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STRUCTURAL ANALYSIS OF EOCENE DIKE SWARMS IN AND NEAR THE
DUNCAN HILL PLUTON, NORTH CASCADES, WASHINGTON

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Kathleen I. Bryant

May 2017

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The Designated Thesis Committee Approves the Thesis Titled

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ABSTRACT

STRUCTURAL ANALYSIS OF EOCENE DIKE SWARMS IN AND NEAR THE DUNCAN HILL PLUTON, NORTH CASCADES, WASHINGTON

by Kathleen I. Bryant

Voluminous Eocene dikes in the North Cascades are thought to provide insights into the regional strain field during postulated ridge–trench interaction in the Pacific Northwest. One understudied area with a large number of dikes is spatially associated with the elongate (NW-SE), ~46 Ma granodioritic Duncan Hill pluton. The ~80 km² study area contains the shallow part of this pluton and the host schist of the Twentyfive Mile Creek unit and tonalite and migmatite of the Cretaceous Chelan Complex. Field observations and petrographic analyses indicate that the dikes in the study area can be sub-divided compositionally and texturally into three types: intermediate-mafic, granite porphyry, and rhyolite. Extension magnitudes from the dikes (n=438) are ~4% to 7%. The dikes have predominantly steep dips, but vary widely in strike and define a broadly bimodal pattern of NW (301°) and NE (026°) strikes. Orientations indicate that the Duncan Hill pluton did not modify the strain field, whereas the strong foliation and anisotropy in the Twentyfive Mile Creek unit may be responsible for some of the NW strikes. The NE-striking dikes likely record the regional NW-SE extension that was active when they intruded. From the data collected in this study, it cannot be ruled out that the NW-striking dikes intruded at different times and under a different regional strain field. This work has shown that dike orientations in the study area are much more complex than those documented elsewhere in the North Cascades.

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TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	ix
INTRODUCTION	1
North Cascades Geology	6
Eocene Deformation	7
Study Area	10
ROCK UNITS.....	10
Host Units to Duncan Hill Pluton and Dikes.....	10
Duncan Hill Pluton	12
Dike Types.....	12
Granite Porphyry Dikes	13
Rhyolite Dikes	18
Intermediate-Mafic Dikes	18
DIKE ORIENTATIONS AND DIKE ABUNDANCE	23
Dike Type Abundance and Mean Dike Strike Per Subdomain	27
Dike Strike Per Host Versus Distance	34
Dike Strike Per Dike Type.....	34
EXTENSION	37
DISCUSSION.....	39
Dike Orientations.....	41
Extension Directions and Magnitudes	44
Global Diking Patterns.....	45
Regional Dike Orientations	45
Regional Dike Age Data	48
Models For Two Dike Trends.....	50
CONCLUSIONS	54
REFERENCES CITED.....	56

LIST OF FIGURES

Figure 1. Block diagram showing processes that potentially influenced the North Cascades as a result of Eocene ridge subduction beneath the North American plate.	2
Figure 2. Model showing inferred Resurrection plate configuration at 45 Ma	3
Figure 3. Simplified map of North Cascades crystalline core and adjacent Chumstick and Swauk basins.	5
Figure 4. Geologic map highlighting (orange) Eocene plutons in the Cascades core and dike trends from other studies.	9
Figure 5. Simplified geologic map of study area.	11
Figure 6. Photo-micrographs of a granite porphyry dike.	14
Figure 7. Large granite porphyry dike demonstrating the resistant outcrop style.	15
Figure 8. Histogram of thicknesses of granite porphyry dikes.	16
Figure 9. Sheeted rhyolite dikes. Red dashed lines outline dikes.	19
Figure 10. Photo-micrographs showing common textures in the rhyolite dikes.	20
Figure 11. Two intermediate-mafic dikes.	21
Figure 12. Photo-micrographs of common textures in intermediate-mafic dikes.	22
Figure 13. Histogram of thicknesses of intermediate-mafic dikes	24
Figure 14. Large dikes identified using Google Earth.	25
Figure 15. Stereographic projection of poles to 438 dikes	26
Figure 16. Distribution of NE-striking (gray) and NW-striking (black) dikes with distance from the Duncan Hill pluton.	28

Figure 17. Rose diagram displaying the mean strike of all dikes (black arrow, n=112) and mean strike of NW-striking dikes (red, n=20) and NE-striking dikes (blue, n=92) in and within 3 km of the margin of the Duncan Hill pluton (Subdomain A).....	29
Figure 18. Rose diagram displaying the mean strike of all dikes (black arrow, n=95) and the mean strike of NW-striking dikes (red, n=49) and NE-striking dikes (blue, n=46) that are between 3 to 5 km from the pluton (Subdomain B).....	31
Figure 19. Rose diagram showing the mean strike of all dikes (black arrow, n=174) and the mean strike of NW-striking dikes (red, n=75) and NE-striking dikes (blue, n=99) that are between 5 to 10 km from the pluton (Subdomain C).....	32
Figure 20. Rose diagram showing the mean strike of all dikes (black arrow, n=57) and the mean strike of NW-striking dikes (red, n=27) and NE-striking dikes (blue, n=30) that are greater than 10 km from the pluton (Subdomain D).....	33
Figure 21. Stereographic projection of poles to intermediate-mafic dikes (n= 279).....	36
Figure 22. Stereographic projection of poles to rhyolite dikes (n=14).....	36
Figure 23. Stereographic projection of poles to granite porphyry dikes (n=51).....	38
Figure 24. Average dike trends for subdomains A-D	42
Figure 25. Dike trends per subdomain and host rocks.....	43
Figure 26. Average dike trends in the North Cascades.....	46
Figure 27. Radiometric dates with uncertainties for dikes in the North Cascades	49
Figure 28. Hypothesized dike trends (black) based on the shape of the Duncan Hill pluton compared with dike trends measured in the field (multi-color lines same as Fig. 5).....	52

LIST OF TABLES

Table 1. Thickness data for all dikes excluding those measured using Google Earth.....	17
Table 2. Summary of strike and extension data in subdomains.....	30
Table 3. Average dike strike based on host rock and subdomain.....	35
Table 4. Average extension magnitude data.....	40
Table 5. Summary of average strike, extension data and age data for this study and other studies in the North Cascades region.....	47

INTRODUCTION

Subduction of mid-oceanic ridges is a fundamental process that occurs along convergent plate boundaries. The subduction of ridge segments is hypothesized to form a slab window, where the upwelling of asthenosphere results in anomalous, high temperatures in the overriding plate (e.g., Sisson et al., 2003; Groome and Thorkelson, 2009). This “blowtorch effect” changes the thermal and mechanical properties of the overriding plate (Groome and Thorkelson, 2009). These changes are marked by anomalous igneous activity and complex strain patterns in the forearc, and potentially in the arc and backarc as well. In regions of postulated ridge subduction, there are distinct temporal and spatial patterns associated with this magmatism and the regional strain field. These patterns are a result of the geometry and configuration of ridge segments subducting with time relative to the trench (Fig. 1) (e.g., Dickinson and Snyder 1979; Thorkelson, 1996; Johnston and Thorkelson, 1997; Sisson et al., 2003; Groome and Thorkelson, 2009).

The Pacific Northwest is one region where a ridge probably interacted with a trench during the Eocene (e.g., Madsen et al., 2006; Eddy et al., 2016). The melting of sedimentary material in the forearc produced Eocene cordierite-bearing granites and in the arc plutons with more alkaline compositions compared to the older, dominantly tonalitic magmatism (i.e. Golden Horn batholith) (Misch, 1966). This forearc melting provides strong evidence for a slab window. The ridge-trench interaction may have induced a period of Eocene transtension, when either the Farrallon-Resurrection ridge or Farrallon-Kula ridge interacted with the North American plate (Fig. 2) (e.g., Haugerud et

Figure 1. Block diagram showing processes that potentially influenced the North Cascades as a result of Eocene ridge subduction beneath the North American plate. In this diagram, as the ridge subducts and continues to spread, it creates localized changes in magmatic activity directly above the spreading center. Modified from Haeussler et al. (2003).

Figure 2. Model showing inferred Resurrection plate configuration at 45 Ma. White areas are the locations of asthenospheric mantle upwelling. The red box shows the approximate location of the study area. The white and black arrows represent 3 m.y. vectors of plate motion. Figure modified from Madsen et al. (2006).

al., 1991; Madsen et al., 2006; Miller et al., 2009b; 2016). Ridge subduction commonly results in extension within the shallow crust, leading to faults and dikes. In a homogeneous material, dikes form parallel to the greatest compressional stress and perpendicular to the least compressional stress, and dike orientations can thus be used to investigate the strain regime. Dike orientations may be deflected from regional stress directions by the anisotropy of the host rocks and faults (e.g., Gudmundsson, 1984). Regional stress fields may also have been modified locally during emplacement of large intrusions and volcanic centers (e.g., Ernst et al., 1995).

Eocene dike orientations in the North Cascades can be used to better understand the local strain field during the period of postulated ridge-trench interaction. One of the least studied areas in the Washington Cascades with abundant dikes is spatially associated with the elongate (NW-SE), granodioritic Duncan Hill pluton (Cater, 1982; Hopson and Dellinger, 1989). Zircons in this pluton were dated at 46.5 ± 0.036 Ma by U-Pb using CA-ID-TIMS (Uranium-Lead Chemical Abrasion-Isotope Dilution-Thermal Ionization Mass Spectrometry) (Fig. 3) (Michael Eddy, written commun., 2016). This pluton is tilted and dikes are most abundant in and near the shallow portion to the southeast (Dellinger, 1989). The orientations, thicknesses, and abundances of these dikes are the focus of this thesis. They are used in conjunction with dike orientations reported by others throughout the North Cascades to better constrain and understand the strain field during the Eocene.

Figure 3. Simplified map of North Cascades crystalline core and adjacent Chumstick and Swauk basins. Eocene plutons are shown in orange. Red lines represent trends of Eocene dikes measured during this study. Other line colors represent dike trends measured by others. BPB (Black Peak batholith); BR (Bearcat Ridge orthogneiss); CH (Chaval pluton); CS (Chiwaukum Schist); DF (Dirtyface pluton); MC (Marble Creek pluton); NQ (Napeequa complex); RP (Riddle Peaks pluton); RRC (Railroad Creek pluton); SC (Sloan Creek pluton); SM (Sulphur Mountain pluton); WPT (Windy Pass thrust); WRG (Wenatchee Ridge Gneiss). Modified from Miller et al. (2009a).

North Cascades Geology

The Duncan Hill pluton and spatially associated dikes intrude rocks of the Cascades core of the North Cascades, the southern extension of the Coast Plutonic Complex, which is a Mesozoic and Paleogene magmatic arc (Fig. 3) (e.g., Misch, 1966; Tabor et al., 1989; Miller et al., 2009a). In the North Cascades and southern Coast Mountains of British Columbia, arc plutons intrude upper Paleozoic–Cretaceous oceanic and arc terranes of the Coast belt, which separates the Insular and Intermontane superterranes (e.g., Journeay and Friedman, 1993).

The tectonostratigraphic framework of the Cascades core includes three major terranes: (1) the Nason terrane; (2) the Swakane terrane; and (3) the Chelan Mountains terrane (Tabor et al., 1987b, 1989). The Nason terrane is dominantly pelitic schist (Plummer, 1980) and as it lacks Eocene deformation and magmatism, it is not considered further in this study. The structurally deepest terrane is composed of the Late Cretaceous Swakane Biotite Gneiss (Paterson et al., 1994). The Chelan Mountain terrane contains the Napeequa Schist, Chelan Complex, Twentyfive Mile Creek unit, and Skagit Gneiss Complex (Fig. 3) (Tabor et al., 1987b, 1989). Amphibolite, siliceous schist, and quartzite dominate the Napeequa unit. The correlative Late Triassic Cascade-Holden River Unit and Twentyfive Mile Creek unit are made up of hornblende-biotite schist, gneiss, amphibolite, calc-silicate rock, and metaconglomerate (Misch, 1966; Cater, 1982; Brown et al., 1994; Miller et al., 1994). Tonalitic rocks characterize the Cretaceous Chelan Complex, much of which is migmatitic (Tabor, 1987b; Hopson and Mattinson, 1994).

Eocene Deformation

During the Paleocene, the tectonic regime in the Pacific Northwest changed from transpression to transtension, and was also marked by the inferred subduction of the Farrallon-Resurrection ridge or Farrallon-Kula ridge (Breitsprecher, 2003; Haeussler et al., 2003; Madsen et al., 2006). The Skagit Gneiss Complex contains the largest area of Eocene ductile deformation in the Cascades core. This deformation is defined by foliation, lineation, and folds (Miller et al., 2009a; 2016). A major Eocene structure is the Dinkelman décollement, which separates the Swakane Gneiss from the Napeequa unit and older (91-72 Ma) arc plutons (Fig. 3) (Matzel et al., 2004; Paterson et al., 2004). Other Eocene ductile deformation in the core includes solid-state foliations and lineations, which have been observed in the northern tip of the 46.5 ± 0.036 Ma Duncan Hill pluton (Cater, 1982; Haugerud et al, 1991).

Eocene brittle deformation is marked by the Straight Creek fault, Entiat fault, and parts of the Ross Lake fault system, all of which are postulated to have components of dextral strike slip (Fig. 3) (Misch, 1966). The north-south-striking Straight Creek fault initiated by ~ 48 Ma and forms the western boundary of the Cascades core (Fig. 3) (e.g., Misch, 1966). Estimates of displacement on the fault range from 80 to 190 km (e.g., Misch, 1977; Vance and Miller, 1981; Tabor et al., 1984; Monger, 1986). The northwest-striking Entiat fault forms the eastern boundary of the Eocene Chumstick basin, and to the NW separates different blocks of the Cascades core. Due to the straightness of the Entiat fault in map view and the rapid deposition in the Chumstick basin, the fault is thought to have a major strike-slip component and down-to-the-southwest normal motion

(e.g., Gresens et al., 1981; Tabor et al., 1987a; Evans, 1994). The Ross Lake fault system (Fig. 3) is a ≥ 10 -km-wide zone of northwest-striking high-angle faults and shear zones (e.g., Misch, 1966; Haugerud et al., 1994; Miller, 1994).

After the transition from transpression to transtension, a hiatus in plutonism that lasted from ~ 60 to 50 Ma ended and a period of significant magmatism occurred from ~ 50 – 45 Ma (Fig. 4) (Miller et al., 2009a; 2016). Magmatism changed from dominantly tonalitic during the Cretaceous to granodioritic in the Eocene (Misch, 1966). Several of the Eocene plutons intrude the Skagit Gneiss Complex. Southwest of the Complex are the Eocene granodioritic Duncan Hill ($\sim 46.5 \pm 0.036$ Ma, Michael Eddy, written commun., 2016) and Railroad Creek plutons (~ 46 Ma, Miller et al., 2016), both of which are elongate parallel to the orogen (Cater, 1982; Dellinger, 1996). The Cooper Mountain batholith is ~ 48 Ma (Shea, 2008; Miller et al., 2016) and forms a large portion of the SE boundary of the Skagit Gneiss Complex. It truncates foliation in Skagit rocks as young as ~ 49 Ma (Miller et al., 2016).

The most abundant and extensively studied Eocene dikes in the region are the mafic Teanaway dike swarm directly south of the Cascades core (Doran, 2009). In several areas in the Cascades core, abundant dikes of varying compositions intrude the Skagit Gneiss Complex, Cooper Mountain batholith, Chelan Complex, Golden Horn batholith, Twenty-Five Mile Creek unit, Seven Fingered Jack pluton, Duncan Hill pluton, and Swakane Gneiss (Fig. 3).

In this study, the strain field around the Duncan Hill pluton is compared to the regional strain field, by comparing dike orientations from the study area with those

Figure 4. Geologic map highlighting (orange) Eocene plutons in the Cascades core and dike trends from other studies. Abbreviations of units are the same as Figure 3. Modified from Miller et al. (2009a).

reported elsewhere in the North Cascades. Major goals include evaluating whether a change occurred in the regional strain field, and determining the influence, if any, of host rock heterogeneity and proximity to the Duncan Hill pluton on dike orientations.

Study Area

The ~80 km² study area is located west of Lake Chelan. The study area was divided into four subdomains based on distance from the margin of the Duncan Hill pluton (Fig. 5). The subdomains contain a variety of host rocks.

ROCK UNITS

Host Units to Duncan Hill Pluton and Dikes

In the study area, dikes intrude the Cardinal Peak pluton (~72 Ma), Twentyfive Mile Creek unit, Chelan Complex, and other dike rocks. The Cardinal Peak pluton is a mid-crustal pluton that varies in composition along strike, but is predominantly granodioritic in the study area. Foliations in the pluton are mainly magmatic and moderate to weak (Miller and Paterson, 2001). The dikes predominantly intrude the Chelan Complex and Twentyfive Mile Creek unit. The Chelan Complex is divided into multiple units. Most of the dikes intrude homogenous tonalite or heterogeneous migmatite, which is weakly to strongly foliated hornblende tonalite gneiss. These foliations are shown by Tabor et al. (1987b) to mostly strike NW to E-W (Fig. 5). The Twentyfive Mile Creek unit likely correlates with the Triassic Cascade River-Holden unit (Miller et al., 1994). It is dominantly fine-grained biotite-hornblende schist and medium-grained biotite-hornblende gneiss, and is strongly foliated. Tabor et al. (1987b) reports that foliation strikes are predominantly NW-striking with some that strike E-W.

Figure 5. Simplified geologic map of study area, showing dike-rich zone denoted by stippled pattern. Lines show the average strike for each dike type: intermediate-mafic (green); granite porphyry (pink); rhyolite (purple); and dikes of unknown composition mapped with Google Earth (yellow). Map modified from Tabor et al. (1987a).

Duncan Hill Pluton

The northwest-striking, ~46 Ma Duncan Hill pluton is the south-westernmost of the Eocene plutons that intrude the Cascades core (Fig. 4) (Cater and Crowder, 1967; Cater and Wright, 1967; Cater, 1982; Dellinger, 1996). The pluton is tadpole-shaped, ~48 km long, and has been tilted so that shallower levels are exposed in the southeast. Al-in-hornblende barometry suggests emplacement depths that range from ~2.2-3.5 km in the southeast to ~9.9-13.5 km in the northwest (Dellinger, 1996). Mirolitic cavities in the southeastern part of the pluton (Cater, 1982) indicate a volatile-rich magma and shallow depths of intrusion, consistent with Al-in-hornblende pressures.

The Duncan Hill pluton varies in composition along its length, but is generally homogeneous except in its northwest tip (Dellinger, 1996). This study focused on the structurally shallow, southern portion of the pluton where it intrudes biotite-hornblende schist and medium-grained biotite-hornblende gneiss of the Twentyfive Mile Creek unit and the homogenous tonalite and heterogeneous migmatite of the Chelan Complex (Fig. 5). Foliations and lineations are weak in the southeastern portion of the pluton and are stronger to the northwest (Dellinger, 1996).

Dike Types

The voluminous Eocene dikes were mapped by Tabor et al. (1987a) and inferred to be associated with intrusion of the Duncan Hill pluton and the nearby Eocene Cooper Mountain batholith (Cater, 1982) (Fig. 5). These dikes are most abundant near the southernmost, shallow end of the pluton. They were divided into the “granite porphyry dike swarm” and “rhyolite dike swarm” (Tabor et al., 1987a). My field investigation

reveals a third dike type, referred to herein as “intermediate-mafic.” One mafic-intermediate dike from the west side of Lake Chelan was dated by U-Pb (CA-ID-TIMS) zircon geochronology. Of the six zircons analyzed, one was an inherited crystal with an age of 49.130 Ma, and the remaining zircons gave a weighted mean of 47.523 ± 0.019 Ma (Michael Eddy, written commun., 2016).

Granite Porphyry Dikes

The granite porphyry dikes are composed of quartz, feldspar, hornblende, and biotite (Fig. 6). Quartz phenocrysts make up 20-30% of the total composition, are typically subhedral to rounded, and range in size from 0.5 to 5 mm. A few phenocrysts are bi-pyramidal with corroded rims. Subhedral feldspar phenocrysts make up 15-25% of the rock, and range in size from ~0.1 to 3 mm. Alteration to clays and/or sericite is very common. Many of the potassium feldspar phenocrysts are perthitic. Biotite forms aggregates and is commonly zoned from dark brown to light green in plane light. It makes up much of the groundmass along with aggregates of plagioclase, augite, magnetite, and minor hornblende and apatite. Secondary minerals include sericite, epidote, sphene, and calcite. In some samples, quartz and feldspar phenocrysts are glomeroporphyritic and are set in a dominantly micrographic groundmass (Fig. 6). A few smaller quartz grains that have coronas of plagioclase are inferred to be xenocrysts.

Tabor et al. (1987a) report that the granite dike thickness is ~5 m. My detailed field investigation reveals that thicknesses range between 0.4 m and 10 m (Fig. 7). A large number of these dikes (41 of 51) are 1-3-m thick (Fig. 8), and the average thickness is ~2.0 m (Table 1). Thicker dikes typically hold up ridges, whereas thinner dikes are found

Figure 6. Photomicrographs showing common textures of a granite porphyry dike. Top shows typical quartz phenocrysts in fine-grained matrix. Bottom illustrates glomeroporphyritic quartz and feldspar phenocrysts set in a dominantly micrographic groundmass.

Figure 7. Large granite porphyry dike demonstrating the resistant outcrop style.

Figure 8. Histogram of thicknesses of granite porphyry dikes.

Table 1. Thickness data for all dikes excluding those measured using Google Earth.

	All types	Granite Porphyry	Rhyolite	Intermediate- Mafic
Total dikes	344	51	14	279
Minimum thickness (m)	0.1	0.4	0.1	0.1
Maximum thickness (m)	10.0	10.0	9.0	10.0
Average thickness (m)	1.0	2.0	1.3	1.0

in the best exposed outcrops. In the case of poor exposure, dikes are typically the only preserved rocks (Fig. 7).

Rhyolite Dikes

The rhyolite dikes are commonly sheeted (Fig. 9) in the study area and are the least abundant dikes (n=14). These dikes have smaller and fewer phenocrysts than the granite porphyry dikes (Fig. 10). Quartz phenocrysts are typically subhedral and make up 10-20% of the rock. Phenocrysts are up to 2 mm in length. A few of the phenocrysts have coronas of spherulite. Feldspar phenocrysts make up 10-20% of the rhyolite. They are generally less than 0.5 mm in length and most form aggregates. Both the quartz and feldspar phenocrysts are set in a devitrified spherulitic groundmass. Fine-grained biotite aggregates are typically zoned from dark brown to light green in plane light and other minor mafic minerals are distributed throughout in the glassy matrix. Secondary minerals include sericite, sphene, epidote and calcite. The thicknesses of these dikes range between 0.1-9.0 m and the average thickness is ~1.3 m (Table 1).

Intermediate-Mafic Dikes

The intermediate-mafic dikes crop out over much of the area that Tabor et al. (1987a) mapped as the “rhyolite swarm”. My observations indicate that many of these dikes are intermediate to mafic in composition (Fig. 11). These dikes are equigranular and light gray to dark gray in color (Fig. 12). The groundmass is primarily small aggregates of plagioclase (~55%), clinopyroxene (25-30%), and hornblende (10-15%), all of which form a felty texture. A few dikes have small phenocrysts (<1 mm long) of plagioclase

Figure 9. Sheeted rhyolite dikes. Red dashed lines outline dikes.

Figure 10. Photomicrographs showing common textures in the rhyolite dikes. Top and bottom photographs display quartz and feldspar set in a devitrified spherulitic matrix (red circle).

Figure 11. Two intermediate-mafic dikes. Note that a thinner mafic dike intrudes a larger intermediate dike. Host rock is Cardinal Peak pluton.

Figure 12. Photomicrographs showing common textures in intermediate-mafic dikes. Both photographs contain small aggregates of plagioclase, clinopyroxene, and hornblende. Note the plagioclase phenocryst in the top photograph.

and hornblende. Most of the hornblende is pseudomorphed by chlorite and oxides, and other secondary minerals include biotite and calcite (Fig. 12). Some of the dikes have chilled margins. Thicknesses of the intermediate-mafic dikes range between 0.1 m and 10 m, and the average thickness is 1.0 m (Table 1). Most of these dikes (253 of 279) are between 1-2 m in thickness (Fig. 13).

DIKE ORIENTATIONS AND DIKE ABUNDANCE

The orientations of 438 dikes were measured in this study. The data were analyzed for the following: abundance of each dike type; spatial distribution relative to the margin of the Duncan Hill pluton; and average dike strike. The average strike was further subdivided into NE- and NW- striking dikes.

Of the 438 measurements, 74 were approximated using Google Earth (Fig. 14). For statistical analyses, Google Earth dikes were assumed to have a dip of 75° , which was the average dip of the dikes measured in this study. Three of the dikes measured using Google Earth were also examined in the field. There is a considerable amount of scatter in dike strike, but there are two maxima, one that is NE (026°) and the other that is NW (301°) (Fig. 15). In order to examine spatial variations, the dike orientation data was further subdivided into four subdomains, which were determined based on distance from the Duncan Hill pluton. Subdomain A includes data in and within 3 km of the Duncan Hill pluton. Subdomain B includes dikes from 3 to 5 km from the pluton. Subdomain C incorporates dikes from 5 to 10 km from the margin, and Subdomain D contains dikes that are greater than 10 km away from the pluton.

Figure 13. Histogram of thicknesses of intermediate-mafic dikes.

Figure 14. Large dikes identified using Google Earth. These dikes strike approximately 030° . Note the orientation of north in the upper right of the image.

Figure 15. Stereographic projection of poles to 438 dikes. The average strike is NE (026° , 75° SE). Kamb contour method with a confidence factor of 2 sigma and a contour interval of 4 sigma. Plotted using Allmendinger (2015).

Dike Type Abundance and Mean Dike Strike Per Subdomain

Intermediate-mafic dikes are the most abundant dike type (279 of 364 petrographically identified). Of the other dikes, 51 are granite porphyries and 14 are rhyolites.

In order to better constrain the mean dike strike, the data were further separated into NW-trending dikes and NE-trending dikes, reflecting the bimodal pattern (Fig. 16). 112 dikes were measured within Subdomain A. These dikes have a mean trend of NE (027°); 92 of the dikes trend NE with a mean strike of 029° , and the other 20 dikes have an average strike of 307° (Fig. 17 and Table 2). In Subdomain B, 95 dikes were measured (Fig. 18). These dikes have a mean strike of 355° . There are 46 NE-trending dikes that have a mean strike of 042° and 49 NW-trending dikes that have a mean strike of 308° (Fig. 18 and Table 2). In Subdomain C, 174 dikes were measured (Fig. 19). These dikes on average strike NE and have a mean strike of 027° . There are 99 NE-trending dikes that have a mean strike of 038° and 75 NW-trending dikes that have a mean strike of 312° (Fig. 19 and Table 2). Dike frequency ($n=57$) decreases in Subdomain D, which is farthest from the pluton. These dikes have a mean strike of 002° (Fig. 20). Of these dikes, 30 trend NE and have a mean strike of 031° , and 27 trend NW with a have a mean strike of 323° (Fig. 20 and Table 2).

The average dike strike varies between 355° and 027° in the subdomains. Subdomain A and C have fewer NW-striking dikes and in these subdomains the average strike is NE (027°). In Subdomain B and D there is roughly equal distribution of NE- and NW-striking dikes, leading to the average N strike of 355° and 002° , respectively.

Figure 16. Distribution of NE-striking (gray) and NW-striking (black) dikes with distance from the Duncan Hill pluton.

Figure 17. Rose diagram displaying the mean strike of all dikes (black arrow, $n=112$) and mean strike of NW-striking dikes (red, $n=20$) and NE-striking dikes (blue, $n=92$) in and within 3 km of the margin of the Duncan Hill pluton (Subdomain A). Plotted using Allmendinger (2015).

Table 2. Summary of strike and extension data in subdomains.

	Strike of Dikes			Extension Direction		
	Average Strike	NW Striking	NE Striking	Average	NW Dikes	NE Dikes
Subdomain A n=112	027°	307°	029°	117°-297°	037°-217°	119°-299°
Subdomain B n=95	355°	308°	042°	085°-265°	038°-218°	132°-312°
Subdomain C n=174	027°	312°	038°	117°-297°	042°-222°	128°-308°
Subdomain D n=57	002°	323°	031°	092°-272°	053°-233°	121°-301°

Figure 18. Rose diagram displaying the mean strike of all dikes (black arrow, $n=95$) and the mean strike of NW-striking dikes (red, $n=49$) and NE-striking dikes (blue, $n=46$) that are between 3 to 5 km from the pluton (Subdomain B). Plotted using Allmendinger (2015).

Figure 19. Rose diagram showing the mean strike of all dikes (black arrow, $n=174$) and the mean strike of NW-striking dikes (red, $n=75$) and NE-striking dikes (blue, $n=99$) that are between 5 to 10 km from the pluton (Subdomain C). Plotted using Allmendinger (2015).

Figure 20 Rose diagram showing the mean strike of all dikes (black arrow, $n=57$) and the mean strike of NW-striking dikes (red, $n=27$) and NE-striking dikes (blue, $n=30$) that are greater than 10 km from the pluton (Subdomain D). Plotted using Allmendinger (2015).

Dike Strike Per Host Versus Distance

Dike attitudes were also plotted based on the host rock and the distance from the margin of the Duncan Hill pluton, in order to determine if either had influenced dike strike (Table 3). In this analysis, the dikes measured using Google Earth were excluded because the host rock was not verified in the field. In Subdomain A, dikes in the Twentyfive Mile Creek unit (n=11) have an average strike of NW (308°) (Table 3). Dikes that intrude the Chelan Complex (n=23) have an average strike of NE (033°) and the few dikes that intrude other dikes rock (n=4) have an average strike of NE (068°) (Table 3). In Subdomain B, the dikes in the Twentyfive Mile Creek unit (n=46) have an average strike of NW (310°), whereas those that intrude the Chelan Complex (n=47) have an average strike of NE (042°) (Table 3). Only one dike (strike of 306°) intruded other dike rock. In Subdomain C, the average dike strike in the Twentyfive Mile Creek unit (n=66) is nearly due E (087°), whereas the average strike in the Chelan Complex (n=66) is NE (033°). The dikes that intruded other dike rock (n=27) have an average strike of roughly N (010°). In Subdomain D only two dikes (mean strike of 035°) were measured in the Twentyfive Mile Creek unit. The average strike in the Chelan Complex (n=50) is roughly N (356°). Only four dikes with a mean strike of 012° intrude other dike rock.

Dike Strike Per Dike Type

The attitudes of each dike type were plotted on stereographic projections. The intermediate-mafic dikes vary significantly in strike, but there are two nearly perpendicular maxima; one strikes NE (033°) and the other strikes NW (306°) (Fig. 21). The less abundant rhyolite dikes strike broadly NE (028°) (Fig. 22). The granite

Table 3. Average dike strike based on host rock and subdomain. Note that dikes measured using Google Earth are not factored in this analysis.

Host	Average Strike 0-3 km	Extension Direction 0-3 km	Average Strike 3-5 km	Extension Direction 3-5 km	Average strike 5-10 km	Extension Direction 5-10 km	Average strike > 10 km	Extension Direction >10 km
25 Mile Creek Unit	308° n=11	038°-218°	310° n=46	040°-220°	087° n=66	177°-357°	035° *n=2	125°-305°
Chelan Complex	033° n=23	123°-307°	042° n=47	132°-312°	033° n=66	123°-303°	356° n=50	086°-266°
Dike Rock	068° *n=4	158°-338°	306° *n=1	036°-216°	010° n=27	100°-280°	012° *n=4	102°-282°

* Denotes averages with less than 10 measurements.

Figure 21. Stereographic projection of poles to intermediate-mafic dikes ($n=279$). Kamb contour method with a confidence factor of 2 sigma and a contour interval of 4 sigma. Plotted using Allmendinger (2015).

Figure 22. Stereographic projection of poles to rhyolite dikes ($n=14$). Plotted using Allmendinger (2015).

porphyry dikes have a strong NE (021°) maxima, and a broad population of dikes that strike approximately E-W (Fig. 23).

EXTENSION

During the Eocene, the regional tectonic strain regime is thought to have been transtensional (e.g., Miller and Bowring, 1990; Haugerud et al., 1994; Miller et al., 2016). Several major high-angle Eocene faults with a component of normal slip involve the Cascades core. The high angle faults closest to the study area are the Entiat fault (~15 km to the southwest) and the Ross Lake fault (~20 km to the northeast), both of which also record dextral slip (Miller et al., 2016). Another contributor to extension is the extensive diking throughout the North Cascades, including the dikes near the Duncan Hill pluton (Miller et al., 2009b; 2016). These dikes were used to analyze the direction of extension and to calculate rough estimates of extension magnitude.

The subdomains delineated in this study were also used to look at spatial variations of extension direction (Table 2). The average extension direction is 117°-297° in Subdomain A, 085°-265° in Subdomain B, 117°-297° in Subdomain C, and 092°-272° in Subdomain D.

The extension directions calculated for the NW-striking dikes were: 037°-217° in Subdomain A (n=20); 038°-218° in Subdomain B (n=49); 042°-222° in Subdomain C (n=75); and 053°-233° in Subdomain D (n=27). The extension directions for the NE-striking dikes were: 119°-299° in Subdomain A (n=91); 132°-312° in Subdomain B (n=46); 128°-308° in Subdomain C (n=99); and 121°-301° in Subdomain D (n=30).

Figure 23. Stereographic projection of poles to granite porphyry dikes (n=51). Kamb contour method with a confidence factor of 2 sigma and a contour interval of 4 sigma. Plotted using Allmendinger (2015).

There is no appreciable variation in extension direction with distance from the Duncan Hill pluton for the NW-striking and NE-striking dikes.

The extension directions calculated for the dikes that intruded into the Twentyfive Mile Creek unit were: 038° - 218° in Subdomain A ($n=11$); 040° - 220° in Subdomain B ($n=46$); 177° - 357° in Subdomain C ($n=66$); and 125° - 305° in Subdomain D (only 2 dikes) (Table 3). The extension directions calculated for the dikes that intruded into the Chelan Complex were: 123° - 307° in Subdomain A ($n=23$); 132° - 312° in Subdomain B ($n=47$); 123° - 303° in Subdomain C ($n=66$); and 086° - 266° in Subdomain D ($n=50$) (Table 3). The extension directions calculated for the dikes intruded into dike rock were: 158° - 338° in Subdomain A (only 4 dikes); 036° - 216° in Subdomain B (only 1 dike); 100° - 280° in Subdomain C ($n=27$); and 102° - 282° in Subdomain D (only 4 dikes) (Table 3).

The magnitude of extension was also calculated from two well-exposed transects that were selected based on the continuous length of outcrop (Table 4). Transect A and Transect B are both road cuts in Subdomain D. Transect A is approximately 11 km from the Duncan Hill pluton and has 13 dikes, which sum to 9 m in thickness along a length of 271 m. The percentage of extension is 4%. Transect B is approximately 13 km from the Duncan Hill pluton and has 17 dikes that sum to 13 m in thickness along a length of 209 m. The percentage of extension for this transect is 7% (Table 4).

DISCUSSION

The main goal of this thesis was to determine the orientations of the abundant dikes that intrude the poorly studied area surrounding the Duncan Hill pluton. These dike

Table 4. Average extension magnitude data.

	Number of Dikes	Sum of Dike Thickness (m)	Station Length (m)	Minimum Extension (m)	Percentage of Extension	Average Strike	Extension Direction
Transect A	13	9	271	30	4%	054°	144°-324°
Transect B	17	13	209	17	7%	027°	117°-297°

orientations were then compared with those reported elsewhere in the North Cascades to determine if the strain field around the Duncan Hill pluton was consistent with the previously inferred regional strain field during the Eocene. The dikes near the Duncan Hill pluton were reported to have a dominant NE trend (e.g., Tabor et al., 1987a; Dellinger, 1996); however, data collected in this study show that there are both NE- and NW- striking dikes. After further analysis, the NE-striking dikes were interpreted to have recorded the regional strain field, whereas the NW-striking dikes reflected a local modification of the strain field. This modification likely resulted from the anisotropy of the host rocks.

Dike Orientations

Dike orientations vary across the study area. The maximum population on a stereographic projection is 026° , 75° SE, but there is also a sizable population that strike NW (Fig. 15). There is no apparent correlation between dike type and strike. The average strike is NE in all subdomains except Subdomain B, where it is NW. There is a strong bimodal distribution of NW- and NE-striking dikes in all subdomains (Fig. 24).

The only significant variation in dike orientation appears to correlate with the type of host rock (Fig. 25 and Table 3). In particular, the dikes that intrude the strongly foliated Twentyfive Mile Creek unit strike NW near the pluton and then rotate counter-clockwise to E-W farther away. Foliations in the Twentyfive Mile Creek unit are shown by Tabor et al. (1987a) to strike predominantly NW near the pluton, whereas farther away foliations strike both E- W and NW (Fig. 5). The Chelan Complex is less strongly-

Figure 24. Average dike trends for subdomains A-D. The dikes were separated into the mean (black), NW-trends (red), and NE-trends (blue). Map modified from Tabor et al. (1987a). Rose diagrams plotted in Allmendinger (2015).

Figure 25. Dike trends per subdomain and host rocks. The Twentyfive Mile Creek unit is shown in red; Chelan Complex in blue; and dikes in purple. Map modified from Tabor et al. (1987a). Rose diagrams plotted in Allmendinger (2015).

foliated, and foliations strike NW to E-W depending on location (Fig. 5). The dikes that intrude it generally strike NE in Subdomains A to C, and rotate to N-S in Subdomain D (Fig. 25 and Table 3) (Fig. 5). The dikes intruding other dike rock generally strike NE. The lack of crosscutting relationships in the study area suggests that the dikes were emplaced close in time and/or that the strain field remained consistent during emplacement episodes.

Extension Directions and Magnitudes

The average extension direction across the whole study area is WNW-ESE; however as described above there is a wide range of dike strikes, and hence a wide range of extension directions. To further consider extension directions, the NE-striking and NW-striking dikes were analyzed separately. There was no significant rotation of extension directions between subdomains for either of these dike trends (Table 2).

Extension directions were derived from dike orientations in each host rock unit. The average extension direction in the Twentyfive Mile Creek unit rotates counter-clockwise from NE-SW to N-S with increasing distance from the Duncan Hill pluton (Table 3). In the Chelan Complex, the extension direction is NW-SE within 10 km of the Duncan Hill pluton, but changes to E-W at a greater distance. Where dikes are the host rock, the extension direction is generally NW-SE, regardless of location (Table 3). The extension magnitude for the study area was calculated to be approximately between 4-7% using two well exposed transects (Table 4).

Global Diking Patterns

Diking patterns observed elsewhere may give insights into the diking patterns in the study area. Ernst et al. (1995) classified dike swarms by their distribution and spatial pattern. The dikes in this study do not correspond in detail with any of the proposed types of Ernst et al. (1995), but they broadly fit within two of their types (Type II and Type IV). Type II is defined as fan-like sub-swarms that are generally separated by dike-poor regions. Within the study area, dikes in sub-swarms separated by dike poor areas are present, but do not exhibit the fan-like pattern. Type IV is defined as sub-parallel dikes over a broad area. The bi-modal orientations measured in the study area are representative of this pattern, when the two orientations are considered separately. More research is needed in the northwestern tip of the Duncan Hill pluton, north of the study area, to see if patterns observed in this study are continuous to the north.

Regional Dike Orientations

The NE-trending dikes in this study are broadly consistent with orientations reported elsewhere in the North Cascades (Fig. 26 and Table 5). Sixty kilometers to the southwest are the voluminous Teanaway dikes, which strike NE (027°) (Doran, 2009). Twenty kilometers northeast of the Duncan Hill pluton, dikes associated with the Eocene Cooper Mountain batholith strike N-S (008°) (Raviola, 1988). The closest measured Eocene dikes to the study area are directly south of the Duncan Hill pluton. The average strike of these dikes (n=74) is NE (058°) (Sylva, 2014). Southeast of the Duncan Hill pluton are dikes (n=71) along the Columbia River, which typically strike NW (314°) (Sylva, 2014). Farther southeast of the Duncan Hill pluton, the Corbaley Canyon dikes (n=82) typically

Figure 26. Average dike trends in the North Cascades. Inset figure shows simplified map of average trends of dikes in the study area plus previously reported dike trends nearby. Dike ages and sources of data are also shown. Abbreviations are same as Figure 3. Modified from Miller et al. (2016).

Table 5. Summary of average strike, extension data and age data for this study and other studies in the North Cascades region. Note that the different data types are not all available for each domain.

Domain	Average strike	Extension direction	Age
Study Area	026° and 301°	116°-296° and 031°-211°	47.523 ± 0.016 Ma (Michael Eddy, written commun., 2016)
South of Duncan Hill pluton (Sylva, 2014)	058°	148°-328°	-
Teanaway mafic dikes (Doran, 2009)	027°	117°-297°	49.341 ± 0.033 Ma, (Eddy et al., 2016)
Cooper Mountain dikes (Raviola, 1988)	008°	095-275°	49.3 Ma, (Michael Eddy, written commun., 2016)
Columbia River dikes (Sylva, 2014)	314°	044°-224°	
Corbaley Canyon dikes (Sylva, 2014)	098°	008°-188°	47.8 ± 1.9 Ma 48.4 ± 2.2 Ma (Tabor et al., 1987a)
Northern Seven Fingered Jack pluton dikes (Sylva, 2014)	075°	165°-345°	-
Central Seven Fingered Jack pluton dikes (this study)	067°	157°-337°	-
Skagit Gneiss Complex dikes (Michels, 2008)	275°	005°-185°	~48 Ma (Michels, 2008)
Skagit Gneiss Complex dikes (Shea, 2008)	211°	121°-301°	~48-49 (Shea, 2008)
Ductilely deformed dike west of Duncan Hill pluton (Matzel, 2004)	-	-	46.39 ± 0.06 Ma (Matzel, 2004)

strike ~E-W (098°) (Sylva, 2014). Dikes ($n=40$) in the tip of the Seven Fingered Jack pluton, a short distance to the northwest of the study area, trend ENE (075°) (Sylva, 2014). West of the Duncan Hill pluton, in the central part of the Seven Fingered Jack pluton, dikes ($n=15$) strike ENE (067°) (this study). Approximately 15 to 19 km north and northwest of the Duncan Hill pluton in the Skagit Gneiss Complex, dikes are reported to strike NE (031°) (Shea, 2008) and E-W (275°) (Michels, 2008), respectively.

Regional Dike Age Data

Dating of the dikes throughout the region has been limited. The extensively studied Teanaway dikes are the oldest known Eocene dikes in the region. A lava flow in the Teanaway Formation is dated at 49.341 ± 0.033 Ma, using U-Pb in zircon, and the dikes are assumed to be the same age (Fig. 27 and Table 5) (Eddy et al., 2016). Field relationships were used to bracket dike ages in the Skagit Gneiss Complex, to the north and northwest of the Duncan Hill pluton, to between ~48 and 49 Ma (Michels, 2008; Shea, 2008). Tabor et al. (1987a) determined two K-Ar dates of 47.8 ± 1.9 and 48.4 ± 2.2 Ma on biotite and hornblende, respectively for the dikes in Corbaley Canyon (Fig. 27 and Table 5). The Cooper Mountain dikes were dated by U-Pb in zircon at 49.3 Ma, although the data showed some dispersal (Michael Eddy, written commun., 2016). One dike from Subdomain D in this study was dated at 47.523 ± 0.016 Ma, also using U-Pb in zircon (Fig. 27 and Table 5) (Michael Eddy, written commun., 2016). Tabor et al. (1987a) reported three hornblende K-Ar dates on dikes near the Duncan Hill pluton. These dates are 44.2 ± 2.0 Ma, 46.9 ± 0.6 Ma, and 47.0 ± 0.7 Ma. Matzel (2004)

Figure 27. Radiometric dates with uncertainties for dikes and the Duncan Hill pluton in the North Cascades. U-Pb zircon ages are triangles and K-Ar hornblende dates are squares. Note that the U-Pb data have very small uncertainties, and the date for the Teanaway dikes is from an associated volcanic rock. Age data was taken from Tabor et al. (1987), Doran (2009), Eddy et al. (2016), and Michael Eddy (written commun., 2016).

reported a U-Pb zircon date of 46.39 ± 0.06 Ma for a ductilely deformed dike that intruded the Seven Fingered Jack pluton (Fig. 27 and Table 5).

The Eocene plutons in the region are ~ 48 - 46 Ma (Miller et al., 2016). The Duncan Hill pluton is 46.5 ± 0.036 Ma (U-Pb zircon, Michael Eddy, written commun., 2016) and the Cooper Mountain batholith is 47.9 Ma (U-Pb zircon, Shea, 2008). The U-Pb dating indicates that at least some of the dikes were intruded before the emplacement of nearby plutons. Based on the limited geochronologic data the dikes near the Duncan Hill pluton and Cooper Mountain batholith are greater than or equal to 1.0 Myr older than the plutons (Fig. 27).

Models For Two Dike Trends

A major question raised by the results of this study is, why do the dikes near the Duncan Hill pluton have two different trends? Four models were evaluated to help address this question. These models included (1) potential changes in the regional strain field, (2) the effect of the shape of the Duncan Hill pluton, (3) block rotation, and (4) the influence of host rock anisotropy on dike orientations.

The simplest explanation for the variation in the observed trends is a change in the regional strain regime. The migration of the slab window during ridge subduction is one mechanism that has been proposed to change the strain field in the North Cascades. A model by Madsen et al. (2006) shows the approximate locations of the slab window at ~ 1 Myr increments, as the inferred slab window progresses inland and northward (Fig. 2). If the regional strain field changed, there should be a correlation between dike age and dike

strike. In the North Cascades, the NE-trending Teanaway mafic dikes are the oldest dated dikes reported. In this model if we assume the Teanaway dikes are the oldest dikes in the region, we then would expect that the NW-striking dikes were intruded after the regional strain field changed. Evidence that would support this model includes crosscutting relationships between Eocene dikes, which were not observed in this study. Further dating of the NW-striking dikes is a critical test for this model. Overall, the data collected in this study are compatible with a changing strain field, but there are insufficient age data to fully evaluate this model.

A second model invokes how the intrusion of a plutonic body affects the local strain field and dike orientations. This model is based upon a study by Gudmundsson et al. (2009), where they used numerical modeling to investigate the development of the stress field around the volcanic system on the Reykjanes Peninsula in Iceland (Fig. 28). The results of this model showed that the maximum and minimum stresses induced by a volcanic system have a large effect on the local strain field, and produce significantly different dike orientations than expected from the regional strain field. The effects of the Duncan Hill pluton on dike orientations can be estimated by assuming a similar geometry to the volcanic system modeled by Gudmundsson et al. (2009) (Fig. 28). The model assumes a three-dimensional strain field, where the margin of the pluton is parallel to the minimum compressive stress. Such a stress field would cause dikes to strike perpendicular to the margin (Fig. 28), depending on the orientation of the margin. This model predicts dikes that strike NW and NE, as well as E- W-trending dikes (Fig. 28). In

Figure 28. Hypothesized dike trends (black) based on the shape of the Duncan Hill pluton compared with dike trends measured in the field (multi-color lines same as Fig. 5).

some areas, dikes follow the predicted trends, but many do not, casting doubt on the applicability of this model.

A third model proposed to account for the strike variations involves vertical axis rotation of a crustal block(s) (Sylva, 2014). This model argues for over 90° of clockwise rotation, along with multiple diking episodes, where each episode takes place roughly every 45° of rotation over a ~1 Myr period. There are no known structures to cause the large rotations in this model and there is apparently a lack of crosscutting dikes. In addition, the foliations reported by Tabor et al. (1987a) are not consistent with the rotations predicted by this model (Sylva, 2014). This is especially true in the Corbaley Canyon domain and the Columbia River domains where the dikes have different strikes, but the foliations generally strike NW and are thus not rotated.

In a fourth model, the anisotropy of the host rock strongly influences dike orientations. When a dike intrudes into a homogeneous medium it will orient perpendicular to the least compressive stress and parallel to the maximum compressive stress. If a dike intrudes an anisotropic material, such as a strongly foliated rock, normal dike mechanics may not hold (e.g., Gudmundsson, 1996; Miller and Paterson, 2001). The Twentyfive Mile Creek unit has a strong foliation that imparts significant anisotropy, and the Chelan Complex contains both relatively weakly foliated tonalite and well-foliated migmatites (Hopson and Mattinson, 1994). The most homogenous host rocks are the other dike rocks.

Dikes intruding the Twentyfive Mile Creek unit generally strike NW near the pluton, and E-W farther away, excluding Subdomain D (where there is minimal data) (Fig. 25).

These trends are similar to the foliations reported by Tabor et al. (1987a), which mainly strike NW, with less than half striking E or NE (Fig. 5). Dikes in the Chelan Complex typically strike NE in all subdomains except in Subdomain D, where strikes rotate to roughly N-S and foliations are mostly NW-striking, with interspersed strikes of E or NE (Figs. 5 and 25) (Tabor et al., 1987a). Dikes intruding other dikes generally strike NE.

The dike orientations measured in this study correlate with the type of host rock. The observations discussed above imply that the anisotropy imparted by the strong foliation of the Twentyfive Mile Creek unit influenced the orientations of the dikes, whereas the weaker foliation in the Chelan Complex had much less effect. The NE-striking dikes intruding the Chelan Complex probably record regional strain.

CONCLUSIONS

This thesis research aimed to understand the widespread Eocene diking in the North Cascades during postulated ridge subduction. Data available from elsewhere in the North Cascades show that Eocene dikes generally strike NE. The results from my study area near the Duncan Hill pluton indicate there are three different dike types: granite-porphyry; rhyolite; and intermediate-mafic. Dike orientations of the Westside Dikery are considerably more complicated than previously reported, as there are both NE- and NW-striking maxima. The lack of crosscutting field relationships suggests these two maxima were not caused by different diking episodes. Extension magnitudes calculated from the dikes are 4% to 7%.

Four models were evaluated to explain the variation in dike orientations: (1) a temporal change in the regional strain field; (2) modification of the regional strain by the

Duncan Hill pluton; (3) rotation of the local strain field by block rotation related to faulting; and (4) host rock anisotropy. Models one and four best fit the data. Precise, but limited dating done across the region shows that the dikes were intruded over a ~3 Myr period. Dikes intruding the strongly-foliated Twentyfive Mile Creek unit more commonly strike NW than those in the less well-foliated Chelan Complex, which implies that the anisotropy of the Twentyfive Mile Creek unit had affected on dike orientations. In contrast, the NE-striking dikes are inferred to record the regional strain field.

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