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Structure, Construction, and Geochemistry of the Cretaceous Seven-Fingered-Jack Intrusive Complex in the Klone Peak Area, North Cascades, Washington

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STRUCTURE, CONSTRUCTION, AND GEOCHEMISTRY OF THE CRETACEOUS
SEVEN-FINGERED-JACK INTRUSIVE COMPLEX IN THE KLONE PEAK AREA,
NORTH CASCADES, WASHINGTON

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfilment

of the Requirements for the Degree

Master of Science

By

Kelly N. Dustin

December 2015

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The Designated Thesis Committee Approves the Thesis Titled

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December 2015

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ABSTRACT

STRUCTURE, CONSTRUCTION, AND GEOCHEMISTRY OF THE CRETACEOUS SEVEN-FINGERED-JACK INTRUSIVE COMPLEX IN THE KLONE PEAK AREA, NORTH CASCADES, WASHINGTON

By Kelly N. Dustin

The highly elongate Seven-Fingered-Jack intrusive complex (SFJIC) of the North Cascades, Washington provides an excellent opportunity to study the construction, geochemistry, and structure of a well-exposed mid-crustal pluton. The interior ~92 Ma Main Body tonalite has markedly heterogeneous and mafic domains that may represent interactions between multiple batches of melt. The ~78 Ma marginal Kelly Mountain suite includes a mafic complex containing abundant hornblende, diorites of variable heterogeneity, and tonalite. Field mapping and structural, petrographic, and geochemical analyses are interpreted to indicate that this intrusive complex was built incrementally by many batches of melt. The dominantly NW-striking and NE-dipping magmatic foliation is overprinted by weak solid-state fabrics. The magmatic foliation is folded in both units and has N-NW hinge lines. These time-transgressive folds are consistent with regional contraction during and shortly after emplacement. Modal analysis by point-counting indicates that the dominant mafic mineral switches from biotite in the older tonalite to hornblende in the younger tonalite. This modal analysis coupled with XRF and ICP-MS geochemical analyses shows that although similar, the younger and older tonalites plot distinctly enough to indicate that they may be derived from different magma sources. Geochemical data also indicates that the Main Body tonalite likely has a shallower magma source than the coeval, but structurally deeper Tenpeak pluton.

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Plate 1. Geologic map of the study area

INTRODUCTION

Pluton construction and emplacement are significant factors in understanding how plutons work as a system at any depth. It was previously thought that plutons were constructed by the diapiric rise of one large magma body, whereas many recent studies have concluded that plutons are commonly constructed by an amalgamation of numerous increments of magma (Miller and Paterson, 2001a; Michel et. al., 2008; Miller, 2008; Schaltegger et. al., 2009; Rocchi et. al., 2010; Tappa et. al., 2011; Davis et. al., 2012; Leuthold et. al., 2012; Stearns and Bartley, 2014). In their review, Paterson et al. (2011) proposed that arc plutons are built from magma fluxes as the result of two end-member processes and a gamut of intermediate possibilities. The first end member suggests that a pluton was built by a surge, a single, connected, closed system of magma that froze during ascent. The second end member suggests that plutons are frozen parts of a complex system that is interconnected and evolves over time. This end member is an open system that reactivates, remobilizes, and reuses materials from older pulses to incrementally construct plutons.

It is increasingly apparent that open systems play a large role in the construction of plutonic complexes, but there are few detailed studies available for comparison (e.g.; Miller, 2008; Miller et al., 2009; Paterson et al., 2011; Leuthold et. al., 2012). Studying these exhumed systems at varying crustal levels can answer questions about how a complex system interconnects and operates. A key aspect to understanding an open system is explained by Bergantz (2000). He noted that reintrusion of magma into a magma chamber can have one of three outcomes. If the chamber has not sufficiently

solidified before reintrusion, extensive mixing between the resident and intruding magma may leave no evidence of multiple pulses. If the chamber has partially solidified, there may be an intervening zone of magma mixing between the resident magma and the intruding magma. Lastly, if sufficient solidification has occurred, there will be a sharp boundary between the new increment and the resident material.

To evaluate models of pluton evolution, studies must be done on how plutons are interconnected at a variety of depths and how the complex plumbing systems of which they are a part are constructed. By studying exhumed magma plumbing systems, we may find evidence of incremental assembly of individual plutons. Examining these plutons and their individual pulses may provide insight into how melt interacts as a pluton or complex is constructed. This evidence, in combination with geochemical and geochronological studies, provides insights into magma ascent, emplacement, sizes of individual injections, and the interactions between different batches of magma.

Several orogenic belts, including the Caledonides, Lachlans, Hercynides, and Coast Plutonic Complex, are made up of highly elongate, internally sheeted intrusive complexes that have been built incrementally (e.g., Pitcher and Berger, 1972; Hutton, 1992; Ingram and Hutton, 1994; Miller and Paterson, 2001a). Within the southern-most part of the Coast Plutonic Complex lies the crystalline core of the North Cascades (Cascades Core) (Fig. 1). The Cascades core consists of plutonic and metamorphic rocks of mostly amphibolite facies (Misch, 1966). It includes many mid-to-Late Cretaceous, ~96-78 Ma plutons (e.g., Miller et al., 2009), and contains a well-exposed crustal section revealing a magmatic system extending from ~5-30 km paleodepth (Fig. 2). This study

Figure 1. Map showing Mesozoic and Cenozoic Cordilleran arc plutons (black). Inset box is the location of the North Cascades, showing Cretaceous rocks that are cut by high-angle Paleogene faults. Teal designates metamorphic rocks and orange designates plutonic rocks. Abbreviations are as follows: RLF=Ross Lake fault zone; SCF=Strait Creek fault; NWCS=Northwest Cascades thrust system; CBTS=Coast Belt thrust system; ECFB=Eastern Cascades fold belt. Modified from Paterson and Miller (1998b).

Figure 2. Geologic map emphasizing the Cascades core. Plutons are shown in orange with approximate ages. BC—Buck Creek Pass pluton; BP—Beckler Peak stock; BR—Bearcat Ridge orthogneiss; CH—Chaval pluton; CS—Chiwaukum Schist; CZ—Cenozoic undifferentiated (mid-Eocene to Quaternary); DF—Dirtyface pluton; HP—High Pass pluton; MC—Marble Creek pluton; NQ—Napeequa unit; RP—Riddle Peaks pluton; RRC—Railroad Creek pluton; SC—Sloan Creek plutons; SM—Sulphur Mountain pluton; SZ—shear zone; TF—Tonga Formation; WPT—Windy Pass thrust; WRG—Wenatchee Ridge Gneiss. Modified from Miller et al. (2009).

focuses on the structure and construction of one of these Cretaceous plutons, the highly elongate, mid-crustal (~6-8 kbar), Seven-Fingered-Jack intrusive complex (SFJIC) (Figs. 2 and 3). This complex was constructed at ~92-90 Ma and 79-78 Ma (Matzel, 2004; Shea, 2014).

Field studies in and near the SFJIC indicate that Cretaceous plutons of varying depths have complex histories of incremental construction. Miller et al. (2009) proposed that during regional shortening, magma rose through the crustal column using a series of interconnected channels. Before complete solidification, these magma bodies were interpreted to have been commonly reactivated by new batches of magma, largely injected as sheets (Paterson and Miller, 1998a; Miller and Paterson, 2001a; Paterson et al., 2011). To better comprehend how sheets ascend, Paterson and Miller (1998a) conducted a detailed study of sheet tips in the SFJIC. They found that magma ascended parallel to axial planes of regional folds and perpendicular to the direction of regional shortening. The proposed ascent mechanism was as visco-elastic diapirs that may have started off as magma fingers, driven upward by an interface instability (e.g., viscosity, density) between the magmas and the surrounding host rock. These fingers then propagated outward into sheets due to the regional contraction and large scale of magma production at this time. In this interpretation, sheets in the SFJIC may have been the advancing front of the magmatic system, not the root of a magma chamber. Due to regional contraction while the SFJIC and other coeval plutons were being emplaced, foliations typically strike NW and dip steeply to the NE (Cater, 1982; Miller and Paterson, 2001a, b; Elkins, 2015).

Figure 3. Geologic map emphasizing the Seven-Fingered-Jack intrusive complex and surrounding rocks. Tcp=Cloudy Pass pluton; Tdh=Duncan Hill pluton. Modified from Miller and Paterson (2001a).

These interpretations need to be tested through more detailed studies of the SFJIC. In particular, such research will help to address the following questions about construction and emplacement of the SFJIC and coeval plutons: What are the geometries of different magmatic bodies that make up the SFJIC? What is the nature of contacts between these bodies? Within the bodies, are internal contacts present; if so, how widespread are they, and how sharp are the contacts? Do contact orientations support construction by sheets and/or more irregularly shaped bodies? Are foliations and lineations magmatic, solid state, or both? What do orientations of these fabrics reveal about emplacement processes and local versus regional deformation? What are the implications of field relationships, combined with U-Pb zircon geochronology done by colleagues, for the timing of emplacement and order of increments of the SFJIC? What does whole rock geochemistry reveal about the different rock units? Do the geochemical compositions provide insight to the sources of the magmas?

Geologic Setting

The North Cascades crystalline core (Cascades core) is the southeastern-most part of the >1500-km-long Coast Plutonic Complex (Fig. 1). The Cascades core underwent regional shortening and crustal thickening during the final accretion of terranes in the mid-Cretaceous. This accretion was associated with amphibolite-facies metamorphism (e.g., McGroder, 1991; Whitney et al., 1999) and arc-related plutonism. The plutonism continued after shortening, and persisted from ~96-45 Ma (Tabor et al., 1989).

The Cascades core, as defined by Misch (1966), consists of pre-Tertiary and Paleogene crystalline rocks bounded by faults (Fig. 1). To the west is the right-lateral, Eocene Straight Creek fault, which separates the Cascades core from low-grade oceanic and arc rocks of the NW Cascades thrust system (Misch 1966). To the northeast, the Cascades core is separated from weakly metamorphosed Jurassic-Cretaceous strata of the Methow basin by the largely dextral, Paleogene Ross Lake fault zone (Misch, 1966; Miller and Bowring, 1990). To the south, the Cascades core is structurally overlain by the Jurassic Ingalls Ophiolite Complex across the mid-Cretaceous Windy Pass thrust (Miller, 1985). The crystalline core is divided by the Tertiary Entiat fault into the southwestern Wenatchee block and the northeastern Chelan block (Tabor et al., 1989) (Figs. 1 and 2). These blocks record different thermal histories. K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages within the Wenatchee block indicate that metamorphism, ductile deformation, and cooling occurred largely before ~80 Ma (Tabor et al., 1989; Miller and Paterson, 1992; Matzel, 2004), whereas magmatism and ductile deformation in the Chelan block continued until ~45 Ma (Tabor et al., 1989).

The Chelan block is comprised of amphibolite-facies rocks of the Swakane and Chelan Mountains tectonostratigraphic terranes (Tabor et al., 1987a, b), which are intruded by a number of ~92-46 Ma, highly elongate plutons in a 20-25-km-wide zone (Fig. 2). These plutons are built at least in part of centimeter-to kilometer-wide sheets (Cater and Crowder, 1967; Cater and Wright, 1967; Tabor et al., 1987a; Dawes, 1993; Paterson and Miller, 1998a; Miller and Paterson, 2001a; Matzel, 2004; Paterson et al., 2011). Two of these plutons, the Seven-Fingered-Jack intrusive complex (SFJIC) and

younger Entiat pluton, form a continuous belt that is ~80 km long and 8 km wide (Figs. 2 and 3) (Cater and Crowder, 1967; Cater and Wright, 1967; Tabor et al., 1987a; Dawes, 1993; Matzel, 2004). The SFJIC intruded at ~92-90 Ma and 79-78 Ma, whereas the Entiat pluton intruded at ~73-71 Ma (Matzel, 2004; Shea, 2014). The SFJIC is ~50 km long and 7 km wide, and consists of steep cm-to km-thick sheets (Paterson and Miller, 1998a; Miller and Paterson, 2001a).

Host rocks to the SFJIC include the Napeequa complex to the southwest and the Triassic Dumbell Mountain plutons and Holden assemblage to the northeast (Figs. 2 and 3) (Cater and Crowder, 1967; Cater and Wright, 1967; Miller et al., 1994). The undated Napeequa complex is a metamorphosed oceanic unit consisting mostly of quartz-rich mica schist, amphibolite, and quartzite (Cater, 1982; Tabor et al., 1989; Brown and Dragovich, 2003). It is physically similar to the Mississippian-Jurassic Bridge River complex (Cater, 1982; Tabor et al., 1989; Brown and Dragovich, 2003). The Triassic Dumbell Mountain pluton has been subdivided into three units (Cater and Crowder, 1967; Cater and Wright, 1967). The largest unit, a gneissic hornblende-quartz diorite, is intruded by the SFJIC. Although they look similar, the Dumbell rocks have a stronger solid-state fabric than the SFJIC (Cater, 1982). The Holden assemblage is an arc sequence that consists of hornblende gneiss, hornblende-biotite schist, leucogneiss, and amphibolite (Tabor et al., 1989; Miller et al., 1994).

The SFJIC is locally intruded by Tertiary plutons (Fig. 3). In the northwest, it is intruded by biotite granodiorite of the Larch Lakes pluton, biotite-quartz monzonite of the Rampart Mountain pluton (Cater 1982), and labradorite granodiorite and granogabbro

of the Cloudy Pass pluton (Cater and Crowder, 1967; Cater and Wright, 1967). To the southeast, the SFJIC is intruded by the granodiorite of the Eocene Duncan Hill pluton (Cater, 1982).

To better understand the original relative structural depths of major tectonostratigraphic units and Cretaceous plutons, such as the SFJIC, Miller and Paterson (2001b) and Miller et al. (2009) reconstructed a Cretaceous crustal column, utilizing cross sections and thermobarometric data on plutons and metamorphic rocks (Fig. 4). This crustal section shows the position of the SFJIC relative to the coeval, deeper Tenpeak pluton and a shallower large intrusion, which are addressed in the discussion.

Seven-Fingered-Jack Intrusive Complex

Our understanding of the SFJIC has evolved due to continued field work and increased precision in radiometric dating techniques. The following section briefly reviews the literature on the SFJIC and how the complex is defined for this study. The northwestern part of the SFJIC was mapped by Cater and Crowder (1967) and Cater and Wright (1967) at a scale of 1:62,500 (Seven-fingered Jack pluton on their map). They noted that the SFJIC, and what they called the Entiat pluton in their area, were separate bodies, and divided them based on rock types and modal abundances. Tabor et al. (1987a) mapped a much larger area at a scale of 1:100,000, and interpreted the intrusions Wright (1967) at a scale of 1:62,500 (Seven-fingered Jack pluton on their map). They noted that the SFJIC, and what they called the Entiat pluton in their area, were separate bodies, and divided them based on rock types and modal abundances. Tabor et al.

Figure 4. Schematic Cascades crustal section indicating the approximate location of the Seven-Fingered-Jack intrusive complex (SFJIC) and related coeval plutons. Numbers on the right indicate P-T conditions, °C and kbar, respectively. BPP=Black Peak pluton; TP=Tenpeak pluton. Vertical dashed lines are representative of major faults. Modified from Miller et al. (2009).

(1987a) mapped a much larger area at a scale of 1:100,000, and interpreted the intrusions as a single body, which they referred to as the Entiat pluton. Matzel (2004) used high precision U-Pb zircon geochronology to show that the northwestern rocks of the SFJIC are significantly older than the Entiat pluton; as a result, she drew an approximate NW-trending contact between these rocks (Fig. 3). Shea (2014) subdivided the SFJIC based on composition and geochronology. For my study, the older interior tonalite will be referred to as the Main Body tonalite, whereas the eastern marginal rocks will be referred to as the younger Kelly Mountain suite (Fig. 3).

Cater and Crowder (1967) and Cater and Wright (1967) mapped the northwestern part of the SFJIC as quartz diorite gneiss, quartz diorite, diorite and gabbro, and a contact complex. The area was subdivided into a number of ~1- to 3.5-km-wide bodies containing internal m- to 100s of m-wide sheets (Cater and Wright, 1967; Paterson and Miller, 1998a; Miller and Paterson, 2001a). The southeastern part was mapped as almost entirely tonalite (Tabor et al., 1987a). In contrast, Dustin's (2012) work indicates that the eastern margin of the SFJIC is heterogeneous in the south, and consists of tonalite, diorite, and a mafic complex that includes abundant hornblendite (Fig. 5). Map-scale (1:10,000) units range from 50 m to >1.8 km in width, and some are made up of numerous thinner sheets and irregularly shaped bodies recording the incremental construction of this part of the pluton (Fig. 5).

Initial U/Pb zircon geochronology on the Seven-Fingered-Jack intrusive complex using thermal ionization mass spectrometry (TIMS) on tonalite from the NW tip and pluton interior yielded inferred crystallization ages of ~91 Ma, whereas mafic rocks in the

Figure 5. Geologic map and cross section of Dustin (2012) in the Klong Peak area. Red dashes in the cross section represent dips of foliations. UTM's are in zone 10, NAD27. Note preliminary U-Pb zircon dates from personal communications with Shea (2014).

NE margin gave ages of ~78 Ma (Fig. 6) (Matzel, 2004). More recent U/Pb zircon geochronology using isotopic dilution thermal ionization mass spectrometry (ID-TIMS) and chemical abrasion determined ages of ~92 Ma from tonalite in the interior of the intrusive complex and ~78 Ma from tonalite and mafic rocks in the NE margin (Fig. 6) (Shea, 2014).

Methods

Geological mapping (1:10,000) and collection of structural data were completed during the summers of 2012 and 2013 in the south-central part of the SFJIC (Klone Peak area) (Fig. 7). Mapping and field characterization focused on different rock types and their contacts, as well as the abundance of internal contacts and the sharpness of these contacts. Orientations and relative intensities of foliations and lineations were determined, and a magmatic or solid-state origin was inferred. Other structures (e.g., sheets, schlieren, xenoliths, and enclaves) were noted and measured where applicable.

Forty-one samples were made into thin sections. Petrographic analysis emphasizing mineral modal abundances, textures, and fabric type (magmatic vs solid state) and strength was carried out on each section. Point counting of 22 samples from the ~92 and 78 Ma tonalite bodies was done to evaluate the homogeneity of these units. A mechanical stage was set with 2-mm spacing between each transect and 1-mm spacing between each mineral count. Each sample had a mineral count of ≥ 350 grains.

Six samples were sent to Washington State University for analyses by X-ray fluorescence spectrometry (XRF) and Inductively Coupled Plasma Mass Spectrometry

Figure 6. Geologic map of Seven-Fingered-Jack intrusive complex and Entiat pluton. Dots mark geochronology sample localities (dates and sample numbers given) of Matzel (2004) and Shea (2014). Asterisk indicates sample dated by Shea (2014). Black ellipse represents study area. Tcp=Cloudy Pass pluton; Tdh=Duncan Hill pluton. Modified from Miller and Paterson (2001a) and Matzel (2004).

Figure 7. Geologic map of the study area emphasizing rock types and locations. Mapping done at 1:10,000. See Plate 1 for more detailed version.

(ICP-MS). Major and trace elements, including rare earth elements (REE), were analyzed. Two of the samples are from the marginal mafic units: one from the mafic complex (a diorite) (KD 13); and one from the heterogeneous diorite (BPX 145-A). The other four samples are tonalites. Three of the tonalites, KD 59, KD 53, and BPX 154-A, are from the ~92 Ma tonalite, and the other sample (BPX 137-1) is from the marginal, ~78 Ma tonalite. These analyses enabled characterization of the compositions of “typical” tonalites and mafic complex rocks in the area. They also allowed for a comparison of the ~92 Ma and 78 Ma tonalites. Data were interpreted to evaluate sources of the ~92 Ma and 78 Ma magmas, and to compare these sources with those of other roughly coeval plutons in the region, such as the deeper Tenpeak pluton.

ROCK UNITS

The Seven-Fingered-Jack intrusive complex (SFJIC) intrudes the Dumbell orthogneiss on the east in the study area (Fig 7). The contact between the orthogneiss and the intrusive complex trends NW, as do almost all contacts in the study area. The intrusive complex is divided into the older Main Body tonalite; and the younger Kelly Mountain suite (Fig. 7). The Kelly Mountain suite is comprised of a variety of rock types: hornblende-biotite tonalite; quartz diorite; diorite; heterogeneous diorite; and a hornblende-rich mafic complex.

Dumbell Orthogneiss

The Dumbell orthogneiss has a Triassic crystallization age (Mattinson, 1972; Matzel, 2004). In the study area, a ~700-m-wide belt of the biotite-hornblende and hornblende-biotite tonalitic orthogneiss was mapped next to the SFJIC (Fig. 7). This unit ranges from medium- to coarse-grained and has a variable color index, but is usually ~35-40% mafic minerals. The Dumbell orthogneiss displays a strong foliation in most outcrops, and local small shear zones deflect the foliation. Mafic and felsic dikes occur locally.

The Dumbell orthogneiss contains plagioclase, quartz, hornblende, and biotite as the principal minerals. Foliation is defined by a strong alignment of large plagioclase and hornblende, small biotite, and small recrystallized quartz. Sphene and epidote form both accessory and secondary phases, whereas chlorite is only secondary.

Plagioclase is elongate to blocky and varies from subhedral to anhedral. Growth and deformation twins are widespread. Solid-state deformation is indicated by kinked and/or broken grains, deformation twins, and smaller, commonly recrystallized, plagioclase grains in mosaics. Hornblende is elongate and subhedral, and is riddled with inclusions of anhedral quartz, plagioclase, and secondary epidote. Biotite is anhedral and mostly occurs as small grains that are partially replaced by chlorite. A few grains of biotite are bent. Quartz is fine grained and anhedral, commonly forms mosaics in elongate aggregates, and records bulging and subgrain-rotation recrystallization. These elongate aggregates define a solid-state foliation that is parallel to subparallel to the magmatic foliation, which is defined by hornblende and biotite. The inferred magmatic

epidote is euhedral against biotite and hornblende, and is in “wormy” intergrowths with quartz and plagioclase. Secondary epidote is irregularly shaped, filling interstices of other minerals. Euhedral sphene is inferred to be magmatic, whereas the anhedral sphene is inferred to be secondary.

Seven-Fingered-Jack Intrusive Complex (~92-78 Ma)

Dating of the Seven-Fingered-Jack intrusive complex indicates that the complex was constructed over ~14 Myr (Matzel, 2004; Shea, 2014) (Fig. 6). It is unknown whether the magma input was continuous or in discrete intervals. South of the study area, Matzel (2004) obtained a date of ~81 Ma and Shea (2014) determined dates of ~88 Ma and ~86 Ma. Currently, dating within the study area indicates only the ~92-91 Ma ~79-78 Ma pulses (Shea, 2014). For simplicity and the purposes of this study, these units are referred to as the ~92 Ma rocks and the ~78 Ma rocks.

Main Body Biotite-Hornblende Tonalite (~92 Ma)

The Main Body biotite-hornblende tonalite is >2500 m in width, and extends to the western boundary of the research area (Fig. 7). It is medium- to coarse-grained with isolated zones (cm-m in scale) of fine-grained material. Color index ranges from 25-40. Magmatic foliation and lineation are moderate to strong, and are best defined by hornblende and biotite. The magmatic foliation is locally overprinted by moderately strong solid-state foliation marked by elongated quartz and quartz aggregates.

The tonalite displays numerous types of magmatic features. Abundant mafic enclaves vary in size and aspect ratio. Very elongate enclaves (17 cm x 5 cm to 28 cm x 2 cm) were only seen in the most heterogeneous areas. Local felsic enclaves are present. Enclaves vary from coarse-grained to very fine-grained and commonly have plagioclase phenocrysts. Mafic dikes range in width from 8 cm to 2 m, and some dikes enclose xenoliths of the host tonalite. Less common felsic dikes range in width from ~1 cm to > 3 m. Centimeter-scale magmatic ductile shear zones, marked by an intensification and minor curvature of magmatic foliation, are found locally. Felsic sheets alternate locally with the host tonalite. Sheets are 9-48 cm in width, whereas the intervening zones of host tonalite are 7 cm-1 m in width. Although the Main Body tonalite is relatively homogeneous, it has distinct domains that are either markedly more heterogeneous or more mafic in composition than the dominant tonalite.

Two heterogeneous domains have been recognized, one in the north and one in the southwest (Fig. 8). The northern domain has a minimum width and length of 275 m and 325 m, respectively, and the southwestern domain has a minimum width of 150 m and is laterally continuous for at least 350 m. These domains are marked by concentrations of enclaves, hornblendite xenoliths, schlieren, mafic dikes, concordant felsic sheets, and magmatic shear zones. Enclaves range from 13 cm x 9 cm to 60 cm x 12 cm, and some are stretched out with intense internal foliation and become schistose (Fig. 9A). Enclaves have a wide variety of compositions, textures, and other features, such as mafic or felsic rinds. Foliated hornblendite xenoliths are concentrated in clusters of >25 xenoliths. The xenoliths range from 1 cm x 0.5 cm to $\geq$ 60 cm by 28 cm, and they

Figure 8. Geologic map emphasizing the heterogeneous and mafic domains within the Main Body tonalite. Red domains are heterogeneous and green ones are more mafic than the dominant tonalite.

Figure 9. Photographs of the heterogeneous domains in the Main Body tonalite. A) Foliated hornblendite xenolith with melt intruding into fractures that are oblique to xenolith foliation. B) Diorite and gabbro dikes with felsic rinds. C) Felsic sheets with diffuse boundaries. Red lines indicate approximate boundaries between sheets.

tend to be tabular. Localized schlieren are marked by the accumulation of hornblende and biotite. Widespread discordant dikes range in width from the centimeter to meter scale (Fig. 9B). The dikes in the heterogeneous domains are similar to those in the dominant Main Body tonalite, as many enclose tonalite xenoliths. Numerous felsic sheets with diffuse boundaries are commonly ~5 cm in width, but are as wide as ~30 cm and strike northwest (Fig. 9C).

The domains of mafic tonalite are only found in the south and are marked by a higher color index (Fig. 8). They range from 10 s to ~100 m in width and are up to ~600 m in length. This tonalite has a color index of ~40 and contains distinctive hornblendes that reach up to 3 cm in length. One outcrop has alternating felsic (color index = 5) and mafic (color index = 35-40) tonalite sheets. Sheets vary in width, and the thickest one is a 70-cm-thick felsic sheet. These sheets strike NE, which is perpendicular to magmatic foliation and typical sheet orientations. Although the tonalite is more mafic in these domains, the heterogeneities tend to be more felsic. Felsic patches, xenoliths, and veinlets are widespread. Schlieren are more localized. The sheets in this area are interpreted to represent different tonalite bodies.

The Main Body tonalite consist of plagioclase (~30-46%), quartz (~ 30-41%), biotite (~0-20%), hornblende (~1-20%), and accessory (epidote, sphene) and secondary minerals (epidote, sphene, calcite, chlorite). Myrmekitic texture, saussuritization, and seritization, range from absent to pervasive.

Plagioclase within the tonalite is ~0.25-5 mm in length and averages ~1.5 mm. Plagioclase grains are commonly elongate or blocky, and vary from subhedral to

anhedral. Oscillatory zoning is uncommon. Solid-state deformation is indicated by minor recrystallization, kinked and broken grains, and common deformation twins. Saussuritization is marked by epidote within plagioclase.

Quartz ranges from ~0.12-2 mm, and has an average length of ~0.6 mm. Grains are anhedral. Strain is indicated by bulging, subgrain-rotation recrystallization, and less common grain-boundary-migration recrystallization. Elongated mosaics are common, and solid-state foliation is parallel or sub-parallel to magmatic foliation. Two thin sections from samples collected in the central area only had interstitial quartz, and showed minimal strain.

Biotite grains are usually elongate to blocky and anhedral, and are locally fan shaped. Grains are ~0.25-4 mm in length, and average ~0.75 mm. The grains typically occur in clusters. Some biotites are kinked and chlorite alteration at grain edges is widespread.

Hornblende typically forms subhedral to anhedral, elongate to blocky grains. The grains are ~0.5-5 mm in length, and average ~2 mm. Simple twinning is common and many grains have inclusions of plagioclase and quartz. The hornblende is locally replaced by epidote. Chlorite alteration along grain margins is common.

Epidote and sphene form both as accessory and secondary minerals, and chlorite and calcite are secondary. Magmatic epidote is euhedral against biotite and commonly equant. The magmatic epidote is ~0.3-1 mm in diameter. Secondary epidote is anhedral and ranges from ~0.12-1.5 mm in length. Magmatic sphene is euhedral to subhedral and ~0.3-2 mm in length. Secondary sphene is anhedral and grains range are ~0.12-1.5 mm

in length. Chlorite is present at the margins of some biotite and hornblende grains. Calcite is common.

Kelly Mountain Suite (~78 Ma)

Mafic Complex

The hornblende-rich mafic complex was mapped as four distinct bodies within the study area (Fig. 7). These elongate bodies range from ~175-400 m in width and consist of medium- to coarse-grained hornblende enclosed in gabbro and diorite (Fig. 10A). The diorite and gabbro interfinger and mingle with each other. A weak magmatic fabric is defined best by hornblende and plagioclase. Hornblendites are 0.5-30 cm long and occur as xenoliths, irregularly shaped patches, pods, enclaves, and “stringers”. Most hornblendites range from 2-8 cm in width by 5-20 cm in length, although enclaves are up to 20 cm by 30 cm (Dustin, 2012). Rarely, magmatic foliations are deflected around the hornblendites. Widespread felsic dikes are 1-50-cm thick, whereas less common mafic dikes are 20 cm-1.5 m thick. Within the mafic complex, diorite of various grain sizes and gabbro are seen as xenoliths, patches, pods, and enclaves. Gneissic bands are also present (Fig. 10B). The patches, pods, and enclaves are widespread and are 1-5 cm wide and 3-40 cm long. Intrusive breccias consist of mainly coarse-grained diorite fragments in a very fine-grained gabbro matrix; rarely, gabbro fragments are seen in a diorite matrix (Fig. 10C).

The diorite of the mafic complex consists of plagioclase (~55%), hornblende (~35%), quartz (~5%), biotite (~5%), and accessory (sphene) and secondary minerals

Figure 10. Photographs of the Kelly Mountain mafic complex. A) Typical outcrop including diorite, gabbro, and hornblendite. B) Gneissic banding within diorite, cut by a magmatic fault (red line). C) Intrusive breccia, note the felsic rind on the mafic xenoliths. D) Diorite with highly variable grain size including hornblende grains up to 3 cm long.

(epidote, sphene, chlorite) (<1%). Weak solid-state deformation is restricted to kinked and broken grains, and local deformation twins (plagioclase). Plagioclase is <0.5- 2 mm in length and averages ~1 mm. The plagioclase is commonly blocky and varies from subhedral to anhedral. Minor saussuritization is marked by epidote within plagioclase. Hornblende forms subhedral to anhedral, elongate to blocky grains that range in length from ~0.5 mm to 3 cm, and average ~2 mm (Fig. 10D). Simple twinning is common and many grains have inclusions of plagioclase and quartz. The hornblende is locally replaced by epidote. Anhedral quartz ranges from ~0.12-2 mm, and has an average length of ~1 mm. There is minor bulging and subgrain-rotation recrystallization, and recrystallized grains are typically ≤ 0.5 mm in diameter. Biotite grains are elongate to blocky and anhedral. Grains are <0.5-2 mm in length, and average ~0.75 mm. Sphene forms as an accessory and secondary mineral; epidote and chlorite are secondary. Magmatic sphene is inferred when at least part of the grain retains its euhedral shape, whereas secondary sphene is anhedral. All sphene is ≤ 0.5 mm in diameter. Epidote is anhedral and ≤ 0.5 mm in diameter. Chlorite replaces the margins of some biotite and hornblende grains.

Heterogeneous Diorite

The heterogeneous diorite is mapped as four separate bodies: two in the southeast; one in the southwest; and one in the north (Fig. 7). In the southeast, the two highly elongate bodies range from 50 m to 140 m in width. The highly elongate southwestern body is up to 650 m wide in the south, whereas in the north it is ~250 m wide. The

northern body is at least 600 m wide, and its eastern and western contacts have not been mapped.

This unit is typically medium- to coarse-grained, but very fine- to fine-grained zones are present. Color index ranges from 30-40. Magmatic foliation is moderately strong and is defined by hornblende and plagioclase. A weaker solid-state foliation is defined by elongated quartz. This diorite includes widespread heterogeneities, such as: hornblende enclaves, patches, and pods; intermediate enclaves, patches, and pods; felsic concentrations; and hornblende, mafic, and felsic dikes (Fig. 11). Hornblende enclaves range from 1 x 3 cm to 12 x 45 cm. Two locations have mafic enclave swarms. In both swarms, enclave boundaries are sharp. One is 1 x 20 m and the boundaries of the swarm have a ~7-cm wide, fine-grained margin that does not deflect the local foliation. Hornblende dikes are up to 3 m wide, mafic dikes are 12 cm-1 m wide, and felsic dikes are 1-75 cm wide. Both mafic and felsic dikes contain xenoliths of, and interfinger with, the host diorite. Rarely, mafic dikes are disaggregated into the host diorite.

The heterogeneous diorite consists of plagioclase (~55%), hornblende (~18-30%), quartz (~3-8%), biotite (~2-18%), and accessory (epidote, sphene) and secondary minerals (epidote, sphene, chlorite) (~1-10%). Saussuritization and sericitization range from mild to widespread.

Plagioclase within the heterogeneous diorite ranges from ~0.25 mm to 1 cm in length and averages ~1.5 mm. The plagioclase is elongate or blocky, and varies from subhedral to anhedral. Some grains have oscillatory zoning. Solid-state deformation is indicated by kinked and broken grains, and widespread deformation twins.

Figure 11. Photographs of the Kelly Mountain heterogeneous diorite. A) Diorite intruded by dikes of hornblendite, gabbro, and diorite with a higher color index. Also note the angular hornblendite enclave (left). B) Top is coarse-grained hornblende and plagioclase diorite, bottom is fine-grained diorite with plagioclase phenocrysts.

Saussuritization is marked by secondary growth of epidote within plagioclase.

Hornblende forms subhedral to anhedral, elongate to blocky grains. They are ~0.75 mm to 1 cm in length, and average ~1.5 mm. Simple twinning is common and many grains have inclusions of plagioclase and quartz. Some grains are broken and kinked, and much of the hornblende is chloritized at grain edges.

Quartz lengths range from ~0.25-2 mm and average ~1 mm. Solid-state deformation is indicated by subgrains and recrystallized grains, which form elongated mosaics, parallel to subparallel to the magmatic foliation. Subgrains and recrystallized grains are typically ≤ 0.5 mm in diameter.

Biotite is anhedral, commonly fan shaped, and some grains are kinked. Much of the biotite is altered partially to fully to chlorite. Grains are ~0.25-2 mm in length and average ~0.75 mm.

Epidote and sphene form both as accessory and secondary minerals. Magmatic epidote is subhedral and ranges in length from ~0.25-0.5 mm. Secondary epidote is anhedral and ~0.12-0.6 mm in diameter. Magmatic sphene is subhedral and ~0.5-1.25 mm in length. Secondary sphene is anhedral and grains are ~0.25-1 mm in length.

Diorite

The hornblende-biotite diorite crops out in four bodies (Fig. 7). An elongate body in the south varies in width from 50-400 m, and a lenticular body in the central part of the eastern margin is up to 400 m wide. Two smaller bodies in the northern and the west-central part of the Kelly Mountain suite are ~200 m wide. The diorite is coarse-grained in the south, fine- to coarse-grained in the central bodies, and fine- to medium-

grained in the north. Color index in the unit ranges from 25-40. Hornblende is the primary mafic mineral and defines strong magmatic foliation. Minor heterogeneities include: mafic enclaves, patches, and pods; felsic enclaves and patches; and mafic and felsic dikes. Only one small outcrop has minor hornblendite. This unit is distinguished from the heterogeneous diorite by its greater homogeneity.

The diorite consists of plagioclase (~60-65%), hornblende (~25%), quartz (~3%), biotite (~2%), and accessory (epidote, sphene) and secondary minerals (epidote, sphene, chlorite) (~5-7%). Samples showed widespread brittle deformation.

Plagioclase within the diorite ranges from ~0.25 mm to 7.5 mm in length and averages ~1.5 mm. The plagioclase is elongate or blocky, and subhedral to anhedral. Oscillatory zoning is widespread. Myrmekitic texture ranges from minor to widespread. Minor solid-state deformation is indicated by broken grains and widespread deformation twins.

Hornblende forms euhedral to anhedral, elongate to blocky grains. They range in length from ~0.75-6 mm, and average ~1.5 mm. Many grains have inclusions of plagioclase, and are partially replaced by epidote and sphene. Much of the hornblende has been replaced by chlorite at grain edges.

Quartz and biotite are minor constituents. Quartz is fine-grained and ranges from ~0.25-0.75 mm. It is anhedral, commonly interstitial, and displays minor bulging recrystallization. Biotite has been altered partially to fully to chlorite. Grains are ≤ 0.75 mm.

Epidote and sphene form both as accessory and secondary minerals. Magmatic epidote is subhedral and ~0.12-0.4 mm in diameter. Anhedral secondary epidote ranges from ~0.3-0.75 mm in length. Magmatic sphene is euhedral to subhedral and ~0.25-1 mm in length. Secondary sphene is anhedral and grains are ~0.25 mm long.

Quartz Diorite

Six bodies of quartz diorite are seen within the ~92 Ma Main Body tonalite and ~78 Ma Kelly Mountain suite (Fig. 7). The quartz diorite ranges from fine- to coarse-grained, although individual outcrops typically only display part of that range. This unit has a color index of ~30-35. Magmatic foliation and lineation are commonly weak, but are well-developed locally, and are best defined by hornblende and biotite. The magmatic foliation is locally overprinted by weak to moderate solid-state fabric, which is denoted by mosaics of elongated quartz. Outcrops include leucocratic dikes (~10 cm wide), thinner felsic veinlets, and enclaves that are the same composition as the host, but are finer-grained and have plagioclase phenocrysts. A magmatic shear zone, with stacked felsic and mafic pods and enclaves, is 45 cm wide by ≥ 4 m long (Fig. 12).

The quartz diorite consists of plagioclase (~50%), hornblende (~20-25%), quartz (~15%), biotite (~5-10%), and accessory (epidote, zircon) and secondary minerals (epidote, sphene, chlorite) (~5%). Saussuritization and seritization are widespread.

Plagioclase is ~0.75 mm to ~1 cm in length and averages ~1.5 mm. The plagioclase is elongate or blocky, and varies from subhedral to anhedral. Some grains have oscillatory zoning. Kinked and broken grains are found, and deformation twins are widespread. Saussuritization is marked by epidote within plagioclase.

Figure 12. Photograph of the Kelly Mountain quartz diorite. Magmatic shear zone with stacked felsic and mafic enclaves and pods within the quartz diorite

Hornblende forms subhedral to anhedral, elongate to blocky grains. They range in length from ~0.75 mm to 1 cm, and average 1.5 mm. Simple twinning is common. Many grains have inclusions of plagioclase and quartz, and are replaced by epidote. A few grains are broken and kinked. Much of the hornblende has been altered to chlorite at grain edges.

Quartz is ~0.12-2 mm and has an average length of ~1 mm. Grains are anhedral and are found in mosaics. Recrystallized grains are typically ≤ 0.5 mm in diameter and form elongated mosaics, which are parallel to subparallel to the magmatic foliation.

Biotite is anhedral and commonly fan shaped. The grains are altered partially to fully to chlorite. Grains range from ~0.25-2 mm in length and average ~0.75 mm. Some grains are kinked.

Epidote and sphene form both as accessory and secondary minerals. Minor, very small zircons are found within biotite grains. Magmatic epidotes are subhedral and ~0.4 mm in length. Secondary epidotes are anhedral and range from ~0.3-0.75 mm in length. Magmatic sphene is euhedral to subhedral and ~0.25-1 mm in length. Secondary sphene is anhedral and grains are ~0.25 mm in diameter.

Tonalite

The ~78 Ma, homogeneous tonalite lays between the Main Body tonalite and the other rocks of the Kelly Mountain suite. The width of the homogeneous tonalite is unknown, and more dating will be needed to definitively delineate the boundary with the older tonalite (Fig. 7). This hornblende-biotite tonalite is medium- to coarse-grained with zones of fine-grained material. It has a color index of 25 to 35. Magmatic foliation and

lineation are moderate to strong and defined by hornblende and biotite. A weak to moderate solid-state foliation locally overprints the magmatic foliation and is best defined by quartz. Minor heterogeneities include: mafic and felsic enclaves; mafic and felsic dikes; and very rare hornblende enclaves. Enclaves range from 5 cm x 7 cm to 50 cm x 1.5 m. Enclaves vary from more to less mafic than the host tonalite. Grains range from fine to coarse, and plagioclase phenocrysts are common. Rarely, enclaves have plagioclase rinds. Enclaves do not deflect magmatic foliations. Multiple outcrops have mafic dikes that mingled and interfingered with the host tonalite (Fig. 13). In contrast, other mafic dikes have chilled margins indicating that the host tonalite was solid when intruded. Dikes range from 1 cm to 60 cm in width. Hornblende was seen in only two outcrops. Each outcrop has a single hornblende enclave, which are 1 cm x 3 cm and 0.75 cm x 1.5 cm, respectively.

The homogeneous tonalite consists of plagioclase (~26-45%), quartz (~27-37%), hornblende (~1-22%), biotite (~1-17 %), and accessory (epidote, sphene) and secondary minerals (epidote, sphene, chlorite) (~0-21%). Myrmekitic texture, saussuritization, seritization, and chloritization range from absent to pervasive.

Plagioclase is ~0.25-7 mm in length and averages ~1 mm. Plagioclase grains are elongate to blocky, and are mostly subhedral to anhedral. Oscillatory zoning is uncommon. There are minor recrystallized, kinked, and broken grains, and common deformation twins. Saussuritization is marked by epidote within plagioclase.

Quartz ranges from ~0.12-1.5 mm, and has an average length of ~0.75 mm. Grains are anhedral. Strain is indicated by bulging, subgrain-rotation recrystallization,

Figure 13. Photograph of an intermediate dike intruding the Kelly Mountain tonalite. Note hornblende phenocrysts in the dike. Stringers of the intermediate dike are seen between its offset ends. The dike also mingles with the host tonalite implying the host was still mushy when the dike intruded.

and less commonly grain-boundary-migration recrystallization. Solid-state foliation, denoted by elongate aggregates of recrystallized grains (≤ 0.5 mm) in mosaics, is parallel or sub-parallel to magmatic foliation. A relatively mafic sample from the northern part of the tonalite showed only minor strain.

Biotite is elongate to blocky and anhedral, and is locally fan shaped. Grains are ~ 0.25 -3 mm in length, and average ~ 0.75 mm. Grains typically occur in clusters and some grains are bent or kinked. Chlorite alteration at grain edges is widespread.

Hornblende grains are elongate to blocky and subhedral to anhedral. They range in length from ~ 0.25 -7 mm, and average ~ 1.5 mm. Simple twinning is common. Many grains have inclusions of plagioclase, quartz, and biotite, and are locally replaced by epidote and sphene. Chlorite alteration at grain edges is common.

Epidote and sphene form both as accessory and secondary minerals, whereas chlorite is only secondary. Magmatic epidote is euhedral against biotite and commonly equant. It is ~ 0.25 -0.75 mm in diameter. Secondary epidote is anhedral and ~ 0.12 -0.75 mm in length. Magmatic sphene is euhedral to subhedral and ~ 0.3 -1.5 mm in length. Secondary sphene is anhedral and ranges from ~ 0.12 -1 mm in length. Chlorite forms in the margins of some biotite and hornblende grains.

MODAL ANALYSIS OF TONALITES

Modal analysis by point counting was completed on 22 tonalite samples. Fifteen of the samples were from the Main Body tonalite (~ 92 Ma) and the other seven were from the Kelly Mountain tonalite (~ 78 Ma). Modal analysis was carried out to evaluate

the homogeneity of each of the tonalites and to compare them (Fig. 14). Both tonalites were also broken up into northern, central, and southern domains to determine whether there are along-strike differences. Modal analysis indicates that the primary mafic mineral in the Main Body and Kelly Mountain tonalites changes from biotite to hornblende, respectively, but that along strike there are no noteworthy differences (Table 1) (Figs. 14 and 15).

Main Body (~92 Ma) Tonalite

Fifteen Main Body tonalite samples revealed that the tonalite has a consistent mineralogy. Plagioclase, quartz, biotite and hornblende are the most abundant magmatic constituents. Epidote and sphene are both minor magmatic and secondary components. Other secondary minerals include chlorite and less commonly calcite. Modal variation of plagioclase and quartz is $\leq 10\%$, excluding one sample from the central area (KD-115) and another from the southern area (KD-164) (Fig. 16).

Biotite typically ranges from $\sim 10\text{--}22\%$, whereas hornblende ranges from $\sim 1\text{--}12\%$ (Table 1). Four samples, three in the central area (KD-137B, KD-141, and KD-115) and one in the southern area (KD-164), fall below the typical biotite range. These low values probably reflect the extensive chloritization ($\geq 11\%$ of mode) of biotite. Modal variations within each mineral were low; approximate means and standard deviations for plagioclase, quartz, biotite and hornblende are $36 \pm 6\%$, $35 \pm 3\%$, $11 \pm 7\%$, and $6.5 \pm 4\%$, respectively.

Figure 14. Geologic map emphasizing petrographic sample localities.

Table 1. Modal Analysis of Tonalite Samples from the SFJIC

~Age	Sample No.	Plagioclase	Potassium Feldspar	Quartz	Biotite	Hornblende	Accessory Minerals	Secondary Minerals	Total Mafic Minerals	Total Count	Sample Locations (UTM)
~92 Ma	KD-59	31.7	0	36.1	11.8	1.9	1.1	17.3	13.7	363	0673114;5318092
	KD-93	34.7	0	34.7	11.1	6.7	2.2	10.5	17.8	360	0672851;3318359
	KD-88	34.6	0	35.4	9.9	1.1	1.4	17.3	11	353	0673710;5317222
	BPX-138A	25.7	0	35.7	17.3	7.3	4.6	8.91	24.6	370	0673810;5316928
	KD-137B	44.4	0	37.7	0.3	3.4	0.8	13.4	3.7	358	0673773;5315328
	KD-141	32.5	0	33.2	0	11.1	0.26	20	11.1	379	0673715;5314997
	KD-53	31.4	0	38.7	10.9	9.5	1.4	8.1	20.4	357	0674444;5314738
	KD-115	46.5	0	30	2.2	1.4	1.4	20.6	3.6	368	0674233;5314812
	KD-51	36.6	0	32	22.3	8.3	0.6	2	30.6	350	0674487;5312977
	KD-33	35.4	0	40.9	16.3	4.6	2.9	1.4	20.9	350	0676996;5312845
~78 Ma	KD-41	43.6	0	38.2	12.8	4.55	0	2.27	17.4	351	0675284;5312622
	KD-136	34.7	0	34.2	15.8	5.3	0.5	9.7	21.1	360	0675647;5314200
	KD-164	43	0	30.1	2.5	11.2	0	13.4	13.7	365	0676664;5312418
	KD-166	30	0	33.7	20.5	9.2	1	5.5	29.7	380	0676979;5312438
	BPX-154A	36.1	0	34.1	15.8	11.7	0.6	1.66	27.5	360	0676240;5313064
	KD-154	44.8	0	27.2	1.1	10.8	2.5	13.6	11.9	353	0673099;5318831
	BPX-137	45	0	31.6	6.8	7.4	2.7	6.5	14.2	367	0673810;5316887
	KD-80	37.7	0	34.6	4.6	3.7	3.1	15.9	8.3	350	0674678;5315686
	KD-99	34.6	1.1	37.1	1.4	2.6	2.3	21.4	4	350	0673996;5316258
	KD-27	43.4	0	31.7	9.1	15.1	0.6	0	24.2	350	0677159;5313637
~78 Ma	KD-133	37.6	0	27.9	7.4	22.5	0.6	4	29.9	351	0676226;5314445
	BPX-148A	39.1	0	33.3	7.5	17.5	0.3	2.2	25	360	0676782;5314237

Sample localities are shown on Figure 14. UTM coordinates are in North American Datum of 1927 (NAD27), zone 10
Red and green highlights indicate samples from the heterogeneous and mafic domains, respectively.

Figure 15. Modal percentages of biotite and hornblende for the Main Body and Kelly Mountain tonalites. For sample localities see Figure 14.

Figure 16. Modal percentages of plagioclase and quartz for the Main Body and Kelly Mountain tonalites. For sample localities see Figure 14.

Kelly Mountain (~78 Ma) Tonalite

The seven samples from the Kelly Mountain tonalite are similar to the older tonalite in many respects. The samples indicate that mineralogy is also consistent throughout the Kelly Mountain tonalite as plagioclase, quartz, biotite and hornblende are the most abundant magmatic constituents, and epidote and sphene are minor components. Epidote and sphene are also secondary constituents, as is chlorite. The dominant mafic mineral in the Kelly Mountain tonalite is hornblende. It ranges from ~7-23%, whereas biotite makes up ~1-9% of the rock (Table 1). Both samples in the central domain (KD-80 and KD-89) have very low mafic modal counts, reflecting the >12% chlorite in these rocks. Approximate means and standard deviations throughout the younger tonalite are as follows: $40 \pm 4\%$; $32 \pm 3.5\%$; $5 \pm 3\%$; and $11 \pm 7\%$, for plagioclase, quartz, biotite, and hornblende, respectively.

STRUCTURES

Magmatic and to a lesser extent solid-state structures provide insight into the construction and emplacement of the SFJIC. These structures include magmatic foliations, lineations, and folds, solid-state foliations, contacts between the SFJIC and its host rock, and contacts within the SFJIC.

Magmatic Foliation

The SFJIC has a well-defined magmatic foliation that is parallel to sub-parallel to some contacts, but intersects and overprints other internal contacts and sheets at higher

angles ($>40^\circ$). Foliation intensity is mostly moderate to strong throughout the study area, although it is weak in parts of the quartz diorite. Foliation is defined by elongate hornblende and biotite, and is best developed in tonalites and diorites. Foliation within the mafic complex is difficult to measure, perhaps reflecting the high level of lithological heterogeneity. It may be that after foliation formed in the complex, blocks of it were rotated by younger injections of melt.

Magmatic foliation typically strikes NW and dips moderately to steeply to the NE, and less commonly to the SW (Fig. 17). Foliation in the Main Body tonalite has an average attitude of $354/84$ NE ($n=83$). Foliation ($n=86$) in Kelly Mountain suite has two maxima in orientations: $351/67$ NE and $299/82$ NE. The stereographic plots, for both the ~ 92 Ma (Fig. 18) and ~ 78 Ma rocks (Fig. 19), show widespread scatter of the poles. Measurements that deviate from the norm are typically found in the Main Body tonalite, and are primarily distributed in the central domain near folds.

Magmatic Lineation

Magmatic lineation is defined by hornblende and biotite. Lineation intensity varies from strong to weak. An overall NW and SE trend is dominant and plunge ranges from shallow to steep, but are typically moderate (~ 32 - 56°) (Fig. 20).

In the southern part of the Main Body tonalite, plunges are moderate to steep in the south, and average $\sim 57^\circ$ to the NW, SE, and less commonly to the NE. Plunges are shallow to moderate in the central and northern domains. Plunges in the Kelly Mountain suite are also moderate to steep in the south, commonly measuring $\sim 47^\circ$ to the SE, NE

Figure 17. Geologic map emphasizing magmatic foliations. See Plate 1 for more detailed version.

Figure 18. Poles to magmatic foliation of the Main Body tonalite. Kamb contour interval of 2σ .

Figure 19. Poles to magmatic foliation of the Kelly Mountain suite rocks. Kamb contour interval of 2σ .

Figure 20. Geologic map emphasizing magmatic lineations. Note plunges are color coded. See Plate 1 for more detailed version.

and less commonly to the NW. Plunges in the central and northern domains are instead split between shallow and steep. Fewer lineations were measured in the northern and central domains, which may be due to weaker linear fabrics and poor exposure.

Magmatic Folds

Magmatic folds of foliation are recognized in both the ~92 Ma and 78 Ma rocks. Folds are most abundant in the central domain, and range from ~150 to 500 m in wavelength. There are at least six tight to isoclinal upright folds. The fold axes trend N-NW, and plunge moderately to the NW and SE (Figs. 21-23). The hinge lines trend N-NW, and plunge moderately to the NW and SE (Figs. 21-23). The orientations of axial surfaces determined from cross section B-B' and B''-B''', are from west to east: 305/79 NE; 326/79 NE; 325/84 NE; 343/78 NE; 350/80 NE; and 172/83 SW. One fold in cross section line C-C' has an axial surface of 104/48 SW.

In the south within the Main Body tonalite, Paterson and Miller (1998a) postulated that the axial trace of a regional synform is a short distance northwest of Marble Meadows. Foliation orientations within the study area do not support the presence of this feature (Fig. 21).

Contacts

Most contacts within the SFJIC, as well as the contact between the SFJIC and Dumbell orthogneiss, are not exposed, but can be constrained within meters or less. These contacts range from sharp to gradational and are differentiated by variations in

Figure 21. Magmatic sheets, folds, and foliations. Lines of cross section are also shown. See Plate 1 for more detailed version.

Figure 22. Folds and foliations within the central domain. Note the location of cross section line B-B' and B''-B'''.

composition, mode, and grain size. They are generally subparallel to each other, although they are weakly to highly curved in map view (Fig. 21). The contacts are commonly discordant to foliations, and are either vertical or steeply dipping to the ENE (Figs. 21 and 23).

Contact of Host Rock and Seven-Fingered-Jack Intrusive Complex

Where the Dumbell orthogneiss is in contact with the younger SFJIC, a sharp, moderate-to-steep, east-dipping boundary has been measured or inferred (Fig. 23). The sharpness of this contact is supported by not only the time gap between the rocks, but also by the proximity of outcrops of the different intrusions, which are only a few meters apart, and by the lack of bodies of the SFJIC intruded into the orthogneiss away from the contact. The steepness and dip direction are inferred by orientations taken near the contact and by similar data from other workers from the surrounding areas (Miller and Paterson, 2001a).

Internal Contacts within the Seven-Fingered-Jack Intrusive Complex

Most internal contacts between units of the SFJIC in the study area are inferred to be gradational (Figs. 21 and 23). The exception is the contact between the ~92 Ma Main Body tonalite and the ~78 Ma Kelly Mountain suite. This contact between the tonalites is poorly constrained due to the lack of obvious modal differentiation in the field.

Contacts within the Kelly Mountain suite range from sharp to gradational. Sharp contacts are implied by the proximity of outcrops of different units to one another,

xenoliths, and a lack of obvious mingling. Gradational contacts are inferred based on areas that display mingling.

Internal Contacts within the ~92 Ma Main Body Tonalite

Within the Main Body tonalite, the few measureable sheets show two distinct orientations (Figs. 21-23). The contacts either have a NW strike and a shallow to steep dip (334/35 NE, 112/59 SW, 169/32 SW, 167/76 SW), or they have a NE strike with a near vertical dip (254/83 NW, 075/84 SE). The sheets with sharp boundaries and measureable widths range from ~5 cm to ≥ 1 m in thickness. Paterson and Miller (1998a) noted that a steeply dipping sheet oriented ~321/85 NE terminated in the Marble Meadows region. This measurement agrees with field observations conducted for this study (Fig. 21); however, the orientation calculated from my data is slightly different at ~167/76. This difference is probably not significant given the uneven distribution of exposures and the common irregularities of contacts where examined in detail within plutons. Paterson and Miller (1998a) also stated that sheets within or just south of the study area are as wide as 0.5- to 2.5 km. The Marble Meadows sheet within the study area is ~1- to 1.5 km wide.

Solid-State Microstructures

Solid-state deformation is found in all units of the SFJIC, and occurs over a range of temperatures, as demonstrated by the different microstructures discussed in the previous section. Solid-state deformation affects mainly quartz, biotite, plagioclase, and hornblende. Such deformation includes bulging, subgrain-rotation, and grain-boundary-

migration recrystallization, deformation twinning, and kinked and broken grains. Within all rocks, quartz subgrains are typically $\leq 0.5\text{mm}$. Elongate quartz grains and recrystallized aggregates define the solid-state foliation, which is subparallel to magmatic foliation. Grain-boundary-migration recrystallization is marked by quartz grains displaying salient or amoeboid boundaries.

The Main Body tonalite records solid-state deformation throughout the study area. Quartz exhibits pervasive bulging and subgrain-rotation recrystallization, and less commonly grain-boundary-migration recrystallization (Fig. 24A and B). Plagioclase shows recrystallization, bent and kinked grains, and extensive deformation twins (Fig. 24B and C). This tonalite also has widespread kinked biotite (Fig. 24D) and local fractured plagioclase.

The Kelly Mountain suite records similar evidence of solid-state deformation, although not as robust or widespread. The mafic complex diorite, heterogeneous diorite, and quartz diorite all display bulging and subgrain-rotation recrystallization of quartz. These rocks also display widespread deformation twinning in plagioclase and kinked and broken grains of plagioclase and hornblende. Only the heterogeneous diorite and quartz diorite have kinked biotite. Deformation in the diorite is limited to minor bulging of quartz and deformation twins and fracturing of plagioclase. The homogeneous tonalite exhibits the highest strain of the Kelly Mountain rocks. The tonalite has pervasive bulging, subgrain-rotation recrystallization, and grain-boundary-migration recrystallization of quartz and less common recrystallization of plagioclase. Deformation twins in plagioclase and broken or kinked grains of plagioclase and biotite are

Figure 24. Photomicrographs of the Main Body tonalite. A) Bulging recrystallization (red circle) and subgrain-rotation recrystallization (blue outlines) of quartz. B) Grain-boundary-migration recrystallization of quartz and aligned, bent plagioclase containing deformation twins. C) Minor recrystallization (red arrow) and bent, deformation twins of plagioclase. D) Kinked biotite.

widespread.

GEOCHEMISTRY

Six samples were analyzed by ICP-MS and XRF to characterize the SFJIC. Major and trace element analyses are given in Tables 2 and 3. Two samples are from relatively mafic rocks within the Kelly Mountain suite, a heterogeneous diorite (BPX-145-A) and a diorite from the mafic complex (KD-13). The other four samples are tonalites. One is a Kelly Mountain tonalite (BPX-137-1) and the others are older Main Body tonalites (KD-59, KD-53, and BPX-154-A) (Fig. 25). All samples analyzed provide baseline data for comparisons with other data from the SFJIC and coeval plutons in the North Cascades, such as the Tenpeak pluton and Black Peak batholith. The tonalite samples of different ages were used to evaluate potential changes in magma composition with time. All REEs were normalized to chondrite values from McDonough and Sun (1995), whereas all trace elements were normalized to N-type MORB values from Sun and McDonough (1989).

All samples have a SiO₂ range of 50-62 wt.% (Table 2). The younger mafic rocks, KD-13 and BPX-145-A, are 50.01 wt.% and 51.53 wt.% SiO₂, respectively, whereas the four tonalites fall within a narrow range of 60.44-61.55 wt.%. Thus, there is no significant difference in SiO₂ between the older and younger tonalites. Harker diagrams of major oxides (e.g., Al₂O₃, FeO, MnO, and CaO) form a linear trend, but TiO₂, MgO, Na₂O, K₂O, and P₂O₅ show appreciable scatter (Fig. 26). Harker diagrams of trace elements lack linear trends, except for V and Sr (Fig. 27).

Table 2. Normalized Major Element Geochemistry for the SFJIC (Weight %)

	Mafic Complex ~78 Ma	Heterogeneous Diorite ~78 Ma	Tonalite ~78 Ma	Tonalite ~92 Ma	Tonalite ~92 Ma
	KD 13	BPX 145-A	BPX 137-1	KD 59	BPX 154-A
SiO ₂	50.01	51.53	61.47	61.40	60.44
TiO ₂	0.804	1.089	0.987	0.856	0.861
Al ₂ O ₃	21.59	19.47	18.05	17.77	17.63
FeO	8.62	8.50	5.49	6.04	6.31
MnO	0.163	0.156	0.077	0.117	0.118
MgO	3.82	5.81	2.12	2.61	2.70
CaO	10.12	8.78	6.56	5.33	5.99
Na ₂ O	4.30	4.09	4.08	3.64	3.76
K ₂ O	0.21	0.36	0.88	2.00	1.93
P ₂ O ₅	0.353	0.212	0.293	0.235	0.257
Total	100.00	100.00	100.00	100.00	100.00

XRF

Table 3. Trace Element Geochemistry for the SFJIC (ppm)

		Mafic Complex ~78 Ma	Heterogeneous Diorite ~78 Ma	Tonalite ~78 Ma	Tonalite ~92 Ma	Tonalite ~92 Ma	Tonalite ~92 Ma
		KD 13	BPX 145-A	BPX 137-1	KD 59	KD 53	BPX 154-A
ICP-MS	La	8.76	7.4	14.97	10.74	12.03	13.15
	Ce	21.09	19.38	31.11	24.16	29.21	29.59
	Pr	3.36	3.11	4.09	3.26	4.38	4.24
	Nd	16.06	15.46	17.63	13.93	19.66	19.12
	Sm	4.25	4.18	4.27	3.46	5.06	4.80
	Eu	1.50	1.36	1.17	1.04	1.35	1.39
	Gd	4.19	4.39	4.06	3.22	4.60	4.53
	Tb	0.66	0.70	0.60	0.49	0.70	0.67
	Dy	3.84	4.34	3.32	2.84	4.13	3.87
	Ho	0.77	0.87	0.59	0.56	0.81	0.76
	Er	2.03	2.32	1.41	1.46	2.14	1.90
	Tm	0.29	0.33	0.19	0.20	0.31	0.27
	Yb	1.76	2.03	1.13	1.32	1.91	1.69
	Lu	0.26	0.31	0.16	0.21	0.29	0.27
	Ba	162	152	422	741	662	773
	Th	0.20	0.30	4.93	1.49	1.85	2.55
	Nb	2.40	3.19	4.53	3.96	7.54	6.04
	Y	19.46	21.90	14.91	14.11	20.95	19.33
	Hf	0.89	2.49	2.46	3.63	4.03	3.62
	Ta	0.17	0.20	0.46	0.26	0.58	0.49
	U	0.10	0.18	2.35	1.23	1.38	2.12
	Pb	1.96	2.62	6.60	7.13	7.42	9.33
	Rb	1.8	5.1	21.4	55.5	43.0	57.6
	Cs	0.11	0.13	1.21	1.26	1.98	3.72
	Sr	995	608	572	590	611	653
	Sc	18.0	24.4	10.2	14.7	15.1	15.3
	Zr	28	93	72	136	154	128
XRF	Ni	15	51	3	5	6	5
	Cr	8	132	7	22	30	20
	V	202	215	104	98	99	106
	Ga	23	21	20	20	21	20
	Cu	18	10	3	6	4	4
	Zn	103	98	69	89	98	98

Figure 25. Geochemical sample localities.

Figure 26. Major element variation diagrams. Major oxides vs. SiO₂ of the SFJIC. Circles represent tonalites and triangles represent diorites. Solid circles are ~92 Ma and hollow symbols are ~78 Ma. Sample localities shown on Figure 25.

Figure 27. Trace element variation diagrams. Trace elements vs. SiO_2 of the SFJIC. Circles represent tonalites and triangles represent diorites. Solid circles are ~92 Ma and hollow symbols are ~78 Ma. Sample localities shown on Figure 25.

The tonalites of the SFJIC display moderately steep REE patterns, as $(\text{La/Yb})_{\text{N}} = 6.31\text{--}13.30$ (Fig. 28). The two relatively mafic samples (KD-13 and BPX-145-A) of the Kelly Mountain suite have a shallower REE pattern, with $(\text{La/Yb})_{\text{N}} = 3.64$ and 4.97 , respectively. All samples, with the exception of KD-13, show a slight negative europium anomaly. A multi-element diagram indicates overall enrichment, relative to N-MORB, in large ion lithophiles (Rb, K, Sr, Ba, Cs) and low high field strength element concentrations (Nb, Zr, Ti) as is typical of igneous rocks (Fig. 28).

Major and trace element data for samples within the Main Body tonalite (KD-59, KD-53, and BPX-154-A) (Figs. 26 and 27) are clustered together. The two exceptions are a markedly lower concentration of Nb and Y in KD-59, the northern-most sample.

The ~ 92 Ma (KD-59, KD-53, and BPX-154-A) and ~ 78 Ma tonalite (BPX-137-1) are fairly similar in most major and trace elements. The younger tonalite is noticeably lower in MnO and K_2O , and is higher in TiO_2 and Na_2O (Fig. 26). It is also markedly lower in Rb, Ba, Y, Zr, Sc, and Nb. The low abundances of Y and Nb correspond closely with the same lows found in one of the older tonalites (KD-59) (Fig. 27).

Samples KD-13 and BPX-145-A (Fig. 25), the ~ 78 Ma diorites, differ widely in major (TiO_2 , Al_2O_3 , MgO, and P_2O_5) and trace (Ni, Cr, Sc, Sr, and Zr) element abundances (Figs. 26 and 27).

DISCUSSION

Magmatic Versus Solid-State Fabrics

Microscopic analysis is the best way to look for evidence of magmatic versus

Figure 28. REE and multi-element plots. REE's are normalized to chondrite values of Sun and McDonough (1989). Multi-element plot normalized to N-type MORB values of McDonough and Sun (1995).

solid-state deformation in plutonic rocks. Using the criteria of Paterson et al. (1989, 1998) it is clear that the SFJIC experienced both types of deformation. It is uncertain, however, whether there was a continuum from magmatic to solid-state fabrics, or if there was a significant hiatus. Magmatic foliation is primarily defined by aligned subhedral plagioclase, hornblende, and biotite, together with interstitial, undeformed quartz. Almost all magmatic fabrics are overprinted by solid-state deformation, which is seen where: 1) quartz and plagioclase are recrystallized; 2) recrystallized quartz forms elongate mosaics; 3) plagioclase, biotite, and hornblende grains are kinked and/or broken; and 4) plagioclase contains deformation twins.

These microstructures indicate that there is superposition of solid-state deformation over magmatic fabrics. Evidence of intermediate temperature solid-state microstructures is present in the Main Body tonalite and Kelly Mountain suite. Intermediate temperatures ($\sim 300\text{-}500^{\circ}\text{C}$) are inferred where quartz displays subgrain-rotation recrystallization and plagioclase shows minor recrystallization (Hirth and Tullis, 1992; Rosenberg and Stunitz, 2003). Higher temperatures ($\sim 500\text{-}700^{\circ}\text{C}$) are assumed where quartz displays salients indicating grain-boundary-migration recrystallization and recrystallized plagioclase is marginally more prevalent. The above microstructures correspond to deformation regimes 2 ($\sim 350\text{-}500^{\circ}\text{C}$) and 3 ($\sim 500\text{-}700^{\circ}\text{C}$), respectively, of Hirth and Tullis (1992).

Interpretation of Origin of Fabrics

Regional NE-SW contraction, coupled with the time it takes deep-seated magma to cool and crystallize (Miller and Paterson, 1994), explains why foliations (magmatic and solid-state) in the study area record regional strain and typically strike NW with moderate to steep NE dips. In the Main Body tonalite, magmatic foliations fluctuate significantly (Fig. 17). This foliation pattern in part reflects N-NW-trending, moderately plunging folds, especially in the central part of the study area. These upright folds are roughly similar to those in the Main Body tonalite noted by Paterson and Miller (1998) and Miller and Paterson (2001a), which plunge moderately to both the NW and SE and are defined by magmatic foliation. The Kelly Mountain suite is also folded in the central domain and the folds have similar orientations to those in the older tonalities. Thus, the consistent hinge line orientations indicate time-transgressive folding that is consistent with a constant regional strain field from at least 92-78 Ma.

Seven-Fingered-Jack Intrusive Complex Tonalite

Textural, modal, geochemical, and structural analysis of the tonalites within the study area provide insights into the degree of heterogeneity of the tonalites, and permits comparison of tonalites of different ages.

Degree of Heterogeneity within the Main Body Tonalite

The heterogeneities of the Main Body tonalite include enclaves, cumulates of hornblende, dikes, magmatic shear zones, and schlieren. Color index (25-40) varies

significantly in this tonalite. This tonalite also includes domains of increased heterogeneity or increased color index. The two more heterogeneous domains (Fig. 8) have abundant mafic and felsic enclaves and dikes, hornblendite xenoliths, and localized schlieren. These domains may represent separate, more heterogeneous injections of melt. Sheets in these domains trend NW, which is in accord with other researchers' observations (Miller and Paterson, 2001a; Elkins, 2015). The three domains of mafic tonalite are confined to the central and southern domain (Fig. 8). Color index increases from ~30-35 to ~40. Although these domains are more mafic, felsic features (i.e. pockets, xenoliths, veinlets) tend to be more common than elsewhere. Sheets in these domains trend WNW and ENE. The sheets oriented ENE are perpendicular to the regional trend.

Field and petrographic analyses demonstrate that much of the Main Body tonalite is homogeneous in many aspects as well. These analyses indicate that throughout the study area, the tonalite is medium- to coarse-grained with local zones of fine-grained material. Modal analyses show that the primary mafic mineral throughout the tonalite is biotite. The findings of Elkins (2015) indicate similar mineralogy and modes to my data presented in Table 1. Thus, the ~92 Ma tonalite, in the study area and to the north is relatively homogeneous in modal composition.

Geochemical analyses of the study area and from Elkins (2015) indicate that the ~92 Ma tonalite varies little in composition (Figs. 26-28). Major and trace element plots show loose clustering and minor outliers (Elkins, 2015), and are thought to indicate hybridized melts. These plots in conjunction with overlapping values on REE and multi-

element plots indicate that although the tonalite was injected incrementally, these injections likely shared a common parental melt source.

Structurally, the older tonalite is relatively homogeneous. Magmatic foliation intensities vary slightly, but the magmatic signature is stronger than the solid-state overprint. Stronger intensity foliations were only seen in or near one of the five more heterogeneous domains. The tonalite locally contains a well-developed linear fabric (L>S), but overall it typically has a stronger planar component (S>L).

Degree of Heterogeneity within the ~78 Ma Kelly Mountain Tonalite

The Kelly Mountain tonalite has a color index of ~30 and is medium- to coarse-grained. Fine-grained zones are rare and only one was seen in the northernmost outcrops. Minor heterogeneities include mafic and felsic enclaves, mafic and felsic dikes, and very rare hornblende enclaves. Modal analyses show that the primary mafic mineral is hornblende. There is insufficient analytical data (1 sample) to assess geochemical heterogeneity.

The Kelly Mountain tonalite is structurally slightly less homogeneous than the Main Body tonalite. Magmatic foliation intensities vary, from weak to strong, but like the older tonalite, the magmatic fabric is stronger than the solid-state overprint. The variation in foliation intensity has no apparent pattern. The Kelly Mountain tonalite locally has stronger linear fabrics (L>S), but overall a stronger planar component (S>L).

Comparison of the Main Body and Kelly Mountain Tonalite

The tonalites within the study area (~92 Ma vs ~78 Ma) are mostly similar in outcrop. They are both medium- to coarse-grained with zones of fine-grained materials,

and have color indices from ~25-40. Magmatic foliation and lineation are moderate to strong and defined by hornblende and biotite. Solid-state deformation is present in both tonalites (see above). The tonalites have a wide variety of magmatic features, including mafic and felsic enclaves, mafic and felsic dikes, and hornblende inclusions (Figs. 9 and 13). Both tonalites also contain evidence of internal sheeting (Fig. 21). The tonalites, however, differ in two distinct ways: the level of heterogeneity at outcrop scale; and the primary mafic mineral as shown by modal analysis.

The Main Body tonalite is more heterogeneous than the Kelly Mountain tonalite, and these heterogeneities are concentrated in domains (Fig. 8). Modal analyses indicate that the primary mafic mineral changes from biotite to hornblende in the Main Body and Kelly Mountain samples, respectively (Figs. 14 and 15). Biotite in the older tonalite typically ranges from ~10-22%, whereas hornblende ranges from ~1-12% (Table 1). The data of Elkins (2015) on the ~92 Ma tonalite of SFJIC directly north of the study area is consistent with my observations. He found that in these rocks biotite averaged ~16%, whereas hornblende averaged ~4.5%. Conversely, hornblende within the younger tonalite ranges from ~7-23% and biotite ranges from ~1-9% (Table 1). Elkins (2015) did not analyze the ~78 Ma tonalite.

Petrogenesis of the Seven-Fingered-Jack Intrusive Complex

Previous studies on the mafic complex, diorites, and mafic enclaves and patches concluded that there were both mantle and crustal sources for the SFJIC (Dawes, 1993; DeBari et al., 1998; Miller et al., 2000; Matzel et al., 2008). The dominance of tonalite

reflects the crustal component. Previous workers concluded that the broad compositional range within the SFJIC could not be accounted for entirely by closed-system fractionation, and proposed that a silicic crustal component mixed with a high-alumina basalt derived from the mantle (Dawes, 1993; DeBari, 1998; Miller et al., 2000; Matzel et al., 2008). Major and trace element analyses from this study (Figs. 26 and 27) support this interpretation, as they indicate that the diorites and tonalites have different signatures, and that the tonalites (due to scatter on the plots) were likely emplaced in separate increments. The mafic source component for both the Main Body and Kelly Mountain tonalites is probably similar. It may be that after the older tonalite was emplaced, a hiatus occurred and that at ~78 Ma a renewed heat source injected a younger tonalite and a separate mafic component that had just enough heat and buoyancy to reach the mid crust, where both were arrested alongside the Main Body tonalite. Both the Main Body tonalite and Kelly Mountain rocks may have stopped at this mid-crustal level due to a density boundary (Petford and Atherton 1996). Even though the Main Body and Kelly Mountain tonalites plot in the same clusters on major and trace element plots, there is sufficient scatter to imply geochemically distinct injections during both time periods and possibly slight variations in the magma source.

The plot of Sr/Y versus Y (Fig. 29) indicates that the tonalites of the SFJIC are within the normal calc-alkaline values (Defant and Drummond, 1990). The lower-crustal source must have been <10 kbar as the geochemical analyses indicate a lack of garnet residue (Topuz et al., 2005). Evidence for this interpretation includes: 1) high values of Al_2O_3 (17-22%) (Fig. 26); 2) high values of Y (>14 ppm) (Fig. 27); 3) plots of La/Yb

Figure 29. Sr/Y versus Y plot for the SFJIC. Circles represent tonalites and triangles represent diorites. Solid circles are ~92 Ma and hollow symbols are ~78 Ma. Sample localities shown on Figure 25. Grey circles are analyses done by Elkins (2015).

versus SiO_2 and Dy/Yb versus SiO_2 (Fig. 30), which have amphibole trends; and 4) moderate depletion of the HREEs (Fig. 28).

The slight Eu anomaly in the tonalites is consistent with melt production in the field of plagioclase stability and/or modest plagioclase fractionation (Fig. 28). The absence of an Eu anomaly or a positive anomaly in the diorites is most likely due to a key amphibole component (e.g., hornblende) (Fig. 28). The small (+ or -) to negligible Eu anomalies seen in the SFJIC may also be due to fractionation of hornblende or appreciable residual hornblende during anatexis (Cullers and Graf, 1986).

Construction of the Seven-Fingered-Jack Intrusive Complex

Sheeted Geometry

Well-recognized and measurable sheet-like bodies within the study area are restricted to the tonalites, and are best developed in the ~92 Ma rocks. Contacts between sheets range from sharp to gradational, and are interpreted from modal and textural variations. Measured sheets are ~5 cm – 1 m wide, but their lateral extent is hard to constrain due to outcrop size. Miller and Paterson (2001a) noted that sheets within the SFJIC could be “up to hundreds of meters wide” and were laterally extensive for up to “hundreds of meters”. Other research (Miller and Paterson, 2001a; Matzel, 2004; Elkins, 2015) outside of the study area, indicates that sheets within the SFJIC consistently strike NW and dip moderately to steeply to the NE. My data differs from these observations (Fig. 20), as sheets within the study area strike NW with shallow to moderate dips to both the SW and NE, and less commonly contacts strike NE and have near vertical dips.

Figure 30. La/Yb and Dy/Yb versus SiO_2 plots for the SFJIC. Garnet versus amphibole fractionation trends after Davidson et al. (2012). Circles represent tonalites and triangles represent diorites. Solid circles are ~92 Ma and hollow symbols are ~78 Ma. Sample localities shown on Figure 25. Grey circles are analyses done by Elkins (2015).

The occurrence of sheets supports Paterson's and Miller's (1998a) and Miller's and Paterson's (2001a) hypothesis that the SFJIC was constructed by multiple injections of sheet-like bodies. The contacts are comparable with Bergantz's (2000) conclusions that melt injected over varied intervals of time allows for different amounts of solidification of the resident magma before new magmatic additions. If melt was injected relatively quickly, gradational boundaries or thoroughly hybridized rocks would be seen. In contrast, if injections were separated by a suitable hiatus, allowing for cooling and crystallization, then sharp contacts would prevail. Both types of contacts are seen implying that the tempo of melt injection varied.

Construction by multiple injections is further supported by geochemical data. A comparison of two Main Body tonalites, KD-53 from the central domain and BPX-154-A from the Marble Meadow sheet in the southern domain, indicates that they have different major and trace element signatures (Figs 26 and 27). BPX-154-A is enriched in Na_2O , Al_2O_3 , K_2O , FeO , P_2O_5 , V, Rb, Ba, Sr, and Pb relative to KD-53 (Figs. 26 and 27). These geochemical differences, combined with structural data, indicate that the Marble Meadows sheet is from a separate injection of melt than KD-53. As noted by Elkins (2015), a much larger pluton-scale geochemical investigation needs to be done to further constrain the dimensions of individual sheets and the order of their injection to advance our understanding of construction of the intrusive complex.

Emplacement Mechanisms

The ascent and emplacement of magma within the crust is still poorly understood, and how large a role different emplacement mechanisms play during construction is widely debated. Faulting, roof uplift, floor subsidence, diking, magma wedging, stoping, and ductile flow (e.g., Buddington, 1959; Paterson et al., 1996; Hutton, 1992; Cruden and McCaffrey, 2001) are proposed as ways to solve the “room problem” for magmatic intrusions. Within the study area, host rocks of the Main Body tonalite are not exposed. Host rocks to the Kelly Mountain suite are the Dumbell orthogneiss and the older Main Body tonalite. In the following, individual emplacement mechanisms are discussed as separate processes, although these material transfer processes probably work together to reach the amount of host rock transfer needed.

Emplacement in dilatational zones along faults is postulated for a number of settings, including arcs (e.g., D’Lemos et al., 1992; Berger et. al., 1996). Paterson and Miller (1998b) noted no significant faults within or at the ends of the SFJIC, and I similarly found no through going faults in the study area. Therefore, faulting was of minimal importance for emplacement.

Construction of plutons by roof uplift or floor subsidence due to continual addition of melt is proposed by many (e.g., Cruden and McCaffrey, 2001). Roof uplift is typically thought to be a viable space-making mechanism only when magmas reach shallow depths ($\sim < 5$ km) (Cruden and McCaffrey, 2001), which is much shallower than the SFJIC and will not be considered. Evidence of floor subsidence includes down-folded wall rock and the progressive steepening of sheets as the pluton grows (Cruden

and McCaffrey, 2001), giving the pluton an overall synformal structure. Wiebe and Collins (1998) also noted that for some plutons constructed by sub-horizontal sheets, features such as flame structures, load-casts, and pipes should form. My study area has no record of these types of features or an overall synformal structure. Furthermore, hornblende thermobarometry by Dawes (1993) shows no evidence of large-scale tilting of the SFJIC. Thus, the moderately to steeply dipping sheet contacts are similar to their original orientation.

Emplacement by diking assumes that the host rock behaves elastically, and that extensional fractures allow melt to be transported upward through the crust (e.g., Shaw, 1980; Takada, 1990; Lister and Kerr, 1991). Dike models require high length-to-width ratios and that dikes be emplaced at high angles to σ^3 and sub-parallel to σ^1 . Paterson and Miller (1998b), Miller and Paterson (2001b), and Elkins (2015) noted that sheets in the SFJIC intruded nearly perpendicular to the inferred regional σ^1 (NE-SW) and sub-parallel to σ^3 (vertical). In contrast, in my study area, some of the sheets are sub-parallel to the inferred direction of σ^1 (NW-SE) and at high angles to σ^3 , suggesting that the diking model may have operated in this part of the SFJIC. Sheets in other parts of the SFJIC may be compatible with Rubin's (1993) work where he noted that if both viscous flow and fracturing were simultaneously at work then melt could be injected at orientations other than those required by the dike model alone.

Magma wedging (cf. Ingram and Hutton, 1994; Weinberg, 1999) requires intruding melt to exploit anisotropies in the host rock. These anisotropies include older sheets and foliation planes. As the intruding magma wedges aside the host rock, it may

incorporate rafts. Paterson and Miller (1998b) and Miller and Paterson (2001a) noted that lateral displacement of the host rock (i.e. magma wedging) was likely at work in the SFJIC, but that most evidence of it was likely removed by simultaneous downward ductile flow. Host rock rafts and local folding may preserve evidence of this process. Elkins (2015) recognized a possible host rock raft in his study area, yet none were recognized in my study area.

If stoping was a significant mechanism of emplacement, abundant xenoliths should be seen. Xenoliths are rare in the study area, and thus, stoping was not a volumetrically significant emplacement mechanism.

Miller and Paterson (2001a) inferred that ductile flow occurred during the emplacement of the SFJIC. They noted that preservation of host-rock markers (foliations, lineations, host-rock contacts) within a (<500 m wide) structural aureole, indicated vertical material transfer by ductile flow. Foliations (magmatic and solid-state) are moderate to steep throughout the study area and show no intensification at contacts between the older tonalite and Kelly Mountain rocks. Lineations are gentle to steep, but like foliation, do not intensify near contacts. Thus no evidence of ductile flow is found in the study area, although the removal of a structural aureole by younger injections of melt cannot be totally precluded.

Comparison of the Main Body Tonalite with the Coeval Tenpeak Pluton

Across the Entiat fault from the SFJIC is the Tenpeak pluton, which is coeval with the Main Body tonalite (Fig. 2). This dominantly tonalitic pluton is ~92-89 Ma, and

was emplaced in the deep crust at 7-10 kb. Chan (2012) completed a detailed geochemical profile on a part of the southwestern margin of the Tenpeak pluton. Comparing the geochemical data of the Tenpeak pluton to the slightly shallower (6-8 kb) Main Body tonalite allows comparison of their magma sources.

Matzel et al. (2008) showed that ϵNd values were fairly similar in the Main Body tonalite and Tenpeak pluton. ϵNd for the Tenpeak pluton ranges from 3.7-5.1, whereas values for the SFJIC range from 4.6-5.2. The numbers also indicate that both plutons have melt components of depleted basaltic mantle and isotopically juvenile crustal terranes, and that the crustal input was more important for controlling ϵNd values. It is important to note that the geometry and depth of the metamorphic host terranes in the area are unknown. However, the values for the plutons in conjunction with the ϵNd values of their metamorphic host terranes are compatible with melts of these host rocks (i.e. Chelan Mountain and Nason terranes) representing the crustal input. The mantle melt most likely pooled under the lower crust causing it to partially melt and the two to mix. Thus, although melts of metamorphic terranes and of depleted mantle look to be the sources for both plutons, the isotopic study does not indicate whether those melt sources were identical. Further major and trace element data may clarify this question.

Comparing Y and REE data, the Tenpeak pluton was fed by a deeper source than the SFJIC. Chan's (2012) Y values for the Tenpeak pluton range from 9.21- 24.54 ppm, and, 60% of the analyses are <13 ppm, whereas Y values for the Main Body tonalite in the SFJIC range from 14.11-22.37 ppm (Fig. 31). The REE plots show that the Tenpeak pluton is more depleted in HREEs than the SFJIC (Fig. 32). Both of these types of

Figure 31. Sr/Y versus Y plot for the Main Body tonalite of the Seven-Fingered-Jack intrusive complex and coeval Tenpeak pluton. Solid circles represent ~92 Ma tonalites. Sample localities shown on Figure 25. Pink dashes represent Tenpeak pluton data from Chan (2012).

Figure 32. REE plots for the Main Body tonalite of the Seven-Fingered-Jack intrusive complex and coeval Tenpeak pluton. REE's are normalized to chondrite values of Sun and McDonough (1989). Tenpeak pluton data from Chan (2012). Sample localities shown on Figure 25.

analyses indicate that the Tenpeak pluton has markedly lower values of garnet-compatible elements and probably a deeper garnet-bearing source (DeBari et al., 1998, Chan 2012) than the SFJIC. Other data that supports a deeper source for the Tenpeak magmas can be seen in Fig. 33. Plots of La/Yb versus SiO₂ and Dy/Yb versus SiO₂ indicate that both plutons follow the amphibole fractionation trends as defined by Davidson et al. (2007). La/Yb increases as SiO₂ increases, and Dy/Yb decreases as SiO₂ increases. The Tenpeak pluton also has higher initial Dy/Yb values indicating a stronger garnet signal than in the SFJIC. Highly compatible elements are much more abundant in the Tenpeak pluton. Ni in the Tenpeak pluton ranges from 25-150 ppm, whereas Cr ranges from 90-600 ppm; these are 3 to 8 times and 4 to 12 times as much, respectively, as Ni and Cr ranges for the SFJIC. In addition, MgO levels in the Tenpeak pluton can be as much as double that of the SFJIC.

Given the above observations, the deep-crustal (15-18 kbar) melt component of the Tenpeak pluton had residual garnet (Dawes, 1993; DeBari et al., 1998; Miller et al., 2000; Matzel et al., 2008), whereas the crustal input of the SFJIC was from above the garnet stability depth. This comparison reveals that although the plutons are coeval, their melt is sourced from different parts of the crustal column.

CONCLUSIONS

1. The SFJIC in the Klone Peak area is at least in part built by multiple injections, some of which are sheet like. Contacts within the Main Body tonalite and Kelly Mountain

Figure 33. La/Yb and Dy/Yb versus SiO_2 plots for the Main Body tonalite of the Seven-Fingered-Jack intrusive complex and coeval Tenpeak pluton. Garnet versus amphibole fractionation trends after Davidson et al. (2012). Solid circles represent Main Body tonalites. Sample localities shown on Figure 25. Pink dashes represent Tenpeak pluton data from Chan (2012).

- suite are recognized by differences in composition and texture, and vary from sharp to gradational.
2. Magmatic foliation is invariably over-printed by a weak to moderate solid-state foliation. Moderately plunging, upright magmatic folds are common in the central domain of both the Main Body tonalite and Kelly Mountain suite. These orientations indicate that over the ~14 million years it took to construct the SFJIC, foliation and fold hinges mainly recorded the NE-SW regional contraction.
 3. The ~92 and ~78 Ma tonalites are broadly similar at an outcrop scale, but differ modally and geochemically. The dominant mafic mineral in the older tonalite is biotite, whereas hornblende is the dominant mafic constituent of the Kelly Mountain tonalite. Tonalites from both units plot geochemically in broad clusters, but the scatter is expansive enough to indicate that different batches of melt built the intrusive complex. There is no discernable injection pattern, implying that the complex was built randomly.
 4. The SFJIC was likely emplaced by a variety of mechanisms, including diking, magmatic wedging, and ductile flow.
 5. The SFJIC and the coeval, deeper Tenpeak pluton do not share the same melt source. The Tenpeak pluton has a strong garnet signature (Chan, 2012), whereas the SFJIC has an amphibole signature. This indicates that the Tenpeak pluton and the SFJIC are not necessarily a part of a single simple “plumbing system”.

REFERENCES CITED

- Allmendinger, R.W., 2013, Stereonet 9, A computer program for stereographic projections, Department of Geology, Cornell University, <http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html>
- Bergantz, G.W., 2000, On the dynamics of magma mixing by reintrusion: Implications for pluton assembly processes: *Journal of Structural Geology*, v. 22, p. 1297-1309.
- Berger, A., Rosenberg, C., and Schmidt, S.M., 1996, Ascent, emplacement, and exhumation of the Bergell pluton within the southern steep belt of the southern Alps: *Schweizerische Mineralogisch Petrographische Mitteilungen*, v. 76, p. 357-382.
- Billings, M.P., 1972, *Structural geology* (third edition): Upper Saddle River, New Jersey, Prentice Hall Inc., 606 p.
- Brown, E. H., and Dragovich, J. D., 2003, Tectonic elements and evolution of northwest Washington: Washington Division of Geology and Earth Resources, Geologic Map GM-2, scale 1:625,000.
- Buddington, A.F., 1959, Granite emplacement with special reference to North America: *Geological Society of America Bulletin*, v. 70, p. 671–748.
- Cater, F.W., 1982, Intrusive rocks of the Holden and Lucerne quadrangles, Washington—the relations of depth zones, compositions, textures, and emplacement of plutons: U.S. Geological Survey Professional Paper 1220, 108 p.
- Cater, F.W., and Crowder, D.F., 1967, Geologic map of the Holden Quadrangle, Snohomish and Chelan Counties, Washington: U.S. Geological Survey Map GQ-646, scale 1:62,500.
- Cater, F.W., and Wright, T.L., 1967, Geologic map of the Lucerne Quadrangle, Chelan County, Washington: U.S. Geological Survey Map GQ-647, scale 1:62,500.
- Chan, C.F., 2012, Constructing a sheeted magmatic complex within the lower arc crust: Insights from the Tenpeak pluton, North Cascades, Washington [M.S. Thesis]: Corvallis, Oregon State University, 333 p.
- Cruden, A.R., and McCaffrey, K.J.W., 2001, Growth of plutons by floor subsidence: Implications for rates of emplacement, intrusion spacing and melt-extension mechanisms: *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, v. 26, p. 303-315.

- Cullers, R.L., and Graf, J.L., 1986, Rare earth elements in igneous rocks of the continental crust: intermediate and silicic rocks – ore petrogenesis, *in* Henderson, P., and Fyfe, W.S., eds., *Developments in Geochemistry, Volume 2: Rare Earth Element Geochemistry*: New York, Elsevier, p. 285-293.
- Davidson, J., Turner, S., Handley, H., Macpherson, C., and Dosseto, A., 2007, Amphibole “sponge” in arc crust?: *Geology*, v. 35, p. 787-790.
- Davis, J.W., Coleman, D.S., Gracely, J.T., Gaschnig, R., and Stearns, M., 2012, Magma accumulation rates and thermal histories of plutons of the Sierra Nevada batholith, CA: *Contributions to Mineralogy and Petrology*, v. 163, p. 449-465.
- Dawes, R.L., 1993, Mid-crustal, Late Cretaceous plutons of the North Cascades: petrogenesis and implications for the growth of continental crust [Ph.D. thesis]: Seattle, University of Washington, 272 p.
- DeBari, S.M., 1998, Genesis of tonalitic plutons in the Cretaceous magmatic arc of the North Cascades: Mixing of mantle-derived mafic magmas and melts of a garnet bearing lower crust: *Geological Society of America Abstracts with Programs*, v. 30, no. 7, p. 257-258.
- Defant, M.J., and Drummond, M.S., 1990, Derivation of some modern arc magmas by melting of young subducted lithosphere: *Nature*, v. 347, p. 662-665.
- D’Lemos, R.S., Brown, M., and Strachan, R.A., 1992, The relationship between granite and shear zones: magma generation, ascent, and emplacement in a transpressional orogen: *Geological Society of London*, v. 149, p. 487-490.
- Dustin, K.D., 2012, Intrusive relationships and deformation of mafic and tonalitic rocks in part of the Seven Fingered Jack pluton, North Cascades, Washington [B.S. thesis]: San Jose, San Jose State University, 22 p.
- Elkins, S.W., 2015, Structure, construction, and geochemistry of the highly elongate Seven-Fingered-Jack pluton in the Devil’s Smokestack area, North Cascades, Washington [M.S. thesis]: San Jose, San Jose State University, 101 p.
- Garcia, M.O., and Jacobson, S.S., 1979, Crystal clots, amphibole fractionation and the evolution of calc-alkaline magmas: *Contributions to Mineralogy and Petrology*, v. 69, p. 319-327.

- Glazner, A.F., Bartley, J.M., 2006, Is stopping a volumetrically significant pluton emplacement process?: *Geological Society of America Bulletin*, v. 118, p. 1185-1195.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation from small magma chambers?: *Geological Society of America Today*, v. 14, no. 4/5, p.4-11
- Hirth, G., and Tullis, J., 1992, Dislocation creep regimes in quartz aggregates: *Journal of Structural Geology*, v. 14, p. 145-159.
- Hutton, D.H.W., 1992, Granite sheeted complexes: Evidence for the dyking ascent mechanism: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 83, p. 377-382.
- Ingram, G.M., and Hutton, D.H.W., 1994, The Great Tonalite sill: Emplacement into a contractional shear zone and implications for Late Cretaceous to Early Eocene tectonics in southeastern Alaska and British Columbia: *Geological Society of America Bulletin*, v. 106, p. 715-728
- Leuthold, J., Müntener, O., Baumgartner, L.P., Putlitz, B., Ovtcharova, M., and Schaltegger, U., 2012, Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia): *Earth and Planetary Science Letters*, v. 325, p. 85-92.
- Lister, J.R., and Kerr, R.C., 1991, Fluid-mechanical models of crack propagation and their application to magma transport in dikes: *Journal of Geophysical Research*, v. 96, p. 10049-10077.
- Matzel, J.P., 2004, Rates of tectonic and magmatic processes in the North Cascades continental magmatic arc [Ph.D. thesis]: Cambridge, Massachusetts, Massachusetts Institute of Technology, 249 p.
- Matzel, J.P., Bowring, S.A., and Miller, R.B., 2008, Spatial and temporal variations in Nd isotopic signatures across the crystalline core of the North Cascades, Washington, *in* Wright, J.E., and Shervais, J.W., eds., *Ophiolites, arcs, and batholiths: A tribute to Cliff Hopson*: *Geological Society of America Special Paper* 438, p. 499-516, doi: 10.1130/2008.2438(18).
- McDonough, W.F. and Sun, S.S., 1995, Composition of the Earth: *Chemical Geology* v. 120, p. 223-253. doi: 10.1016/0009-2541(94)00140-4.
- McGroder, M.F., 1991, Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia: *Geological Society of America Bulletin*, v. 103, p. 189-209.

- Michel, J., Baumgartner, L., Putlitz, B., Schaltegger, U., and Ovtcharova, M., 2008, Incremental growth of the Patagonian Torres del Paine laccolith over 90 ky: *Geology*, v. 36, p. 459-462.
- Miller, C.F., Watson, E.B., and Harrison, T.M., 1988, Perspectives on the source, segregation and transport of granitoid magmas: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 79, p. 135-156.
- Miller, J.S., 2008, Assembling a pluton... one increment at a time: *Geology*, v. 36, p. 511-512.
- Miller, R.B., 1985, The ophiolitic Ingalls Complex, North Cascades, Washington: *Geological Society of America Bulletin*, v. 96, p. 27-42.
- Miller, R.B., and Bowring, S. A., 1990, Structure and chronology of the Oval Peak batholith and adjacent rocks: Implications for the Ross Lake fault zone, North Cascades, Washington: *Geological Society of America Bulletin*, v. 102, p. 1361-1377.
- Miller, R.B., and Paterson, S.R., 1992, Tectonic implications of syn- and post-emplacement deformation of the Mount Stuart batholith for mid-Cretaceous orogenesis in the North Cascades: *Canadian Journal of Earth Sciences*, v. 29, p. 479-485.
- Miller, R.B., and Paterson, S.R., 1999, In defense of magmatic diapirs: *Journal of Structural Geology*, v. 21, p. 1161-1173.
- Miller, R.B., and Paterson, S.R., 2001a, Construction of mid-crustal sheeted plutons: Examples from the North Cascades, Washington: *Geological Society of America Bulletin*, v. 113, p. 1423-1442.
- Miller, R.B., and Paterson, S.R., 2001b, Influence of lithological heterogeneity, mechanical anisotropy, and magmatism on the rheology of an arc, North Cascades, Washington: *Tectonophysics*, v. 342, p. 351-370.
- Miller, R.B., Haugerud, R.A., Murphy, F., and Nicholson, L. S., 1994, Tectonostratigraphic framework of the northeastern Cascades: *Washington Division of Geology and Earth Resources Bulletin*, v. 80, p. 73-92.
- Miller, R.B., Paterson, S.R., DeBari, S.R., and Whitney, D.L., 2000, North Cascades Cretaceous crustal section: Changing kinematics, rheology, metamorphism, pluton emplacement, and petrogenesis from 0-40 km depth, *in* Woodsworth, G.J., Jackson, L.E., Jr., Nelson, J.L., and Ward, B.C., eds., *Guidebook for Geological*

Field Trips in Southwestern British Columbia and Northern Washington:
Vancouver, Geological Association of Canada, p. 229-278.

- Miller, R.B., Matzel, J.P., Paterson, S.R., and Stowell, H., 2003, Cretaceous to Paleogene Cascades arc: Structure, metamorphism, and timescales of magmatism, burial, and exhumation of a crustal section, *in* Swanson, T., ed., Western Cordillera and Adjacent Areas Boulder, Colorado: Geological Society of America Field Guide 4, p. 107-135.
- Miller, R.B., Paterson, S.R., and Matzel, J.P., 2009, Plutonism at different crustal levels: Insights from the ~5–40 km (paleodepth) North Cascades crustal section, Washington, *in* Miller, R.B., and Snoke, A.W., eds., Crustal cross sections from the western North American Cordillera and elsewhere: Implications for tectonic and petrologic processes: Geological Society of America Special Paper 456, p. 125–149, doi: 10.1130/2009.2456(05).
- Misch, P., 1966, Tectonic evolution of the Northern Cascades of Washington State- A west-Cordilleran case history, *in* Gunning, H.C., ed., A symposium on the tectonic history and mineral deposits of the western Cordillera in British Columbia and neighboring parts of the United States: Canadian Institute of Mining and Metallurgy Special Volume 8, p. 101-148.
- Paterson, S.R., and Miller, R.B., 1998a, Mid-crustal magmatic sheets in the Cascades Mountains, Washington: Implications for magma ascent: *Journal of Structural Geology*, v. 20, p. 1345-1363.
- Paterson, S.R., and Miller, R.B., 1998b, Magma emplacement during arc-perpendicular shortening: An example from the Cascades crystalline core, Washington, *Tectonics*, v. 17, p. 571-586.
- Paterson, S.R., Vernon, R.H., and Tobisch, O.T., 1989, A review of criteria for the identification of magmatic and tectonic foliations in granitoids: *Journal of Structural Geology*, v. 11, p. 349-363.
- Paterson, S.R., Fowler, T.K., and Miller, R.B., 1996, Pluton emplacement in arcs: a crustal-scale exchange process: *Geological Society of America Special Paper*, 315, p. 115-123.
- Paterson, S.R., Fowler, T.K., Schmidt, K.L., Yoshinobu, A.S., Yuan, E.S., and Miller, R.B., 1998, Interpreting magmatic fabric patterns in plutons: *Lithos*, v. 44, p. 53-82.

- Petford, N., and Atherton, M., 1996, Na-rich partial melts from newly underplated basaltic crust: the Cordillera Blancas Batholith, Peru: *Journal of Petrology*, v. 37, p. 1491-1521.
- Petford, N., Cruden, A.R., McCaffrey, K.J.W., and Vigneresse, J.L., 2000, Granite magma formation, transport and emplacement in the Earth's crust: *Nature*, v. 408, p. 669-673.
- Pitcher, W.S., and Beger, A.R., 1972, *The geology of Donegal: A study of granite emplacement and unroofing*: New York, Wiley, 435 p.
- Rocchi, S., Westerman, D.S., Dini, A., and Farina, F., 2010, Intrusive sheets and sheeted intrusions at Elba Island, Italy: *Geosphere*, v. 6, p. 225-236.
- Rosenberg, C.L., and Stünitz, H., 2003, Deformation and recrystallization of plagioclase along a temperature gradient: an example from the Bergell tonalite. *Journal of Structural Geology*, v. 25, p. 389-408.
- Rubin, A.M., 1993, Dikes vs diapirs in viscoelastic rock: *Earth and Planetary Science Letters*, v. 199, p. 641-659.
- Schaltegger, U., Brack, P., Ovtcharova, M., Peytcheva, I., Schoene, B., Stracke, A., Marocchi, M., and Bargossi, G.M., 2009, Zircon and titanite recording 1.5 million years of magma accretion, crystallization and initial cooling in a composite pluton (southern Adamello batholith, northern Italy): *Earth and Planetary Science Letters*, v. 286, p. 208-218.
- Shaw, H.R., 1980, The fracture mechanism of magma transport from the mantle to the surface, *in* Hargraves, R.B., ed., *Physics of Magmatic Processes*: Princeton, New Jersey, Princeton University Press, p.201-264.
- Shea, E., 2014, Arc magmatism at different crustal levels, North Cascades, WA [Ph.D. thesis]: Cambridge, Massachusetts, Massachusetts Institute of Technology, 555 p.
- Stearns, M.A., and Bartley, J.M., 2014, Multistage emplacement of the McDoogie pluton, an early phase of the John Muir intrusive suite, Sierra Nevada, California, by magmatic crack-seal growth: *Geological Society of America Bulletin*, v. 126, p. 1569-1579.
- Sun, S.S., and W.F. McDonough, 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes: *Geological Society, London, Special Publications*, v. 42, p. 313-345, doi: 10.1144/GSL.SP.1989.042.01.19

- Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Zartman, R.E., 1987a, Geologic map of the Chelan 30-minute by 60-minute Quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1661, scale 1:100,000.
- Tabor, R.W., Zartman, R.E., and Frizzell, V.A., 1987b, Possible tectonostratigraphic terranes in the North Cascades crystalline core, Washington, *in* Schuster, J.E., ed., Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 107-127.
- Tabor, R.W., Haugerud, R.A., and Miller, R.B., 1989, Overview of the geology of the North Cascades: American Geophysical Union, International Geological Congress Trip T307, 62 p.
- Takada, A., 1990, Experimental study on propagation of liquid filled crack in gelatin: Shape and velocity in hydrostatic stress condition: *Journal of Geophysical Research: Solid Earth*, v. 95, p. 8471-8481.
- Tappa, M.J., Coleman, D.S., Mills, R.D., and Samperton, K.M., 2011, The plutonic record of a silicic ignimbrite from the Latir volcanic field, New Mexico: *Geochemistry, Geophysics, Geosystems*, v. 12, 16 p. doi: 10.1029/2011GC003700.
- Topuz, G., Altherr, R., Schwarz, W.H., Siebel, W., Satır, M., and Dokuz, A., 2005, Post-collisional plutonism with adakite-like signatures: the Eocene Saraycık granodiorite (Eastern Pontides, Turkey): *Contributions to Mineralogy and Petrology*, v. 150, p. 441-455.
- Weinberg, R.F., 1999, Mesoscale pervasive felsic magma migration: alternatives to dyking: *Lithos*, v. 46, p. 393-410. doi:10.1016/S0024-4937(98)00075-9
- Whitney, D.L., Miller, R.B., and Paterson, S.R., 1999, P-T-t constraints on mechanisms of vertical tectonic motion in a contractional orogen: *Journal of Metamorphic Geology*, v. 17, p. 75-90.
- Winter, J.D., 2010, *Principles of Igneous and Metamorphic Petrology: Second Edition*: New Jersey, Pearson Education, Inc, 702 p.
- Wiebe, R.A., and Collins, W.J., 1998, Depositional features and stratigraphic sections in granitic plutons: implications for the emplacement and crystallization of granitic magmas: *Journal of Structural Geology*, v. 20, p. 1272-1289.