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Structure, Construction, and Geochemistry of the Highly Elongate, Cretaceous Seven-Fingered Jack Pluton in the Devil's Smokestack Area, North Cascades, Washington

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STRUCTURE, CONSTRUCTION, AND GEOCHEMISTRY OF THE HIGHLY
ELONGATE, CRETACEOUS SEVEN-FINGERED JACK PLUTON IN THE
DEVIL'S SMOKESTACK AREA, NORTH CASCADES, WASHINGTON

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

By

Scott W. Elkins

May 2015

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The Designated Thesis Committee Approves the Thesis Titled

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May 2015

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ABSTRACT
STRUCTURE, CONSTRUCTION, AND GEOCHEMISTRY OF THE HIGHLY
ELONGATE, CRETACEOUS SEVEN-FINGERED JACK PLUTON IN THE
DEVIL'S SMOKESTACK AREA, NORTH CASCADES, WASHINGTON

By Scott W. Elkins

This thesis provides an analysis of magmatic structures and geochemistry from a portion of the mid-crustal, ~92-90 Ma Seven-Fingered Jack pluton, North Cascades, Washington. The study area was divided into three separate domains. Rocks in the northern domain (~9 km²) are characterized by N-NNW-trending, moderately to steeply plunging magmatic folds that reflect regional shortening. The central (~3 km²) and southern (~3.5 km²) domains are structurally homogeneous and contain a dominant NW-striking magmatic foliation. Schlieren are locally developed, several meters long, thin (cm-scale), and strike NW and dip steeply to the NE. Field data indicate the pluton is constructed of numerous, ≤300 m-wide, ≤1 km-long, sheet-like bodies separated by sharp and gradational contacts that are identified by textural and/or compositional differences. During construction, earlier sheets acted as host rocks to younger increments of melt. Detailed modal analyses (n=39) by point counting, coupled with XRF and ICP-MS geochemical analyses (n=8), indicate that the hornblende-biotite tonalite that comprises the study area is overall chemically and texturally homogeneous. Geochemical data further indicate that parental magmas may have come from a relatively shallow source, compared to the deeper, coeval Tenpeak pluton, and incorporated evolved crustal material.

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INTRODUCTION

Plutons constitute a large portion of the continental crust. Despite many advances in the past 25 years, there is still much to learn concerning magmatic processes during pluton construction, including magma ascent and emplacement, the sizes of magmatic increments, the sizes of magma chambers, and the time scales of pluton construction (e.g., Saleeby, 1990; Wiebe and Collins, 1998; Miller and Paterson, 2001a; Ducea et al., 2003; Cruden, 2006; Matzel et al., 2006; Paterson et al., 2011). These questions are difficult to answer, in part, because plutons range in size, geometry, depth of emplacement, and tectonic setting and intrude host rocks with variable characteristics. Furthermore, the record of ascent is obscured by subsequent processes at the emplacement level, and therefore only mechanisms active during final stages of construction are typically well preserved (e.g., Marsh, 1982; Paterson et al., 1998; Bergantz, 2000). Despite these complications, plutons provide the most comprehensive records of crustal magmatic processes and are critical for understanding continental arc evolution. Plutons also commonly record a longer history than modern volcanic systems and thus provide a window into magmatic “plumbing systems” that are active over millions of years. Therefore, it is important to consider what a pluton represents.

In their review of magma fluxes for incrementally constructed, continental arc plutons, Paterson et al. (2011) proposed two end members and a wide variety of intermediate possibilities for how to view these intrusions. In one end member, a pluton represents a former single, connected, and relatively closed system that froze during ascent. In the other end member, plutons are solidified complex transfer zones that may be extensive, be utilized during several ascent events, recycle and remobilize material, and therefore remain open systems. Within these crustal-scale magma plumbing systems, distinct magma batches range in size from $<10 \text{ m}^3$ to $>1000 \text{ km}^3$ according to some workers (Paterson et al., 2011). It remains uncertain, however, whether these systems ever consisted of large, eruptible magma chambers (Glazner, 2004), as the development of chambers depends on initial boundary conditions and the volumetric flux of magma into the growing body. A greater degree of interaction between different increments occurs when volumetric flux is larger than conductive cooling and/or where magma is spatially focused (e.g., Wilson et al., 1988; Hanson and Glazner, 1995; Yoshinobu et al., 1998; Paterson et al., 2011).

The view of plutons representing a single magma chamber constructed over a short time interval has been replaced by the more recent view that they formed incrementally and potentially over a protracted time interval (Wiebe and Collins, 1998; Miller and Paterson, 2001a; Mahan et al., 2003; Glazner et al., 2004; Paterson et al., 2008; Miller et al., 2009; Annen, 2011; Michaut and Jaupart, 2011). Intrusive sheets preserved within plutons provide evidence for

incremental growth. The nature of internal contacts separating different sheets offers insights into the degree to which successive inputs interacted. To preserve sharp, near-vertical internal contacts requires a large rheological contrast and a high absolute viscosity of the resident material when the next magmatic increment intrudes (Bergantz, 2000). This resident material must be essentially solid or have a low percentage of melt that permits grain-grain continuity and thus a supporting “framework” (Bergantz, 2000).

To better understand plutons, and the magmatic systems which they represent, well-exposed crustal sections that record processes at varying crustal depths are studied (e.g., Saleeby, 1990; Miller and Snoke, 2009). A vertically extensive, Cretaceous crustal section preserved in the crystalline core of the North Cascades (Fig. 1) records physical and chemical properties bearing on pluton construction, emplacement, geometry, composition, and deformation at paleodepths of ~5-40 km (Miller and Paterson, 2001b; Miller et al., 2009). The Seven-Fingered Jack pluton is part of this crustal section and represents a highly elongate (~50 km by 7 km), mid-crustal (20-25 km) intrusion that is the focus of this study (Figs. 2-4). The Seven-Fingered Jack pluton, together with the younger Entiat pluton to the south, form an ~80-km by 8-km outcrop belt. Previous mapping studies considered them as one pluton (Entiat pluton; Tabor et al., 1987), but because of an ~20 Myr gap between these intrusions, Matzel (2004) used the term Seven-Fingered Jack intrusive suite (following Cater and Crowder, 1967) to describe the northwestern, ~92-90 Ma rocks, and Entiat

Figure 1. Location of the Cascades crystalline core. Inset shows major features of the Cascades core. Perpendicular dashes are plutons and parallel dashes are metamorphic units. Abbreviations are as follows: CBTS-Coast Belt thrust system; ECFB-Eastern Cascades fold-thrust belt; NWCS-Northwest Cascades thrust system; SCF-Tertiary Straight Creek fault. Modified from Miller and Paterson (2001a).

Figure 2. Simplified geologic map of part of the eastern Cascades core. CS—Chiwaukum Schist (Early Cretaceous protolith), H—Holden unit (Triassic protolith and includes Triassic Dumbell plutons and other orthogneisses), N—Napeequa Complex (probable Mississippian to Jurassic protolith), SFJ—Seven-Fingered Jack pluton, SG—Skagit Gneiss, SW—Swakane Gneiss (Cretaceous protolith). Numbers denote age. Modified from Miller and Paterson (2001a).

Figure 3. General geologic map of part of the Seven-Fingered Jack pluton. Boxes indicate the three detailed mapping domains: northern, central, and southern. Numbers correspond to stations with modal analysis data (Table 2). Modified from Cater and Wright (1967).

Figure 4. Picture of northern part of the Seven-Fingered Jack pluton. View is to the south of Cow Creek Meadows.

intrusive suite for the southeastern, ~72 Ma rocks. More recent geochronological data from the Seven-Fingered Jack intrusive suite, including dates from within the study area, suggest a ~4 Myr intrusive duration for the suite, and a ~1.02 Myr duration for the study area, from 91.77-90.75 Ma (Shea, 2014).

Several fundamental questions regarding pluton construction remain unanswered. For example, what are the shapes, sizes, and orientations of individual magmatic increments? What is the extent of physical interaction between increments, and what influence, if any, did tectonic processes have on the emplacement of these magmas?

To better assess magma ascent and emplacement processes in the mid-crust (20-25 km), Paterson and Miller (1998) conducted a detailed study on the magmatic sheet tips in the northwestern and central parts of the Seven-Fingered Jack pluton. They showed that sheet thicknesses ranged from ~1-2 m to at least 10s of m with sheets coalescing to form larger km-scale bodies. Based on sheet-tip length-to-width ratios, radius of curvatures, and tip diameter to sheet-width ratios, Paterson and Miller (1998) proposed diapiric rise of magma associated with viscoelastic flow of host rock. They also noted that foliation patterns in the host rock at, and in front of, sheet tips define upright, gently plunging folds. Some folds are in older parts of the pluton and, therefore, indicate protracted deformation during assembly. Furthermore, sheets margins are parallel to the axial planes of these folds (Paterson and Miller, 1998).

Miller and Paterson (2001a) also described in detail the Seven-Fingered Jack (considered part of the Entiat pluton at that time) intrusion, emphasizing the structure and emplacement mechanisms of mid-crustal sheeted plutons. They and Cater (1982) noted that the pluton consisted of a marginal heterogeneous mafic complex, which they inferred graded into thicker sheets of tonalite towards the interior. This marginal mafic complex is now known to be younger than interior tonalite bodies (Matzel, 2004). Miller and Paterson (2001a) speculated that early injections of mafic and more felsic crustal melts led to the development of heated pathways, which were employed by later batches of felsic magma to feed shallower, more homogenized magma bodies. They presented a scenario for magma chamber construction in which initial intrusion of magmatic sheets wedged aside host rock and coalesced, eventually forming a chamber devoid of host rock inclusions as a result of detachment and vertical downward transport.

Geologic Setting

The crystalline core of the North Cascades represents the southeastern extent of the >1500-km-long Coast Plutonic Complex (Fig. 1) and preserves a complex history of Cretaceous to Paleogene deformation, magmatism, and metamorphism (e.g., Misch, 1966; Tabor et al., 1987, 1989; Miller et al., 2009). The Cascades core, along with several other orogenic belts (i.e. Caledonides, Hercynian, Lachlan), contains zones of highly elongate, internally sheeted

plutons constructed by injection of multiple steep magmatic sheets (Miller and Paterson, 2001a). In the Chelan block of the Cascades core (Fig. 1), a 20-25-km-wide region of ~92-46 Ma, markedly elongate, and commonly internally sheeted plutons intrude metamorphosed (amphibolite facies) host rocks (Fig. 2) (Cater, 1982; Tabor et al., 1989).

Separating the Cascades core from Paleozoic and Mesozoic oceanic and island-arc terranes to the west is the Eocene, dextral Straight Creek-Fraser River fault (Fig. 1) (Misch, 1966). To the east, the core is juxtaposed against dominantly Mesozoic strata of the Methow basin by the Late Cretaceous(?)–Paleogene Ross Lake fault zone (Misch, 1966; Miller and Bowring, 1990). The Eocene Entiat fault splits the core into two structural blocks, the southwestern Wenatchee block and the northeastern Chelan block (Fig. 2) (Tabor et al., 1989).

Host rocks to the Seven-Fingered Jack pluton are the Napeequa unit to the southwest, the Holden assemblage to the northeast, and the Dumbell orthogneiss, which primarily occurs to the northeast (Fig. 3) (Cater and Crowder, 1967; Cater and Wright, 1967; Miller et al., 1994). The Napeequa complex is mostly siliceous mica schist, micaceous quartzite, and fine-grained amphibolite, along with minor metaperidotite and marble lenses, and has an inferred oceanic protolith of Mississippian–Jurassic age (Misch, 1966; Cater, 1982; Tabor et al., 1989; Miller et al., 1994; Brown and Dragovich, 2002). The Holden assemblage consists of hornblende- and biotite-hornblende schist and gneiss, leucocratic

biotite gneiss, and clinopyroxene-biotite schist, and is part of a Triassic arc sequence (Cater, 1982; Tabor et al., 1989; Miller et al., 1994). The Dumbell Mountain plutons are composed of three units, the largest of which is intruded by the Seven-Fingered Jack pluton. This unit is a gneissic hornblende-quartz diorite (Cater, 1982) and is more strongly deformed in the solid state than is the Seven-Fingered Jack pluton.

Tertiary plutons locally intrude the Seven-Fingered Jack pluton (Fig. 3). The Larch Lakes pluton (Cater, 1982) is biotite granodiorite and intrudes the northernmost extent of the study area. The Rampart Mountain pluton (Cater, 1982) consists of biotite quartz monzonite and intrudes the western margin of the Seven-Fingered Jack pluton in the northern map domain. Lastly, the Duncan Hill pluton locally intruded the northeastern margin of the pluton and does not occur in the study area. The Duncan Hill pluton is dominantly biotite-and hornblende-biotite tonalite and granodiorite (Cater, 1982).

In the Cretaceous, peak metamorphism in the Cascades core reached middle-to upper-amphibolite facies (Misch, 1966; Tabor et al., 1989; Whitney et al., 1999). Within the Chelan block, the Napeequa unit records peak metamorphism at 640-740°C and 10-11 kbar (Valley et al., 2003). Directly southwest of the ~72 Ma Entiat pluton, Napeequa rocks record lower pressures (6-7 kbar) that may indicate 3-5 kbar of unroofing prior to emplacement of this intrusion (Valley et al., 2003; Paterson et al., 2004). These lower pressures are

similar to the 6-8 kbar values from Al-in-hornblende barometry from localities within both the Entiat and Seven-Fingered Jack plutons (Dawes, 1993).

Methods

Field mapping and data collection were completed during the summer of 2012. Mapping of the study area (~13 km²) at a 1:24,000 scale was coupled with more detailed mapping at 1:10,000 scale of three ~2.5 km² to 7.5 km² areas, referred to as the northern, central, and southern domains (Fig. 3). These detailed study map areas were chosen to maximize along- and across-strike coverage. Rock units were differentiated on the basis of variations in grain size and color index. Orientations of foliations, lineations, internal contacts, and other magmatic features (e.g., schlieren, syn-plutonic dikes, and magmatic shear zones) were measured.

To evaluate along-strike and across-strike variations in enclave properties, enclaves were divided into five types (A-E) based on differences in texture, color index, and modal abundances. Enclave abundance, defined as the number of enclaves within an imaginary ~4x4 meter box around the location that foliations were measured, and enclave type were recorded at each station.

Samples were collected and 44 thin sections studied and described (Appendix). Modal analysis of 39 thin sections was performed with a mechanical stage set at 1.0 mm spacing separating each transect and 2.0 mm spacing

between each mineral count with an average of approximately 350 counts per thin section.

Eight samples were analyzed by x-ray fluorescence (XRF) (Johnson et al., 1999) and ICP-MS at Washington State University (see soe.wsu.edu for further description of technique). Major and trace elements, including rare-earth elements (REE), were determined. Four samples from the northern domain were collected from either side of internal contacts (SFJ-85a/b and SFJ-2a/c). To better constrain the along-strike geochemical characteristics of the “homogeneous tonalite,” two samples from the central (SFJ-96 and SFJ-124) and southern (SFJ-162 and SFJ-174) domains were chosen as representative of each area.

UNITS OF THE SEVEN-FINGERED JACK PLUTON

This section provides petrographic descriptions of rock units in the study area. The majority of the chapter is dedicated to the most abundant and best studied unit, the Seven-Fingered Jack hornblende-biotite tonalite. I briefly describe the mafic complex; however, because of the ~13 Myr age gap between the mafic complex and tonalite, I do not include rocks of the complex as part of the Seven-Fingered Jack pluton for this study.

Hornblende-Biotite Tonalite of the Seven-Fingered Jack Pluton

The most abundant unit within the study area is an equigranular hornblende-biotite tonalite. It is typically medium- to coarse-grained, has a moderate color index (~20), a well-developed magmatic foliation and lineation defined by hornblende and biotite, contains mafic enclaves, and is locally overprinted by a weak-to-moderate solid-state fabric. The term “solid-state fabric” refers to the alignment of crystals during subsolidus plastic deformation and recrystallization (Paterson et al., 1989). The hornblende-biotite tonalite consists of plagioclase (49.2%), quartz (25.8%), biotite (16%), hornblende (4.5%), secondary and accessory minerals (i.e. sphene, epidote, chlorite) (4.5%), and potassium feldspar (.04%). Although described in previous studies (Cater, 1982; Paterson and Miller, 1998; Miller and Paterson, 2001a), no biotite-hornblende tonalite was found in the study area.

Plagioclase within the hornblende-biotite tonalite ranges from ~2 mm to 7.8 mm in length and averages 4.9 mm, is subhedral to anhedral, and contains locally well-developed oscillatory zoning. Growth (albite) and mechanical twins are present in all samples. Myrmekite occurs locally in samples with a higher degree of solid-state deformation. Saussuritization of plagioclase is common, especially in samples that show larger degrees of deformation.

Quartz occurs as inequigranular-interlobate to seriate-amoeboid aggregates and mosaics. Individual quartz crystals are fine- to coarse-grained, ranging from <1 mm to ~4.5 mm long and averaging ~1.9 mm, and exhibit

undulose extinction and subgrains. Subgrains are typically <0.5 mm in diameter and commonly grade into recrystallized quartz grains, indicating subgrain rotation recrystallization.

Biotite ranges from <1 mm to ~6 mm in length, averaging 2.7 mm, and is typically kinked. It has a bimodal crystal-size distribution consisting of larger magmatic crystals and smaller, recrystallized grains and aggregates. Biotite is altered to chlorite in several samples and replaces hornblende along cleavage planes. Chlorite occurs as an alteration product of biotite in several samples.

Hornblende forms subhedral to anhedral crystals that range from 1 mm to 8 mm in length and average 3.2 mm. It typically occurs as larger magmatic crystals and smaller recrystallized grains. These magmatic grains form aggregates with biotite, epidote, and sphene.

Epidote and sphene are the most abundant secondary and accessory minerals, and are present in all samples. Magmatic epidote is typically subhedral and averages ~1 mm in diameter, whereas secondary crystals are smaller ($\leq$ ~0.25 mm wide) and anhedral. Primary sphene is similarly larger (~1-3.5 mm wide) and occurs as subhedral to locally euhedral crystals, whereas secondary sphene averages less than 0.5 mm in width and is anhedral. Minor zircon typically forms very small crystals in biotite.

Mafic Complex

Rocks of the heterogeneous mafic complex occur primarily next to the eastern contact of the Seven-Fingered Jack pluton and at one locality in the northern region where an ~15 m-thick mafic dike cross-cuts the hornblende-biotite tonalite. Hornblende diorite and gabbro are most abundant, whereas hornblendite, quartz diorite, tonalite, trondhjemite, and granodiorite occur in lesser amounts (Cater, 1982; Miller and Paterson, 2001a). A body of hornblende diorite and gabbro found a short distance (~1 km) north of the northern domain was dated at ~79.1 Ma by Matzel (2004); Shea (2014) determined an age of ~77.7 Ma for a hornblende dike in the study area.

The rocks vary from fine-grained to locally pegmatitic. Cater (1982) noted that hornblende and plagioclase (An_{38} - An_{50}) are the only major phases that are common to all rock types. Field observations suggest that within the complexes, mafic rocks were the first to form and were later mingled with, or brecciated by, tonalitic to trondhjemitic magma (Miller and Paterson, 2001a; Matzel, 2004).

The dated (Shea, 2014), ~15 m-thick hornblendite and pegmatitic gabbro dike that intrudes tonalite in the northern region is separated from the hornblende-biotite tonalite on either side by felsic, fine-grained, Eocene dikes. Outcrop patterns indicate that the mafic dike strikes NW and dips moderately to the NE. The hornblendite is very coarse-grained to pegmatitic and contains thin, centimeter-scale, wispy, fine-grained plagioclase pods and veinlets.

INTERNAL FEATURES OF THE SEVEN-FINGERED JACK PLUTON

Enclaves

Enclaves are common throughout the Seven-Fingered Jack pluton. They range from intermediate to mafic and fine- to medium-grained. Enclaves range from elongate ($\leq 55 \times 5$ cm) to approximately equi-dimensional (~3 to 60 cm in diameter). Enclaves are typically elongate parallel to foliation, but foliation and lineation were not recognized in the enclaves. At a few locations, foliation in the host tonalite deflects and wraps around enclaves (Fig. 5). Locally, enclaves occur in swarms that tend to have large aspect ratios (i.e. 10s of m by 10s of cm) and resemble disaggregated syn-plutonic dikes. The enclaves in these swarms are elongate parallel to the long axis of the swarm. The swarms have gradational boundaries over 10s of centimeters to several meters, whereas enclave-host rock contacts are typically sharp. Some enclaves with similar texture and composition as the host tonalite (type-A enclaves; see below) have diffuse contacts, presumably reflecting higher degrees of interaction with the host. Locally, enclaves have a ≤ 2 -cm-wide reaction rim of fine- to medium-grained biotite and/or hornblende.

Enclaves were divided into separate “types” based on textures and mineral modes (Table 1). Type-A enclaves are tonalitic, have moderate color indices (~35-45), are medium-grained, and contain plagioclase phenocrysts.

Figure 5. Foliation wrapping around type-E enclave. Lines represent foliation trace. Lip balm is 6.5 cm for scale.

Table 1. Enclave Descriptions from the Seven-Fingerd Jack Pluton.

Enclave Type	Characteristics
A	Medium-grained, moderate color index (~35-45), similar in texture to host, plagioclase phenocrysts
B	Fine-grained, moderate to high color index (~50-60), $\pm$ plagioclase phenocrysts, "salt and pepper-like" appearance
C	Fine- to medium-grained, high color index (~70-80), $\pm$ plagioclase phenocrysts
D	Same as type B but hornblende and/or biotite phenocrysts rather than plagioclase
E	Fine- to medium-grained, very high color index (~90) hornblendite, no phenocrysts

They most closely resemble the medium-grained tonalities in which they are found. Type-B enclaves are quartz diorites characterized by a fine-grained texture, moderate-to-high color index (~50-60), and fewer plagioclase phenocrysts relative to type-A. Type-C enclaves are mafic-rich diorites, generally show a higher color index (~70-80) than A and B, are fine- to medium-grained, and have fewer plagioclase phenocrysts relative to type-A. Type-D enclaves are hornblende- and biotite-rich diorites with similar textures to type-B enclaves, but have hornblende and/or biotite phenocrysts rather than plagioclase. Lastly, type-E enclaves are biotite-rich hornblendite, are fine- to medium-grained, have a characteristically very high color index (>95), and lack phenocrysts.

The relative abundances of enclaves at each station were determined by counting the number of enclaves within an approximately 4x4 m grid at the site where foliation was measured. No data were recorded at stations with insufficient outcrop free of lichen or other obstructions. Some outcrops did not have any enclaves within the 4x4 m grid and received a value of 0. The relative enclave abundances for the northern, central, and southern regions are 0-25, 0-20, and 0-13, respectively. This corresponds to an average of 8.0 enclaves per station in the north, 7.9 in the central domain, and 4.2 in the south. Furthermore, recordable enclaves occurred at ~72% of the stations in the northern domain, 69% in the central domain, and 52% of the stations in the southern domain. The higher abundances exhibited by the northern and central regions agrees with the percentages of stations with enclaves.

Enclave types A and C are the most widely encountered. Type-A enclaves were recorded at 64% of the stations and type-C were counted at 93% of the stations. Type-B enclaves were recorded at 28% of the stations. Type-D and type-E enclaves occurred at only 4.7% and 7% of the stations, respectively.

Schlieren

Mafic schlieren are locally developed in the Seven-Fingered Jack pluton. Individual schlieren are typically several meters long, thin (cm-scale), wispy, and biotite-rich (color indices from ~60-90). Internal schlieren zones typically strike NW and dip steeply to the NE (Fig. 6). Schlieren are best-developed near sharp contacts and mafic enclave swarms.

Mafic schlieren are defined by the alignment of centimeter-scale zones of mafic and felsic rock. Schlieren are either parallel, or at a small angle to, magmatic foliation. Schlieren wrap around enclaves that are typically elongate parallel to the schlieren. Locally within schlieren zones, enclaves become extremely elongate and begin to resemble the schlieren layering (Fig. 7).

Schlieren are concentrated at internal contacts and may represent mingling between separate injections of melt. The sub-parallelism of the schlieren layers and the long axes of minerals in them to internal contacts probably results from magma flow during intrusion, and not stratification from compaction because of the sub-vertical dips (Barriere, 1981; Bergantz, 2000).

Figure 6. Poles to schlieren.

Figure 7. Type-A enclave with a diffuse boundary. Card for scale is 15 cm long. Note strong foliation parallel to boundary.

Internal Contacts

Internal contacts are recognized throughout the Seven-Fingered Jack pluton but are not abundant. Internal contacts are interpreted to represent boundaries between separate batches of melt. These individual pulses of melt are responsible for the sheeted geometry of the pluton. Abrupt variations in color index or composition are the most common distinguishing characteristics between sheets. Magmatic foliation orientations and relative intensity of solid-state fabrics may also indicate the presence of an internal contact. Sharp internal contacts are much more easily recognized than gradational contacts.

The few measureable internal contacts strike NW and dip moderately to steeply to the NE (320/54, 354/88, 358/84). Schlieren are commonly parallel to these sharp contacts (Fig. 8). Sharp internal contacts are traceable along strike for $\leq \sim 15$ m and locally truncate other internal structures, such as syn-plutonic dikes. Enclaves are typically elongate parallel to contacts (Fig. 9). Many gradational internal contacts are inferred on the basis of textural and compositional variations from one outcrop to the next. Some of the gradational “contacts” may result from internal processes rather than intrusion (e.g., crystal fractionation-induced compositional variations). For example, tonalite at

Figure 8. Example of a sharp internal contact. From the central region, this NW striking and NE-dipping contact separates two tonalite units distinguished by a change in color index. Note the parallelism of the schlieren right of the contact. Book is 19-cm long.

Figure 9. Sharp internal contact. The contact strikes WNW and is distinguished by a change in color index. Abundant enclaves are visible in the darker unit on the right, and are elongate parallel to the contact. Note the offset of contact by magmatic fault on the left above the ruler. Ruler is 15-cm long.

station SFJ-8 is coarser-grained and has a higher ratio of biotite to hornblende than tonalite at station SFJ-7. Therefore it is inferred that somewhere between these two stations (approximately 200 m across strike) there is a contact, and because outcrop exposure is sufficient to identify sharp internal contacts, the contact is deemed gradational.

Modal Compositional Variations

Modal analysis by point counting reveals subtle pluton-wide compositional variations. Plagioclase is the most abundant phase in tonalite and represents an average of 49.2% of samples point counted. The next most abundant phase is quartz, which comprises nearly 26% of the rocks. A pluton-wide biotite average of 16% represents a minimum because in some samples biotite is altered to chlorite. Hornblende averages only 4.5% of the rocks. Potassium feldspar is present in only two samples where it represents $\leq 0.04\%$. The remaining $\sim 4\%$ of the rock is comprised of magmatic and secondary epidote and sphene, secondary chlorite, and opaque minerals. These modal analyses correspond to a pluton-wide average color index of approximately 25.

The modal analysis results (Table 2) reveal systematic trends. As plagioclase abundances decrease there is an increase in quartz. Similarly, as biotite percentages decrease there is an increase in hornblende; thus quartz and biotite percentages are linked. As expected from these observations, an

Table 2. Modal Analysis of Tonalite Samples from the Seven-Fingered Jack Pluton.

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Counts/Alteration	Sample locations (UTM)
SFJ-2a	49.0	0	30.6	19.3	0.3	0.9	19.5	353	0669622;5324396
SFJ-2c	53.1	0	27.9	15.4	2.7	1.1	18.0	377	0669622;5324396
SFJ-8	44.4	0.5	21.7	25.9	4.0	3.4	29.9	378	0668804;5324278
SFJ-10	46.2	0	6.6	15.7	3.0	28.6	18.7	364/Dike; bt→chl	0668692;5324141
SFJ-22a	54.1	0	25.1	0.3	0	20.5	0.3	351/ bt→chl	0670473;5323596
SFJ-22b	37.4	0	44.5	17.0	0.3	0.9	17.3	353	0670460;5323596
SFJ-25	36.7	0	20.3	24.3	15.8	2.9	40.1	379, bt→chl	0670511;5323871
SFJ-32	47.8	0	24.3	18.2	8.1	1.7	26.3	358	0669574;5324479
SFJ-36	51.1	0	28.5	16.3	2.2	1.9	18.5	368	0669781;5324672
SFJ-37	48.9	0	23.9	22.0	1.4	3.9	23.4	364	0669421;5324289
SFJ-41	51.3	0	36.6	10.7	0	1.4	10.7	355	0669252;5324068
SFJ-45	51.1	0	20.6	21.5	3.9	2.9	25.4	311	0669140;5324177
SFJ-48	47.2	0	22.7	20.5	7.7		28.3	375	0669453;5323411
SFJ-59	49.6	0	26.9	18.6	4.4	0.6	23.0	365	0668947;5325295
SFJ-63	48.1	0	28.4	9.7	9.2	4.6	18.9	370	0669108;5325021
SFJ-67a	52.4	0	14.6	25.6	3.7	3.7	29.3	328	0669536;5325238
SFJ-75a	55.5	0	16.4	17.0	8.8	2.2	25.9	317	0668706;5324535
SFJ-75b	58.3	0	18.2	16.5	4.2	2.8	20.7	357	0668706;5324535
SFJ-77	46.9	1.1	28.7	16.1	4.3	3.0	20.4	373	0668598;5324363
SFJ-84	48.1	0	28.1	16.4	0	7.5	16.4	335	0668235;5324313
SFJ-85a	48.4	0	24.5	18.5	2.7	6.0	21.2	335	0668224;5324277
SFJ-85b	48.1	0	19.9	14.4	11.8	6.6	26.2	347	0668224;5324277
SFJ-86a	46.4	0	29.5	14.2	7.8	2.2	22.0	373	0668838;5323915
SFJ-96	48.3	0	33.4	14.9	0	3.4	14.9	356	0669831;5321137
SFJ-101	49.3	0	30.1	15.9	1.2	3.5	17.1	345	0670002;5321181
SFJ-120	41.1	0	27.8	18.8	8.4	3.8	27.2	765	0670414;5321248
SFJ-132	43.9	0	28.2	21.3	3.0	3.6	24.3	362	0670804;5321208
SFJ-138	40.6	0	31.5	20.4	4.3	3.2	24.7	372	0670371;5320369
SFJ-143a	53.9	0	22.9	7.3	6.5	9.2	14.0	371/ bt→chl	0672313;5318539
SFJ-143b	51.4	0	21.9	0.0	9.6	17.1	9.6	356/ bt→chl	0672313;5318539
SFJ-145a	58.2	0	10.9	18.2	8.4	4.4	26.6	368/ bt→chl	0672145;5318829
SFJ-145b	50.8	0	18.6	21.9	4.2	4.5	26.1	360/ bt→chl	0672145;5318829
SFJ-155	62.4	0	21.3	10.5	3.5	2.3	14.0	343/ bt→chl	0671267;5319516
SFJ-162	58.5	0	22.2	12.5	6.0	0.9	18.5	352/ bt→chl	0671913;5319492
SFJ-169	51.6	0	22.0	19.6	4.0	2.7	23.7	372/ bt→chl	0672363;5318210
SFJ-171	55.8	0	26.1	9.1	6.0	3.0	15.1	364	0672154;5317938
SFJ-172	56.1	0	22.6	4.9	2.4	14.0	7.3	328/ bt→chl	0672154;5317938
SFJ-174	50.8	0	25.4	16.5	3.5	3.8	20.0	370	0670934;5319611
SFJ-181	48.0	0	24.8	18.6	5.1	3.5	23.7	371	0670563;5320386

Sample localities are shown on Fig. 3. UTM coordinates are in North American Datum of 1983 (NAD 83), zone 10.

increase in plagioclase corresponds to a decrease in biotite. The three detailed study areas have systematic differences in modal abundance (Figs. 10-12). The southern domain has the lowest average percentage of quartz (21.7%) and the highest average percentage of plagioclase (54.3%). It also exhibits the highest hornblende average (5.4%) and the lowest biotite average (12.6%). In contrast, the central domain has the lowest average percentage of plagioclase (44.6%) and hornblende (3.4%), and the highest of quartz (30.2%) and biotite (18.3%). Intermediate modal abundances are found in the northern area.

Textural Variations

Textural variations are recognized by fluctuations in grain-size from one outcrop to the next and at the outcrop scale. Unlike the modal abundances, variations in grain-size show no predictable trends, but grain-sizes of biotite and/or hornblende are noticeably different across internal contacts (Figs. 13 and 14), and similar to compositions, grain-sizes vary more within units than across internal contacts. In general, biotite grain-sizes are more variable than those of hornblende.

Figure 10. General geologic map showing locations of transects. Data displayed in Figures 11 and 12. Modified from Cater and Wright (1967).

Figure 11. Modal percentages of biotite and hornblende from the northern domain. Transects shown in Figure 10.

Figure 12.
Modal
percentages of
biotite and
hornblende
from the central
and southern
domains.
Transects
shown in
Figure 10.

Figure 13.
Grain-size
distribution of
biotite and
hornblende
from the
northern
domain.
Transect
locations are
shown in Fig.
10.

Figure 14. Grain-size distribution of biotite and hornblende from the central and southern domains. Transect locations are shown in Fig. 10.

Geochemistry

Eight XRF and ICP-MS trace element analyses are provided in Tables 3 and 4, respectively. To assess variation across internal contacts and “heterogeneities,” four samples were analyzed from the northern region from both sides of internal contacts (SFJ-85a/b and SFJ-2a/c). Two representative tonalite samples were analyzed from both the central (SFJ-96 and SFJ-124) and southern (SFJ-162 and SFJ-174) domains to constrain the geochemical characteristics of the “homogeneous tonalite.”

Samples range from 55-63% SiO₂ (Table 3), and six of the eight contain 61-63%. The low silica value for SFJ-85b can be attributed to its higher percentage of biotite and hornblende, whereas SFJ-124 is anomalous. Harker diagrams of major oxides (e.g., TiO₂, Al₂O₃, FeO, CaO, K₂O, Na₂O) (Fig. 15) and trace elements (e.g., Ni, Ba, Sc, Rb, Sr, Cr) (Figs. 16 and 17) do not show linear trends. The REE trends range from shallow to moderately steep ((La/Yb)_N=3.06-9.08) (Fig. 18). Most samples show similar slight upward concavity of REE trends with depletion in HREE and minimal europium anomalies. Sample SFJ-124 has a relatively enriched LREE trend and depleted K, Rb, and Ba values on a normalized trace element diagram (Fig. 18).

Samples SFJ-2a and 2c have similar major and trace element characteristics, except SFJ-2a has slightly higher TiO₂ and Y and lower MnO and Cu than SFJ-2c. Samples SFJ-85a and 85b are from either side of a meter-scale

Table 3. Major Element Geochemistry for the Seven-Fingered Jack Pluton.

	SFJ-2a	SFJ-2c	SFJ-85A	SFJ-85b	SFJ-96	SFJ-124	SFJ-162	SFJ-174
SiO₂	62.942	54.931	62.859	59.549	62.312	61.427	61.464	61.838
TiO₂	0.711	0.853	0.724	0.862	0.833	0.717	0.800	0.765
Al₂O₃	16.885	18.352	16.622	17.875	16.461	16.806	17.026	17.021
FeO*	5.122	7.261	5.272	6.209	5.589	5.375	5.528	5.633
MnO	0.093	0.123	0.107	0.116	0.097	0.099	0.099	0.111
MgO	2.347	3.404	2.321	2.845	2.553	2.323	2.409	2.510
CaO	5.425	6.859	4.853	6.801	5.156	5.288	5.444	5.567
Na₂O	3.854	3.419	3.413	3.643	3.258	3.530	3.498	3.551
K₂O	1.525	1.764	2.020	0.767	2.204	2.177	1.882	1.973
P₂O₅	0.211	0.223	0.189	0.230	0.214	0.196	0.205	0.208
Sum	99.114	97.189	98.381	98.896	98.676	97.938	98.357	99.177

Values given in wt. %.

Table 4. Trace Element Geochemistry from the Seven-Fingered Jack Pluton.

	SFJ-2a	SFJ-2c	SFJ-85a	SFJ-85b	SFJ-96	SFJ-124	SFJ-162	SFJ-174
La	10.55	11.85	7.95	9.70	15.30	26.42	10.51	7.19
Ce	24.59	25.04	20.18	21.36	32.13	53.07	27.32	17.82
Pr	3.59	3.43	3.23	3.11	4.23	6.50	4.25	2.79
Nd	16.35	14.90	15.89	14.89	18.18	25.65	19.85	13.48
Sm	4.36	3.71	4.54	4.15	4.37	5.21	5.25	3.69
Eu	1.28	1.14	1.23	1.24	1.25	1.46	1.38	1.11
Gd	3.89	3.46	4.34	4.26	3.88	4.56	4.77	3.54
Tb	0.63	0.53	0.68	0.69	0.62	0.71	0.75	0.57
Dy	3.56	3.14	4.04	4.32	3.60	4.12	4.37	3.32
Ho	0.71	0.62	0.79	0.88	0.71	0.80	0.85	0.67
Er	1.84	1.63	2.07	2.35	1.90	2.15	2.22	1.77
Tm	0.27	0.24	0.30	0.34	0.27	0.31	0.32	0.26
Yb	1.70	1.51	1.86	2.10	1.72	1.94	2.00	1.64
Lu	0.26	0.24	0.30	0.33	0.27	0.31	0.30	0.25
Ba	721	772	650	592	600	358	983	768
Th	2.29	2.62	2.05	2.94	4.63	5.38	1.58	1.32
Nb	6.51	5.53	5.29	3.97	6.71	6.04	6.82	5.60
Y	18.29	16.16	20.34	22.37	18.40	21.17	22.27	17.38
Hf	3.61	3.58	3.29	3.40	3.73	3.55	3.91	3.63
Ta	0.57	0.32	0.45	0.22	0.59	0.35	0.47	0.36
U	1.37	1.50	1.97	1.89	2.28	1.39	1.34	1.87
Pb	6.54	6.73	7.80	7.07	8.72	6.33	7.41	8.49
Rb	56.5	56.9	52.9	52.1	66.9	19.9	60.2	62.8
Cs	2.17	2.39	4.36	3.82	4.05	0.83	1.90	3.43
Sr	555	551	527	517	505	722	560	537
Sc	13.8	13.9	15.5	21.1	12.9	16.6	15.3	13.7
Zr	134	132	114	131	132	131	142	129

Values given in ppm.

Figure 15. Major element variation diagrams. Oxide abundances are given in wt. %.

Figure 16. Trace element variation diagrams. Elemental abundances are in ppm.

Figure 17. Trace element variation diagrams (continued). Elemental abundances are in ppm.

Figure 18. Normalized REE and trace element diagrams. Trace elements normalized to chondrite (C1) values from (Sun and McDonough, 1989).

gradational contact in the northern area and show opposite major and trace element behaviors. Sample SFJ-85b has lower SiO₂ and higher TiO₂, Al₂O₃, FeO, MgO, MnO, and CaO values. These trends may reflect the increased amounts of hornblende in SFJ-85b (11.9%) relative to SFJ-85a (2.7%).

Samples SFJ-96 and SFJ-124 represent the “homogeneous tonalite” from the central domain, and samples SFJ-162 and SFJ-174 were from the southern domain. These samples were chosen because they best represent the interior tonalite from the study area. They are medium-grained hornblende-biotite tonalites with no visible alteration. Sample SFJ-124 has a slightly lower SiO₂ value (59.6%) and shows anomalously elevated values of TiO₂, Al₂O₃, FeO, MnO, P₂O₅, MgO, and Sr when compared to the other three samples, and especially SFJ-96. Sample SFJ-162 has moderately elevated TiO₂, P₂O₅, Ba, Sc, and Zr relative to SFJ-174.

STRUCTURE OF THE SEVEN-FINGERED JACK PLUTON

Internal structures provide insights into the processes active during, and shortly after, the formation of the Seven-Fingered Jack pluton. These structures include magmatic foliations and lineations, dikes, folds, and ductile shear zones.

Magmatic Foliation

The Seven-Fingered Jack pluton contains a well-developed magmatic foliation defined by aligned biotite and hornblende grains. This foliation typically strikes NW and dips moderately to steeply to the NE (Figs. 19-24). Deviations from this strike are most pronounced in the northern domain where foliation orientations commonly vary from one outcrop to the next and magmatic foliations define steeply plunging folds. Foliation intensity remains relatively constant throughout the study area. Locally, foliation is weaker in very coarse-grained rocks.

Foliations are mostly parallel to internal contacts or intersect them at low angles (typically $\leq \sim 30^\circ$); locally, however, foliations intersect internal contacts at angles of 50° or higher. In the northern region, where foliations are less consistently oriented, foliations are more commonly oblique to internal contacts than in the central and southern regions.

Foliation strikes rotate towards a consistent NW trend from north to south (Figs. 19-21). Average strikes and dips for the northern, central, and southern regions are 226/70 (n=86), 304/68 (n=40), and 321/72 (n=51), respectively. The standard deviations of foliation strikes are 123.9, 95.3, and 56.1 for the northern, central, and southern regions, respectively. The significantly higher standard deviations in the north reflect the folding of foliation. The standard deviations of the dips are similar for the central and southern areas (6.3 and 6.5, respectively),

Figure 19. Poles to foliation from the northern domain. Kamb contour interval of 26.

Figure 20. Poles to foliation from the central domain. Kamb contour interval of 26.

Figure 21. Poles to foliation from the southern domain. Kamb contour interval of 26.

Figure 22. Map emphasizing magmatic foliations and schlieren in northern domain. Black line corresponds with cross-section in Fig. 28. Location of inset shown in Figure 3.

Figure 23. Map of magmatic foliations and schlieren in central domain. Black line corresponds to cross-section in Fig. 26. Location of inset shown in Figure 3.

Figure 24. Map of magmatic foliations and schlieren in southern domain. Location of inset shown in Figure 3.

and are higher (12.1) in the north. The northern domain can be divided into three separate zones based on patterns of foliation strikes. Zone 1 lies at the southeastern corner of the northern domain (Fig. 22) and is characterized by similar strikes to those observed in the central domain (Fig. 23), and therefore is interpreted as being the northern continuation of NW-striking foliations from the central domain. Zone 2 is characterized by large swings in strikes over short distances (Fig. 22), presumably caused by extensive folding in the region (see below). Lastly, zone 3 is characterized by more gradual shifts in strikes that define a large, ESE-plunging antiform (Fig. 22). These gradual changes of strike (occurring over 100s of meters) observed in zone 3 contrast with the abrupt changes reflecting smaller-wavelength folds in zone 2. Foliations are less consistent to the south within in the southern domain. There, a change in foliation strike orientations may represent a regional fold that continues south of the study area (cf., Dustin and Miller, 2013).

Magmatic Lineation

Magmatic lineations in the Seven-Fingered Jack pluton are defined by aligned hornblende and biotite. Lineations typically plunge $\sim 30\text{-}70^\circ$ to the N to NE, and less commonly plunge to the NW (Figs. 25-27). Rake is generally moderate to steep. Rake averages 70° in the north, 67° in the central domain, and 86° in the south. The shallowest lineations are in the central domain, where

Figure 25. Magmatic lineations in northern domain. Location shown in Figure 3.

Figure 26. Magmatic lineations in central domain. Location of inset shown in Figure 3.

Figure 27. Magmatic lineations in southern domain. Location of inset shown in Figure 3.

the average plunge is 36° , and the steepest lineations are in the southern domain where the average plunge is 54° . Lineation orientations in the central and southern regions are more consistent than those from the north (Figs. 25-27). For example, of the 26 lineations measured in the central domain only six stray from the prevailing northwest trend. Similar to foliation, lineation trends and plunges in the north are characterized by large variations from one outcrop to the next, and there is a progressive swing from an E to a NW trend in the northwestern extent of the study area.

Lineation is generally moderately developed and intensity varies, but not in a consistent manner. Rocks typically have stronger planar than linear components ($S > L$), but locally contain a well-developed linear fabric ($L > S$). Strongly linear fabrics are common in the northern domain where enclaves are stretched ($\sim 5:1$ aspect ratios) parallel to $L \gg S$ fabrics.

Dikes

Abundant dikes intrude the Seven-Fingered Jack pluton and are broadly similar to Eocene dikes in the region (e.g., Tabor et al., 1987). Dacite dikes are most common and generally strike WNW and dip moderately to the NNE. Less abundant are rhyodacite and rhyodacite porphyry dikes. Local mafic dikes are likely associated with the ~ 79 Ma mafic complex. Eocene dikes are typically fine-grained and light-colored, range in width from ~ 5 cm to 15 m and are

traceable for ~2 m to ≥ 50 m. All dikes have sharp contacts and commonly truncate magmatic foliation and enclaves.

Dikes are abundant near contacts, especially significant lithological contacts. For example, a fine-grained, light-colored dike ~2 m wide, separates Seven-Fingered Jack tonalite from coarse-grained gabbros of the contact complex in the northern domain. This relationship holds for the five locations where the contact between the tonalite and outer mafic complex was observed, and the three places where the dike-like body of mafic complex intrudes tonalite in the interior of the northern domain.

Dikes are typically at oblique angles to the magmatic foliation in the host tonalite, and locally cut foliations at high angles. At some locations, where dikes are biotite-rich, they contain a weak foliation. Dikes next to well-developed schlieren are typically parallel to this layering, suggesting that this anisotropy may have influenced dike emplacement.

Magmatic Folds

In the study area, magmatic folds are observed in the northern domain. In zone 2 of the northern domain, N-NNW trending, steeply plunging, tight to sub-isoclinal folds are defined by magmatic foliations (Fig. 28). These folds lack an axial planar cleavage. Fold wavelengths are typically ≤ 50 m. In zone 3 of the

Figure 28. Cross-sections through the northern and central domains. Note the abundant folds of foliations in the north compared to the central domain. Dashed lines represent foliations and double lines indicate schlieren. Transect lines shown in Figures 20 and 21.

northern domain a moderately ESE-plunging antiform has a wavelength of ~1 km. This larger fold is defined by a continuous rotation of foliation strikes from ENE to NW (Fig. 22). Folds are more abundant in zone 2 and have shorter wavelengths than those of zone 3. In the southern domain a subsolidus, NE-trending, moderately plunging fold of magmatic foliation wraps around a leucocratic dike and has a wavelength of ≤ 1 m.

Ductile Shear Zones

Ductile shear zones occur locally in the Seven-Fingered Jack pluton. They are typically 2-10-cm-wide, discontinuous zones with contacts ranging from planar to wavy, and typically exhibit a normal sense of shear. Ductile shear zones do not show preferential formation along internal contacts, near schlieren, dikes, or any other internal feature. They are characterized by zones of intensified magmatic foliation to subsolidus foliation.

DISCUSSION

Petrogenesis of the Seven-Fingered Jack Pluton

Magma Source

Geochemical analyses provide a means of evaluating possible variations in the source region of magmas. For example, if a rock displays a negative Eu anomaly then it is widely accepted that the source had residual plagioclase or that plagioclase was removed by fractionation. Also, depletion of HREEs signifies the presence of garnet in the source because garnet shows a strong affinity for the HREEs relative to the LREEs.

Seven-Fingered Jack samples show modest depletions in HREEs (Fig. 18), as evidenced by slight upward concavity of the REE trend, Y, and Sc. These trends, coupled with high levels of Al_2O_3 (16.5-18.4 wt. %), indicate little to no garnet residuum in the source (Muir et al., 1995; Petford and Atherton, 1996; Topuz et al., 2005), and that magmas were generated by partial melting of a crustal source shallower than the depth of garnet stability. The slight upward concavity and slight Eu anomaly are consistent with partial melting of amphibole-rich mafic crust with relatively modest proportions of residual plagioclase, but detailed calculations examining possible source mineralogies and melt fractions, all of which will influence the REE patterns and element ratios (e.g., initial Sr and REE contents) have not been carried out. Low LREE content (<100x chondrite)

with low La/Lu (2.8-9.1) may indicate little interaction with juvenile crustal material. All samples have Sr/Y values that fall within the normal, rather than adakitic, arc crust field of Drummond and Defant (1990) (Fig. 29).

Comparison with Coeval Plutons from the North Cascades

The ~92-89 Ma, deep-crustal (7-10 kb), dominantly tonalitic, Tenpeak pluton lies ~20 km to the WNW across the Entiat fault from the ~92-90 Ma, mid-crustal (6-8 kb) Seven-Fingered Jack pluton (Fig. 2). A comparative analysis of geochemical data from these two coeval arc plutons reveals distinct differences in the sources.

The Tenpeak pluton is characterized by a stronger influence from a garnet-bearing source (DeBari et al., 1998; Chan, 2013), possibly reflecting a deeper source of melt. Comparing Chan's (2013) Tenpeak pluton data with the new Seven-Fingered Jack data, it is clear that the Tenpeak pluton has significantly lower values of the garnet-compatible elements Y and HREE (Figs. 29 and 30). On Dy/Yb versus SiO₂ and La/Yb versus SiO₂ plots, both plutons follow amphibole fractionation trends of lower Dy/Yb and higher La/Yb with increasing SiO₂, but the Tenpeak pluton appears to have higher initial Dy/Yb and La/Yb values and, thus, a stronger initial garnet signature (Fig. 31). Furthermore, the Tenpeak pluton has approximately 3-8 times as much Ni, five to eight times as much Cr, and 2-3 times as much MgO than the Seven-

Figure 29. Sr/Y versus Y plot for Seven-Fingered Jack and Tenpeak plutons. TP-Tenpeak pluton; SFJ-Seven-Fingered Jack pluton. Tenpeak pluton data from Chan (2013).

Figure 30. Normalized REE diagrams for the Seven-Fingered Jack and Tenpeak plutons. Values normalized to Sun and McDonough (1989). Tenpeak pluton data from Chan (2013).

Figure 31. Garnet versus amphibole fractionation trends. Fractionation trends after Davidson et al. (2007). TP-Tenpeak pluton; SFJ-Seven-Fingered Jack pluton.

Fingered Jack pluton. Trace element and REE values indicate that the Tenpeak pluton was influenced by a deeper source than the Seven-Fingered Jack pluton.

Based on the range of ϵNd values in the Tenpeak pluton, Matzel et al. (2008) proposed a model of mixing between mantle-derived melts and melts produced by partial anatexis of juvenile terranes. Following the North Cascades crustal section model of Miller et al. (2009) (Fig. 32), the Seven-Fingered Jack pluton may have originated from a deeper crustal body of melt that underwent variable amounts of crystal fractionation and crustal assimilation. The melt ascended and was eventually arrested at the level of emplacement.

Pluton Formation: Evaluation of Sheet Geometry and Emplacement Mechanisms of Individual Sheets

Numerous studies have addressed the formation of sheeted intrusions (e.g., Hamilton and Meyers, 1967; Hutton, 1992; Ingram and Hutton, 1994; Paterson and Miller, 1998; Wiebe and Collins, 1998; Miller and Paterson, 2001a; Paterson et al., 2011). For example, one model predicts that sheeted plutons are subhorizontal tabular bodies that are fed by dikes and/or fracture networks (Hamilton and Meyers, 1967; Wiebe and Collins, 1998; Weinberg, 1999; Brown, 2004), whereas others envision that they form from visco-elastic magmatic diapirs (Paterson and Miller, 1998; Miller and Paterson, 1999, 2001a). Moreover,

Cascades Crustal Section

Figure 32. Schematic diagram of the Cascades crustal section. Black circle represents an example of the location where the Seven-Fingered Jack pluton may have formed and acted as a conduit to higher crustal levels. Vertical dashed lines are faults. WPT-Windy Pass thrust. Figure after Miller et al. (2009).

the type(s) of mechanisms operating during magma ascent and emplacement may change with time or depth during construction of intrusions, and evidence for ascent is commonly obscured by subsequent processes (e.g., Paterson et al., 1996).

Sheeted Geometry of the Seven-Fingered Jack Pluton

Individual sheets in the pluton are elongate and separated by sharp to gradational contacts. Gradational contacts are more abundant than sharp contacts and, therefore, the dimensions of sheets are not well constrained, but are $\leq$ ~300-m wide and potentially up to 3-km long. Despite the increased heterogeneity in the northern domain, initial sheet geometries were presumably the same as those in the central and southern domains. Individual sheets are distinguishable from other sheets by textural and modal variations. The sharp contacts are relatively planar and generally strike NW, dip moderately to steeply to the NE, and are approximately parallel to the overall strike of the pluton. These planar boundaries are the best evidence for sheet-like geometries of the bodies. The shapes of bodies marked by gradational internal contacts are more difficult to interpret. This is particularly the case for contacts that are gradational over 10s to 100s of meters. The results of this study agree with previous mapping studies (e.g., Paterson and Miller, 1998; Miller and Paterson, 2001a),

which concluded that the Seven-Fingered Jack pluton is constructed of numerous sheet-like bodies.

The presence of sharp internal contacts separating sheets in the Seven-Fingered Jack pluton supports construction via injection of multiple increments of melt. Extensive mixing between new melt injections and host may have occurred if, during intrusion of new magma batches, the host body graded towards its margin from mostly solid to liquid-crystal mush, which then collapsed and was eroded by the new increment (Bergantz, 2000). This scouring of the margin would effectively remove “mushy” portions that would then get mixed with the intruding melt (Bergantz, 2000). In short, sharp contacts represent a larger thermal and rheological contrast between the two magmatic increments, whereas materials separated by a contact that is gradational over 10s of m likely experienced a higher degree of interaction.

The presence of both gradational and sharp internal contacts indicates that the patterns of intrusion varied over the course of the construction of the pluton. In places, a rapid turnover of successive injections produced a relatively gradational internal contact. Elsewhere, a sufficiently long hiatus between magmatic increments led to the preservation of a sharp internal contact. Alternatively, depending on local thermal conditions, a sharp internal contact was preserved because the previous increment cooled quickly. The above assertions are compatible with Shea’s (2014) data, which show that the Seven-Fingered Jack pluton was constructed over ~4 Myr.

Although comprehensive pluton-scale geochemical data is lacking, data presented here indicate that internal boundaries are relevant to the interpretation of the emplacement of individual magmatic increments. Each sample from a pair, except SFJ-2a and SFJ-2c, can be distinguished from its partner, which represents the same region (e.g., central domain) on either side of an internal contact. Samples SFJ-85a and SFJ-85b are from either side of a gradational contact and, therefore, are also expected to have different compositions. Sample pairs SFJ-96 and SFJ-124 from the central region, and SFJ-162 and SFJ-174 from the southern region are chemically different, despite all representing the “homogeneous tonalite.” For example, SFJ-124 has very different major and trace element signatures relative to SFJ-96, which was taken a few hundred meters away. Sample SFJ-124 shows enrichment of nearly all major oxides and trace elements, except K₂O, Pb, Nb, Rb, and Zr, relative to SFJ-96 (Figs. 15-17). Therefore, each sample is interpreted to represent a different magmatic increment.

Emplacement Mechanisms

Despite much advancement in our understanding of pluton formation, the roles of individual emplacement mechanisms during construction are still widely debated. Faults and elongate plutons are commonly assumed to be connected because of a close spatial relationship between the two in arcs (e.g., Hutton,

1988; D'Lemos et al., 1992). In the study area, no through-going faults were observed. This observation is in agreement with Paterson and Miller (1998) who found no faults along the margins of internal sheets or extending from sheet tips throughout the Seven-Fingered Jack pluton.

A hypothesis put forth by Wiebe and Collins (1998) states that some plutons formed by magma deposition onto a chamber floor that subsequently sank during continuous episodes of replenishment. Alternating mafic and felsic sheets preserve flame structures, pipes, load casts, and other features that can be used as way-up indicators (Wiebe and Collins, 1998). None of these features were observed in the study area, and all observed contacts are moderately to steeply dipping. Furthermore, Dawes' (1993) hornblende barometry data from the Seven-Fingered Jack pluton indicate no large-scale pressure differences and argues against major tilting of the pluton. Thus, this model does not work for the Seven-Fingered Jack pluton.

Dike models assume elastic behavior of host rock during extensional fracturing and rise of magma through fracture networks, which ultimately leads to sheet-like bodies (e.g., Takada, 1990; Lister and Kerr, 1991). The Seven-Fingered Jack pluton is constructed of sheet-like bodies, which may support diking. Dike models, however, predict that dikes form at high angles to σ_3 , which is inconsistent with sheet orientations within the Seven-Fingered Jack pluton (cf. Paterson and Miller, 1998). During pluton construction, the regional strain field in the North Cascades was marked by NE-SW shortening, and the shortening

direction (likely close to σ_1) was oriented roughly perpendicular to the NW-striking arc.

Magma wedging was proposed by Paterson and Miller (1998) and Miller and Paterson (2001a) as an emplacement mechanism for the Seven-Fingered Jack pluton. In the northern domain, an ~10-m-long and ~15-20-cm-wide zone of alternating mafic-felsic bands is interpreted as a potential host rock raft, and may provide evidence of small-scale wedging by intruding melt (Fig. 33). Fine-grained mafic bands are $\leq$ 2-cm wide and may be biotite amphibolite from the Napeequa unit. Alternatively, the zone may be part of a ductile shear zone that represents flow between two bodies during emplacement of melt. Magma may have preferentially intruded between older sheets. However, nowhere else in the study area were ductile shear zones observed at sheet contacts, nor was there an increase in solid-state deformation, which would be expected if ductile flow was an important emplacement mechanism.

Enclaves and Construction of the Seven-Fingered Jack Pluton

The large number of enclaves within host tonalites indicates a magmatic flow velocity of 1-10 m/yr for magmas in the Seven-Fingered Jack pluton (Williams and Tobisch, 1994). The flow velocity estimate can be further refined by the presence of silica-rich enclaves, as type-A enclaves are one of the two most abundant types in the area (Table. 2). Type-A enclaves display similar

Figure 33. Possible host rock raft within Seven-Fingered Jack tonalite. Lip balm for scale is ~6.5 cm.

textures and color indices as their host tonalities, and thus are less stable at higher strain rates (Williams and Tobisch, 1994). This relationship indicates that at least locally, flow velocity was low during enclave formation.

The abundance of elongate enclaves in the Seven-Fingered Jack pluton indicates that the temperatures during deformation may have been ~950°-1050°C (Williams and Tobisch, 1994). If the solidus temperature of tonalite is ~700-750°C (Sigh and Johanes, 1996), then these temperatures correspond to deformation during high-temperature magmatic flow.

The variable compositions and abundances of enclaves in the Seven-Fingered Jack pluton indicate that magma mingling was more important than magma mixing (e.g., Vernon et al., 1988). The occurrence of five mineralogically similar, yet texturally distinct, types of enclaves (types-A-E) suggests mingling between many magma batches of similar compositions (Vernon et al., 1988). Hybridization (interaction and mixing of melt + crystals) is a mechanism that explains the diverse textural variations observed in the enclaves (e.g., Wiebe et al., 1997; Feeley et al., 2008; Chen et al., 2009).

Evidence of Magmatic Versus Solid-State Fabrics

The best evidence for determining magmatic versus solid-state flow in the Seven-Fingered Jack pluton comes from microscopic analysis. Using the criteria of Paterson et al. (1989), Seven-Fingered Jack tonalites preserve a magmatic

foliation defined by aligned subhedral hornblende and/or biotite. Moderately aligned plagioclase with igneous textures (e.g., oscillatory zoning) (Fig. 34 A), surrounded by anhedral, non-deformed to weakly deformed quartz indicates magmatic flow. Evidence of solid-state strain is provided by mosaics of quartz and mafic minerals that separate plagioclase crystals (Fig. 34 B), kinking of plagioclase and biotite (Fig. 34 C), elongate quartz (Fig. 34 D), and quartz-and biotite-filled fractures in plagioclase (Fig. 34 E) and hornblende. Further evidence is provided by aligned biotite and hornblende in recrystallized aggregates. The above microstructures are consistent with superimposition of solid-state fabrics on magmatic fabrics in the Seven-Fingered Jack pluton.

Deformation in the solid-state occurred at high temperatures and may have formed at the high end of a continuum from magmatic flow to high-temperature solid-state flow. Evidence for moderate to high temperatures includes local recrystallization of plagioclase and hornblende. The best evidence for deformation of quartz at high temperatures comes from recrystallized and elongate mosaics with amoeboid grain boundaries, which indicate grain boundary migration recrystallization.

Lower temperature microstructures are also present. For example, quartz exhibits undulose extinction and bulging recrystallization structures, which are characteristic of deformation at lower temperatures. These microstructures imply recrystallization corresponding to regimes 2 and 3 of Hirth and Tullis (1992), which indicate a temperature range from ~400°C to 700°C.

Figure 34. Photomicrographs of the Seven-Fingered Jack tonalite. (A) oscillatory zoning in plagioclase, (B) recrystallized quartz between magmatic plagioclase grains, and (C) highly bent magmatic biotite crystal. Abbreviations: bt- biotite; plag- plagioclase; qtz- quartz.

Figure 34 (continued). (D) grain-size reduction and elongation of fine-grained quartz aggregate. Note bent plagioclase grain. (E) recrystallized quartz filling a fracture in a single plagioclase crystal. Abbreviations: bt-biotite; plag-plagioclase; qtz-quartz.

Interpretation of Magmatic Foliation and Lineation Patterns in the Seven-Fingered Jack Pluton

Magmatic fabrics form late in the crystallization process, thus preserving late increments of strain before solidification (e.g., Paterson et al., 1998). It follows that fabrics do not generally record information regarding ascent, but rather provide information on syn- to post-emplacement internal processes and/or regional strain.

Foliations in the central and southern regions strike NW and dip moderately to steeply, mostly to the NE, and lineations commonly trend N or NE and plunge gently to steeply. Foliation orientations are more complex in the northern region. Orientations are consistent with regional strain during the NE-SW contraction that characterizes the North Cascades crystalline core and probably reflects subduction in the Late Cretaceous. Foliations locally cut internal contacts at moderate angles, further supporting an origin by regional deformation rather than internal magmatic processes.

The northern region is characterized by large outcrop- and map-scale swings in magmatic foliation strikes (Fig. 22). Foliations there define N-, S-, and ESE-trending, meter-to 100s of meters-scale, steeply plunging folds. These folds are interpreted to reflect regional strain during crystallization. The orientations of these fold axes indicate a NW-SE shortening direction.

The fold trends are broadly similar to those of Paterson and Miller (1998) and Miller and Paterson (2001a) who noted foliation-defined, meso- and macro-

scale, upright, NW-trending magmatic folds south of the study area. Folds described by these workers, however, plunge shallowly to moderately, in contrast to the moderate to steep fold plunges in the northern domain of the study area. It is unclear why folds in the northern area vary from those described elsewhere in the pluton. One possible explanation comes from the apparent domain-like pattern of foliation strike orientations in the study area. Local fluctuations in the relative intensity and/or orientation of the strain field may account for these observations. Paterson and Miller (1998) concluded that folds were synchronous with emplacement during regional deformation, and on the basis of the lack of solid-state deformation I reach a similar interpretation.

The structural homogeneity in the central and southern regions is also attributed to regional deformation during the Late Cretaceous. The NW strikes and moderate-to-steep dips of foliations are consistent with this conclusion, and they match well with other parts of the pluton (Dustin and Miller, 2013) and plutons of the Cascades core (e.g., Cater, 1982; Miller and Paterson, 2001a,b; Miller et al., 2009). Foliation orientations are less consistent than in the central and southern domains of the study area, and Dustin and Miller (2013) interpreted these foliations to record regional strain.

Internal Features and the Construction of the Seven-Fingered Jack Pluton

Compositional variations accompany internal contacts and behave in a relatively predictable manner. For example, if biotite increases across an internal

contact then, in every case, hornblende decreases (Figs. 11 and 12). The inverse is also true. Overall, the amount that each mineral increases or decreases is such that the total mafic mineral percentages are not significantly different ($\pm \sim 0.4 - 4.0\%$). Compositional variations across some internal contacts are less than within units (Figs. 11 and 12). This assumes that all contacts, and therefore units, were mapped and are represented in the data. One scenario that would lead to a higher degree of internal compositional heterogeneity is if gradational contacts do not represent boundaries between separate units, but rather represent internal magmatic processes (e.g., migrating crystallization front, local convection within a body) during crystallization (Bergantz, 2000). This scenario, however, does not hold for all cases, as samples SFJ-85a and SFJ-85b were mapped on either side of a gradational internal contact and show widely different chemical compositions.

It is difficult to comprehensively analyze pluton-wide compositional and textural variations based only on modal analysis and limited geochemical data from part of the pluton. Keeping in mind the limitations of these data, however, they do provide important insights. On a local scale, textures and modal compositions appear to randomly change, but on a larger scale, patterns emerge. In the northern region, biotite concentrations in two of the three transects (B-B' and C-C') (Fig. 10) gradually rise and then decrease from southwest to northeast, whereas in the central and southern regions, biotite

concentrations increase towards the northeast in two of three transects. These data may suggest different intrusive bodies intruded with no systematic pattern.

Degree of Homogeneity in the Seven-Fingered Jack 'Homogeneous Tonalite'

The Seven-Fingered Jack tonalite has been mapped nearly exclusively as a single body of biotite-hornblende and hornblende-biotite tonalite (e.g., Cater and Crowder, 1967; Cater and Wright, 1967; Cater, 1982), or as multiple sheeted units (Paterson and Miller, 1998; Miller and Paterson, 2001a). Prior to this study the required mapping and structural analysis at a resolution to better evaluate these questions had remained absent. It is still not possible to quantitatively evaluate the degree to which a rock unit is homogeneous, but this qualitative evaluation of the textural, compositional, geochemical, and structural homogeneity of the study area provides insights into the degree of homogeneity throughout the pluton.

Modal analysis reveals that tonalites within the study area are consistently medium-grained and locally coarse-grained. Analyses from 42 samples reveal that grain size ranges of plagioclase, quartz, biotite, and hornblende (the four most abundant mineral constituents) are ~0.5-7.75 mm, 0.2-5 mm, 0.5-4.5 mm, and 0.5-8 mm, respectively. Low standard deviation values away from average values of 1.32 mm, 0.93 mm, 1.08 mm, and 1.91 mm, respectively, indicate that

these calculated averages are accurate representations of mineral-size distributions in the study region.

The mineralogy of the tonalites is very consistent. All samples are composed of only six magmatic minerals (plagioclase, quartz, biotite, hornblende, epidote, and sphene) in significant abundances with secondary chlorite, epidote, and sphene. Modal variation is low, with standard deviations of 5.5%, 6.6%, 5.9%, and 3.5% for plagioclase, quartz, biotite, and hornblende, respectively. These low deviation values are noteworthy, as they represent the differences in modal composition over $\sim 10 \text{ km}^2$.

Despite the limited number of geochemical analyses, major and trace element differences within the study area and across internal contacts can be addressed. Six out of eight samples plot together on major and trace element variation plots (Figs. 15-17) with two outliers (SFJ-85b and SFJ-124). Sample SFJ-85b is a fine-grained, mafic-rich rock from within a gradational contact and may represent a hybridized melt. Samples do not vary significantly on chondrite-normalized REE plots and multi-element variation diagrams (Fig. 30). Furthermore, new geochemical data from directly south of the study area indicate little deviation in major element values from those of the tonalites in my study area (Kelly Dustin, pers. commun.). This low degree of geochemical variation suggests that the tonalites, although separated by internal contacts, share a common parental melt source.

The Seven-Fingered Jack pluton is structurally homogeneous in the central and southern regions, and heterogeneous in the northern region (Figs. 19-24). It remains unknown why folding is so pervasive in the north and not in the other domains.

CONCLUSIONS

Detailed field mapping, petrographic and microstructural analysis, modal analysis, and major and trace element geochemistry have led to the following main conclusions on the assembly and deformation of the Seven-Fingered Jack pluton:

1. Field observations suggest the Seven-Fingered Jack pluton is composed of multiple sheet-like bodies and was emplaced as a series of separate injections. These bodies are separated by either sharp or gradational contacts, and are identified by variations in texture and composition.
2. Diking and/or faulting did not play a significant role in the emplacement of the pluton. The lack of evidence for ductile flow between sheets indicates that material transfer of host rocks was not achieved through ductile flow. Similarly, the scarcity of host rock rafts may indicate that emplacement by magma wedging was not important during construction. Emplacement mechanisms for the pluton thus remain unclear.

3. The Seven-Fingered Jack pluton contains five types of mafic enclaves. Each enclave type has a different texture and/or modal mineralogy. Enclaves are typically elongate in the foliation plane and locally occur in swarms.
4. The northern map domain is structurally heterogeneous relative to the central and southern map domains, and was divided into three zones. Zone 1 lacks folds and contains similar NW-striking magmatic foliation trends as those observed in the central and southern regions. In zone 2, magmatic foliation defines moderately to steeply plunging, N-NNW-trending folds that formed in response to regional shortening. Fold wavelengths are typically ≤ 50 m. In zone 3, magmatic foliation strikes gradually rotate from ENE-striking to NW-striking, and define a large ESE-plunging antiform with a wavelength of ~ 1 km. The central and southern domains exhibit dominant NW-striking magmatic foliations with little variation.
5. Pluton-wide textural variations exhibit no predictable behavior, which suggests that different magmatic bodies intruded without a systematic pattern.
6. The hornblende-biotite tonalite of the Seven-Fingered Jack pluton is largely chemically homogeneous. Samples from each map domain show very little variation of major and trace elements. Geochemical data also indicate chemically evolved parental magmas, with a significant crustal component, for the Seven-Finger Jack pluton tonalite.

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APPENDIX

Petrographic Descriptions

SFJ-2a: Medium-grained, well-foliated, equigranular, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral, mechanically twinned, and oscillatory zoned.

Quartz: Bimodal grain size, seriate-interlobate, contains subgrains, and is finer-grained around biotite aggregates and plagioclase.

Biotite: Bimodal grain size, subhedral to anhedral, aggregate-forming, bent and kinked, and locally fractured.

Hornblende: Bimodal grain size, subhedral to anhedral, locally fractured, commonly associated with biotite and epidote.

Epidote: Fine-grained, anhedral, commonly associated with biotite aggregates, locally fractured, and mostly secondary.

Sphene: Fine-grained to coarse-grained, subhedral to anhedral.

Alteration minerals: Saussuritization common in plagioclase, secondary biotite replaces hornblende, and minor amounts of chlorite replaces biotite.

SFJ-2c: Medium-grained, well-foliated, equigranular, hornblende-biotite tonalite.

Plagioclase: Medium- to coarse-grained, subhedral, mechanically twinned, oscillatory zoned, locally myrmekitic, locally kinked and recrystallized, and locally exhibits core-and-mantle structure with fine-grained quartz.

Quartz: Bimodal grain size, inequigranular-interlobate aggregates, contains subgrains, exhibits undulatory extinction, locally recrystallized and forms fine-grained mosaics around plagioclase.

Biotite: Bimodal grain size, subhedral to anhedral, aggregate-forming, bent and locally fractured grains, and locally moderately recrystallized.

Hornblende: Medium-grained, anhedral, and locally recrystallized.

Epidote: Rare, fine-grained, anhedral, and secondary.

Sphene: Rare, fine-grained, anhedral.

Alteration minerals: Secondary biotite replaces hornblende and minor amounts of biotite to chlorite.

SFJ-8: Medium-grained, well-foliated, hornblende-biotite tonalite.

Plagioclase: Coarse-grained, subhedral to anhedral, mechanically twinned, and locally bent.

Quartz: Bimodal grain size, inequigranular-interlobate, contains well-developed subgrains, and forms fine- to medium grained mosaics.

Biotite: Bimodal grain size, subhedral to anhedral, and aggregate-forming.

Hornblende: Bimodal grain size, subhedral, equigranular, and locally fractured.

Epidote: Fine-grained, subhedral to anhedral, and always associated with biotite and biotite aggregates.

Sphene: Fine-grained, anhedral.

Potassium Feldspar: Extremely rare, medium-grained, subhedral, and exhibits tartan twinning.

Alteration minerals: Minor biotite altered to chlorite, and hornblende to biotite.

SFJ-22a: Medium-grained, moderately-developed foliation, plagioclase porphyritic, biotite tonalite.

Plagioclase: Medium- to coarse-grained, subhedral to anhedral, inequigranular-polygonal, mechanically twinned, weakly oscillatory zoned, locally bent, and moderately recrystallized at grain boundaries.

Quartz: Bimodal grain size, subhedral to anhedral, seriate-interlobate, with subgrains, undulatory extinction, and mosaics approximately parallel to the fabric.

Biotite: Bimodal grain size, subhedral to anhedral, bent and kinked grains, and locally recrystallized quartz and secondary epidote within grains.

Epidote: Fine-grained, subhedral to anhedral, commonly associated with biotite, and locally fractured.

Sphene: Bimodal grain size, subhedral to approximately euhedral.

Alteration minerals: Abundant saussuritization of plagioclase and biotite to chlorite.

SFJ-22b: Fine-grained, plagioclase porphyritic, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Fine-grained, anhedral, oscillatory zoned, moderately recrystallized, and present as phenocrysts.

Quartz: Very fine-grained, equigranular to inequigranular-interlobate, and exhibits subgrains and mosaics of recrystallized grains.

Biotite: Fine-grained, acicular-like crystal shapes, anhedral, and locally fractured.

Sphene: Fine-grained, anhedral, and aggregate-forming.

Alteration minerals: Abundant saussuritization in plagioclase.

SFJ-32: Medium-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral, oscillatory zoned, locally bent, locally myrmekitic, and minor recrystallization at grain boundaries.

Quartz: Bimodal grain size, seriate-interlobate to amoeboid, moderately-developed mosaics, and exhibits subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, bent and kinked, aggregate-forming, and locally recrystallized grains surrounding magmatic grains.

Hornblende: Bimodal grain size, subhedral to anhedral, commonly associated with biotite aggregates, locally fractured, and locally surrounded by fine-grained quartz and biotite.

Epidote: Fine-grained, subhedral, and commonly associated with biotite-hornblende aggregates.

Sphene: Bimodal grain size and subhedral to anhedral.

Alteration minerals: Hornblende replaced by biotite.

SFJ-36: Medium-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium- to coarse-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, locally bent, locally myrmekitic, and shows minor recrystallization at grain boundaries.

Quartz: Fine-grained, seriate-amoeboid and locally interlobate, shows undulatory extinction, subgrains, and mosaics.

Biotite: Bimodal grain size, subhedral to anhedral, bent, moderately recrystallized, and aggregate-forming.

Hornblende: Bimodal grain size, subhedral to anhedral, locally aggregate-forming, and locally fractured.

Epidote: Rare, fine-grained, subhedral to anhedral, and commonly associated with biotite-hornblende aggregates.

Sphene: Fine-grained, subhedral to anhedral, and locally fractured.

Alteration minerals: Hornblende replaced by biotite.

SFJ-45: Medium- to coarse-grained, moderately foliated, plagioclase porphyritic, hornblende-biotite tonalite.

Plagioclase: Coarse-grained, subhedral, inequigranular, oscillatory zoned, mechanically twinned, and locally recrystallized along grain boundaries.

Quartz: Bimodal grain size, inequigranular-interlobate, exhibits deformation bands, subgrains, undulatory extinction, and contains fine-grained mosaics.

Biotite: Bimodal grain size, subhedral to locally acicular crystals, bent and locally fractured, and typically aggregate-forming.

Hornblende: Bimodal grain size, subhedral to anhedral, and commonly aggregate-forming with biotite.

Epidote: Fine-grained, subhedral, common around and within biotite-hornblende aggregates.

Sphene: Fine-grained, and subhedral to anhedral.

Alteration minerals: Minor replacement of biotite by chlorite.

SFJ-63: Medium-grained, weakly to moderately foliated, hornblende-biotite tonalite.

Plagioclase: Coarse-grained, subhedral, oscillatory zoned, mechanically twinned, locally bent, locally myrmekitic, and minor recrystallization at grain boundaries.

Quartz: Fine-grained, seriate-interlobate to amoeboid, and exhibits subgrains and interstitial mosaics (especially near plagioclase).

Biotite: Bimodal grain size, commonly bent and recrystallized, locally fractured, and aggregate-forming.

Hornblende: Bimodal grain size, subhedral to anhedral, locally fractured, commonly occurs with biotite aggregates.

Epidote: Fine-grained, anhedral, mostly secondary rather than magmatic, and locally fractured.

Sphene: Bimodal grain size, subhedral to anhedral, and commonly occurs with opaques.

Alteration minerals: Hornblende replaced by biotite.

SFJ-67: Medium-grained well-foliated, hornblende-biotite tonalite.

Plagioclase: Coarse-grained, subhedral, mechanically twinned, inequigranular polygonal, with minor recrystallization at grain boundaries.

Quartz: Bimodal grain size, inequigranular interlobate and locally amoeboid, with subgrains and deformation bands.

Biotite: Medium-grained, subhedral to anhedral to acicular, bent and kinked, recrystallized, and cluster-forming.

Hornblende: Medium-grained, subhedral to anhedral, and locally recrystallized.

Epidote: Fine-grained, subhedral to anhedral, typically aggregate-forming with biotite.

Sphene: Fine-grained and anhedral.

Alteration minerals: Minor saussuritization of plagioclase and hornblende replaced by biotite.

SFJ-75a: Medium-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium-to coarse-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, and locally bent.

Quartz: Bimodal grain size, inequigranular-interlobate to seriate-interlobate, exhibits undulatory extinction, recrystallized, with subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent, and aggregate-forming.

Hornblende: Fine- to medium-grained and subhedral to anhedral.

Epidote: Fine-grained, subhedral to anhedral, and cluster-forming with biotite.

Sphene: Fine-grained and subhedral to anhedral.

Alteration minerals: Minor saussuritization of plagioclase, minor biotite to chlorite, and hornblende to biotite.

SFJ-75b: Fine- to medium-grained, leucocratic, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium- to coarse-grained, subhedral to locally anhedral, oscillatory zoned, locally bent, locally recrystallized, and locally myrmekitic.

Quartz: Bimodal grain size, inequigranular-interlobate, exhibits undulatory extinction, with subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent, and aggregate-forming.

Hornblende: Medium-to coarse-grained, subhedral, and typically forms cluster with biotite.

Epidote: Fine-grained and subhedral to anhedral.

Sphene: Fine-grained, subhedral to anhedral, and locally is aggregate-forming with biotite.

Alteration minerals: Minor biotite to chlorite and hornblende to biotite.

SFJ-77: Medium-grained, weakly foliated, hornblende-biotite tonalite.

Plagioclase: Coarse-grained, subhedral, oscillatory zoned, mechanically twinned, locally recrystallized, and locally myrmekitic.

Quartz: Bimodal grain size, subhedral to anhedral, moderately recrystallized, with subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent and kinked, recrystallized, and locally aggregate-forming.

Hornblende: Medium-grained, subhedral to anhedral, and locally aggregate-forming with biotite and epidote.

Epidote: Fine-grained, subhedral to anhedral, and primarily secondary.

Sphene: Fine-grained, rare, and anhedral.

Alteration minerals: Biotite to chlorite and minor hornblende to biotite.

SFJ-85a: Medium-to coarse-grained, weakly foliated, hornblende-biotite tonalite.

Plagioclase: Medium-to coarse-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, and bent.

Quartz: Bimodal grain size, inequigranular-interlobate, with subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, recrystallized, and aggregate-forming.

Hornblende: Fine-grained, subhedral to anhedral, and recrystallized.

Epidote: Fine-grained, subhedral to anhedral, and primarily secondary.

Sphene: Fine-grained, anhedral, with abundant oxides within crystals.

Alteration minerals: Saussuritization of plagioclase, biotite to chlorite, and locally hornblende to biotite.

SFJ-85b: Medium-grained hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral (abundant), oscillatory zoned, mechanically twinned, moderately recrystallized, and contains mica, quartz, and epidote inclusions.

Quartz: Fine-to medium-grained, inequigranular-interlobate, highly recrystallized, with subgrains.

Biotite: Fine-grained, subhedral to anhedral to acicular, and locally aggregate-forming.

Hornblende: Fine-to medium-grained, subhedral to anhedral, recrystallized, and locally aggregate-forming with biotite.

Epidote: Fine-grained, subhedral to anhedral, recrystallized, and mostly secondary.

Sphene: Fine-grained, rare, and anhedral.

Alteration minerals: Saussuritization of plagioclase, biotite to chlorite, and hornblende to biotite.

SFJ-86: Medium-grained, well-foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, and locally recrystallized.

Quartz: Bimodal grain size, inequigranular-interlobate, exhibits undulatory extinction and subgrains, and locally contains coarse, strain-free crystals.

Biotite: Bimodal grain size, anhedral, locally bent, and recrystallized.

Hornblende: Medium-grained, rare, and subhedral.

Epidote: Fine-grained, subhedral to anhedral, and typically aggregate-forming with biotite.

Sphene: Fine-grained and subhedral.

Alteration minerals: Biotite to chlorite and minor hornblende to biotite.

SFJ-96: Medium-grained, well-foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral, oscillatory zoned, mechanically twinned, locally recrystallized, locally myrmekitic, and locally quartz-filled fractures.

Quartz: Bimodal grain size, inequigranular-interlobate to amoeboid, recrystallized, exhibits undulatory extinction, with subgrains and deformation bands.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent, and aggregate-forming.

Epidote: Fine-grained, subhedral, and mostly secondary.

Sphene: Fine-grained and subhedral to euhedral.

Alteration minerals: Biotite to chlorite and hornblende to biotite.

SFJ-101: Medium-grained, moderately foliated, plagioclase porphyritic, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, locally recrystallized, and locally bent.

Quartz: Fine-to coarse-grained, inequigranular-interlobate, with subgrains and mosaics parallel to fabric.

Biotite: Bimodal grain size, subhedral to anhedral, recrystallized, and locally bent.

Hornblende: Fine-grained and subhedral to anhedral.

Epidote: Fine-grained, subhedral to anhedral, and concentrated in quartz and biotite veins.

Sphene: Fine-grained, rare, and subhedral.

Alteration minerals: Saussuritization of plagioclase, biotite to chlorite, and minor hornblende to biotite.

SFJ-120: Medium-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Bimodal grain size, subhedral, oscillatory zoned, mechanically twinned, and locally myrmekitic and recrystallized.

Quartz: Fine-grained, inequigranular-interlobate, and recrystallized with subgrains.

Biotite: Fine-grained, subhedral to anhedral, and locally recrystallized.

Hornblende: Medium-grained, subhedral to anhedral, locally recrystallized, and aggregate-forming with biotite and epidote.

Epidote: Fine-grained, subhedral, mostly secondary, and typically associated with biotite clusters.

Spene: Fine-grained and subhedral.

Alteration minerals: Minor biotite to chlorite and hornblende to biotite.

SFJ-132: Medium-grained, moderately-to well-foliated, plagioclase porphyritic, hornblende-biotite tonalite.

Plagioclase: Medium-to coarse-grained, subhedral to locally anhedral, locally oscillatory zoned, mechanically twinned, and locally bent.

Quartz: Fine-to medium-grained, inequigranular-interlobate, with well-developed undulatory extinction and subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, recrystallized, and locally bent.

Hornblende: Bimodal grain size, subhedral to anhedral, and typically associated with biotite and epidote.

Epidote: Fine-grained, subhedral to anhedral, and locally exhibits quartz-filled fractures.

Spene: Fine-grained, subhedral to anhedral, and typically occurs near hornblende.

Alteration minerals: Minor biotite to chlorite and hornblende to biotite.

SFJ-138: Medium-to coarse-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to locally anhedral, oscillatory zoned, mechanically twinned, and locally has quartz-filled fractures.

Quartz: Bimodal grain size, inequigranular-to seriate-interlobate, with well-developed undulatory extinction and subgrains, and moderately recrystallized.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent, recrystallized, and shows a weak preferred orientation in foliation plane.

Hornblende: Medium-grained, subhedral to anhedral, and aggregate-forming with biotite.

Epidote: Fine-grained, anhedral to locally euhedral, and is typically associated with biotite and hornblende.

Sphene: Fine-grained and anhedral.

Alteration minerals: Minor saussuritization of plagioclase, minor biotite to chlorite, and hornblende to biotite.

SFJ-143a: Fine-to medium-grained, well-foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral, weakly oscillatory zoned, mechanically twinned, locally recrystallized at grain boundaries, locally myrmekitic, and mica-filled fractures along cleavage planes.

Quartz: Fine-grained, inequigranular-interlobate to amoeboid, with abundant subgrains and mosaics.

Biotite: Fine-grained, subhedral to anhedral, recrystallized, with aggregates elongate approximately parallel in foliation plane.

Hornblende: Fine-grained, subhedral to anhedral, and less abundant than biotite and coarser-grained.

Epidote: Fine-grained, subhedral, and typically found with hornblende and biotite aggregates.

Sphene: Fine-grained and subhedral.

Alteration minerals: Saussuritization of plagioclase and biotite to chlorite.

SFJ-143b: Medium-grained, weakly foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral, weakly oscillatory zoned, mechanically twinned, and locally bent.

Quartz: Fine-grained, inequigranular-interlobate to seriate, with undulatory extinction and poorly-developed subgrains.

Biotite: Fine-grained, highly altered to chlorite, and locally bent.

Hornblende: Fine-grained and subhedral.

Epidote: Fine-grained and anhedral, and typically associated with plagioclase.

Sphene: Fine-grained and subhedral.

Alteration minerals: Saussuritization of plagioclase, abundant biotite to chlorite, and hornblende to biotite.

SFJ-145a: Medium-grained, moderately foliated, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, locally recrystallized at grain boundaries, and shows local preferred orientation with long axes parallel to foliation plane.

Quartz: Fine-grained, seriate-interlobate, exhibits undulatory extinction, with well-developed subgrains.

Biotite: Bimodal grain size, subhedral to anhedral, locally bent, moderately recrystallized, and shows weak preferred orientation with long axes parallel to foliation plane.

Hornblende: Medium-to coarse-grained, subhedral to anhedral, and locally shows moderately-developed preferred orientation with long axes parallel to foliation plane.

Epidote: Fine-grained, rare, anhedral, and typically found near biotite and hornblende.

Sphene: Fine-grained and subhedral to anhedral.

Alteration minerals: Biotite to chlorite and hornblende to biotite.

SFJ-145b: Fine-to medium-grained, well-foliated, mafic-rich, hornblende-biotite tonalite.

Plagioclase: Fine-grained, subhedral to anhedral, weakly oscillatory zoned, mechanically twinned, and shows a moderate preferred orientation with long axes parallel to foliation plane.

Quartz: Fine-grained, inequigranular-interlobate to locally amoeboid, with deformation bands and undulatory extinction, and shows minor subgrain development.

Biotite: Fine-grained, subhedral to locally euhedral, with abundant grains oriented approximately parallel to one another.

Hornblende: Fine-grained, subhedral, and homogeneously distributed.

Epidote: Fine-grained, subhedral, and typically associated with biotite.

Sphene: Fine-grained, subhedral, and relatively abundant.

Alteration minerals: Biotite to chlorite.

SFJ-172: Medium-grained, well-foliated, mafic-rich, hornblende-biotite tonalite.

Plagioclase: Medium-grained, subhedral to anhedral, oscillatory zoned, mechanically twinned, locally myrmekitic, and locally recrystallized at grain boundaries.

Quartz: Fine-grained, seriate-interlobate to amoeboid, with undulatory extinction and subgrains, and local deformation bands, and is abundant around plagioclase.

Biotite: Fine-grained, subhedral to anhedral, and recrystallized.

Hornblende: Fine-grained and subhedral to anhedral.

Epidote: Fine-grained, subhedral to anhedral, and mostly secondary.

Sphene: Fine-grained and subhedral to anhedral.

Alteration minerals: Saussuritization of plagioclase, biotite to chlorite, and hornblende to biotite.

SFJ-181: Medium-to coarse-grained, well-foliated, hornblende-biotite tonalite.

Plagioclase: Medium-to coarse-grained, subhedral to anhedral, weakly oscillatory zoned, mechanically twinned, locally myrmekitic, and locally recrystallized at boundaries.

Quartz: Fine-grained, inequigranular-interlobate, recrystallized, and exhibits subgrains.

Biotite: Medium-grained, subhedral, locally bent, and aggregate-forming parallel to foliation plane.

Hornblende: Bimodal grain size and subhedral to anhedral.

Epidote: Fine-grained, anhedral, and primarily secondary.

Sphene: Fine-grained, rare, and subhedral to anhedral.

Alteration minerals: Saussuritization of plagioclase and hornblende to biotite.