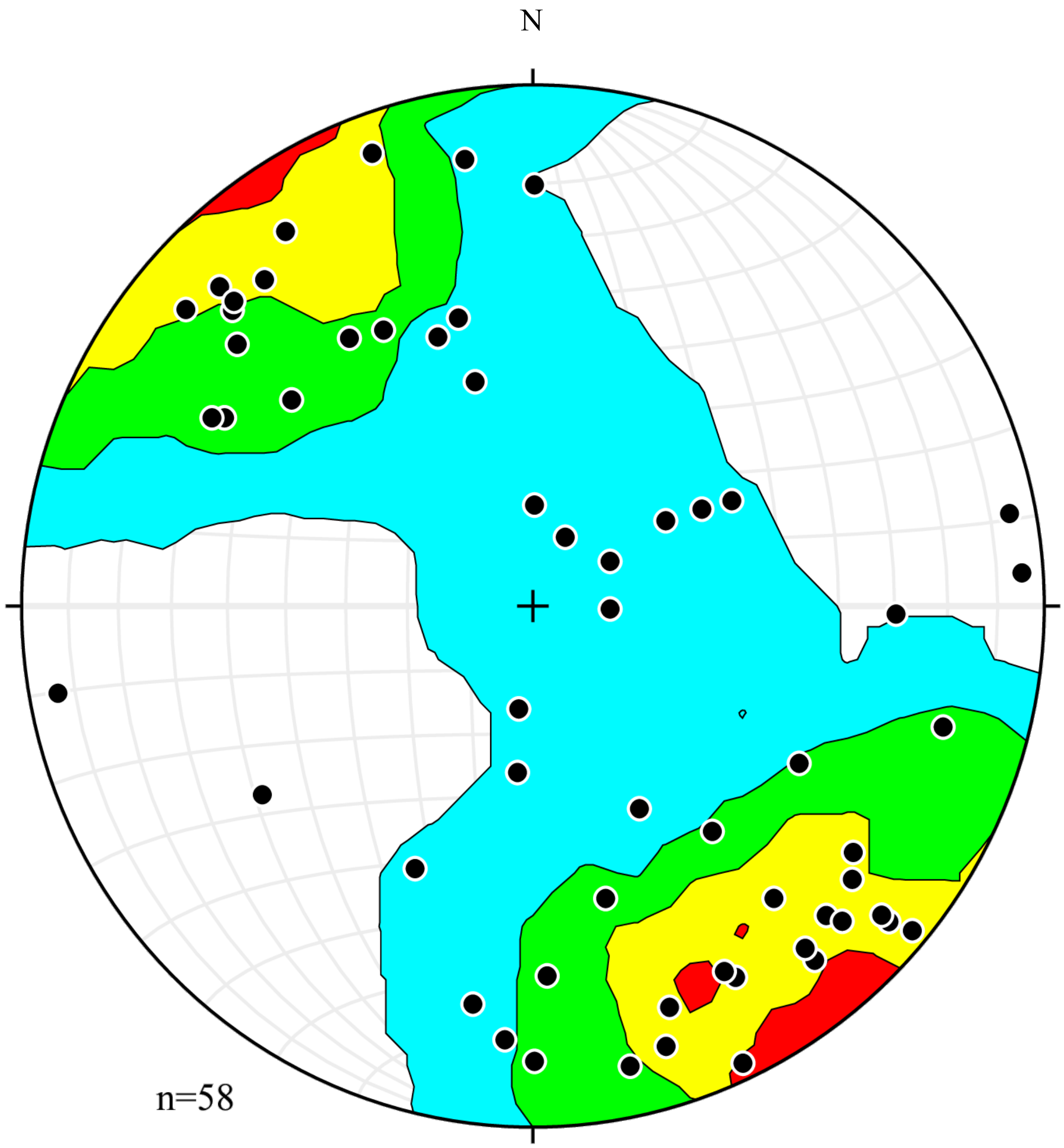


Figure 22. Lineations in the Eagle tonalite. Kamb (1959) contouring at 2σ.

Roadcuts in the Champion Creek area along Lodestone Road are fresh and mostly continuous, enabling detailed examination of the Eagle tonalite structure in an ≥500-m-wide zone extending from the Nicola Group contact (Plate 1). Near the eastern contact of the Eagle Plutonic Complex, an ~200-m-wide zone of Eagle tonalite contains nine, 20-cm- to 50-cm-thick rafts of the Nicola Group. The contacts of the rafts are parallel to the adjacent tonalite sheets. The rafts typically contain 2- to 5-cm-thick, closely folded tonalite veins with 5- to 15-cm wavelengths. Tonalite stringers in Nicola Group rafts are partly discordant to the internal foliation of the rafts. Some of the stringers are deformed into complex cuspate-lobate structures. The rafts and adjacent Eagle tonalite sheets are also deformed by several NW-striking, SW-dipping ~30-cm-thick reverse shear zones that are defined by deflected foliations and have SSE plunging lineations (Figure 23). The shear zones are interpreted to show reverse and dextral shear with displacements of 10 cm to 1 m. One prominent ~1-m-wide shear zone contains tight, parallel folds of foliation with 1- to 2-cm wavelengths. Biotite schlieren are common here.

East of the shear zones is an ~40-m-wide sheeted zone of fine- to coarse-grained, equigranular Eagle tonalite. Sheet contacts are marked by sharp changes in modal abundances of mafic minerals. Ptygmatic folds of felsic material and ~10-cm-thick pegmatite veins occur locally.

The Eagle tonalite locally contains a weakly developed S-C fabric. This fabric is more common near the western and eastern contacts. The S-surfaces are defined by euhedral biotite and epidote grains. The C-surfaces are defined by more finely recrystallized biotite, quartz, and chlorite grains. Quartz is moderately elongate and shows evidence for bulging and subgrain rotation recrystallization indicating that the C-surfaces formed at low to medium temperatures (Hirth and Tullis, 1992). Three oriented thin sections with an S-C fabric were analyzed for kinematics. Two samples from the Champion Creek transect have foliations that dip 78˚ and 30˚ SW, respectively, and a down-dip lineation. They record NE-vergent, reverse shear. The third sample was collected NE of Granite Mountain in the Arrastra Creek watershed, in the interior of the tonalite (Plate 1). The foliation there dips 51˚ SW and lineation plunges 9˚ SE; the S-C fabrics indicate sinistral shear with a reverse component (Plate 1).

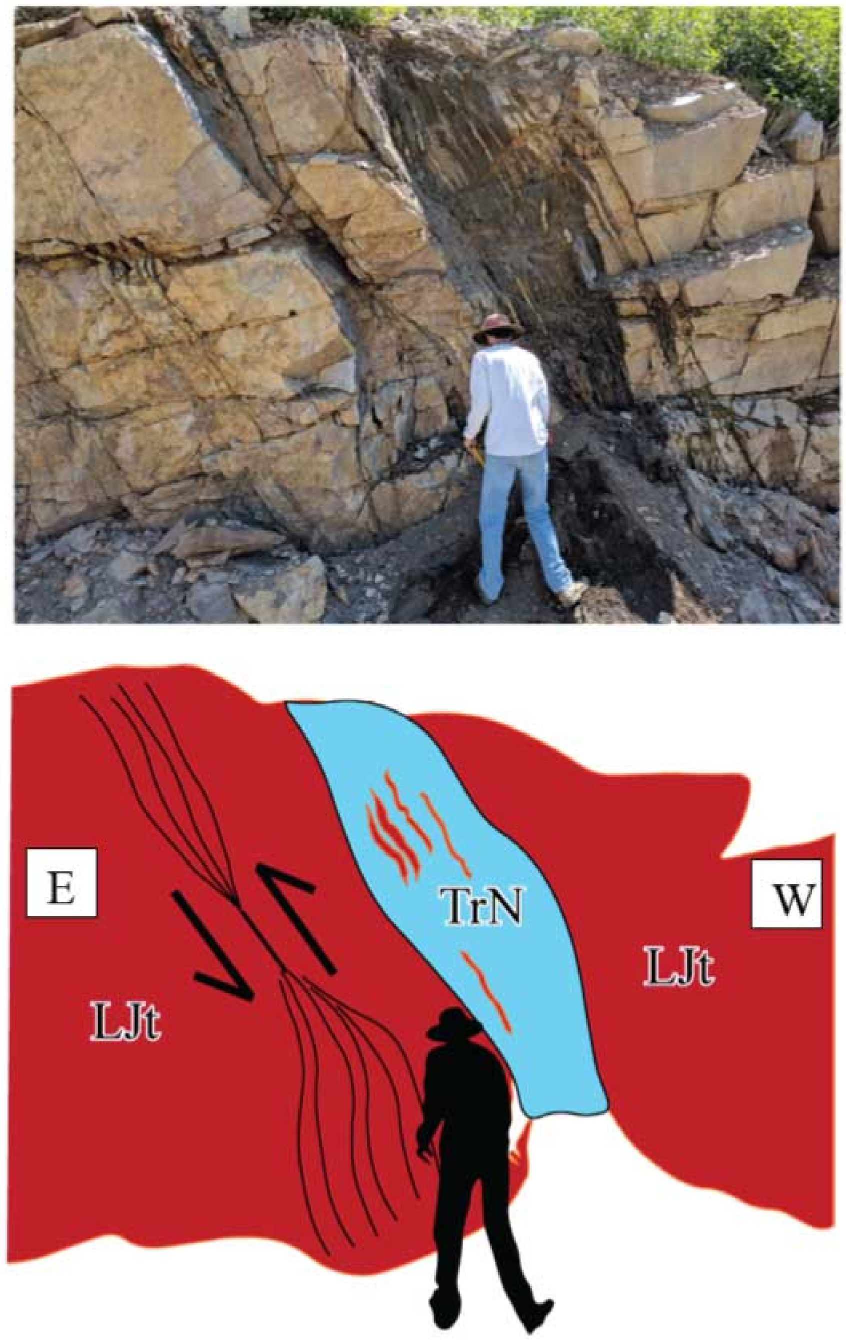


Figure 23. Nicola Group raft enclosed in Eagle tonalite. Note northeast-vergent folds of tonalite stringers that intrude along foliation. A reverse shear zone defined by deflected foliations is shown to the left of photo. TrN=Nicola Group, LJt=Eagle tonalite. Author for scale.

Fallslake Plutonic Suite

The Fallslake Plutonic Suite is exposed in a NW-striking, 1- to 2.5-km-wide body along the Pasayten fault and as numerous ~100 m^2 stocks east of this body (Plate 1). Only one of these stocks was mappable. It is in the Arrastra Creek area and trends NW (Plate 1). The eastern contact of the main body of the Fallslake Plutonic Suite with the Eagle tonalite is curvilinear and has an overall NW trend.

The main body of the Fallslake Plutonic Suite extends from the northern boundary of the study area to the Copper Creek area (Plate 1). Deformation in the body generally increases towards the Pasayten fault. Mylonites and protomylonites derived from the Fallslake Plutonic Suite are exposed in a 100-m- to 300-m-wide zone next to the fault, as observed near Tulameen Falls and Skaist Mountain (Plate 1). Locally, the Fallslake mylonites are juxtaposed against mylonites of the Zoa Complex across the Pasayten fault. Folds occur throughout the main body, but are better developed in the Fallslake-Eagle contact zone and within ~100 m of the Pasayten fault.

Foliations in the main Fallslake body strike NW and dip NE and SW (Figure 24). Dips increase approaching the Pasayten fault. Lineations in the Fallslake Plutonic Suite are typically weak and difficult to measure. They plunge from sub-vertical to sub-horizontal and trends are scattered, although in the mylonites the lineations plunge S and NW (Figure 24). Quartz microstructures include bulging and subgrain rotation recrystallization of grains, which indicate that foliation and lineation formed at low- to medium-temperature.

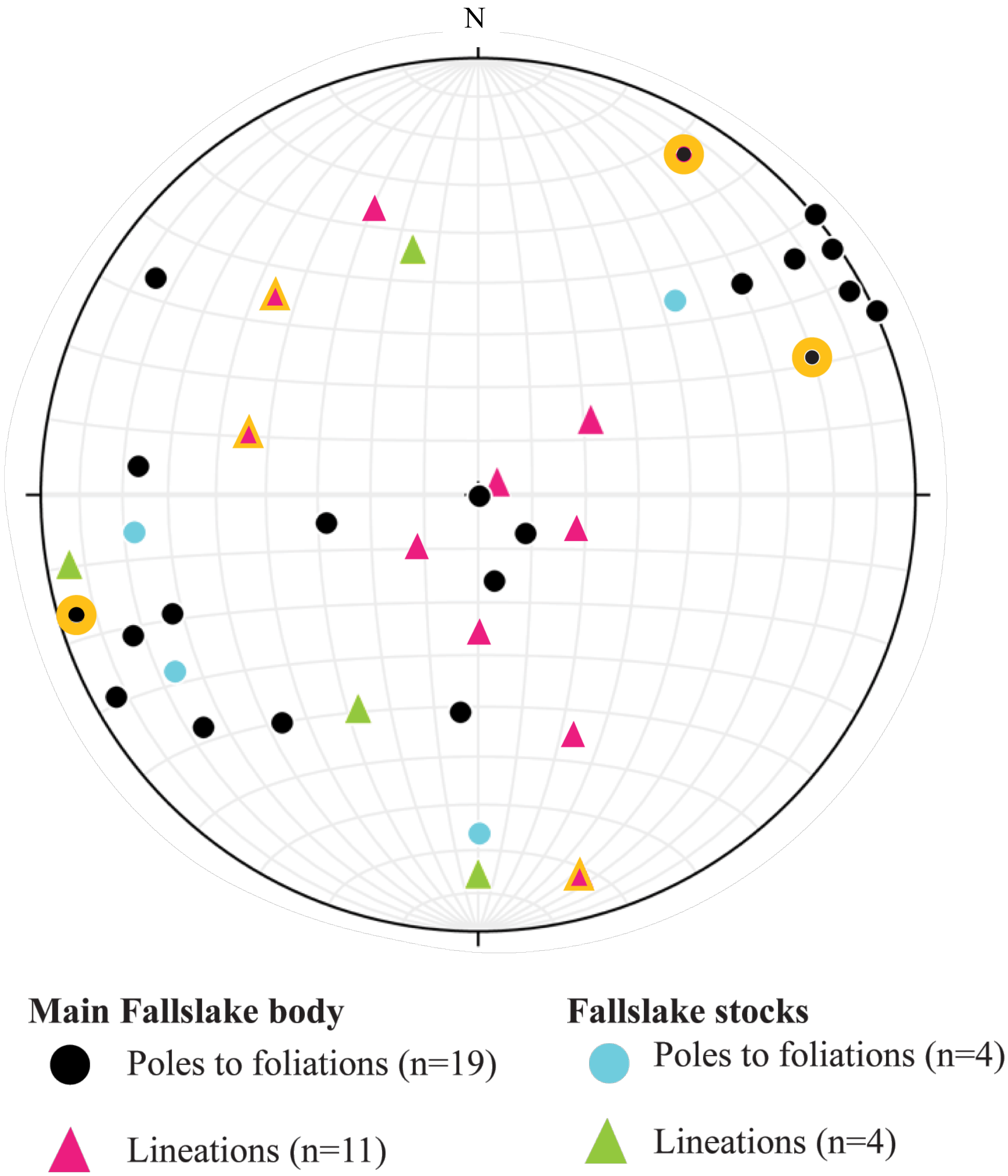


Figure 24. Stereographic projection of lineations and poles to foliations in the main Fallslake body and in Fallslake stocks. The yellow halo indicates samples used for kinematic analysis.

Kinematics were obtained from a protomylonite in the Sutter Creek area and two mylonites from the Skaist Mountain area (Plate 1). The foliation of the protomylonite dips 85˚ SW and strikes parallel to the Pasayten fault, and has a lineation that plunges 11˚ SSE. The protomylonite has a shape preferred orientation of elongate quartz grains that is oblique to the main foliation. This quartz fabric and rare muscovite fish indicate sinistral shear across the Pasayten fault with a small normal component. The mylonites have foliations that dip 78˚ and 79˚ SW, and have lineations that plunge 35˚ SSE and 45˚ S, respectively. Both samples fit the Lister and Snoke (1984) description of a type II S-C mylonite. They contain a strong shape preferred orientation of recrystallized quartz (Fig 25), which along with the long axis of the well-developed muscovite fish define the S-surface. The C-surface is defined by trails of muscovite on the fish. The obliquity of the quartz fabric and muscovite fish indicate sinistral shear with a east-side-down, normal component across the Pasayten fault (Figure 26).

Near the Fallslake Plutonic Suite-Eagle tonalite contact, banded muscovite-biotite tonalite sheets are variably folded. One 4-m-thick sheet contains prominent felsic veins and ~3-mm-thick biotite schlieren (Figure 27). The folds plunge moderately NE and have 5- to 10-cm wavelengths (Figure 27).

The few measured foliations in the equigranular Fallslake stocks are not consistently oriented. They strike NW and E-W, and dip moderately steep to the SW, NE, and N (53˚-69˚) (Figure 24). The few measured mineral lineations plunge S, NNW, and SW at 14˚, 42˚, and 43˚, respectively (Figure 24). An additional W-SW-trending lineation plunges 6˚ (Figure 24).

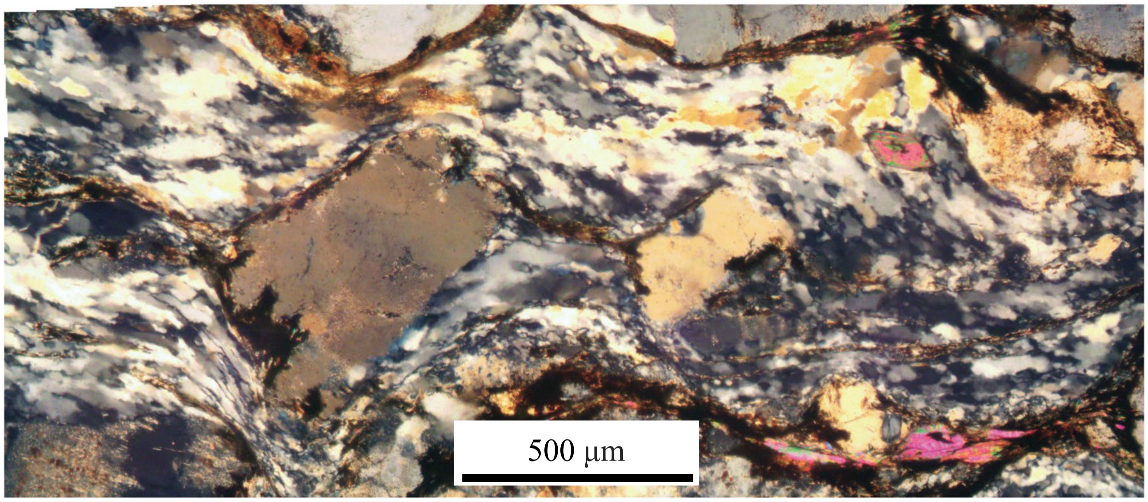


Figure 25. Fallslake mylonite showing intensely deformed quartz. Also note feldspar porphyroclasts and muscovite fish (lower right corner).

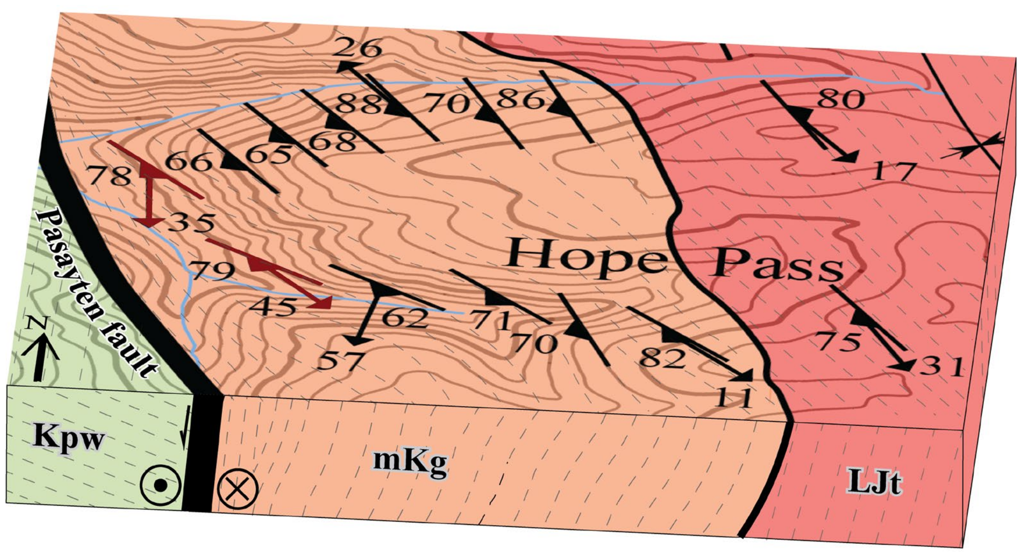


Figure 26. Block diagram showing motion of Pasayten fault obtained from mylonites of the Fallslake Plutonic Suite. The foliation and lineation symbols of stations used for kinematics are shown in red. Kpw=Winthrop Formation, mKg=Fallslake Plutonic Suite, LJt=Eagle tonalite.

Figure 27. Folded felsic veins in Fallslake muscovite-biotite granodiorite. Pencil is ~8 cm long.

The ~300-m-wide curvilinear contact zone of the main body of the Fallslake Plutonic Suite with the Eagle tonalite was observed in the Dear Mountain, Hope Pass, and Granite Mountain areas (Plate 1). In this zone, the Fallslake Plutonic Suite commonly contains 1-m-long inclusions of the Eagle tonalite, and the tonalite encloses ~30-cm-long inclusions of the Fallslake Plutonic Suite. The foliations generally strike NW and dip ~30˚ to 80˚ NE or SW. In the Dear Mountain area, zones of ptygmatically folded Fallslake sheets wrap around inclusions of Eagle tonalite (Figure 28). The sheets are 5 cm to 20 cm in thickness and are delineated by changes in color index and are associated with schlieren. More commonly, the sheets intrude the Eagle tonalite in 2- to 3-m-wide zones marked by cuspate lobate folds (Figure 28B). Additional discordant, ~1-m-thick sheeted zones consisting of cm-scale sheets are deformed into tight folds and occur adjacent to the cuspate lobate zones (Figure 28C).

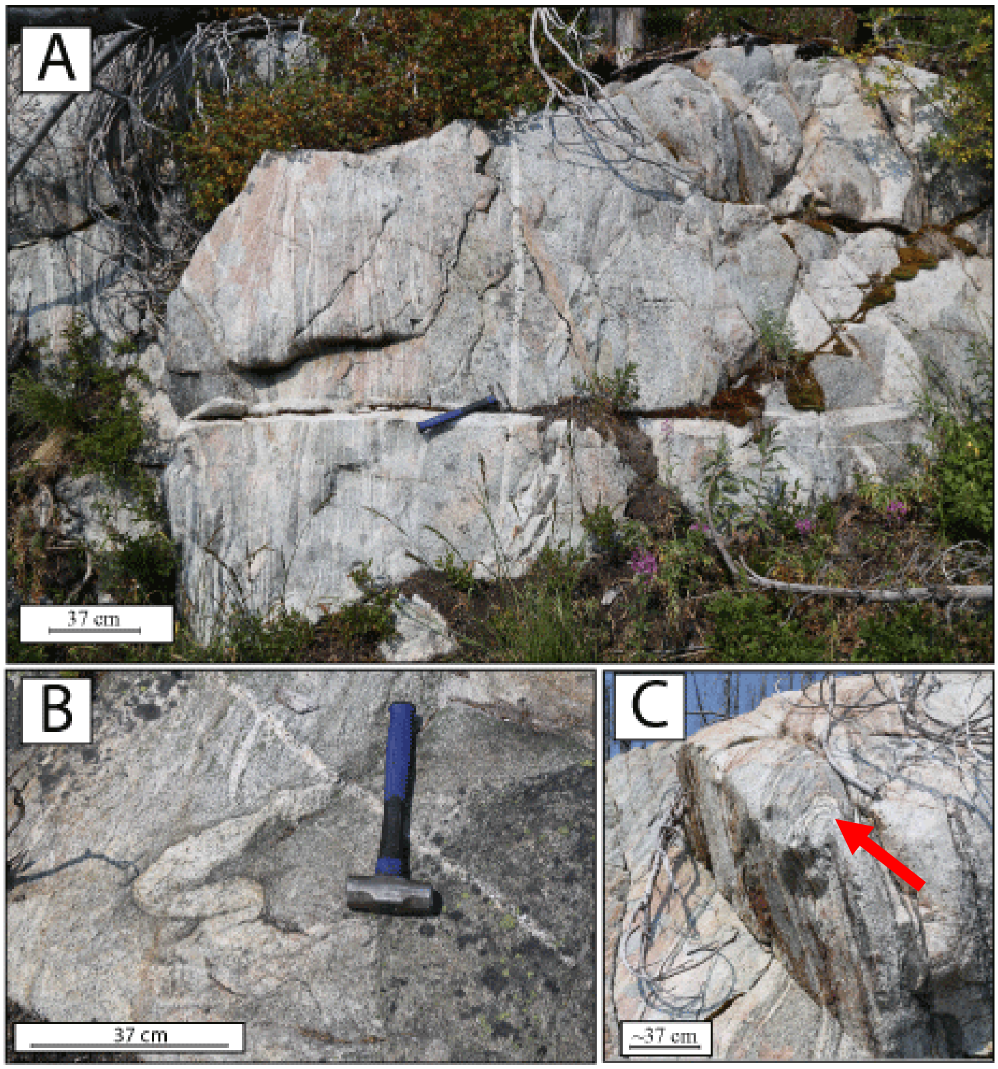


Figure 28. Field photographs of the Fallslake-Eagle tonalite contact zone. (A) Sheeted zone cut by several thin felsic intrusions. (B) Felsic rock with cuspate-lobate fold geometry. (C) Tightly folded and steeply dipping Fallslake sheets. Red arrow points to fold of Fallslake.

Methow Basin

A ~400-m-thick section of the Methow basin was examined during this study (Plate 1). The rocks consist of the Virginian Ridge Formation and the Winthrop Formation. Virginian Ridge rocks make up ~90% of exposures. The strata are typically well-bedded.

Strikes and dip directions of beds in the Virginian Ridge Formation are variable, presumably due to folding rotation from nearby faults (Plate 1). Dips range from 18˚ to 74˚ (Figure 29). Near the northern Zoa body, Virginian Ridge beds strike NE and NW (Plate 1).

In an ~300-m-wide zone next to the Pasayten fault, beds are deformed into gentle folds that have ~1-m wavelengths. In this zone, the dip of beds also steepens towards the fault (Plate 1) where they average ~62˚. Mudstone near the Sutter Creek and Vuich Creek confluence has been deformed into pencil structures defined by sets of closely spaced fractures that intersect beds. The pencils have NE plunges of ~61˚. Gentle SW-plunging folds of beds are common in the mudstone. Next to the Pasayten fault, beds are deformed by outcrop-scale brittle shear zones, and one z-fold was observed. The shear zones strike ~040°, at nearly right angles to the fault, and are defined by deflected sandstone and mudstone beds. Beds are highly silicified in this area.

The Winthrop Formation lacks the silicification and deformation observed in the Virginian Ridge Formation. The few (n=4) measured beds strike N, NE, and SE, and dip between 61˚ and 80˚ (Figure 29). Next to the Pasayten fault, Winthrop beds dip steeply SW.

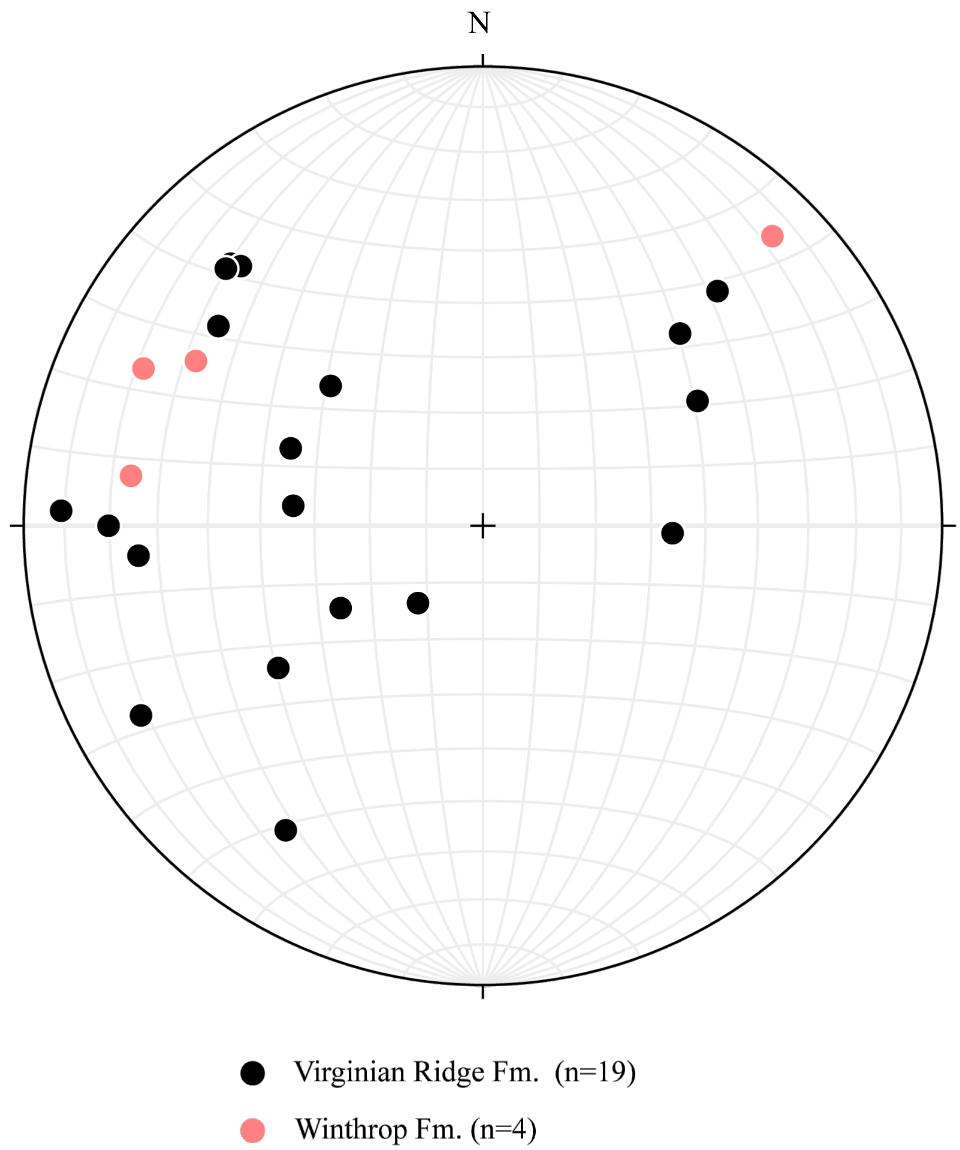


Figure 29. Poles to beds from the Virginian Ridge Formation and Winthrop Formation.

Northeast-Striking Faults

A series of sub-parallel and subvertical, NE-striking faults offset the Pasayten fault by up to 2 km (Plate 1). Slickenlines along several of the fault planes plunge steeply NE. Similar high-angle, NE-striking faults are mapped to the north of the study area (Monger, 1989; Greig, 1992). The youngest unit cut by these faults is Miocene in age.

The Pasayten fault is offset by several NE-striking faults with dextral separation near the confluence of Sutter Creek and the Tulameen River. NE-striking slickensides were observed at least 1 km into the Eagle Plutonic Complex.

The southern body of the Zoa Complex is also bounded in part by NE-striking high-angle faults (Plate 1). The northern fault displays ~1.5 km of sinistral separation and places the Zoa Complex against the Fallslake Plutonic Suite and the Virginian Ridge Formation (Plate 1). The southern fault displays ~2 km of dextral separation of the Pasayten fault. A series of smaller NE-striking faults cut the southern Zoa Complex body, but are too small to show at the scale of the map. Thus, the sparse exposure in several areas suggests there are likely to be more faults offsetting the Pasayten fault.

ELECTRON BACKSCATTER DIFFRACTION ANALYSIS

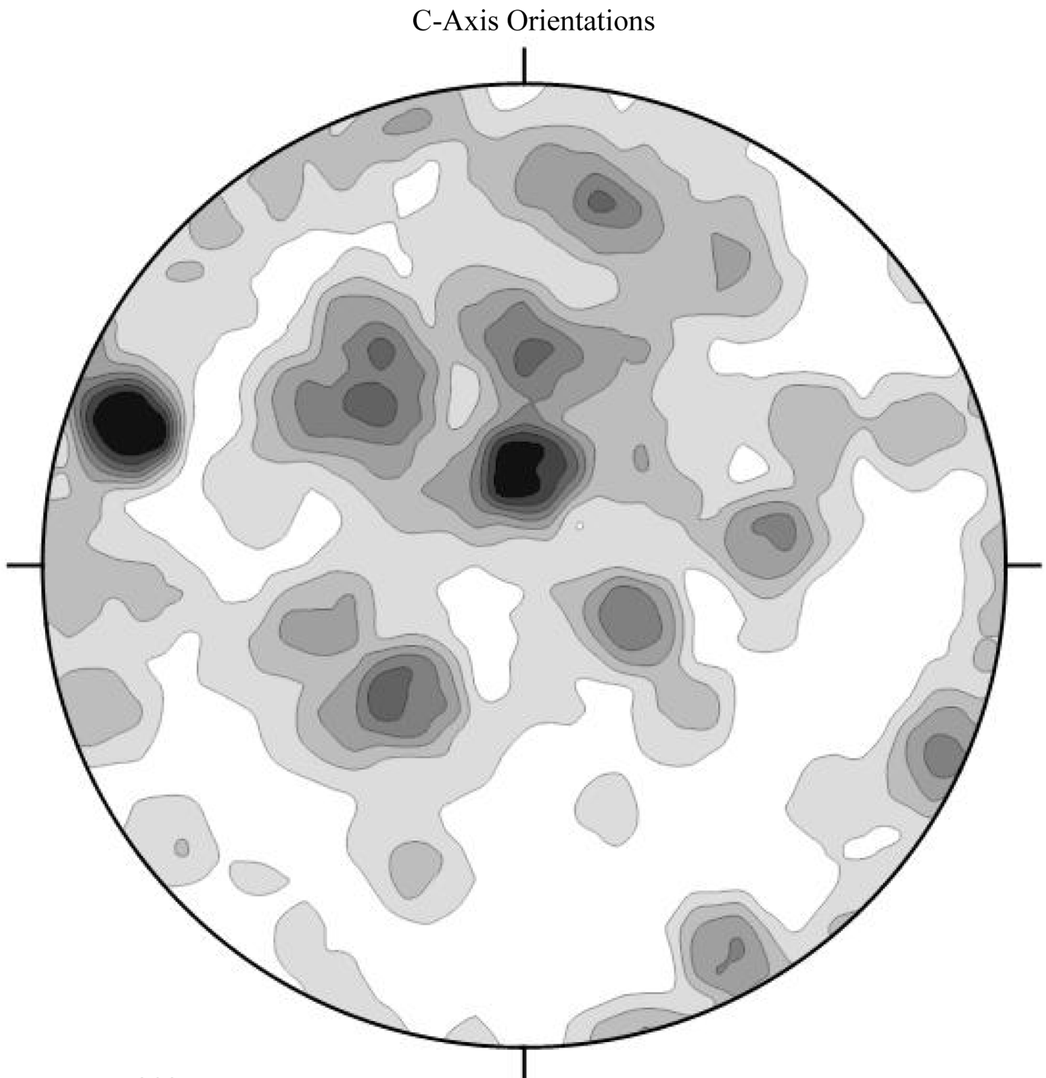
Quartz crystallographic orientations were analyzed by electron backscatter diffraction (EBSD) from two samples. These were chosen to compare the range of quartz deformation in plutonic rocks in the study area. One sample is a tonalite from the Mount Lytton Complex hosted by Eagle tonalite in the Granite Mountain area (Plate 1). The second sample is a mylonitic muscovite-granodiorite of the Fallslake Plutonic Suite from the Hope Pass area near the Pasayten fault (Plate 1).

Crystallographic orientations from the Mount Lytton Complex sample are scattered. There are several maxima and empty areas on the pole diagrams, but no recognizable pattern is evident (Figs. 30 and 31). These results are comparable to thin section observations. Quartz is weakly elongate and shows evidence for minor bulging recrystallization. Foliation in the sample is poorly developed, but is more recognizable than the very weak lineation.

Foliation in the Fallslake Plutonic Suite mylonite is partly defined by highly elongate aggregates of recrystallized quartz, which show evidence for bulging and subgrain rotation recrystallization. The foliation is strongly developed and dips 78˚ to the SW. Recrystallized elongate quartz aggregates define a lineation that plunges 35˚ to the S.

On a contoured pole figure, the “c” axes in the Fallslake mylonite display a single girdle with two maxima and a fabric-attractor plane that strikes 080˚ (Figure 32). The girdle is inclined to foliation and lineation (Figure 32). The “a” axes plot in a single maximum within the SW quadrant of the pole diagram (Figure 33).

Lattice preferred orientation (LPO) patterns result from the different slip planes operating in quartz with respect to temperature. On the basis of microstructures, the Fallslake sample was probably deformed at relatively low temperature (<500˚C) and matches low-temperature LPOs that indicate quartz-slip was concentrated in the <a> rhomb planes (Schmid and Casey, 1986). Inclination of the c-axis girdle is typically inferred to indicate an accumulation of non-coaxial shear and so, this LPO pattern is interpreted to show sinistral and normal shear in the Pasayten fault zone (Figure 32).



N = 29275

Contour Interval = 0.508%

Contour Values: 0.604%, 1.11%, 1.62%, 2.13%, 2.64%, 3.14%, 3.65%

Figure 30. Equal area projection of C-axis orientations from the sample of Mount Lytton Complex.

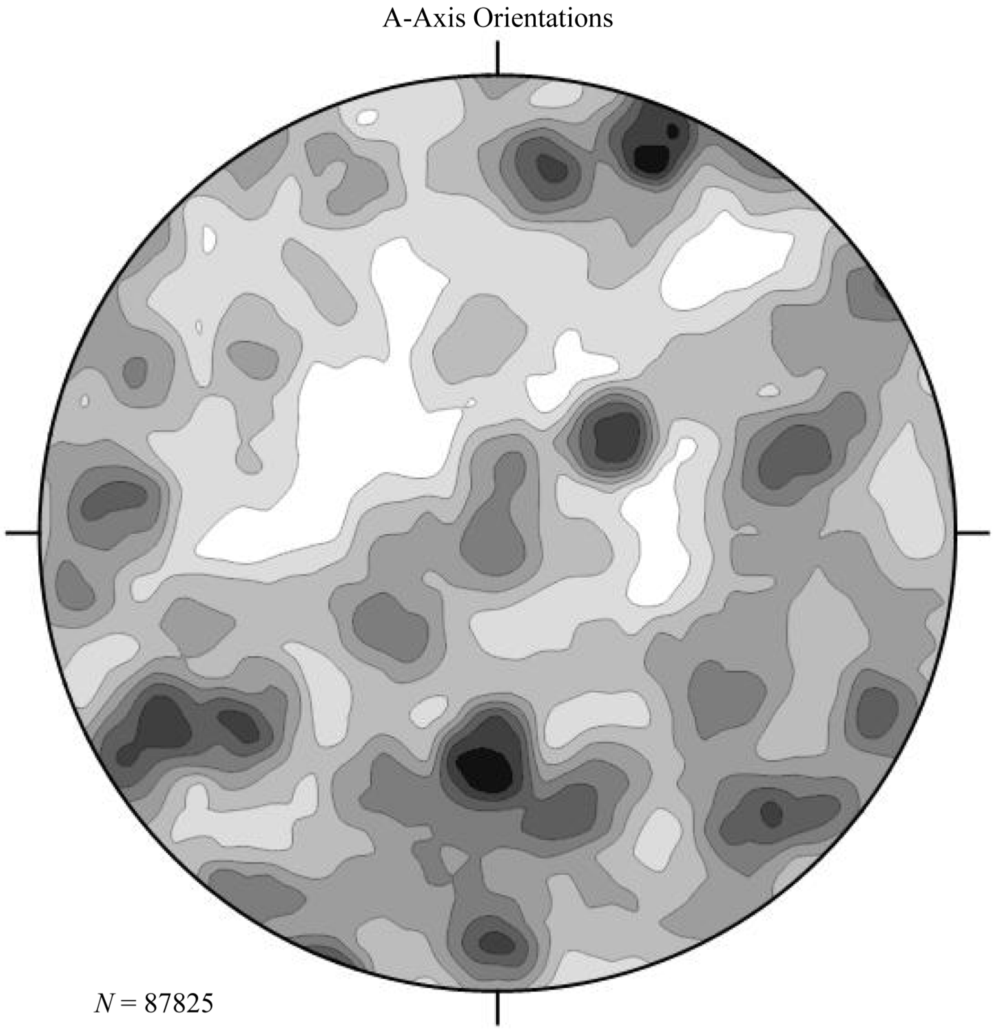
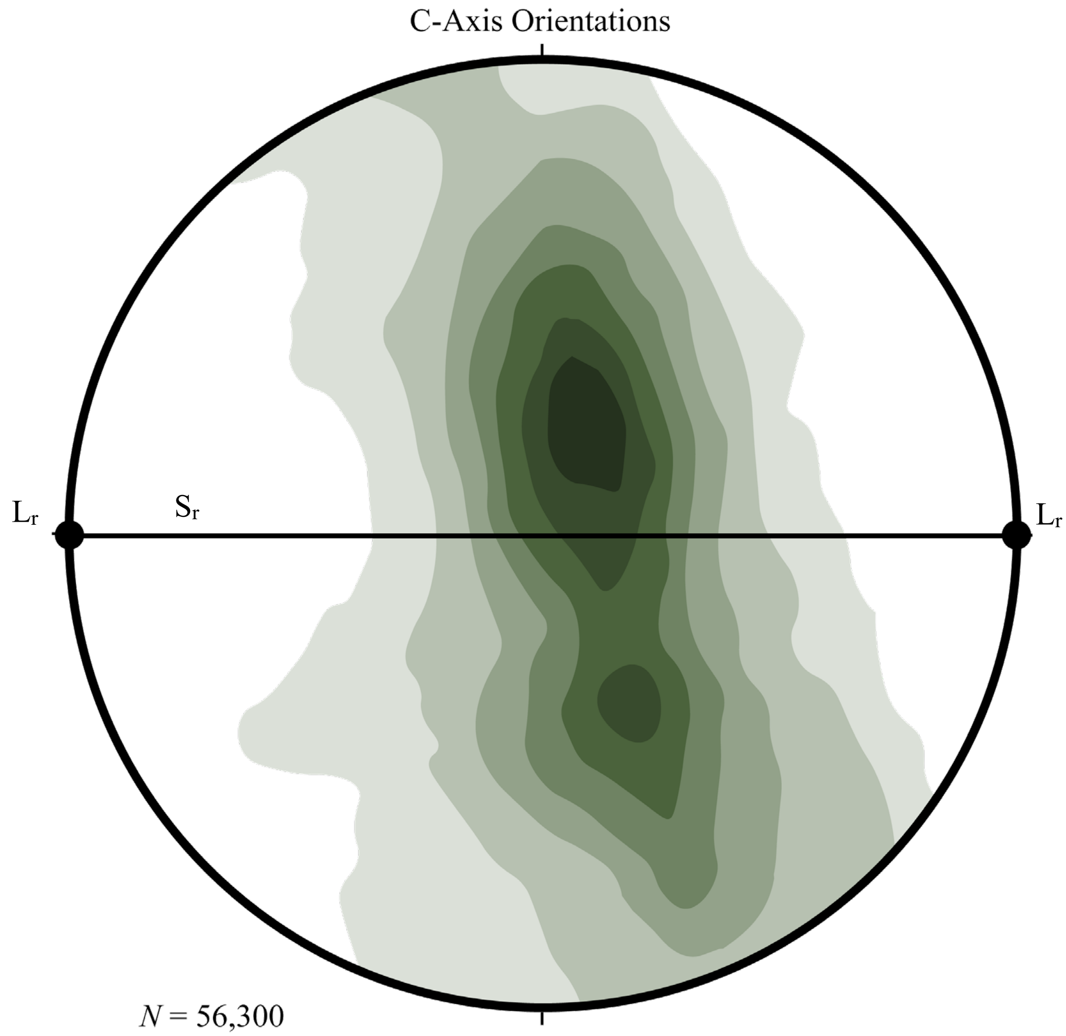


Figure 31. Equal area projection of A-axis orientations from the sample of Mount Lytton Complex.



N = 56,300

Contour Interval = 0.312%
Contour Values: 0.639%, 0.950%, 1.26%, 1.57%, 1.89%, 2.20%, 2.51%

Figure 32. Equal area projection of C-axis orientations from a Fallslake Plutonic Suite mylonite. Note that the girdle is inclined to foliation. S_r=foliation, L_r=lineation.

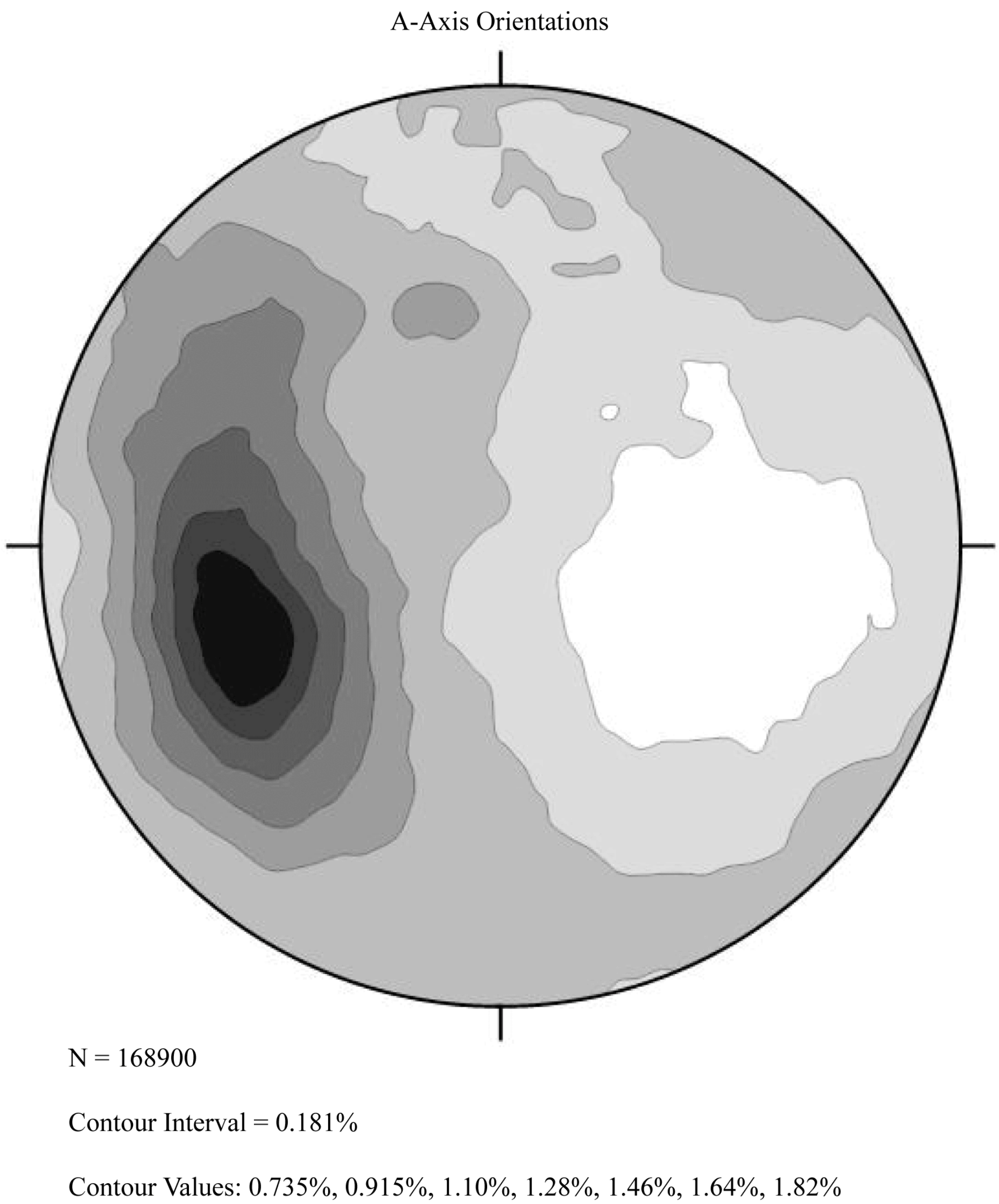


Figure 33. Contoured pole diagram of A-axis orientations from a Fallslake Plutonic Suite mylonite. Note the single maximum of "A" axes.

DISCUSSION

Controversy over the Baja BC hypothesis is a prominent issue in the tectonics of western North America. In southern British Columbia, the large dextral offset required by the Baja BC hypothesis is postulated to have occurred within ~40 km of the Pasayten fault (e.g., Cowan, 1997). However, previous researchers have not found evidence for dextral motion on this fault (Lawrence, 1978; Greig, 1992; Hurlow, 1993). Below, the motion of the Pasayten fault is discussed to evaluate potential large-scale transport. Other major nearby structures, including the Eagle shear zone and Similkameen Falls fault, are also considered, particularly their timing and kinematics relative to the Pasayten fault. Other topics discussed to a lesser extent are the emplacement depth of the Eagle tonalite, the distribution of pluton ages adjacent to the Pasayten fault, the southern Canadian Cordillera transect, the zircon signature of Eocene clastic rocks, and the Baja BC hypothesis.

Constraints on Motion of the Pasayten Fault

In the study area, direct evidence for motion of the Pasayten fault consists of mylonites from the Zoa Complex and the Fallslake Plutonic Suite. Mylonites of the Zoa Complex were observed in an 8-10-m-wide, NNW-striking and moderately NE-dipping zone next to the Pasayten fault (Plate 1). Two samples from this zone with gently SSE plunging lineations indicate sinistral shear with a minor east-side-up reverse component across the fault. Greig (1992) also reported sinistral motion from mylonitic rocks of the Zoa Complex north of the study area, but did not report lineation orientation. Information on the timing of motion recorded by the Zoa Complex mylonites is limited.

The mylonites are juxtaposed against mylonitic rocks of the Fallslake Plutonic Suite across the Pasayten fault in the study area, and the foliation strike in both units is subparallel near the fault. Quartz microstructures in the Zoa Complex indicate relatively low (~300-500 ˚C) deformation temperatures, which are similar to those in the Fallslake Plutonic Suite. Thus, mylonites of the Zoa Complex and Fallslake Plutonic Suite may be coeval.

The Fallslake mylonites occur in a ~300-m-wide, NW-striking zone parallel to the Pasayten fault and grade into weakly deformed rocks ~600 m to the NE. In this zone, foliation consistently strikes NW and dips steeply SW and NE. Lineation varies from down-dip to nearly horizontal. Lineations in mylonites closest to the fault plunge obliquely SE with rakes of 24˚ to 37˚. Quartz microstructures indicate low- to medium-temperature deformation compatible with regime 2 of Hirth and Tullis (1992). Kinematic indicators in two samples record sinistral shear with a west-side-down normal component across the Pasayten fault. The EBSD analysis of quartz in a Fallslake mylonite indicates a similar sense of shear. Thus, sinistral-normal motion postdates crystallization of the Fallslake Plutonic Suite at ~110 Ma (Figure 34).

The consistent, nearly straight, ≥ 250-km-long map trace of the Pasayten fault has been interpreted to reflect a steep or subvertical subsurface geometry (Lawrence, 1978; Monger, 1989; Greig, 1992; Hurlow, 1993). Mylonites of the Zoa Complex dip considerably less steeply (moderately NE) near the Pasayten fault, and thus are likely unrelated to the most recent episode of fault motion (Plate 1). In contrast, mylonites of the Fallslake Plutonic Suite dip steeply SW and approach subvertical within ~100 m of

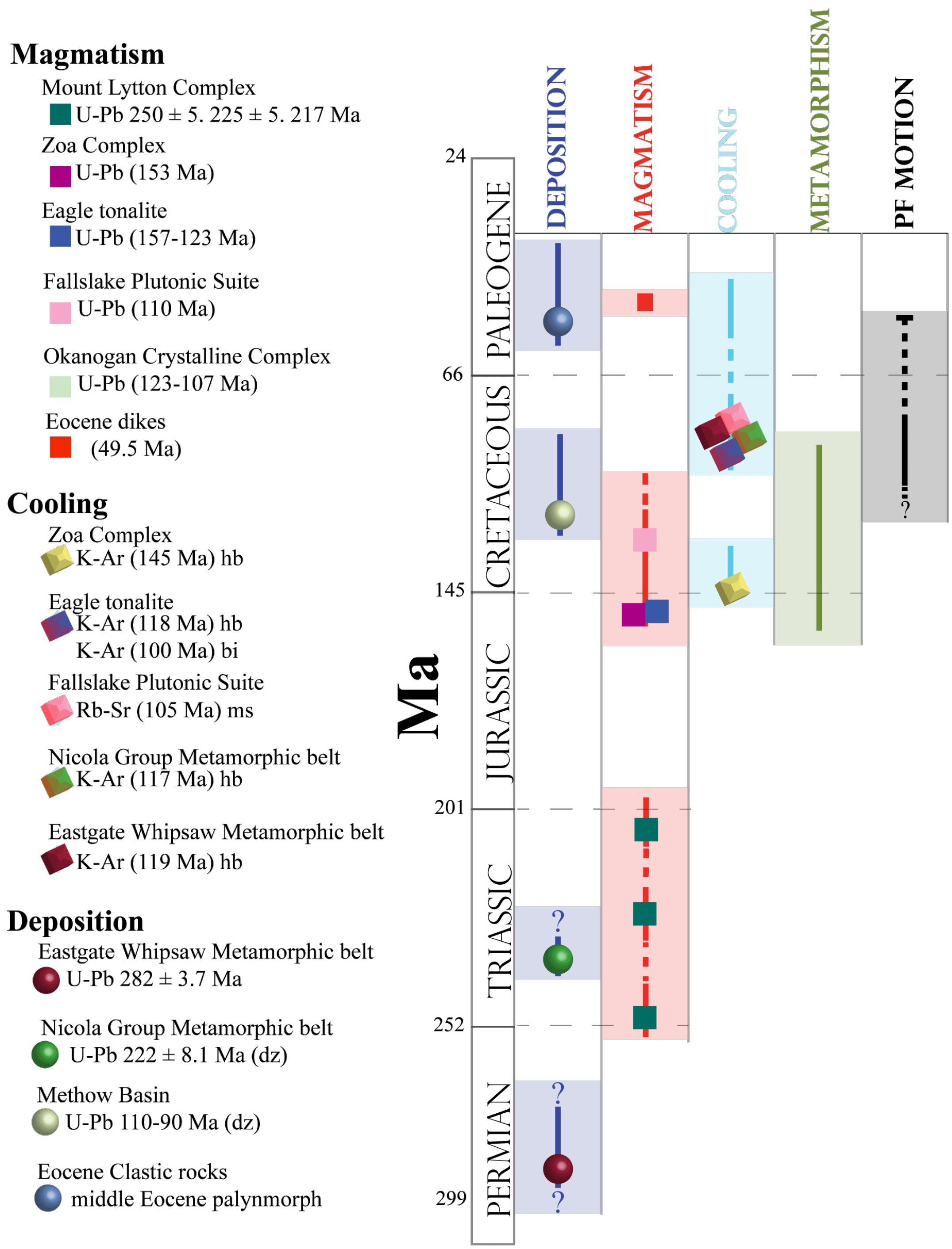


Figure 34. Summary of ages of magmatism, deposition, cooling, metamorphism, and Pasayten fault motion. Modified from Friedman and van der Heyden (1992), Greig et al. (1992), Hurlow (1993), Parrish and Monger (1992), DeGraaff-Surpless et al. (2003), Oliver (2008), and Mihalynuk and Friedman, written communication. bt=biotite, dz=detrital zircon, hb=hornblende, ms=muscovite, PF=Pasayten fault.

the fault (Plate 1), and thus are the clearest record of fault motion. Chronologic results (Figure 34) from Greig et al. (1992) imply that mylonitization of the Fallslake Plutonic Suite is tightly bracketed between the crystallization age of 110±5 Ma and the muscovite Rb-Sr cooling age of 104±4 Ma (Greig et al., 1992) (Figure 341). Given the ~350˚ C closure temperature of muscovite (Dodson, 1973), this date is interpreted to signal the end of sinistral-normal ductile shear of the Fallslake Plutonic Suite (Figure 34).

The dips of mylonitic foliation and plunges of lineation, in the Fallslake Plutonic Suite change along strike. Approximately ~30 km NNW of the study area, moderately east-dipping mylonites resembling the Fallslake Plutonic Suite are reported (Price and Monger, 2003; R.B. Miller, written communication). Price and Monger (2003) interpreted these rocks to record reverse slip. If these mylonites are coeval with those in the study area the presence of both reverse and strike slip on the Pasayten fault at ~110-105 Ma indicates that the fault zone may be transpressional. The normal component of shear in the study area, however, is not compatible with this interpretation.

The long axis of the Eagle tonalite in map view and the consistent NW-striking foliations in the tonalite are parallel to the mylonitic foliation in the Fallslake Plutonic Suite. Greig (1992) postulated that the proximity of the Pasayten fault to the tonalite suggests that foliation in the Eagle tonalite developed during intrusion. Similar scenarios have been published for the highly elongate Okanogan Range batholith, which is on-strike with the Eagle Plutonic Complex (Hurlow, 1993). Hurlow (1993) reasoned that solid-state fabrics in ~117-107 Ma tonalitic rocks of the Okanogan Range batholith and those reported in the Eagle Plutonic Complex likely developed during emplacement, which was accommodated by extension along the fault. Given the >40 Ma age range of these intrusions, a protracted period of motion on the Pasayten fault is implied by these interpretations. However, in the study area the Eagle tonalite is not mylonitic and no direct evidence links motion of the fault with the emplacement of the Eagle tonalite. Instead, during an unknown time after the ~157-123 Ma crystallization of the tonalite, solid-state fabrics may have formed due to NE-SW regional contraction.

In the study area, the Virginian Ridge Formation of the Methow basin is juxtaposed against mylonites of the Fallslake Plutonic Suite across the Pasayten fault. Mudstones and sandstones of the Virginian Ridge Formation are more silicic and resistant within ~100 m of the fault, but are not recrystallized. This arrangement implies a period of brittle motion that postdates mylonitization of the Fallslake Plutonic Suite and probably a component of west-side-down slip.

The single (~53 Ma) date from a detrital zircon in the Eocene clastic rocks suggests that brittle slip continued until that time. Several NE-striking, ~49.5 Ma hornblende porphyry dikes and NE-striking faults that cut the Pasayten fault in the study area and elsewhere provide an upper bracket for brittle motion (Figure 34; Plate 1) (e.g., Monger, 1989; Greig et al., 1992). Approximately 30 km south of the international border, the ~48 Ma (U-Pb, fission track zircon) Island Mountain Group overlaps the fault (White, 1986). Thus, brittle shear on the Pasayten fault in the study area could have occurred anytime from ~105 Ma, the cooling age of the Fallslake Plutonic Suite, to ~49.5 Ma.

High Strain Rocks Next to the Eastern Margin of the Eagle Plutonic Complex

The Eagle Plutonic Complex is bound on the east by a continuous 1- to 2-km-wide, contact-parallel zone of highly strained rocks belonging to the Nicola Group and EWm belt (Plate 1). Greig et al. (1992) named these rocks the Eagle shear zone. Next to the highly strained metamorphic rocks in an ~200-m-wide belt the foliation in the Eagle tonalite is locally deformed into close cuspate and lobate folds with wavelengths of 10-50 cm, and the tonalite hosts meter-scale rafts of the Nicola Group and EWm belt. Both the highly strained rocks of the Nicola Group and EWm belt, and the marginal Eagle tonalite are intruded by stocks of weakly foliated, muscovite-bearing granodiorite resembling the Fallslake Plutonic Suite.

Formation of the high strain zone has been attributed to east-vergent reverse shear during intrusion of the Eagle tonalite into the Nicola Group (Monger, 1985; Greig, 1992). This interpretation is based on local kinematic indicators and down-dip lineations in the Nicola Group, and the westward increase in foliation intensity and metamorphic grade toward the tonalite in the Nicola Group and EWm belt (Greig, 1992). Dextral shear has also been reported in the Nicola Group (Greig, 1992), but has been correlated with intrusion of the Triassic Tulameen Ultramafic Complex (Nixon and Rublee, 1988). Greig (1992) also suggested that the dominant SW-dipping foliation in the high strain zone near the Tulameen Ultramafic Complex may have developed during intrusion of the Complex (Figure 35). Given that foliations in the high strain zone are consistent for > 40 km north and south of the Tulameen Ultramafic Complex it is unlikely that intrusion of the

Complex played a large role in the development of this zone. The available evidence associates formation of the high strain zone with the emplacement of the Eagle tonalite.

A model for the high strain zone that incorporates emplacement of the Eagle tonalite would best account for the consistent spatial relationship of deformation between the Eagle tonalite and its host rocks. During emplacement, heat from the Eagle tonalite presumably weakened rocks of the Nicola Group and EWm belt, which allowed strain to accumulate near the tonalite. The Eagle tonalite near the margin does not show an increase in solid state deformation, but in the zone of rafts the tonalite is deformed into cuspate lobate folds and local top-to-NE shear zones may be associated with the high strain zone. Thus, the high strain zone likely extends ~200 m into the Eagle tonalite and includes rafts of the Nicola Group and EWm belt. The parallelism of the SW-dipping foliation in the high strain zone and eastern margin of the Eagle Plutonic Complex also supports coeval deformation.

Oliver (2008) evaluated the potential relationship between the intrusion of the Eagle Plutonic Complex and the metamorphic gradient in the highly strained rocks of the EWm belt by modeling heat flow from intrusion of the Eagle tonalite. Her model assumed that the tonalite was instantaneously emplaced along a steeply dipping contact, an assumption which is not compatible with the range of U-Pb ages from the Complex (Figure 34). She concluded that heat from the Eagle Plutonic Complex is suitable for the observed metamorphic conditions in the westernmost 2 km of the EWm belt, but is insufficient for metamorphic temperatures in the easternmost 3 km of the belt (Oliver, 2008).

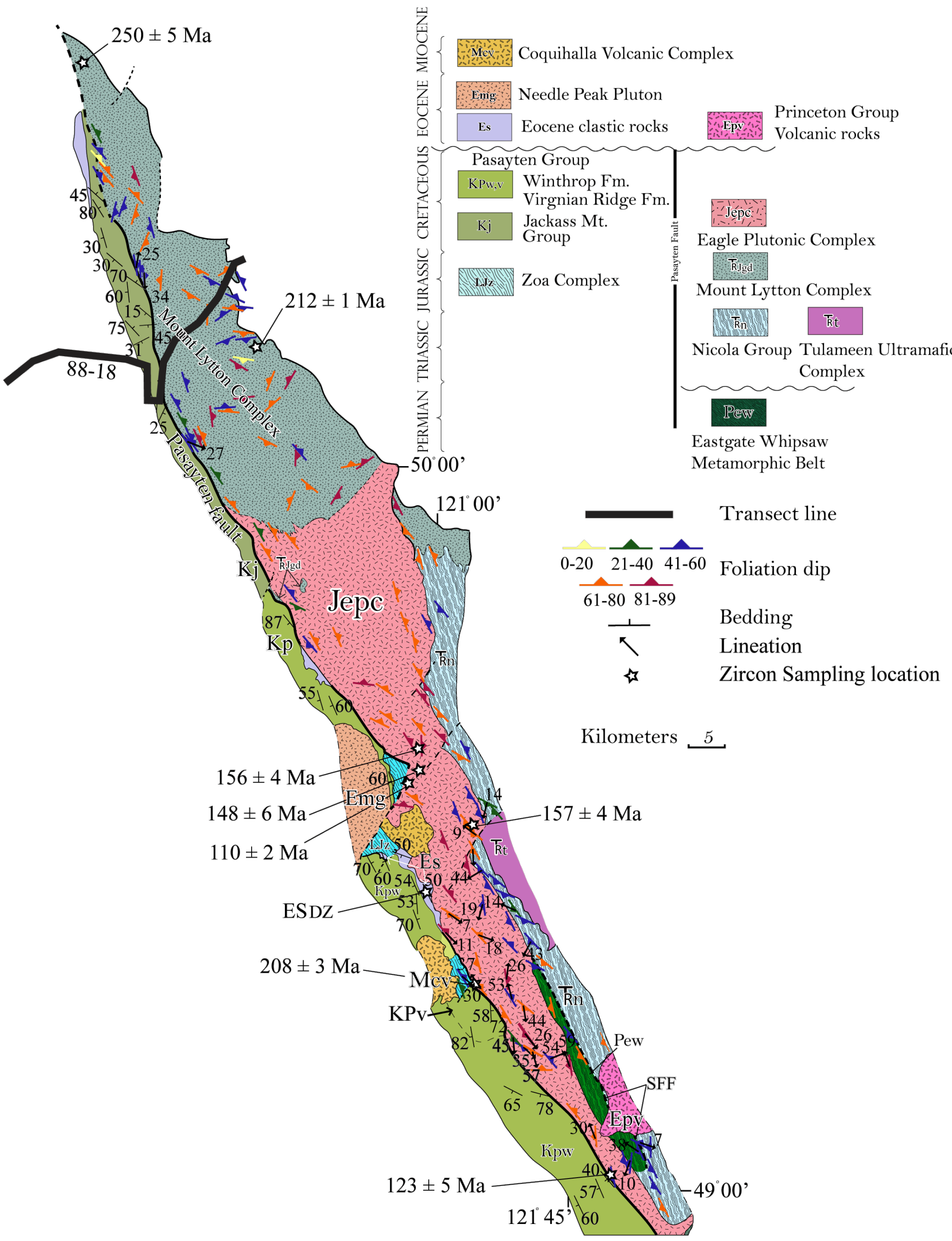


Figure 35. Caption on next page.

Figure 35. Schematic geologic map of the Pasayten fault zone. Note the location of the southern Canadian Cordillera Lithoprobe transect line 88-18 and zircon age locations from the Mount Lytton Complex, Eagle Plutonic Complex, and Eocene clastic rocks. Modified from Monger (1989), Monger and McMillan (1989), Friedman and van der Heyden (1992), Parrish and Monger (1992), and Oliver (2008). Lineations are from this study and R.B. Miller, unpublished data. ESDZ=zircon sampling location of Eocene clastic rocks.

If the high strain zone formed due to intrusion of the Eagle tonalite, as discussed by Oliver (2008), then the timing of deformation can be refined to the crystallization ages (157-123 Ma) of the tonalite (Figure 32) (Greig et al., 1992). The crystallization ages are from tonalites ~3 to 1 km from the host rocks (Figure 35), and since the crystallization ages span ~30 Ma it is unlikely that the eastern margin of the Eagle Plutonic Complex, or as noted by Oliver (2008) its host rocks, would retain heat this long. Given these issues, the timing of deformation in the high strain zone would benefit from additional geochronology. Moreover, formation of the high strain zone by 123 Ma in this model predates the oldest (110-105 Ma) documented ductile motion on the Pasayten fault. So, if these interpretations are valid then the high strain zone and the Pasayten fault are probably not directly related.

Sparse kinematic indicators and dominant flattening fabrics in the high strain zone make it difficult to determine the non-coaxial component of strain. Lineations measured in this zone plunge moderately to shallowly NW and SE, and thus are compatible with strike slip or oblique motion. The gentle lineation orientations and sparse kinematic indicators in the EWm belt and Nicola Group may result from partitioned transpression with a major pure shear component. In the Eagle tonalite, outcrop-scale shear zones that dip SW, verge NE, and are in the high strain zone indicate reverse motion. If these shear zones are representative of the SW-dipping (average 62˚) high strain zone in the host rocks, then this implies that the Eagle Plutonic Complex was displaced over the Nicola Group and the EWm belt. This interpretation applies to at least a ~75-km-long SW-dipping segment of the zone (Figure 35). Monger (1985) and Greig et al. (1991) speculated that a Late Jurassic thrust belt near Ashcroft ~180 km along strike to the NNW may be part of the same contractional belt.

Similkameen Falls Fault

The Similkameen Falls fault was proposed by Massey et al. (2008) as a structure separating the EWm belt from the southern end of the Nicola Group metamorphic belt on the basis of Permian zircon U-Pb dates from metavolcanic rocks of the EWm belt, which contrast with the Triassic age of the Nicola Group (Figure 2). However, no direct evidence for a fault between the Nicola Group and the EWm belt, such as mylonites or cataclasites, has been recognized in the study area. Motion was also inferred from temperature constraints determined by Oliver (2008), which indicate increased metamorphic temperatures in the western and eastern parts relative to the central part of the EWm belt. The lack of a suitable heat source for the eastern part of the belt is explained by dextral transport of the EWm belt along the Similkameen Falls fault an unknown distance to its present location according to Oliver, (2008). Oliver (2008) proposed the Okanogan Range batholith as a possible heat source for the eastern part of the belt, but evidence that the EWm belt was against the batholith has not been recognized.

The northern termination of the Similkameen Falls fault at the eastern contact of Eagle tonalite suggests that the fault is pre ~123 Ma, or potentially pre ~157 Ma (Figs. 34 and 35), depending on the local age of the tonalite. These age constraints are incompatible with the ~123 to 107 Ma Okanogan Range batholith as a heat source. Alternatively, the Similkameen Falls fault could be interpreted to merge with the ca ≥ 118 Ma rocks of the high strain zone, but this arrangement does not significantly change the minimum age. Furthermore, the Similkameen Falls fault probably predates the earliest known ductile episode of the Pasayten fault and so it is unlikely they are closely related.

The contact between the EWm belt and the Nicola Group may alternatively be an unconformity overprinted by ductile deformation. An unconformity is compatible with the ages and lack of evidence for faulting. Given the oblique strike of the Similkameen Falls fault relative to other nearby structures and truncation of individual members of the EWm belt this is a more likely scenario in my view.

Implications of the Southern Canadian Cordillera Lithoprobe Transect

From a geophysical transect across the Pasayten fault zone ~80 km northwest of the study area the fault zone was inferred to consist of two listric, east-dipping splays (Varsek et al., 1993; Bustin et al., 2013) (Figure 35). Varsek et al. (1993) and Bustin et al. (2013) state that dextral and reverse motion occurred on these structures during the mid-Cretaceous on the basis of magnetic lineaments. Dextral motion is problematic as this study and previous workers have only found evidence for sinistral motion in the mid-Cretaceous (e.g., Lawrence, 1978; Greig, 1992; Hurlow, 1993). In the area of the transect, foliations in the Mount Lytton Complex dip 40˚ to 55˚ NE (Monger, 1989) (Figure 35), and are interpreted to steepen at depth (Varsek et al., 1993; Bustin et al., 2013).

In the study area, mylonitic foliations in the Fallslake Plutonic Suite dip 75˚ to 85˚ SW in a zone that extends ~200 m from the Pasayten fault (Plate 1). Lineations in this zone plunge obliquely, 45˚ to 11˚ S-SSE (Figure 35; Plate 1). The different foliation orientations in the Lithoprobe transect and study area, and the combination of strike slip and reverse slip along different segments, may indicate that the fault zone is transpressional. Moreover, transpression commonly results in flattening fabrics which is compatible with this fault zone in the study area where lineations are weakly developed. The normal shear component in the study area is problematic.

The eastern fault splay is situated near the eastern margin of the Mount Lytton Complex. Foliations near this splay dip moderately to steeply SW and NE, which given the limited data probably provides little evidence of the subsurface geometry (Figure 35) (Monger, 1989; Varsek et al., 1993). The eastern margin of the Eagle Plutonic Complex dips SW and so is not compatible with the geophysical interpretation (Plate 1). A satisfactory resolution clearly requires additional study of the Mount Lytton Complex.

Emplacement Depth of the Eagle Tonalite

The Eagle tonalite contains epidote with textures that match criteria presented by Zen and Hammarstrom (1984) for magmatic crystallization, which occurs at a minimum of 5-

6 kbar. Greig (1992) interpreted the epidote as magmatic, but discounted deep emplacement of the tonalite due to the lack of medium- to high-pressure metamorphic assemblages in host rocks of the Nicola Group. He instead favored partial crystallization of the Eagle tonalite and growth of epidote at depth followed by ascent to shallower crustal levels. More recently, Oliver (2008) analyzed plagioclase and amphibole compositions to determine metamorphic conditions across the EWm belt. She compared these compositions with the results of Laird and Albee (1981) and concluded that the EWm belt plots in their experimentally derived, medium-pressure zone. Some of the compositions corresponded to pressures of 4-9 kbars (Laird and Albee, 1981), and therefore, metamorphism may have reached pressures suitable for crystallization of magmatic epidote in the Eagle tonalite. Thus, crystallization of the Eagle tonalite at depths of ≥15 km is reasonable and the two-stage model of Greig (1992) is not needed.

Primary magmatic epidote has not been recognized in the Triassic Mount Lytton Complex (Friedman and van der Heyden, 1992; Parrish and Monger, 1992) to the north or in the Okonagan Range batholith (Hurlow et al., 1993) to the south. The absence of magmatic epidote in the Fallslake Plutonic Suite of the study area may indicate that the Eagle tonalite was partially exhumed before intrusion of the Suite. This interpretation is compatible with the K-Ar cooling ages (Figure 34). Alternatively, this may reflect the composition of the Fallslake rocks.

The unconformity between the Spences Bridge Group and the Eagle Plutonic Complex indicates that the Complex was at the surface by ~104 Ma (Thorkelson and

Rouse, 1989). Crystallization of the Complex at ~157 Ma to 123 Ma thus implies an ~20 Ma time span to ascend from ≥15 km to the surface.

Age Distribution of Plutons Adjacent to the Pasayten Fault

Compilation of zircon U-Pb ages from plutons cut by the Pasayten fault shows a general decrease in age by at least 100 Ma from NW to SE (Figs. 2 and 34). The oldest ages are from the Mount Lytton Complex, from which Friedman and van der Heyden (1992) determined a U-Pb zircon age of 250±5 Ma, and Parrish and Monger (1992) reported a U-Pb zircon age of 212±1 Ma (Figs. 2 and 35). The youngest ages in the belt come from the southern end of the Okanogan Range batholith in northern Washington ~250 km to the SE, where Hurlow (1993) reported a zircon U-Pb age of 107±1.1 (Figs. 2 and 35).

In this study, zircons from a screen of medium-grained weakly foliated tonalite enclosed within the Eagle tonalite yielded a U-Pb age of 207±8 Ma (Plate 1). This screen is similar in age to the Mount Lytton Complex, ~100 km to the NW, and to Triassic inclusions near the Complex (Monger, 1989) (Figure 35). Thus, the Mount Lytton Complex may be part of a belt of Triassic plutons that extended a distance of more than 100 km to the SE of its present distribution and was largely obliterated during the intrusion of the Eagle Plutonic Complex.

Eocene Clastic Rocks

The distinctive dark-red Eocene clastic rocks exposed west of the Pasayten fault yielded predominantly Jurassic to Cretaceous detrital zircon U-Pb ages with peaks at circa 93, 130, and 150 Ma, and a smaller number of Triassic grains (Figure 36). One zircon yielded an Eocene age of 53±1 Ma that is compatible with the middle Eocene epositional age derived from a palynmorph collected in the unit (Figure 2) (Greig et al., 1992).

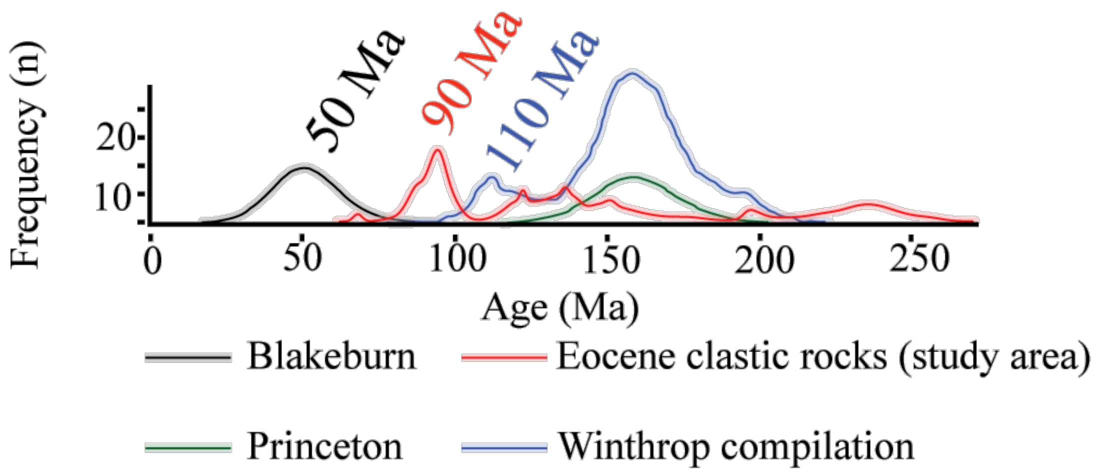


Figure 36. Zircon distributions from Eocene clastic rocks in the study area, nearby Eocene basins, and the Winthrop Formation. Data from DeGraaff-Surpless et al. (2003), Rubino (2018), and this study.

The sediments in the study area may be coeval with those deposited in other Eocene basins within the Intermontane belt east of the Pasayten fault (Figure 37). Rubino (2018) analyzed several thousand zircons from these basins. Zircons from an ~30 km^2 isolated basin of Eocene sedimentary rocks near Blakeburn and the Princeton basin are the closest to the study area (Figure 37). Eocene rocks sampled near Blakeburn (Figs. 36 and 37) yielded only Eocene ages, which is attributed to nearby Eocene intrusive and volcanic rocks of the Princeton Group (Rubino, 2018). The sediments near Princeton contain primarily Jurassic through Cretaceous zircons with a peak at ~160 Ma (Figs. 36 and 37) (Rubino, 2018). The strong Jurassic-Cretaceous signal matches broadly with the results of this study (Figure 36), although the peaks are different. Rare Eocene zircons in the

Princeton sample and single Eocene zircon in my study is unusual as regionally most of the Eocene basins contain abundant Eocene zircons derived from local sources (Rubino, 2018). All three basins lack Precambrian zircons indicating the basins were cut off from older material to the east and south, and that recycled Precambrian zircons were not in the source region.

The dated body of Eocene clastic rocks in this study is in contact with the Winthrop Formation of the Pasayten Group to the west (Monger, 1989). Thus, given the lack of a strong Eocene peak it is useful to evaluate the validity of the palynmorph age and to compare the detrital zircon age signatures of each body to evaluate whether the "Eocene clastic rocks" are a part of the Pasayten Group. DeGraaff-Surpless et al. (2003) analyzed several hundred zircons from a ~600 m section of the Winthrop Formation ~30 km southeast of the study area in Manning Park. The bulk of zircons from the Manning Park strata yield ages from the Early Cretaceous to the Late Triassic (DeGraaff-Surpless et al., 2003). Eocene clastic rocks in the study area also contain zircons of this age range, but the age peaks (Figure 36) do not match and the strong circa 93 Ma peak in the Eocene rocks is younger than the depositional age of the Winthrop Formation. The Midnight Peak Formation of the Methow basin may have accumulated at ca. 90 Ma, but no nearby exposures have been recognized, and zircons are sparse or absent in samples of intermediate volcanic rocks in the Formation (Shea et al., 2016; R.B. Miller, written communication). Plutons of approximately this age occur in the North Cascades >60 km to the SE and west of the Fraser fault (e.g., Brown et al., 2000), but have not been recognized locally or east of the Pasayten fault.

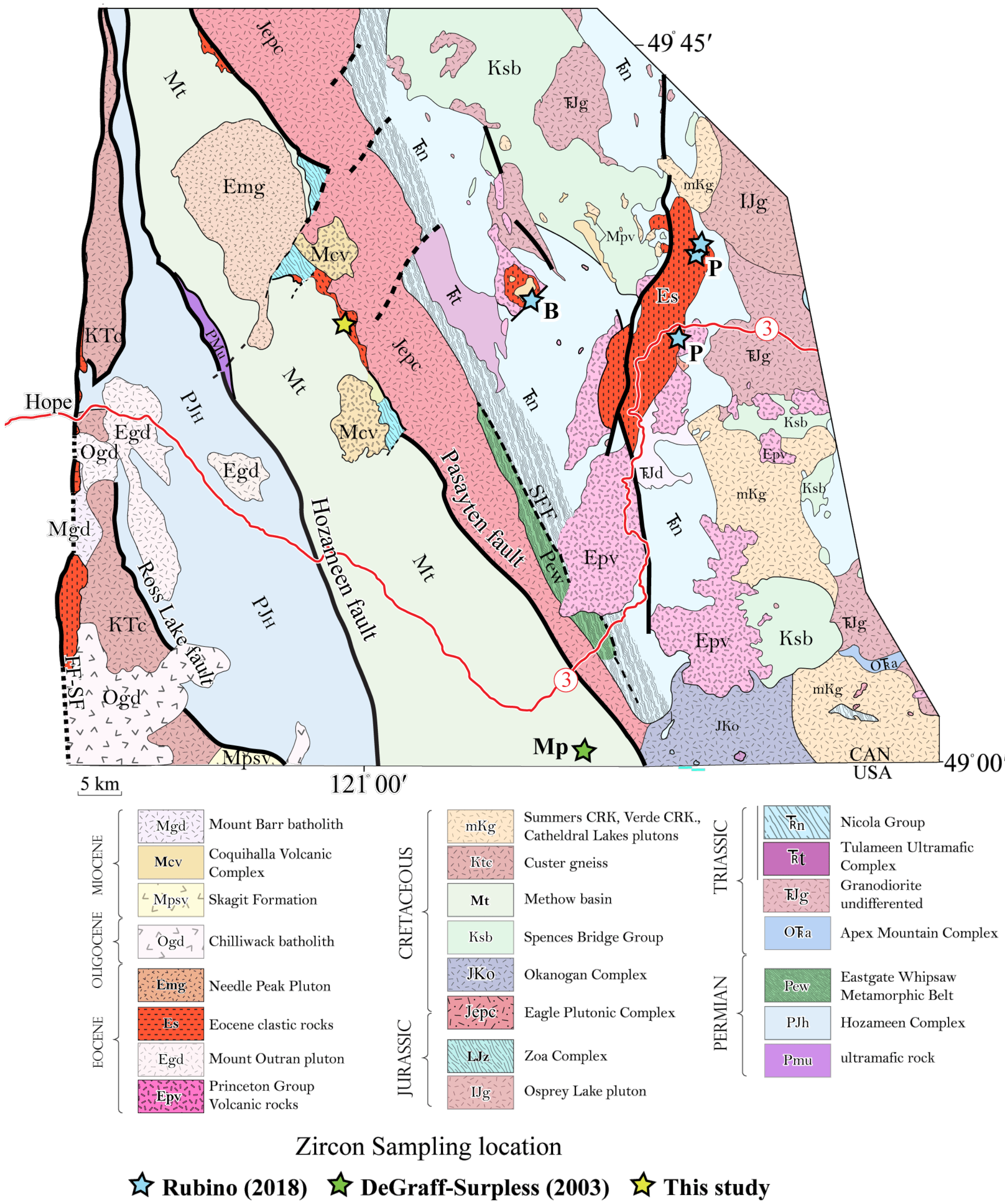


Figure 37. Caption on next page

Figure 37. Map of dated Eocene basins in south-central British Columbia near the study area. Location of closest dated Winthrop Formation is also shown. Modified from Monger (1989), DeGraff-Surpless et al. (2003) and Rubino (2018). Location of Similkameen Falls fault from Massey et al. 2008. B=Blakeburn, FF-SF=Fraser-Straight Creek fault, SFF=Similkameen falls fault, Mp=Manning Park, P=Princeton.

Mapping by Greig (1992) shows that the belt of Eocene clastic rocks, including the dated sample, is in depositional contact with the Zoa Complex to the east (Figure 35), and locally the Eocene clastic rocks are separated from the Fallslake Plutonic Suite by the Pasayten fault (Greig, 1992). Zircons in the Zoa Complex are ~150 Ma, which matches one of the smaller peaks from the Eocene clastic rocks. Rocks of approximately this age also occur in the Eagle Plutonic Complex (Greig et al., 1992) (Figs. 2, and 37). Thus, the Zoa Complex and/or the Eagle Plutonic Complex may be an additional source for the Eocene strata. If they are solely derived the Zoa Complex, then the Eocene clastic rocks may have been cutoff from the Eagle Plutonic Complex by the Zoa rocks. Plutonic clasts were observed in the Eocene clastic rocks, but magmatic epidote was not identified in them, and makes it uncertain whether they are derived from the Eagle Plutonic Complex. Otherwise the range (~157-123 Ma) of zircon ages in the Eagle tonalite make it a likely source.

Overall, source areas for zircons in the Eocene clastic rocks of this study are not well constrained. The main peak at ~90 Ma has not been recognized in nearby units, and the closest reasonable source is ~40 km west of the Fraser River (Brown et al., 2000). Moreover, logical nearby sources in the Fallslake Plutonic Suite are 110 Ma (e.g., Greig et al., 1992), an age which is missing in the Eocene clastic rocks. Eocene basins east of the Eagle Plutonic Complex have a peak at 160 Ma (Rubino, 2018) and the Methow basin has one at 110 Ma (DeGraaff-Surpless et al., 2003). One possibility is that an eastward flowing stream network operated in the Eocene that was separate from the Methow basin and largely cutoff from material to the east in the Eagle Plutonic Complex.

Rubino (2018) interpreted the age distributions of detrital zircons in Eocene strata throughout the region to indicate deposition in local isolated basins. Given the elongate geometry of the Eocene strata and the eastern fault contact, deposition of the rocks in this study may also have been fault-controlled. However, the lack of nearby sources for the basin of this study is not supportive of this interpretation.

Implication of Pasayten Fault Movement History for the Baja BC Hypothesis and Strike-Slip in the Northern Cordillera

The Baja BC hypothesis requires that a large amount of dextral slip occurred between ~90 Ma and 50 Ma near the Pasayten fault. However, evidence from this study suggests sinistral and normal ductile shear between 110 Ma and 104 Ma (Figure 34). Any subsequent dextral motion along the fault would have been brittle. Brittle shear occurred sometime after 104 Ma, but the slip was likely SW-side down normal shear; thus no direct field evidence for dextral slip was found in this study nor reported by Greig et al. (1992) or Hurlow (1993) along strike to the NW and SE, respectively.

The sinistral motion on the Pasayten fault also supports the hypothesis that in the Early Cretaceous the northern Cordillera was marked by left-lateral strike slip (e.g., Monger et al., 1994; Umhoefer et al., 1996; 2002). Regionally, sinistral motion in the Cordillera occurred from ~155 Ma (Monger et al., 1994) to 105 Ma and thus, the

Pasayten fault records some of the youngest documented sinistral slip in southern British Columbia and Washington.

CONCLUSIONS

1. Mylonites from the Fallslake Plutonic Suite record low- to medium-temperature sinistral and normal ductile shear across the Pasayten fault in the study area. One EBSD analysis from a mylonite in the Fallslake Plutonic Suite is compatible with this motion.
2. Mylonitization occurred between the ~110 Ma U-Pb, zircon and ~104 Ma Rb-Sr muscovite ages for the Fallslake Plutonic Suite.
3. Deformation in host rocks of the Eagle tonalite was likely facilitated by thermal weakening during emplacement. Thermal weakening caused strain to accumulate in the host rocks, and gentle lineations and sparse kinematics therein suggest partitioned transpression with a major pure shear component.
4. Primary magmatic epidote in the Eagle tonalite probably indicates that the Eagle tonalite crystallized at ≥15 km.
5. The change in recorded motion along the Pasayten fault from sinistral with a normal component in the study area, to reverse along strike to the NW, and the decrease in foliation dips to the NW in the Eagle Plutonic Complex and Mount Lytton Complex may suggest transpression.
6. The U-Pb age of 207.9±2.1 determined from an inclusion in the Eagle Plutonic Complex implies that Triassic rocks extend ~100 km SE of the main body of the Triassic Mount Lytton Complex.
7. Detrital zircon results from the Eocene clastic rocks do not definitively constrain the age of the unit, but are clearly different than those from the adjacent Methow

basin. The closest source for the main peak of ~90 Ma in the Eocene clastic rocks is ~40 km to the west.

8. The Pasayten fault records some of the youngest documented sinistral motion in the northern Cordillera, but this ductile shear predates the large dextral motion required by the Baja BC hypothesis.

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