2000

Structural analysis of the Swakane Terrane, North Cascades core, Washington

Helge Alsleben
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Alsleben, Helge, "Structural analysis of the Swakane Terrane, North Cascades core, Washington" (2000).
Master's Theses. 1969.

DOI: <https://doi.org/10.31979/etd.5k7s-dcn3>

https://scholarworks.sjsu.edu/etd_theses/1969

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI[®]

NOTE TO USERS

This reproduction is the best copy available.

UMI

**STRUCTURAL ANALYSIS OF THE SWAKANE TERRANE, NORTH CASCADES
CORE, 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

Helge Alsleben

May 2000

UMI Number: 1399773

UMI Microform 1399773

Copyright 2000 by Bell & Howell Information and Learning Company.

All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2000

Helge Alsleben

ALL RIGHTS RESERVED

APPROVED FOR THE DEPARTMENT OF GEOLOGY

Dr. Robert B. Miller

Dr. Ellen P. Metzger

Dr. Richard Sedlock

APPROVED FOR THE UNIVERSITY

ABSTRACT

STRUCTURAL ANALYSIS OF THE SWAKANE TERRANE, NORTH CASCADES CORE, WASHINGTON

By Helge Alsleben

Structural analysis of the deep-crustal, amphibolite-facies Swakane terrane reveals generally gently dipping compositional layering (S_{CL}) and transposition foliation (S_T), north- to north-northeast-trending mineral lineation (L_M), and a minimum of three cycles of folding. Extensional crenulation cleavage (S_{ec}) and other asymmetric structures, which record top-to-the-north shear in lineation-parallel surfaces, cut S_T throughout the terrane. Shearing postdates crenulated inclusions in porphyroblasts and subsequent isoclinal, recumbent folds; it mostly predates open, upright folds of S_{ec} and L_M .

Age data constrain the north-vergent shear and associated movement on a subhorizontal decollement between the Swakane terrane and overlying amphibolite-facies Napeequa Complex to between 72 and 48 Ma. This shear is oblique to the regional strike of the Cretaceous Cascades crystalline core and does not fit current models for the core. North-directed shear is in part synchronous with exhumation and may represent the dominant displacement direction in the core from the latest Cretaceous to Eocene.

ACKNOWLEDGEMENTS

I am greatly indebted to R.B. Miller for guidance and encouragement from the beginning of this project and for the critical reviews of this manuscript. I would also like to thank E. P. Metzger and R. Sedlock for helpful comments to the final draft and for serving on my thesis committee. Special thanks are due to S. R. Paterson, who increased my understanding of Cascades geology and provided helpful discussions about the structural relationships in the field area. I am also grateful for technical assistance at San Jose State University provided by V. Smith and A. Odisho. All stereoplots were produced with the GEORient7.2© program by R.J. Holcombe.

Financial support was provided by a Penrose Research grant from the Geological Society of America, lottery funds from San Jose State University, and NSF Grant EAR-9614521 to R.B. Miller.

Most of all I would like to thank my parents, Wolfgang and Petra Alsleben, for their love, encouragement, and financial support, which made my studies at San Jose State University possible.

TABLE OF CONTENTS

	Page:
INTRODUCTION	1
Purpose of Study.....	1
Geologic Setting.....	7
Regional Geology.....	7
Cascades Core.....	9
Swakane Terrane and Adjacent Units.....	10
Location.....	13
Review of Previous Work.....	20
Swakane Terrane.....	20
Mineral Lineations.....	23
Kinematic Indicators.....	25
ROCK UNITS	26
Swakane Biotite Gneiss.....	26
Introduction.....	26
Quartz-Biotite Gneiss.....	26
Hornblende-Plagioclase-Garnet Gneiss.....	27
Hornblende Gneiss.....	29
Calc-Silicate Rock.....	30
Quartzite.....	30
Ultramafite (?).....	31
Quartz-Biotite Gneiss in the Swakane – Napeequa Contact Zone.....	31
Quartz Veins.....	33
Pegmatite Intrusions.....	33
Napeequa Complex.....	35
Introduction.....	35

Hornblende Schist and Amphibolite.....	38
Quartz-Mica Schist.....	39
Quartzite.....	39
Marble and Calc-Silicate Rock.....	40
Ultramafite.....	40
Orthogneiss.....	40
Entiat Pluton.....	42
Entiat Pluton with Rafts of Napeequa Complex.....	42
Undifferentiated Tertiary Intrusions.....	43
STRUCTURAL ANALYSIS.....	44
Introduction.....	44
Foliation and Lineation.....	44
Introduction.....	44
Area 1.....	45
Swakane Terrane.....	45
Area 2.....	48
Swakane Terrane.....	48
Napeequa Complex.....	61
Entiat Pluton.....	64
Entiat Pluton with Rafts of Napeequa Complex.....	64
Area 3.....	64
Swakane Terrane.....	64
Summary of Foliation and Mineral Lineation Patterns.....	68
Folding History.....	74
Introduction.....	74
Swakane Terrane.....	76
Early Mesoscopic Folds.....	76
Late Mesoscopic Folds.....	80
Kink Folds.....	80

Napeequa Complex.....	84
Relationship between Fold Axes and Mineral Lineations (L_{m1}).....	87
Swakane Terrane.....	87
Napeequa Complex.....	87
Microstructures.....	90
Introduction.....	90
Kinematic Indicators.....	91
Area 1 (Hinge of the Regional Antiform).....	91
Area 2 (Northeast Limb of the Regional Antiform).....	100
Swakane Terrane.....	100
Napeequa Complex.....	102
Entiat Pluton.....	106
Area 3 (Southwest Limb of the Regional Antiform).....	108
Summary.....	108
Relationships between Folding and Kinematic Indicators.....	109
Porphyroblast – Matrix Relationships in the Swakane Terrane.....	109
Introduction.....	109
Biotite.....	113
Plagioclase.....	117
Garnet.....	119
Muscovite.....	131
Microscopic Folds.....	131
Summary and Conclusions on Porphyroblast – Matrix Relationships.....	133
Shear Zones and Faults.....	133
Dinkelman Decollement.....	133
Relationships between Non-Coaxial Shearing and Orientation of Fold Axes and Mineral Lineations.....	136
Ductile Shear Zones.....	137

Brittle Faults	138
DISCUSSION	141
Timing of Deformational Events in the Study Area	141
Introduction	141
Scenario 1	141
Scenario 2	147
Scenario 3	149
Scenario 4	149
Implications for Significance of Lineations and Kinematic Indicators	153
Distribution of Shear (Coaxial versus Non-Coaxial) in the Swakane	
Terrane	154
Implications for Regional Tectonics	156
Remaining Kinematic Problems	158
CONCLUSIONS	159
REFERENCES CITED	161

LIST OF ILLUSTRATIONS

Figure	Page
1. Regional Map.....	2
2. Map of Cascades Core.....	3
3. Tectonic Models.....	8
4. Outline of Study Areas.....	14
5a. Foliation Map of Swakane Terrane, Napeequa Complex, and Entiat Pluton.....	15
5b. Cross-Section through Area of Fig. 5a.....	16
6. Lineation Map of Swakane Terrane, Napeequa Complex, and Entiat Pluton.....	17
7. Map of Kinematic Indicators of Swakane Terrane, Napeequa Complex, and Entiat Pluton.....	18
8. Station Map of Area 1.....	19
9. Map of Units in Napeequa Complex (Area 2).....	21
10. Station Map of Area 3.....	22
11. Photomicrograph of Fibrous Sillimanite.....	28
12. Photomicrograph of Twinned Kyanite.....	32
13. Photograph of Hand Sample with Kyanite.....	34
14. Photograph of Asymmetric Boudins (Swakane Terrane).....	36
15. Photograph of Asymmetric Quartz Boudin and Neck Folds (Swakane terrane).....	37
16. Photograph of Calcite Lineation (Area 2, Napeequa Complex Marble).....	46

17.	Map of Foliation Data (Area 1).....	47
18.	Stereonet Plot of Poles to Foliation (Area 1, Southwest of Regional Antiform).....	49
19.	Stereonet Plot of Poles to Foliation (Area 1, Northeast of Regional Antiform).....	49
20.	Cross-Section through Area 1.....	50
21.	Map of Lineation Data (Area 1, L_{m1}).....	51
22.	Map of Lineation Data (Area 1, L_{m2}).....	52
23.	Stereonet Plot of L_{m1} (Area 1).....	53
24.	Stereonet Plot of L_{m2} (Area 1).....	53
25.	Photograph of Hand Sample with Curved L_{m2}	54
26.	Stereonet Plot of Poles to Foliation (Area 2, Southern Highway 97 Domain).....	55
27.	Stereonet Plot of Poles to Foliation (Area 2, Northern Highway 97 Domain).....	55
28.	Stereonet Plot of Poles to Foliation (Area 2, Contact Domain).....	56
29.	Stereonet Plot of Poles to Foliation (Area 2, Mills Canyon Domain).....	58
30.	Stereonet Plot of L_{m1} (Area 2, Southern Highway 97 Domain).....	58
31.	Stereonet Plot of L_{m1} (Area 2, Northern Highway 97 Domain).....	59
32.	Stereonet Plot of L_{m1} (Area 2, Contact Domain).....	59
33.	Stereonet Plot of L_{m1} (Area 2, Mills Canyon Domain).....	60
34.	Stereonet Plot of L_{m2} (Area 2, All Domains).....	60
35.	Stereonet Plot of Poles to Foliation (Area 2, Napeequa Complex).....	62
36.	Stereonet Plot of L_{m1} (Area 2, Napeequa Complex).....	62

37. Stereonet Plot of L_{m2} (Area 2, Napeequa Complex).....	63
38. Stereonet Plot of Poles to Magmatic Foliation (Area 2, Entiat Pluton).....	65
39. Stereonet Plot of Lineation (Area 2, Entiat Pluton).....	65
40. Stereonet Plot of Poles to Foliation (Area 2, Entiat Pluton with Rafts of Napeequa Complex).....	66
41. Stereonet Plot of Lineation (Area 2, Entiat Pluton with Rafts of Napeequa Complex).....	66
42. Map of Foliation Data (Area 3).....	67
43. Stereonet Plot of Poles to Foliation (Area 3).....	69
44. Cross-Section through Area 3	70
45. Map of Lineation Data (Area 3).....	71
46. Stereonet Plot of L_{m1} (Area 3).....	72
47. Stereonet Plot of L_{m2} (Area 3).....	72
48. Stereonet Plot of Poles to Foliation in Swakane Terrane (All Data).....	73
49. Stereonet Plot of L_{m1} (All Data).....	73
50. Stereonet Plot of L_{m2} (All Data).....	75
51. Photograph of Isoclinal, Recumbent Fold (Swakane Terrane).....	77
52. Stereonet Plot of Axes of Isoclinal, Recumbent Folds (Area 3, Swakane Terrane).....	78
53. Stereonet Plot of Axes of Isoclinal, Recumbent Folds (Area 1, Swakane Terrane).....	78
54. Stereonet Plot of Axes of Isoclinal, Recumbent Folds (Area 2, Swakane Terrane).....	79
55. Stereonet Plot of Poles to Axial Planes of Isoclinal, Recumbent folds (Swakane Terrane, All Data).....	81

56. Photograph of Open, Upright Fold (Swakane Terrane).....	82
57. Stereonet Plot of Axes of Open, Upright Folds (Swakane Terrane, All Data) ..	83
58. Stereonet Plot of Axes of Isoclinal, Recumbent Folds (Napeequa Complex)....	85
59. Stereonet Plot of Poles to Axial Planes of Isoclinal, Recumbent Folds (Napeequa Complex, All Data).....	85
60. Stereonet Plot of Axes and Poles to Axial Planes of Open, Upright Folds (Napeequa Complex, All Data).....	86
61. Stereonet Plot of L_{m1} and Axes of Isoclinal, Recumbent Folds (Area 1, Swakane Terrane).....	88
62. Stereonet plot of L_{m1} and Axes of Isoclinal, Recumbent Folds (Area 3, Swakane Terrane).....	88
63. Stereonet plot of L_{m1} and Axes of Isoclinal, Recumbent Folds (Area 2, Swakane Terrane).....	89
64. Stereonet Plot of L_{m1} and Axes of Isoclinal, Recumbent Folds (Napeequa Complex).....	89
65. Photograph of Meso-Scale Shear Bands (Swakane Terrane).....	92
66. Photograph of Asymmetric Boudins (Swakane Terrane).....	93
67. Photomicrograph of Shear Bands (X-Z Plane; Swakane Terrane).....	95
68. Photomicrograph of Minerals in Shear Band (Swakane Terrane).....	96
69. Photomicrograph of Weakly Recrystallized Biotite Fish (Swakane Terrane).....	97
70. Photomicrograph of Strongly Recrystallized Muscovite Fish (Swakane Terrane).....	98
71. Photomicrograph of Asymmetric Garnet Porphyroblast Tails (Swakane Terrane).....	99
72. Photomicrograph of Plagioclase Porphyroblast Overgrowing Garnet (Swakane Terrane).....	101

73.	Photomicrograph of Shear Bands (Y-Z Plane; Swakane Terrane).....	103
74.	Photomicrograph of Sheared Hornblende (Swakane Terrane).....	104
75.	Photograph of Boudinaged Calc-Silicate Rock (Napeequa Complex).....	105
76.	Photomicrograph of Muscovite Fish (Napeequa Complex).....	107
77.	Photomicrograph of Inclusion Trails in Garnet and Plagioclase (Swakane Terrane).....	114
78.	Photomicrograph of Inclusion Trails in Biotite Parallel to External Foliation (Swakane Terrane).....	115
79.	Photomicrograph of Inclusion Trails in Biotite Oblique to External Foliation (Swakane Terrane).....	116
80.	Photomicrograph of Folded Inclusion Trails in Biotite (Swakane Terrane)....	118
81.	Photomicrograph of Two Fabrics of Inclusion Trails in Plagioclase (Swakane Terrane).....	120
82.	Photomicrograph of Openly Folded Inclusion Trails (Swakane Terrane).....	121
83.	Photomicrograph of Tightly Folded Inclusion Trails (Swakane Terrane).....	122
84.	Photomicrograph of Openly to Tightly Folded Inclusion Trails (Swakane Terrane).....	123
85.	Photomicrograph of Inclusion Trails in Plagioclase Oblique to External Foliation (Swakane Terrane).....	124
86.	Photomicrograph of Inclusion Trails in Plagioclase Parallel to External Foliation (Swakane Terrane).....	125
87.	Photomicrograph of Folded or Rotated Inclusion Trails in Garnet (Swakane Terrane).....	127
88.	Photomicrograph of Folded Inclusion Trails in Garnet (Swakane Terrane)....	128
89.	Photomicrograph of Sigmoidal Inclusion Trails in Garnet (Swakane Terrane).....	129

90.	Photomicrograph of Inclusion Trails with Spiral Form (Swakane Terrane).....	130
91.	Photomicrograph of Microscopic, Isoclinal F_P Fold (Swakane Terrane).....	132
92.	Stereonet Plot of Poles to Ductile Shear Zones (Swakane Terrane).....	138
93.	Stereonet Plot of Axes of Folds in Ductile Shear Zones (Swakane Terrane)....	138
94.	Stereonet Plot of Normal Faults and Associated Slickenside Striae (Swakane Terrane).....	139
95.	Stereonet Plot of Faults with Strike-Slip Component and Associated Slickenside Striae (Swakane Terrane).....	139
96.	Stereonet Plot of High-Angle Faults and Associated Slickenside Striae (Swakane Terrane).....	140
97.	Cartoon Depicting Scenario 1.....	144
98.	Cartoon Depicting Scenario 2.....	148
99.	Cartoon Depicting Scenario 3.....	150
100.	Cartoon Depicting Scenario 4.....	151

LIST OF TABLES

Table

1.	Summary of Porphyroblast Observations.....	110
2.	Summary of Subscript Explanations for Deformational Stages.....	142
3.	Summary of Scenarios 1 through 4.....	143

LIST OF PLATES

Plate

1. Station Map of Area 2.....in pocket
2. Map and Cross-Section of Foliation Data (Area 2).....in pocket
3. Map of Lineation Data (Area 2).....in pocket

INTRODUCTION

Purpose of Study

This study focuses on the significance of mineral lineations and associated kinematic indicators in the ductilely deformed rocks of the Swakane terrane, which is part of the Cretaceous to Paleogene North Cascades crystalline core (referred to hereafter as Cascades core) of Washington (Fig. 1). A variety of lineations are described in the literature (e.g., Twiss and Moores, 1992). Structural lineations (e.g., stretched pebbles, ooids, intersections) are distinguished from mineral lineations (e.g., grains with acicular habit, elongated grains, mineral fibers). In the Swakane terrane, mineral lineations dominate and consist of either stretched quartz grains or aligned biotite and muscovite that have grown in a preferred orientation.

A homogeneous quartz-biotite gneiss associated with minor metasedimentary and metaigneous lithologies (described below) forms the Swakane terrane or Swakane Biotite Gneiss (Tabor et al., 1987a, b), which is the deepest exposed unit (30 to 40 km paleodepth) in the Cascades core (Miller and Paterson, 2000). The terrane is mainly exposed in two outcrop belts that are separated by the Entiat fault (Fig. 2), which divides the core into the Chelan block on its northeast side and the Wenatchee block on the southwest side (Fig. 2).

A number of interesting and important structural and tectonic questions arise from previous observations (e.g., Miller et al., 1996) about the kinematic regime and the timing of events in this terrane and adjacent units. Based on previous reconnaissance data

Fig. 1. Map of major tectonic elements in the northwestern North American Cordillera. CC=Cascades Core, FF=Fraser River fault, NWCS=Northwest Cascades System, S.=Seattle, WA, SCF=Straight Creek fault, V.=Vancouver, VI=Vancouver Island.

Fig. 2. Map of plutons (with ages) and host rocks in eastern part of the Cascades core. Map shows regional antiform in Swakane terrane, but no other regional folds. CP=Cardinal Peak pluton, CRB=Columbia River Basalt, CS=Chiwaukum Schist of Nason terrane, DD= Dinkelmann decollement, H=Holden unit, IC=Ingalls Complex, N=Napeequa unit, RC=Railroad Creek pluton, SG=Skagit Gneiss, SW=Swakane terrane, T=Tertiary, WPT=Late Cretaceous Windy Pass Thrust, WRG=Wenatchee Ridge Gneiss, WRSZ=Late Cretaceous White River shear zone. 1, 2, 3=Approximate locations of study areas. (Note that North is to upper right).

northeast of the fault, the contact between the Swakane terrane and the structurally overlying amphibolite-facies Napeequa Complex has been identified as a mid-crustal decollement (Miller et al., 1996), herein called the Dinkelman decollement (Fig. 2). Miller et al. (1996) report evidence for north-directed non-coaxial shear within the Swakane terrane and along this contact. Thus far, the Dinkelman decollement is the only major decollement recognized in the Cascades core. Major regional tectonic problems are the significance and extent of this decollement, and the apparent discordance between north-directed shear on the decollement and models suggesting southwest-directed thrusting (e.g., Miller and Paterson, 1992; Hurlow, 1992; Paterson et al., 1994; Miller et al., 1996) or northwest-southeast-directed dextral strike-slip shear (Brown and Talbot, 1989) during the Cretaceous in other parts of the Cascades core. The 73 to 72 Ma Entiat pluton structurally overlies the Napeequa Complex to the northeast (Fig. 2) (e.g., Tabor et al., 1987a, b). Southwest-directed shear has been described on the moderately northeast-dipping contact between the pluton and the Napeequa Complex (Hurlow, 1992). Possible effects of this shear and the emplacement of the pluton on structures in the Swakane terrane and the Napeequa Complex are poorly known and were investigated as part of this study.

This investigation includes a more detailed examination of the folding history of the Swakane terrane, and in particular examines the timing relationships of folding to north-directed shear. Miller et al. (1996) described local isoclinal, recumbent to gently inclined, outcrop-scale folds that deform compositional layering and a parallel transposition foliation and are refolded by gently northwest-plunging, regional to local outcrop-scale, open, upright folds. The entire Swakane terrane now defines a northwest-

southeast trending regional antiform (Tabor et al., 1987b; Fig. 2). Besides measuring and interpreting the above meso-scale structures, this study also included a microstructural analysis of porphyroblasts in oriented thin sections to obtain information on the timing of metamorphism relative to folding and the possible presence of earlier, now largely obliterated, cycles of folding and/or other deformational events.

This project also addresses the recent proposal by Paterson and Miller (1998c) that, in contrast to common belief, regional-scale kinematic indicators in ductilely deformed rocks may not form parallel to the contemporaneous mineral lineation. Instead, they found outcrop-scale structures in other parts of the Cascades core (outside the Swakane terrane) in which kinematic indicators were best developed in sections perpendicular to the mineral lineation. Mineral lineations at a high angle to the displacement direction have been reported elsewhere in transpressional shear zones (e.g., Robin and Cruden, 1994; Lin et al., 1998). Most studies only examine surfaces parallel to lineation and perpendicular to foliation, but this analysis of surfaces parallel and perpendicular to mineral lineation and perpendicular to foliation evaluates the possible occurrence of kinematic indicators at high angles to the mineral lineation. The Swakane terrane is a suitable area for such an analysis because previous work suggests that shear-sense indicators are widespread. Furthermore, determining when kinematic indicators formed relative to the cycles of folding (see above) may constrain the relative timing of the postulated shear.

Other significant problems involving these deep-crustal rocks are the distribution of coaxial and non-coaxial shear, the pervasiveness of resulting structures, and possible strain partitioning within the compositionally layered Swakane terrane. Throughout the

Cascades core, rocks are heterogeneously deformed and strain and kinematic partitioning are common at different crustal levels (< 5 to ~ 40 km) (Miller and Paterson, 2000). Important questions in the study area include the following: (1) Is the entire Swakane terrane affected by north-directed non-coaxial shear? (2) Is such shear restricted to a narrow zone near the Dinkelman decollement at the contact between the Swakane terrane and the Napeequa Complex? (3) Is strain partitioned between different layers? Strain partitioning would support the view that deformation in the deep crust is controlled by structural and/or lithological anisotropy (e.g., Cosgrove, 1997), and is not homogeneous as is commonly assumed (e.g., Dewey, 1986; Rannali, 1997). In the Swakane terrane, individual layers of different quartz/mica ratios may have reacted differently to imposed strain. Layers with a larger component of weaker minerals (e.g., micas) are presumably more likely to record non-coaxial shear, whereas more competent (e.g., quartz-rich) layers may be dominated by coaxial shear (e.g., Lister and Williams, 1983; Bell, 1985; Platt and Behrmann, 1986). This type of strain partitioning in mid-crustal rocks is often assumed (e.g., Bell, 1985; Ridley, 1986), but only rarely has such partitioning been quantitatively documented. The well-exposed Swakane terrane offers an opportunity to examine this potential partitioning in detail.

The structural controversies described above are addressed in the following chapters, and interpretations are supported by field observations, structural data collected during field work, and microstructural analysis. The major aspects of the study include: (1) evaluation of the development of kinematic indicators in relation to mineral lineation, which will have implications for the general importance of mineral lineations as indicators of regional displacement directions; (2) determination of the type of strain

(non-coaxial and/or coaxial) and possible strain partitioning; (3) determination of the displacement direction of the Dinkelman decollement; (4) analysis of the effects of the emplacement of the Entiat pluton on the structures in the Swakane terrane and the Napeequa Complex; and (5) synthesis of the results in the context of the regional tectonic regime that dominated the Cascades crystalline core, which will thus have significant implications for regional tectonic interpretations.

Geologic Setting

Regional Geology

The northern North American Cordillera consists, from west to east, of the Insular superterrane, the Coast Belt (including the Cascades Core), the Intermontane superterrane, the Omineca belt, and the foreland belt, which adjoins the North American craton (Fig. 1; e.g., Monger et al., 1982). The origin of magmatism and crustal shortening in the >1800-km-long, mid-Cretaceous Coast Belt, which extends from southeastern Alaska to central Washington (Fig. 1), is controversial (Monger et al., 1982; Rubin et al., 1990; van der Heyden, 1992; Monger et al., 1994). Monger et al. (1982) suggest the Coast Belt resulted from mid-Cretaceous collision of the Insular superterrane oceanic arc with the Intermontane superterrane, which was accreted to North America during the Middle Jurassic (Fig. 3a). In a second model (e.g., Rubin et al., 1990; van der Heyden, 1992), mid-Cretaceous crustal shortening and magmatism occurred in an intra-arc setting, above a single east-dipping subduction zone. A possible change in plate motion direction and/or velocity, produced compression (Fig. 3b) that led to the collapse

Fig. 3. Tectonic models for the origin of mid-Cretaceous deformation in the Coast Belt (after Rubin et al., 1990). a) Deformation occurs during collision (e.g. Monger et al., 1982). b) Deformation occurs within a single convergent margin system (Rubin et al., 1990). IM=Intermontane superterrane, IS=Insular superterrane. See text for discussion.

of several marginal basins. In a third model, Monger et al. (1994) propose that compressional structures were produced by northward translation and accretion of the Insular superterrane. This model also postulates the presence of Late Jurassic to Early Cretaceous inter- and intra-arc basins. Early Cretaceous sinistral faulting led to duplication of the western and eastern parts of the southern Coast Belt, which were parts of the same Jurassic magmatic arc system (Monger et al., 1994).

Cascades Core

The Cascades core consists dominantly of Paleozoic to Mesozoic island arc and oceanic assemblages that underwent Cretaceous metamorphism and were intruded by Cretaceous to Eocene plutons (Tabor et al., 1989). The Cascades core is offset from the Coast Belt by right-lateral strike-slip along the dominantly Eocene Straight Creek-Fraser River fault (Fig. 1; e.g., Misch, 1966; Tabor et al., 1989). Low-grade Paleozoic and Mesozoic rocks of oceanic and arc origin lie across the fault to the west of the Cascades core. The Windy Pass thrust, which forms the southern boundary of the Cascades core, places low- to medium-grade ophiolitic rocks of the Late Jurassic Ingalls Complex above the core (Fig. 2; Miller, 1985). To the southeast, the Cascades core is overlain by Miocene Columbia River basalts, and to the northeast is separated from the Jurassic to Cretaceous Methow basin by the Ross Lake fault zone (Fig. 2; Misch, 1966).

The Cascades core is divided into the Nason terrane, which contains the Chiwaukum Schist as its major unit, the Swakane terrane, and Chelan Mountains terrane; the latter includes the Napeequa Complex (Fig. 2). The geologic history of these terranes

is complicated and partly enigmatic. Amalgamation of terranes that form the Cascades core was completed by 96 Ma (Tabor et al., 1987a). Plutons are common throughout the core and range in age from 96 to 45 Ma (e.g., Miller et al., 1989). Mid-Cretaceous (96 to 88 Ma) magmatism was widespread, but subsequent intrusions migrated in three episodes (78 to 72 Ma; 68 to 59 Ma; 50 to 45 Ma) to the northeast (Miller et al., 1989).

Miller et al. (1993a) summarized different arguments for the origin of the plutonism, metamorphism, and ductile deformation in the crystalline core. Brown and Talbot (1989) suggested that the Cascades core represents a broad, northwest-striking, right-lateral shear zone, whereas McGroder (1991), Miller and Paterson (1992), Umhoefer and Miller (1996), and Paterson and Miller (1998a) view the orogen as a southwest-directed contractional system with orogen-parallel (northwest-southeast) stretching. McGroder (1991), Miller and Paterson (1992), and Whitney et al. (1999) proposed that folds and 12- to 18-km-thick ductile thrust sheets (Whitney et al., 1999), deeply buried the core, while contemporaneous plutonism provided heat for metamorphism (cf. Whitney et al., 1999). In contrast, Brown and Walker (1993) proposed that crustal thickening and burial resulted from magmatic loading by Cretaceous plutons.

Swakane Terrane and Adjacent Units

The Swakane terrane contrasts sharply in several respects with the other terranes in the Cascades core. It is composed dominantly of quartz-biotite gneiss with a Precambrian isotopic signature [1300 to 1600 Ma zircons, Rb-Sr and Sm-Nd model ages

(Mattinson, 1972; Rasbury and Walker, 1992)]. The homogeneity of the gneiss has led to different interpretations of the protolith. Several petrologic studies have been conducted, and Waters (1932) favored an arkosic protolith, whereas Mattinson (1972) and Sawkyo (1994) concluded that the protolith was a dacitic volcanic pile with numerous sedimentary interbeds.

The Swakane terrane is exposed in southwestern and northeastern outcrop belts, which are offset by the Entiat fault (Fig. 2). Normal slip (southwest-side down) on this fault is well-documented (Evans, 1994; Paterson et al., 1996b), but postulated strike slip is uncertain. Tabor et al. (1989) estimated a maximum dextral slip of 40 km by using the displacement of a major fold axis in the Swakane terrane. Paterson et al. (1996b) suggested normal-slip and moderate amounts of strike-slip displacement, but did not specify the amount of offset.

The northeastern belt is in contact with Eocene clastic rocks of the Chumstick basin across the Entiat fault. In the basin, Swakane rocks are locally exposed in a horst-like structure (Fig. 2; Tabor et al., 1987b). Miocene Columbia River basalts unconformably overlie the northeastern belt to the southeast, and the Napeequa Complex overlies to the northeast across the Dinkelman decollement (Fig. 2). For much of its length, the decollement dips gently northeast, leading some workers to infer that this terrane boundary was an early thrust fault (Tabor et al., 1987a) that was reactivated (Miller et al., 1996; Alsleben et al., 1999).

The Napeequa Complex is exposed in a narrow zone that widens to the northwest between the Swakane terrane and the 73 to 72 Ma Entiat pluton (Fig. 2). The complex consists dominantly of quartz-mica schist, quartzite, and fine-grained amphibolite (Tabor

et al., 1989). Other rock types include local bodies of gneiss, ultramafite, marble, and calc-silicate rock (Tabor et al., 1987a, b). These rock types indicate a probable deep marine origin (Tabor et al., 1989; Miller et al., 1994). The Napeequa Complex is pre-Late Cretaceous (Tabor et al., 1987a), as it is intruded by plutons as old as 96 Ma. Otherwise, age controls are poor and the protolith may be Mississippian to Middle Jurassic, if the correlation to the fossil-bearing Bridge River-Hozameen terrane of the eastern Coast Belt is correct (e.g., Tabor et al., 1989; Miller et al., 1993b). Between 73 and 68 Ma, while at 20 to 24 km depth, this complex was intruded by the Entiat pluton and by numerous granodiorite and tonalite sheets, ranging in thickness from centimeter- to kilometer-scale (Paterson and Miller, 1998b).

The Entiat pluton was emplaced during regional contraction at 6.0 to 7.2 kbar (Hurlow, 1992; Dawes, 1993; Paterson and Miller, 1998b). It overlies the Napeequa Complex on a moderately northeast-dipping contact that steepens along strike to the northwest and records southwest-directed reverse shear (Hurlow, 1992; Paterson and Miller, 1998b). No thermal aureole developed around the pluton and only a narrow structural aureole formed (Paterson and Miller, 1998b). This hornblende-biotite and biotite-hornblende tonalite (Tabor et al., 1987b) is an excellent example of a sheeted pluton, with sheets ranging in thickness from a few centimeters to several hundred meters (Paterson and Miller, 1998b). Sheets are defined by different grain sizes and varying amounts of mafic (hornblende + biotite) and felsic (plagioclase + quartz) minerals. Color indices range from 10 to 45, with an average of 25 to 35 (Tabor et al., 1987b).

The southwestern belt of the Swakane terrane (Fig. 2) is structurally overlain to the southwest by the Napeequa Complex along an inferred thrust contact (Cater and

Crowder, 1967; Tabor et al., 1987a). The southwestern belt is faulted against the Eocene Chumstick basin to the southeast and the Napeequa Complex to the northeast and is intruded by Tertiary granitic rocks to the northwest.

Location

To address the problems outlined above, three generally well-exposed and easily accessible areas were chosen for detailed mapping (Fig. 4). These areas are located in the northeastern belt of the Swakane terrane directly west of the canyon of the Columbia River along and near U.S. Highway 97A. Mapping was done at scales ranging from 1:15,000 to 1:24,000. Regional maps, which contain additional data collected by R.B. Miller and S.R. Paterson (unpublished), Tabor et al. (1987b), and Hurlow (1992), were also compiled (Fig. 5-7).

A short description of the three mapped areas follows.

1) Area 1 is an approximately 4 km² domain (Fig. 8) located in the hinge zone of the regional antiform near the Columbia River (Fig. 2; Tabor et al., 1987b).

Approximately four weeks of mapping were completed in the summer of 1997, and structural data were collected at 212 outcrop stations.

2) Area 2 is circa a 6.5 km² area on the northeastern limb of the regional antiform (Plate 1) and was mapped for four weeks in the summer of 1998. This area also includes parts of the structurally overlying Napeequa Complex and the 73 to 72 Ma Entiat pluton. Structural data were collected at 273 outcrop stations. During the summer of 1999, field work focused mainly on the Napeequa Complex in Area 2. The area was extended to the

Fig. 4. Outline of study areas. DD=Dinkelman decollement.

Fig. 5a. Regional foliation map compiled with data from this study, Hurlow (1992), R.B. Miller and S.R. Paterson (unpublished), and Tabor et al. (1987b). A-A' indicates line of cross-section in Fig. 5b.

Fig. 5b. Cross-section through the study area with additional data from R.B. Miller and S.R. Paterson (unpublished) and Tabor et al. (1987b). Cross-section shows general foliation pattern (dashes) that defines an antiform in the Swakane terrane. Note steepening of the foliation close to the Dinkelmann decollement (DD). EF=Entiat fault, EP=Entiat pluton, NQ=Napeequa Complex, SWK=Swakane terrane. Cross-section line is shown on Fig. 5a. Thick dashes show measured foliations, whereas thin dashes indicate the inferred foliation pattern.

Fig. 6. Regional lineation map compiled with data from this study, Hurlow (1992), R.B. Miller and S.R. Paterson (unpublished), and Tabor et al. (1987b).

Fig. 7. Direction of shear deduced from kinematic indicators. Map compiled with data from this study, Hurlow (1992), and R.B. Miller and S.R. Paterson (unpublished). Half arrows indicate the displacement direction in the hanging wall.

Fig. 8. Station map of Area 1 in the hinge of regional antiform. ● = Station with number (bold and enlarged mentioned in text)

northwest and to the east across the Columbia River (Plate 1), and eight days were spent mapping units in the Napeequa Complex (Fig. 9). Data were collected at 120 stations.

3) Area 3 is an approximately 24 km² area on the southwestern limb of the regional antiform (Fig. 10) and four days were spent conducting reconnaissance mapping of this area in 1998. Data were gathered at 40 stations for comparison with the hinge and northeastern limb of the regional antiform.

Review of Previous Work

Swakane Terrane

Waters (1932) provided the first detailed petrographic description of the Swakane terrane and included descriptions of rocks now assigned to the Napeequa Complex. He also briefly described structures in these units. In later years, several researchers studied different parts and aspects of this terrane (e.g., Cater and Crowder, 1967; Mattinson, 1972; Tabor et al., 1987a, b; Hurlow, 1992; Sawkyo, 1994; Miller et al., 1996).

Sawkyo's (1994) analysis of the metamorphism revealed different temperature/pressure regimes for the two belts of the Swakane terrane (Fig. 2). Northeast of the Entiat fault, peak temperatures are estimated to have been between 580 to 625°C. Garnet cores yield pressures of about 8 kbar, but pressures increased to 10 to 12 kbar during crystallization of the garnet rims. Garnets in the southwestern belt do not show the pressure increase, and maximum pressures are estimated at 8 to 9 kbar with temperatures between 650 and 700°C (Sawkyo, 1994).

Fig. 9. Map of Area 2 emphasizing units in the Napeequa Complex. DD=Dinkelman decollement.

Fig. 10. Station map of Area 3 on the southwestern limb of the regional antiform.
 • = Station with number (bold and enlarged mentioned in text).

Before this study, structural studies of the Swakane terrane were completed only in reconnaissance (e.g., Tabor et al., 1987a, b; Hurlow, 1992; Miller et al., 1996). Current studies are in progress in the southwestern belt by R.B. Miller and in the northeastern belt by S.R. Paterson, who works in the Swakane-Napeequa contact zone to the northwest of this study area. Only preliminary interpretations of the structural history have been presented (Miller et al., 1996; Miller and Paterson, 1998c; Paterson et al., 1998b; Alsleben et al., 1998, 1999). Foliation in the northeastern belt is mostly gently southwest- or northeast-dipping, whereas in the southwestern belt it generally dips moderately to steeply southwest. The lineation in the southwestern belt trends northwest-southeast and plunges gently. Throughout the northeastern belt the mineral lineation trends generally north-south (Miller et al., 1996; Tabor et al., 1987a), and kinematic indicators recording north-directed shear postdate recumbent folds but most predate upright folds (Miller et al., 1996). Timing of shear on this decollement has been estimated by Miller et al. (1996) to have occurred between 72 Ma and about 48 Ma. This age range is based on the continuity of foliation in the Napeequa Complex with the magmatic foliation in the 73 to 72 Ma Entiat pluton and the presence of north-directed kinematic indicators in coeval sills. Sparse biotite cooling ages and absence of ductile deformation in Eocene dikes provide estimates for the lower age limit (Miller et al., 1996).

Mineral Lineations

It is commonly believed that mineral lineations form subparallel to the regional

displacement direction (e.g., Shackleton and Ries, 1984) and, thus, that the flow direction for non-coaxial shear can be determined from kinematic indicators in sections parallel to the lineation and perpendicular to the foliation (e.g., Simpson and Schmid, 1983). It is well-documented that mineral lineation generally forms parallel to the X-axis of the strain ellipsoid ($X > Y > Z$) and thus indicates the direction of maximum stretch (e.g., Ramsay, 1980; Ramsay and Huber, 1983). The maximum stretching direction, however, does not have to be the direction of regional displacement (e.g., Sanderson and Marchini, 1984; Robin and Cruden, 1994; Tikoff and Teyssier, 1994; Lin et al., 1998). Tectonic transport at high angles to mineral lineations has been reported from several orogens, including the Alps (Hubbard and Mancktelow, 1992), Sierra Nevada (Tikoff and Teyssier, 1992), North Cascades (Miller and Paterson, 1992), and Canadian Shield (Robin and Cruden, 1994). Several explanations have been proposed: transport at high angles to mineral lineations may develop (1) in transpressional or transtensional shear zones (e.g., Sanderson and Marchini, 1984; Robin and Cruden, 1994; Lin et al., 1998), (2) near tear faults in an overall thrust regime (Ridley, 1986), (3) in regions where flow is partitioned into non-coaxial and coaxial shear (Ridley, 1986), or (4) in fold hinges (Ramsay and Huber, 1987).

The mineral lineation that formed in the Cascades core during the Cretaceous to Paleogene orogeny has been interpreted to represent either the regional displacement direction (Brown and Talbot, 1989) or, in contrast, the maximum stretching direction, but not the direction of regional displacement (Miller and Paterson, 1992).

Kinematic Indicators

The asymmetry of meso- and microstructures is commonly used to establish the sense of shear (e.g., Berthé et al., 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984). On a mesoscopic scale, kinematic indicators include S-C fabrics, extensional crenulation cleavages (shear bands), asymmetric boudins, and foliation curvature in ductile shear zones. On a microscopic scale, they include mica fish, asymmetric porphyroclast and/or porphyroblast tails, broken grains, and preferred orientations of crystallographic axes and long axes of subgrains (e.g., Simpson and Schmid, 1983, Simpson, 1986) in addition to S-C fabrics and shear bands. Berthé et al. (1979) and Lister and Snoke (1984) addressed the formation of S-C fabrics and shear bands. In the original definition of S-C fabrics by Berthé et al. (1979) both fabric elements are coeval; S (schistosité) is related to the accumulation of finite strain, while C (cisaillement) is related to localized high shear strains. Lister and Snoke (1984) used these terms to identify similar fabrics, but demonstrated that the foliations do not have to develop contemporaneously. This latter use is adopted in this study. Lister and Snoke (1984) also described asymmetric mica fish, which are produced by deformation of pre-existing large mica flakes through a combination of ductile and brittle processes (e.g., asymmetric boudinage, microfaulting) during decreasing P-T-conditions. Passchier and Simpson (1986) provided a classification of asymmetric porphyroclast tails as kinematic indicators. Strong minerals (e.g., plagioclase, garnet) in a fine-grained matrix develop tails of dynamically recrystallized material during progressive deformation. Shape and position of the tail form the basis of the σ - and δ -type classification scheme (Passchier and Simpson, 1986).

ROCK UNITS

Swakane Biotite Gneiss

Introduction

The map pattern of the Swakane terrane defines a broad, regional, gently northwest-plunging antiform (Fig. 2) with about 1000 m of structural section exposed, as measured from the south side of Swakane Canyon to the top of Burch Mountain (Tabor et al., 1987b; Sawkyo, 1994). Approximately 90% of the exposed rock consists of quartz-biotite gneiss (Sawkyo, 1994). Minor hornblende-plagioclase-garnet gneiss of uncertain origin and unequivocal metasedimentary (pelitic schist, calc-silicate gneiss, marble, quartzite) and metaigneous (amphibolite, hornblende gneiss, ultramafic rock) rocks make up the remaining 10% (Tabor et al., 1987a, b; Sawkyo, 1994). A large number of variably oriented pegmatite sheets and quartz veins cut the unit. The dominance of quartz-biotite gneiss and the small outcrops of metaigneous and metasedimentary units described by Sawkyo (1994) were verified by this study.

Quartz-Biotite Gneiss

The quartz-biotite gneiss displays well-developed, millimeter to meter scale compositional layering (S_{CL}), which may be the product of segregation during sedimentation, medium- to high-temperature metamorphism, or both. Mica-rich layers are commonly identified in the field by a schistose appearance, in contrast to quartz-rich layers that appear gneissic. The compositional variation also creates differences in color

and resistance to weathering and erosion. Quartz-rich layers are generally light to medium gray and show little weathering. More micaceous layers, which are mainly medium to dark gray, are more eroded and subdued than protruding gneissic layers.

The gneiss is chiefly fine- to medium-grained. The typical assemblage is quartz-plagioclase-biotite-clinzoisite $\pm$ muscovite $\pm$ garnet. Staurolite and sillimanite (Fig. 11) occur locally, and other common accessories include sphene, apatite, epidote, tourmaline, opaque minerals (graphite, ilmenite, and/or magnetite), and calcite, which is probably secondary. Quartz displays undulose extinction, subgrains, and recrystallized mosaics. Plagioclase is generally polysynthetically twinned and locally has strain shadows composed of recrystallized plagioclase, quartz, and biotite. Plagioclase porphyroblasts contain inclusion trails defined by quartz and/or opaque (graphite?) minerals (see below). Biotite occurs as (1) relict, large, weakly deformed grains with undulose extinction, (2) mica fish, or (3) small, recrystallized grains. Small and large grains of muscovite are locally present. Biotite $\pm$ muscovite grew in a preferred orientation and define the foliation throughout the Swakane terrane. Garnets are commonly skeletal, but idioblastic grains are developed locally; porphyroblast tails and, in a few places, quartz inclusions are abundant. In many cases, garnets are replaced by biotite, chlorite, or both. Alteration of biotite to chlorite and plagioclase to sericite are common throughout the Swakane terrane; the amount of replacement varies from sample to sample, but is generally minor.

Hornblende-Plagioclase-Garnet Gneiss

Hornblende-plagioclase-garnet gneiss is the second most common rock type in the

Fig. 11. Photomicrograph of fibrous sillimanite (center) defining a micro-fold in muscovite. Other minerals visible are quartz and plagioclase. Sample 2-131-2 (X-Z plane) from quartz-rich Swakane Biotite Gneiss in Area 2 (Plate 1). Picture taken with cross-polarized light. Field of view 1.32 mm in long dimension.

northeastern belt of the Swakane terrane. In outcrop, this rock is dark gray to black. Rocks range from relatively fine- to coarse-grained, and garnet porphyroblasts range in size from 3 to 10 mm. Compositional layering and foliation are moderately well-developed. Layers are defined by variations in concentrations of plagioclase $\pm$ quartz and hornblende $\pm$ biotite and range from a few millimeters to $\sim$ 1 cm in thickness. Hornblende, plagioclase, and garnet are the dominant phases; quartz, biotite, and clinozoisite are common; and sphene, calcite, apatite, and zircon are accessories. Well-aligned acicular hornblende defines the foliation. Plagioclase is irregular in shape and commonly contains inclusions of quartz, biotite, or both. Garnet is mostly xenoblastic, in places idioblastic, and commonly skeletal with abundant quartz inclusions. Quartz displays undulose extinction and subgrains. Biotite is generally preserved as relict, large flakes with weak undulose extinction. Only minor retrogression, mainly sericitization of plagioclase, is observed.

Hornblende Gneiss

A strongly layered, mesoscopically folded (see Chapter 3), approximately 30-m-thick hornblende gneiss (metaandesite?) is exposed on the northeastern limb of the regional antiform (Area 2, Station 2-135, Plate 1). Individual layers of acicular hornblende $\pm$ biotite, quartz, and plagioclase are $\sim$ 2- to 5-cm-thick. The dominant mineral assemblage in this medium- to coarse-grained gneiss is hornblende-plagioclase-quartz $\pm$ biotite $\pm$ garnet $\pm$ sphene $\pm$ apatite. Minerals are in places cut by microfaults or fractures, which give the rock a cataclastic appearance in thin section. Plagioclase

commonly shows weak normal zoning and quartz displays undulose extinction and subgrains and forms abundant mosaics. Biotite also shows strong undulose extinction, but only incipient recrystallization along its rims. Replacement of biotite by chlorite is common. Garnets are mostly skeletal, in a few places idiomorphic, and replaced locally by chlorite. Sericitization of plagioclase is common.

Calc-Silicate Rock

A 1-m-thick epidote-rich rock with 1- to 2-cm-thick compositional layers is exposed at Station 128 (Fig. 8); the lateral continuity could not be determined because of alluvium. Hornblende defines the foliation, and layers are marked by variations in the ratio of hornblende and epidote to plagioclase. The plagioclase-rich layers are commonly boudinaged. Large (~ 4 mm) skeletal garnet porphyroblasts (probably grossular) are very common and quartz, biotite, sphene, and calcite are accessories. Plagioclase is weakly normally zoned and replaced locally by sericite. Quartz is weakly to strongly undulose and only a few subgrains are observed.

Quartzite

An approximately 1.5-m-thick, nearly monomineralic quartzite unit is present in Area 2 (Station 2-176, Plate 1). Minor muscovite, biotite, and opaque minerals produce layering, which ranges from a few millimeters to ≤ 2 cm in thickness, and color variations from light to dark gray to reddish-brown.

Ultramafite (?)

Along Highway 97A, ultramafic (?) rock is exposed as a thin, ~ 2-m-thick layer (Station 3-2, Fig. 10). Actinolite (~ 35%), chlorite (~ 35%), and biotite (~ 30%) were identified with a hand lens. The rock is greenish-black, foliated with weak compositional layering, and breaks easily into small fragments. Sawkyo (1994) described a biotite-chlorite-actinolite schist as one of two exposures of ultramafic rocks he recognized in the Swakane Biotite Gneiss.

An ~ 3-m-thick massive lens of actinolite-talc rock is present at another locality (Station 2-267, Plate 1).

Quartz-Biotite Gneiss in the Swakane – Napeequa Contact Zone

A coarse-grained quartz-biotite gneiss differing from typical Swakane Biotite Gneiss is located next to the contact between the Swakane terrane and Napeequa Complex. The unit is distinguished from the main body of Swakane Biotite Gneiss by the occurrence of large (3 to 30 mm) plagioclase porphyroblasts. Garnet porphyroblasts are also common and range in size from 5 to 15 mm. Compositional layering is well-developed and individual layers are ~ 5 mm thick. The dominant assemblage is quartz-plagioclase-garnet-biotite $\pm$ muscovite $\pm$ kyanite (Fig. 12). Accessory minerals are mostly sphene and secondary calcite. Deformation of quartz, plagioclase, and biotite resembles that in the typical Swakane Biotite Gneiss. Kyanite ranges from 2 to 8 mm (average ~ 3 mm), is generally twinned and kinked, and is commonly replaced by muscovite. A kyanite-bearing gneiss from the same unit along strike to the northwest of

Fig. 12. Photomicrograph of twinned and kinked kyanite from quartz-biotite gneiss in the Swakane-Napeequa contact zone. Kyanite is replaced by muscovite and oriented subparallel to the biotite-defined foliation. Other minerals visible are quartz and plagioclase. Sample 2-204-2 (X-Z plane). Picture taken with cross-polarized light. Field of view 3.3 mm in long dimension.

the study area yielded pressures of 10 to 12 kbar (Valley et al., 2000). Retrograde replacement of biotite and plagioclase by chlorite and sericite, respectively, is common. Garnets are retrograded to biotite and are present as skeletal grains with abundant inclusions of quartz and opaque minerals.

The rock more closely resembles the main quartz-biotite gneiss in the Swakane terrane than rock types in the Napeequa Complex (see below), and is thus assigned to the Swakane terrane.

Quartz Veins

Quartz veins are locally abundant in Area 1, but decrease in abundance in structurally higher parts of the Swakane terrane (Area 2 and 3). These veins, which are commonly <1 to 5 cm thick but locally up to ~ 50 cm thick, are typically subparallel to foliation, and form pinch-and-swell structure and boudinage. On the northeastern limb of the antiform near the kyanite-bearing quartz-biotite gneiss in the Swakane – Napeequa contact zone, a float sample of a quartz vein (sample 2-133-1) contains large, kinked kyanite (Fig. 13).

Pegmatite Intrusions

Intrusive rocks are rare in the Swakane terrane. Pegmatites occur in the structurally lowest exposed part of the hinge of the regional antiform (Area 1) where they

Fig. 13. Picture of hand sample with large (blue) kyanite in quartz vein (Sample 2-133, Plate 1). Scale on ruler is in centimeters (top) and inches (below).

locally constitute 30 to 35% of the total outcrop. In the structurally higher parts of the Swakane terrane, pegmatites are not observed.

The pegmatites are composed dominantly of quartz + plagioclase $\pm$ potassium feldspar $\pm$ muscovite and are commonly 5 to 30 cm thick, but locally reach 1.5 m in thickness. Muscovite defines a weak foliation, which is subparallel to that in the host rock. The pegmatites mainly occur as subvertical dikes, at high angles to host rock foliation, or as subhorizontal sills, subparallel to host rock foliation. Most sills define either pinch-and-swell structure or boudinage, with widespread symmetrical and asymmetrical boudins (Fig. 14). Neck folds form locally around the boudins (Fig. 15). The age of the pegmatites is constrained by a single U-Pb zircon date of ~ 69 Ma on a sample located ~ 4 km south of Spencer Canyon along Highway 97A (Plate 1; Mattinson, 1972). Pegmatites are weakly to strongly deformed, and some are tightly folded and form floating hinges. Based on the variations in deformation intensity, intrusion likely occurred over a protracted period of time [pre-(?) and syn-deformational; see also Sawkyo, 1994].

Napeequa Complex

Introduction

The heterogeneous Napeequa Complex consists of metasedimentary and metavolcanic rock, and abundant intrusive sheets (Tabor et al., 1987a, b). Four mappable units were distinguished in this study (Fig. 9). Hornblende schist, amphibolite, quartz-mica schist, and quartzite (metachert) with local orthogneiss dominate one of the units

Fig. 14. Asymmetric boudins of pegmatite sheet in Swakane Biotite Gneiss near station 1 (Fig. 8). Boudins indicate top-to-the-north (left) shear.

Fig. 15. Picture of asymmetric boudins of quartz vein and neck folds (arrow) in biotite-rich Swakane Biotite Gneiss near station 151 (Fig. 8). Boudins show top-to-the-north (right) shear. (Penny for scale).

(Nqs). Next to the Entiat pluton the Napeequa Complex is mainly marble and calc-silicate rock (Nqm), with minor hornblende and quartz-mica schist and quartzite. Orthogneiss, which is interlayered with minor schist, makes up > 90% of a third unit (Nqo). Ultramafic rock is observed throughout the Napeequa Complex, but only one lens is of sufficient size to map (Nqum). The area east of the Columbia River was only mapped in reconnaissance and is shown as undifferentiated Napeequa Complex (Nq). Descriptions of the individual rock types follow.

Hornblende Schist and Amphibolite

Hornblende schist is the most common type of schist in the Napeequa Complex of the study area. Amphibolite is distinguished by its smaller amount of biotite and quartz. These rocks are described together because they are both probably metamorphosed basalts and/or gabbros.

The fine- to medium-grained hornblende schists display generally well-developed compositional and grain-size layering and a moderately developed foliation defined by hornblende. Felsic layers are composed of plagioclase and minor quartz, whereas mafic layers consist of hornblende and subordinate biotite. The felsic layers form pinch-and-swell structures and/or boudins, and the mafic layers flow into the necks. Epidote is common, and sphene and tourmaline are widespread accessories. Chlorite (replacing biotite), sericite (replacing plagioclase), and calcite are typical alteration minerals.

The amphibolites are commonly medium-grained and generally show the same, although commonly less well-developed, features as the hornblende schist.

Quartz-Mica Schist

A brown to medium- to dark-gray quartz-mica schist is composed mainly of quartz, muscovite, plagioclase, and biotite. Rocks display moderate to strong compositional layering and muscovite $\pm$ biotite define a commonly anastomosing foliation. Quartz $\pm$ plagioclase layers are commonly 2 to 3 mm thick, but locally reach up to 10 mm and are in places boudinaged. Quartz shows undulose extinction and subgrains. Aligned muscovite and minor biotite, which is commonly replaced by chlorite, form thin (≤ 1 mm) layers that define the foliation. Plagioclase occurs in minor amounts and is weakly sericitized.

At Station 2-154 (Plate 1), the quartz-mica schist is strongly mylonitized and only a few quartz, plagioclase, and muscovite porphyroclasts remain in a fine-grained matrix of quartz, muscovite, biotite, and chlorite.

Quartzite

Gray quartzites (metacherts), containing minor biotite, muscovite, plagioclase, and opaque minerals are moderately abundant and form resistant outcrops. The rock shows strong foliation defined by aligned micas that form ≤ 1 -mm-thick layers. Compositional layering is defined by variations in the ratio of quartz to micas and opaque minerals.

Marble and Calc-Silicate Rock

Marble layers ranging from 1 to 10 m in thickness are found throughout the Napeequa Complex. Individual layers persist along strike for several hundred meters. Color variation (white to dark gray) is probably caused by the presence or absence of opaque accessory minerals. The dominant constituents are calcite and opaque minerals (graphite?). Layering and foliation are generally not discernible, but at one outcrop (Station 2-115, Plate 1) well-developed 5- to 10-mm-thick compositional layers that vary in their opaque mineral content define a weak foliation.

Calc-silicate rocks are rare and are commonly interlayered with marbles, where they form 1- to 30-cm-long boudins.

Ultramafite

Two- to ten-meter-thick lenses of ultramafic rock are common throughout the study area. The mapped body (Fig. 9) is ~ 150 m thick. Coarse-grained (2 to 3 cm) hornblendites and actinolite-talc lenses (e.g., Station 2-195, Plate 1) lack internal structure and were not examined in detail.

Orthogneiss

Metamorphosed granodioritic to tonalitic intrusive sheets constitute the largest population (~ 60%) of rocks in the Napeequa Complex of the study area. These sheets range in thickness from a few centimeters to several meters and are similar in

composition to the Entiat pluton (Miller and Paterson, 2000). Quartz, plagioclase, hornblende, and biotite are the main constituents. At one locality (Station 4-201, Plate 1) near the contact with the Swakane terrane, a sheet contains garnets ~ 5 mm in diameter. In general, the intrusive rocks are fine- to medium-grained, and color indices range from 10 to 50. A moderately strong solid-state foliation is typically developed and overprints locally preserved magmatic foliation. Both foliations are concordant to foliation and layering in the metasedimentary and metavolcanic host rocks. Leucocratic orthogneisses are present locally and consist dominantly of plagioclase and quartz with minor biotite. Leucogneisses display compositional layering defined by plagioclase, quartz, and scarce biotite. Small amounts of biotite define the barely visible foliation. Scattered mafic orthogneiss lenses show well-developed compositional layering. The main constituents are fine-grained biotite and hornblende with minor medium- to coarse-grained plagioclase and quartz. Plagioclase size ranges from 3 to 15 mm and in some places plagioclase forms augen. Accessories are sphene and apatite. Calcite veins are present locally in all orthogneisses, and some rocks show extensive retrogression of biotite by chlorite and plagioclase by sericite.

Hurlow (1992) obtained a U-Pb date of 68.6 ± 1 Ma along strike ~ 10 km to the northwest from a leucocratic biotite-granodiorite dike in the Napeequa Complex. Based on similar lithology and similar ages, these intrusive rocks are probably related to the 73 to 72 Ma Entiat pluton (see below).

Entiat Pluton

In the study area (Fig. 4), the Entiat pluton is a sheeted intrusive body with sheets ranging from a few centimeters to several tens of meters in width. Magmatic foliation ranges from weak to strong in individual sheets. The dominant rock type is hornblende-biotite tonalite; lenses of leucocratic tonalite [color index (CI) < 5] and mafic rocks (CI ~ 60) are exposed locally. The CI ranges from < 5 to 60 with an average of 30 to 35. Plagioclase and hornblende grains are commonly subhedral to euhedral and range in length from < 1 to 10 mm. Biotite may be a minor constituent, or may be present in amounts that equal or exceed those of hornblende (biotite-hornblende tonalite). Quartz forms the commonly undeformed interstitial matrix. Magmatic epidote, sphene, and opaque minerals are common accessories. Widespread chloritization makes measuring foliation and identifying original rock types difficult.

Entiat Pluton with Rafts of Napeequa Complex

Fine- to coarse-grained tonalite is interlayered with less abundant amphibolite, gneiss, and schist in three places in the contact zone with the Napeequa Complex (Fig. 9). The intrusive rocks form sheets that are concordant to slightly discordant to the foliation in the rafts, which generally occur in lenses ranging from < 1 meter to several meters in thickness, with an average near the lower end. Individual lenses can be followed for only 2 to 3 m along strike, and the entire unit was traced for 300 m along Highway 97A. In places, rafts and intrusive rocks are folded. Small outcrops of similar rock types have also been observed in the contact zone along the Entiat River and east of the Columbia

River along Highway 2 (Fig. 9). The extent of the unit east of the Columbia River (Fig. 9) is uncertain because of the reconnaissance level of mapping. The intrusive rocks resemble the Entiat pluton and the metamorphic rocks are common rock types in the Napeequa Complex.

Tertiary Intrusions

Tertiary intrusive rocks, which are probably part of an ~ 48 Ma Eocene dike swarm (Tabor et al., 1987b), intrude the Swakane terrane, the Napeequa Complex, and the Entiat pluton in Area 2 (Fig. 9). Dikes range in thickness from 1 to 10 m and locally dominate over host rocks. They are resistant to erosion and commonly form cliffs, whereas the host rocks form slopes. Contacts with host rocks are sharp and deflection of host rock fabrics has not been observed. In contrast to the pegmatites intruding the Swakane terrane, these bodies do not record ductile deformation.

The most abundant variety of dikes is a dark brown to black, generally aphanitic andesite (Tabor et al., 1987b), several of which can be followed continuously for many hundreds of meters. White to yellow rhyolite dikes with plagioclase and quartz phenocrysts are also abundant.

Andesite dikes of limited extent are observed in the hinge zone of the regional antiform (Area 1) and in the Napeequa Complex. These porphyritic dikes are 2 to 3 m thick and contain 2- to 10-mm-long plagioclase phenocrysts in an aphanitic gray matrix. They are resistant to weathering, which makes them easily recognizable in outcrop.

STRUCTURAL ANALYSIS

Introduction

This chapter describes the structures (foliations, mineral lineations, kinematic indicators, folds, etc.) observed and measured (using the 'Right Hand rule') during about 10 weeks of field work. Structural analysis was performed at a total of 656 outcrop stations in three areas (Fig. 8, 10, Plate 1). Sampling of oriented hand specimens provided good coverage of the field area of the Swakane terrane, and no particular preference was given to any rock type. Less detailed sampling was completed for the Napeequa Complex and the Entiat pluton, but samples were collected from these units throughout the study area and all rock types were covered. This chapter also describes observations from microscopic analysis of approximately 125 thin sections. One-hundred-and-three thin sections were produced from ~ 50 samples of the Swakane terrane, mostly from the quartz-biotite gneiss. A similar number of thin sections were made from quartz- and mica-rich rocks. Fewer thin sections were cut from samples of the Napeequa Complex (18) and Entiat pluton (4).

Foliation and Lineation

Introduction

A strong transposition foliation (S_T) is developed throughout the Swakane Biotite Gneiss and the Napeequa Complex. In the Swakane terrane, rocks show compositional layers (S_{CL}) and a well-developed extensional crenulation cleavage (S_{ec}), which cross-cut

S_T . This results in deflection and curvature of S_T and leads to an anastomosing fabric. The Entiat pluton displays a magmatic foliation that varies in intensity.

Two mineral lineations are recognized in the Swakane terrane. The dominant one is a medium- to high-temperature lineation (L_{m1}) defined by stretched quartz grains, aligned biotite, and locally by aligned hornblende. Biotite and locally chlorite and/or muscovite define the second lineation (L_{m2}), which formed at lower temperatures, as indicated by a streaky, striae-like appearance, less pervasive development, and the presence of chlorite. In the Napeequa Complex, a medium- to high-temperature mineral lineation is marked by aligned quartz, biotite, and locally hornblende and calcite (Fig. 16), and is generally less well-developed than that in the Swakane terrane. The low-temperature mineral lineation is very scarce in the complex. The Entiat pluton locally displays a mineral lineation defined by acicular hornblende and biotite.

Area 1

Swakane Terrane. Structural measurements were taken at 212 stations in the hinge of the regional antiform (Fig. 8). This area represents the structurally lowest part of the Swakane terrane. Most outcrops display an equally intense foliation (S_T) and lineation (L_{m1}). L_{m2} is widespread, but not as pervasive as L_{m1} . Dominance of S_T or L_{m1} is rare. Foliation is usually defined by biotite $\pm$ muscovite and centimeter- to meter-scale compositional layering. Very shallow dips are predominant, which leads to a wide scatter in strikes (Fig. 17). The average orientation southwest of the fold hinge is 101° ,

Fig. 16. Picture of lineation in Napeequa Complex marble defined by calcite and graphite. Camera lens is ~ 5 cm in diameter.

Fig. 17. Foliation data in the hinge area of the regional antiform of the Swakane terrane (Area 1) collected during this study. B-B' indicates line of cross-section in Fig. 20. Data represents only about half of collected data for easier visualization. Fold hinge as mapped by Tabor et al. (1987b).

8° and to the northeast it is 056°, 6° (Fig. 18, 19). The difference in strikes probably reflects parasitic folds in this broad hinge (Fig. 20).

L_{m1} and L_{m2} trend north-northwest – south-southeast (Fig. 21, 22) and plunge gently (average 6°, 175° and 0°, 172°, respectively; Fig. 23, 24). Even though averages almost coincide, at individual outcrops, L_{m2} is usually ~ 10° to 15° more southeasterly or northwesterly (counterclockwise) than L_{m1} . At 2 stations (163-1 and 115-1), L_{m2} bends ~ 25-30° clockwise in the foliation plane into a more northeasterly orientation (Fig. 25).

Area 2

Swakane Terrane. The transposition foliation (S_T) strikes northwest-southeast and dips gently to steeply northeast at 113 stations (Plate 1) in four domains (Plate 2) in the Swakane terrane of Area 2. The following domains have been distinguished based on differences in the dips of foliation and the orientation of mineral lineation: (1) The Southern Highway 97 domain is located south of Spencer Canyon and shows gentle to moderate foliation dips (average 297°, 25°; Fig. 26). (2) The Northern Highway 97 domain lies north of Spencer Canyon and southwest of the Contact domain. Here, the foliation dips steeply to the northeast (average 295°, 70°; Fig. 27). (3) Moderate northeast dips dominate the Contact domain (average 292°, 46°; Fig. 28), which is positioned in a narrow band next to the Dinkelman decollement. (4) Foliation in the Mills Canyon domain shows orientations similar to those of the Contact domain, but is distinguished from the latter domain by a slightly steeper average dip of foliation

Fig. 18. Stereonet plot of poles to foliation southwest of the hinge of the regional antiform in the Swakane terrane. Average orientation of foliation is 101° , 8° ($n=181$ data).

Fig. 19. Stereonet plot of poles to foliation northeast of the hinge of the regional antiform in the Swakane terrane. Average orientation of foliation is 056° , 6° ($n=89$ data).

Fig. 20. Cross-section of Area 1 across the hinge of the regional antiform. Note the parasitic folds, which indicate that the hinge is not a simple antiform (see text for discussion). Thick dashes show measured foliations, whereas thin dashes indicate the inferred foliation pattern. See Fig. 17 for cross-section line.

Fig. 21. Lineation data (Lm1) in hinge area of regional antiform of the Swakane terrane (Area 1) collected during this study.

Fig. 22. Low-temperature mineral lineation (L_{m2}) in the hinge area of the regional antiform of the Swakane terrane (Area 1).

Fig. 23. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in the hinge of the regional antiform (Area 1). Maximum is 6° , 175° ($n=280$ data).

Fig. 24. Stereonet plot of low-temperature lineation (L_{m2}) in the hinge of the regional antiform (Area 1). Maximum is 0° , 172° ($n=33$ data).

Fig. 25. Hand sample (bottom-side up) with curved low-temperature mineral lineation in foliation plane in micaceous quartz-biotite gneiss (Sample 163-1, Fig. 8). Mineral lineation is defined by biotite and minor chlorite, which replaces biotite. Lineation curves $\sim 30^\circ$ clockwise from lower center to upper right (see text for discussion). Scale on ruler is in centimeters (top) and inches (bottom).

Fig. 26. Stereonet plot of poles to foliation in Swakane terrane in the Southern Highway 97 domain on the northeast limb of the regional antiform (Area 2). Average orientation of foliation is 297° , 25° (n=51 data).

Fig. 27. Stereonet plot of poles to foliation in Swakane terrane in the Northern Highway 97 domain on the northeast limb of the regional antiform (Area 2). Average orientation of foliation is 295° , 70° (n=26 data).

Fig. 28. Stereonet plot of poles to foliation in Swakane terrane in the Contact domain on the northeast limb of the regional antiform (Area 2). Average orientation of foliation is $292^{\circ}, 46^{\circ}$ (n=71 data).

(average 292° , 58° ; Fig. 29) and, more importantly, by a more steeply plunging mineral lineation (see below).

L_{m1} (Plate 3) is weaker in all domains than in the hinge of the regional antiform, and S_T is generally stronger than L_{m1} . Pitches of lineation steepen from low to moderate to, in places, almost down-dip as the Dinkelman decollement is approached. In the Southern Highway 97 domain, gentle north to northwest plunges predominate (average 23° , 353° ; Fig. 30). L_{m1} plunges are steeper and more northwesterly (average 40° , 323° ; Fig. 31) in the Northern Highway 97 domain. In the Contact domain, L_{m1} plunges gently to moderately to the northeast (average 39° , 067° ; Fig. 32), and in the Mills Canyon area moderate to steep northeast plunges are predominant (average 55° , 054° ; Fig. 33). The mineral lineation is oriented counterclockwise when traced from the Southern to the Northern Highway 97 domain, but then trends clockwise from the Northern Highway 97 domain to the Contact domain. Plunges increase on average from gentle to moderate south of Spencer Canyon (average 23°) to moderate to steep (average 40°) closer to the Dinkelman decollement (Plate 3).

The lower-temperature lineation (L_{m2}) is rare in Area 2. South of Spencer Canyon, L_{m2} is oriented $\sim 30^\circ$ counterclockwise (average 13° , 322° , Fig. 34) from L_{m1} (Fig. 30). L_{m2} was measured at only one outcrop ($n=2$ data) in the Northern Highway 97 domain (Fig. 34) and was at right angles to L_{m1} (Fig. 31). In the Contact domain, northeasterly trends with moderate plunges (average 42° , 061° , Fig. 34) are subparallel to L_{m1} (Fig. 32). One data point in the Mills Canyon domain gives a northerly orientation (Fig. 34), oriented $\sim 50^\circ$ counterclockwise from L_{m1} (Fig. 33). The limited data (total of

Fig. 29. Stereonet plot of poles to foliation in Swakane terrane in the Mills Canyon domain on the northeast limb of the regional antiform (Area 2). Average orientation of foliation is 292° , 58° ($n=39$ data).

Fig. 30. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in Swakane terrane in the Southern Highway 97 domain on the northeast limb of the regional antiform (Area 2). Maximum is 23° , 353° ($n=45$ data).

Fig. 31. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in Swakane terrane in the Northern Highway 97 domain on the northeast limb of the regional antiform (Area 2). Maximum is 40° , 323° ($n=16$ data).

Fig. 32. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in Swakane terrane in the Contact domain on the northeast limb of the regional antiform (Area 2). Maximum is 39° , 067° ($n=46$ data).

Fig. 33. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in Swakane terrane in the Mills Canyon domain on the northeast limb of the regional antiform (Area 2). Maximum is $55^\circ, 054^\circ$ ($n=35$ data).

Fig. 34. Stereonet plot of low-temperature lineation (L_{m2}) in Swakane terrane on the northeast limb of the regional antiform (Area 2). $\circ$ =Southern Highway 97 domain. Maximum is $13^\circ, 322^\circ$ ($n=9$ data), $\square$ =Northern Highway 97 domain ($n=2$ data), Δ =Contact domain. Maximum is $42^\circ, 061^\circ$ ($n=4$ data), $\diamond$ =Mills Canyon domain ($n=1$ data).

17 measurements in the four domains), however, makes average orientations questionable.

The steepening of the foliation and scatter in orientations of L_{m1} in this area may be directly related to the emplacement of the Entiat pluton at 73 to 72 Ma, which may have caused deflection of structures such as foliation and lineation in its structural aureole. Another possibility is that the emplacement indirectly affected the orientation of mineral lineations by deflecting the Dinkelman decollement. If mineral lineations formed after this deflection during continued movement on the decollement, their orientations may be influenced by the curvature of the decollement.

Napeequa Complex. The foliation on the northeastern limb of the regional antiform is continuous across the Dinkelman decollement into the Napeequa Complex (Plate 2) and strikes northwest-southeast with moderate to steep northeast dips (average 302° , 45° ; Fig. 35). The foliation is well-developed in most rock types with the exception of marble and ultramafite. The weak, medium- to high-temperature mineral lineation (L_{m1}) plunges moderately northeast (average 39° , 055° , Fig. 36 and Plate 3). As in the Swakane terrane in Area 2, a wide scatter in orientation may be directly or indirectly related to the emplacement of the Entiat pluton (see above). The biotite and/or chlorite-defined, lower-temperature lineation (L_{m2}) is scarce and is oriented clockwise ($\sim 15^\circ$) from L_{m1} (average 40° , 071° , Fig. 37).

Fig. 35. Stereonet plot of poles to foliation in Napeequa Complex on the northeast limb of the regional antiform (Area 2). Average orientation of foliation is 302° , 45° ($n=180$ data).

Fig. 36. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in the Napeequa Complex on the northeast limb of the regional antiform (Area 2). Maximum is 39° , 055° ($n=84$ data).

Fig. 37. Stereonet plot of low-temperature lineation (L_{m2}) in the Napuequa Complex on the northeast limb of the regional antiform (Area 2). Maximum is 40° , 071° ($n=6$ data).

Entiat Pluton. The Entiat pluton displays a generally well-developed magmatic foliation defined by hornblende and plagioclase. Foliation strikes dominantly northwest-southeast and dips moderately northeast (average 314° , 47° ; Fig. 38). Dips generally shallow and become more variable, and the development of foliation weakens to the northeast, with increasing distance from the Napeequa Complex (Plate 2). In the field area, the pluton generally lacks a mineral lineation, although a weak, north- to northeast trending magmatic one occurs locally (Fig. 39, Plate 3).

In the study area, the foliation is continuous across the contact with the Napeequa Complex and discordant to pluton contacts. Discordance to internal sheet contacts has also been reported (Paterson and Miller, 1998b). The continuity of foliation implies strong coupling between the pluton and its host rock and that foliation largely records regional strain rather than internal, magmatic processes (Paterson et al., 1996a, Paterson et al., 1998a).

Entiat Pluton with Rafts of Napeequa Complex. The average orientation of foliation (291° , 42° ; Fig. 40) is subparallel to that in the adjacent Napeequa Complex and Entiat pluton (Fig. 35 and 38, respectively). A moderately east-plunging quartz- and hornblende lineation occurs in one raft (Fig. 41).

Area 3

Swakane Terrane. Forty stations (Fig. 10) on the southwestern limb of the antiform (Fig. 42) indicate that, on average, the foliation strikes northwest-southeast and

Fig. 38. Stereonet plot of poles to magmatic foliation in Entiat pluton (Area 2). Average orientation of foliation is 314° , 47° ($n=83$ data).

Fig. 39. Stereonet plot of magmatic lineation (L_{m1}) in the Entiat pluton (Area 2) ($n=4$ data).

Fig. 40. Stereonet plot of poles to foliation in magmatic sheets and host rock rafts in Entiat pluton with Napeequa Complex rafts (Area 2). Average orientation of foliation is 291° , 42° (n=17 data).

Fig. 41. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in one raft of the Napeequa Complex in the Entiat pluton (see text)(Area 2). Maximum is 44° , 073° (n=3 data).

Fig. 42. Foliation data from the southwest limb of the regional antiform of the Swakane terrane. D-D' indicates line of cross-section in Fig. 44.

dips gently southwest (average 160° , 16° ; Fig. 43). However, the cross-section reveals parasitic folds in this part of the Swakane terrane (Fig. 44). A weak L_{m1} plunges gently south (average 7° , 181° ; Fig. 45, 46). L_{m2} is scarce (4 data points) and does not show a distinct maximum (Fig. 47).

Summary of Foliation and Mineral Lineation Patterns

Field observations led to the above stated results, which are briefly summarized below:

1) The foliation measurements in the Swakane terrane define a regional antiform with a northwest-southeast trending axis (0° , 296° ; Fig. 48). This axis is oriented 14° northwest of the axial trace mapped by Tabor et al. (1987b) ($\sim 310^\circ$). On the southwestern limb (Fig. 42, 43) and in the hinge (Fig. 17, 18, 19), foliation orientations suggest parasitic folds (Fig. 20, 44). On the northeastern limb (Area 2), foliation becomes moderately steep towards the contact with the Napeequa Complex and is continuous with the foliation in the complex and the Entiat pluton (Plate 2). Parasitic folds are not recognized in Area 2 (Plate 2).

2) In the Swakane terrane, the medium- to high-temperature lineation (L_{m1}) delineates a complex pattern (Fig. 49). In the hinge (Area 1, Fig. 21) and on the southwestern limb (Area 3, Fig. 45) of the antiform, L_{m1} trends approximately north-south (Fig. 23, 46). L_{m1} changes from north-south to overall more northeasterly trends in the Swakane terrane close to the Dinkelman decollement (Fig. 30-33) and throughout the Napeequa Complex (Fig. 36) (Plate 3).

Fig. 43. Stereonet plot of poles to foliation in Swakane terrane on the southwest limb of the regional antiform (Area 3). Average orientation of foliation is 160° , 16° ($n=52$ data).

Fig. 44. Cross-section of Area 3 across the southwestern limb of the regional antiform. See Fig. 42 for cross-section line. Note the parasitic folds on this limb. Thick dashes show measured foliations, whereas thin dashes indicate the inferred foliation pattern.

Fig. 45. Lineation (L_{m1}) on southwest limb of regional antiform of the Swakane terrane.

Fig. 46. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in the Swakane terrane on the southwest limb of the regional antiform (Area 3). Maximum is 7° , 181° ($n=39$ data).

Fig. 47. Stereonet plot of low-temperature lineation (L_{m2}) in the Swakane terrane on the southwest limb of the regional antiform (Area 3) ($n=4$ data).

Fig. 48. Stereonet plot of poles to foliation in Swakane terrane of all data (Areas 1 through 3). Pole to best fit girdle is $0^\circ, 296^\circ$ ($n=513$ data).

Fig. 49. Stereonet plot of moderate- to high-temperature lineation (L_{m1}) in all areas of the Swakane terrane ($n=461$ data). $\bullet$ =Area 1, Δ =Area 2, Southern Highway 97 domain, ∇ =Area 2, Northern Highway 97 domain, $\circ$ =Area 2, Mills Canyon domain, ∇ =Area 2, Contact domain, $\square$ =Area 3.

3) The lower temperature lineation (L_{m2}) shows a north-northwest – south-southeast trending, gently plunging maximum (average 4° , 349° ; Fig. 50). L_{m2} trends counterclockwise (10° to 15°) from L_{m1} where both are present.

4) The steepening of the foliation and the scatter of trends of L_{m1} may be related to the emplacement of the Entiat pluton (Hurlow, 1992; Paterson and Miller, 1998b).

Folding History

Introduction

Folding of the Swakane Biotite Gneiss is analyzed in detail in order to determine the relative timing of folding and non-coaxial shear. At the outcrop scale, two cycles of folding are widely recognized in the Swakane terrane (Miller et al., 1996). Minor late kinks, localized folds in ductile shear zones, and microfolds preserved in porphyroblasts probably represent separate events and are described separately. Individual cycles of folding may have been active over long time periods, and a cycle need not have been synchronous throughout an area (cf. Williams, 1985; Tobisch and Paterson, 1988). Thus, the assignment of specific numeric deformational stages (D_x) is probably an oversimplification and is avoided for the mesoscopic folds.

Folding of the Napeequa Complex was not examined in detail. Folds in the Napeequa Complex resemble those in the Swakane terrane but are oriented differently, and the number of cycles of folding may differ.

Fig. 50. Stereonet plot of low-temperature lineation (L_{m2}) in all areas of the Swakane terrane ($n=53$ data). $\circ$ =Area 1, Δ =Area 2, $\square$ =Area 3. Maximum is 4° , 349°

Swakane Terrane

Early Mesoscopic Folds. In domains throughout the Swakane terrane, pegmatite sheets, quartz veins, compositional layering, and S_T are deformed by locally abundant, outcrop-scale, recumbent to gently inclined, tight to isoclinal folds (Fig. 51). These folds are most abundant where compositional layering is best developed or where abundant pegmatite sheets or quartz veins are present to produce a sufficient competence contrast for buckling. Folds are commonly thickened in rounded hinges and most are symmetrical. In places, “m-folds” are developed in the hinge and “s-” and “z-folds” occur on the limbs of higher-order folds. Wavelengths are variable and range from a few centimeters to 3 meters. An incipient axial-planar cleavage is developed in a few places. Subhorizontal pegmatites and quartz veins are locally parasitically folded, but are more commonly boudinaged, and subvertical dikes are typically ptgymatically folded. This indicates a vertical shortening (Z) direction compatible with pure shear orthogonal to the subhorizontal surface or very high values of simple shear nearly parallel to the surface (e.g., Ramsay and Huber, 1983).

A total of 128 tight to isoclinal, recumbent folds were measured in the three study areas in the Swakane terrane. These folds plunge shallowly, but the three areas show different maxima. Maxima are south- (average 15° , 192°) and south- to southwest-trending (average 10° , 201°) on the southwestern limb (Fig. 52) and in the hinge zone of the regional antiform (Fig. 53), respectively. On the northeastern limb, folds measured in the Southern Highway 97 domain away from the Dinkelman decollement have a north-trending maximum (average 24° , 358° ; Fig. 54). The other three domains on the northeastern limb did not contain recumbent folds.

Fig. 51. Photograph of isoclinal, recumbent fold of strong compositional layering and transposition foliation. Station 75 in Area 1 (Fig. 8).

Fig. 52. Stereonet plot of axes of tight to isoclinal, recumbent folds on the southwestern limb of the regional antiform (Area 3). Maximum is 15° , 192° ($n=14$ data).

Fig. 53. Stereonet plot of axes of tight to isoclinal, recumbent folds in the hinge of the regional antiform (Area 1). Maximum is 10° , 201° ($n=61$ data).

Fig. 54. Stereonet plot of axes of tight to isoclinal, recumbent folds on the northeastern limb of the regional antiform (Area 2, Southern Highway 97 domain). Maximum is 24° , 358° ($n=53$ data).

Axial planes throughout the Swakane terrane dip gently to moderately (Fig. 55). Strikes are variable in Area 1, which may be related to shallow dips or to refolding (see below), whereas a northeast-dipping maximum occurs in Area 2. In Area 3, axial planes for 2 folds show shallow southerly dips.

Late Mesoscopic Folds. The tight to isoclinal folds, dominant S_T , and both mineral lineations are refolded by the regional, upright antiform (Fig. 2) and by local, mesoscopic, upright, possibly parasitic folds to the regional antiform (Fig. 56). These folds are scarce in the study area (8 measurements). They show wide scatter (Fig. 57) and do not define a maximum near the regional fold axis (0° , 296°) determined by this study (Fig. 48) or the axial trace mapped by Tabor et al. (1987b) (oriented $\sim 310^\circ$). This suggests that mesoscopic upright folds may not be closely related to the regional antiform.

Kink Folds. The relationship of local kink folds to the open, upright folds is uncertain. Kink folds in two samples from Area 1 (67-2, 157-1; Fig. 8) fold S_T and S_{ec} , and microfaults are developed along the axial planes. Brittle deformation associated with kink folds indicates that they probably postdate all other folds.

Fig. 55. Stereonet plot of poles to axial planes of tight to isoclinal, recumbent folds for all areas (1 through 3) of the Swakane terrane. Folds are refolded by regional antiform. Pole to best fit girdle is 10°, 101°. Δ =Area 1 (n=38 data), $\square$ =Area 2 (n=42 data), $\circ$ =Area 3 (n=2 data).

Fig. 56. Photograph from the Roaring Creek Canyon area (northwestward along strike from field area) of open, upright folds refolding tight to isoclinal, recumbent folds (see text for discussion). Arrow points to isoclinal folds in lower left center. Picture courtesy of S.R. Paterson.

Fig. 57. Stereonet plot of axes of open, upright folds from all areas (n=9 data).

Napeequa Complex

Outcrop-scale, tight to isoclinal, recumbent to steeply inclined folds of layering and S_T with wavelength of a few centimeters to ~ 1 meter are present in all units of the Napeequa Complex and resemble folds in the Swakane terrane. These folds are commonly symmetrical and thickened in their hinges. A new axial-planar cleavage, which is subparallel to S_T , is only developed locally in biotite-rich layers. Two broad maxima of gently to moderately plunging fold axes can be discerned (Fig. 58). A generally north-south trending maximum (13° , 351°) is oriented similarly to fold axes in the Swakane Biotite Gneiss in the Southern Highway 97 domain (24° , 358° ; Fig. 54), whereas an east-northeast – west-southwest trending maximum (11° , 074°) does not have a correlative in the Swakane terrane. Axial planes for both maxima are highly variable, ranging from shallow to steeply dipping (Fig. 59), and are generally steeper than axial planes in the Swakane terrane.

Open folds with wavelengths of a few centimeters are also observed in the Napeequa Complex. Axes of these symmetric and asymmetric folds have various trends (Fig. 60), and axial planes are also variably oriented (Fig. 60).

Data for the Napeequa Complex suggest that the folding history is more complicated than that of the Swakane terrane. The variable orientations may reflect the heterogeneity of the unit. The greater competence contrasts between layers and units at a variety of scales, and the lenticular shape of some units possibly cause more complex fold patterns. Emplacement of the Entiat pluton and southwest-directed shear (Hurlow, 1992) or downward flow in the structural aureole (Paterson and Miller, 1998b) may also have affected orientations by steepening axes near the pluton. If tight to isoclinal folding

Fig. 58. Stereonet plot of axes of tight to isoclinal, recumbent folds in the Napeequa Complex (Area 2). Two maxima are discernable. A north-south trending ($\square$) maximum has a preferred orientation of 13° , 351° ($n=34$ data) and a weaker east-northeast-west-southwest (Δ) maximum has a preferred orientation of 11° , 074° ($n=27$ data).

Fig. 59. Stereonet plot of poles to axial planes for tight to isoclinal, recumbent folds in the Napeequa Complex (Area 2). $\square$ = poles to axial planes of the north-south trending folds ($n=19$ data). Δ = poles to axial planes of northeast-southwest trending folds ($n=20$ data). Pole to best fit girdle is 20° , 089° ($n=39$ data). Folds may be refolded.

Fig. 60. Stereonet plot of axes (□) (n=12 data) and poles to axial planes (Δ) (n=6 data) of open, upright folds in the Napaequa Complex (Area 2).

started prior to, but was partly coeval with, emplacement of the pluton, then older folds may have been deflected more steeply than later ones. Alternatively, a complex strain field with along-strike variations may have developed in the Napeequa Complex due to the obliquity between the Dinkelman decollement and the contact of the Napeequa Complex and Entiat pluton (Fig. 2).

Relationships between Fold Axes and Mineral Lineations (L_{m1})

Swakane Terrane. In Area 1 (hinge zone of the antiform), the maximum of axes of tight to isoclinal recumbent folds (10° , 201°) is oriented $\sim 25^\circ$ clockwise from the maximum of L_{m1} (6° , 175°) (Fig. 61). Lineation is similarly oriented $\sim 20^\circ$ to 25° clockwise from the hinge of individual folds in three hand samples. The maxima of fold axes (15° , 192°) and mineral lineations (7° , 181°) are gently south-plunging (Fig. 62) in Area 3 (southwestern limb) and are closer to each other than in Area 1. In Area 2 (northeastern limb), all folds were measured in the Southern Highway 97 domain away from the Dinkelman decollement. Here, the lineation shows gentle to moderate northerly plunges (average 23° , 353°), which coincide with those of the fold axes (average 24° , 358° ; Fig. 63). In two individual folds, however, the lineation is oriented $\sim 15^\circ$ clockwise from the hinge line.

Napeequa Complex. In the Napeequa Complex, the mineral lineation (L_{m1}) (40° , 056° ; Fig. 64) is oriented 20° counterclockwise from east-northeast – west-southwest

Fig. 61. Stereonet plot of axes of tight to isoclinal, recumbent folds ($\square$) and moderate- to high-temperature lineation ($\bullet$) in the hinge of the regional antiform (Area 1). Maximum of fold axes is 10° , 201° ($n=61$ data) and of lineation 6° , 175° ($n=280$ data). Note that the maximum of fold axes is approximately 25° clockwise from mineral lineation maximum.

Fig. 62. Stereonet plot of axes of tight to isoclinal, recumbent folds ($\square$) and moderate- to high-temperature lineation ($\bullet$) on the southwestern limb of the regional antiform (Area 3). Maximum of fold axes is 15° , 192° ($n=14$ data) and of lineation 7° , 181° ($n=39$ data). Note that the maxima are closer to subparallelism than in Fig. 61.

Fig. 63. Stereonet plot of axes of tight to isoclinal, recumbent folds ($\square$) and moderate- to high-temperature lineation ($\bullet$) on the northeastern limb of the regional antiform in the Southern Highway 97 domain (Area 2). Maximum of fold axes is $24^\circ, 358^\circ$ ($n=53$ data) and of lineation $23^\circ, 353^\circ$ ($n=45$ data). Note that the maxima nearly coincide.

Fig. 64. Stereonet plot of axes of tight to isoclinal, recumbent folds and moderate- to high-temperature lineation ($\bullet$) in the Napeequa Complex (Area 2). Note north-south trending ($\square$) [$13^\circ, 351^\circ$ ($n=34$ data)] and east-northeast – west-southwest trending (Δ) [$11^\circ, 074^\circ$ ($n=27$ data)] maximum of fold axes. The mineral lineations [maximum $39^\circ, 055^\circ$ ($n=84$ data)] overlap with the northeast trending fold axes, but maxima are different.

trending fold axes (11° , 074°) and plunges are significantly steeper. North-south trending folds (13° , 351°) are at a greater angle to L_{m1} ($\sim 60^\circ$ counterclockwise) and plunges are much shallower.

Microstructures

Introduction

Thin sections were analyzed to obtain detailed information about kinematic indicators, which are commonly associated with L_{m1} and L_{m2} ; these record non-coaxial shear and thus allow interpretations about the kinematic regime. Microstructures confirm outcrop observations, and meso-scale shear bands and asymmetrically deformed pegmatites are also briefly described below. Thin sections show kinematic indicators such as shear bands, mica fish, and asymmetric strain shadows. Rocks dominated by coaxial shear were not identified unequivocally in the study area, although strong flattening fabrics are reported in the Napeequa Complex farther to the northwest along strike in the structural aureole of the Entiat pluton (R.B. Miller and S.R. Paterson, unpublished). Approximately 125 thin sections of oriented hand samples were examined for kinematic indicators to infer displacement directions in the Swakane terrane, the Napeequa Complex, and the Entiat pluton. In addition to the standard thin section cut in the X-Z plane (parallel to lineation and perpendicular to foliation) of the strain ellipsoid (where $X > Y > Z$), about 35 thin sections were cut along the Y-Z plane (perpendicular to foliation and lineation). This was done to obtain information about the possible development of kinematic indicators in sections perpendicular to the lineation. In

addition to facilitating an evaluation of kinematic indicators, the thin sections provide information on deformation mechanisms in minerals and, by using porphyroblasts, the timing of metamorphism relative to deformational stages.

Kinematic Indicators

Area 1 (Hinge of the Regional Antiform). In Area 1, discontinuous shear bands were recognized in outcrop at 111 of 212 stations (52%). These shear bands cross-cut and deflect S_T in X-Z (lineation-parallel) surfaces (Fig. 65), and indicate top-to-the-north shear. At the remaining stations, shear bands could not be identified with a hand lens and thus are either absent or weakly developed, which is supported by thin section analysis (see below). Meso-scale shear bands are not observed in sections perpendicular to the lineation (Y-Z plane) and are rare at the microscopic scale (see below). Asymmetric boudinage and pinch-and-swell of pegmatites and quartz veins that are parallel or close to foliation also consistently indicate top-to-the-north shear in lineation-parallel outcrop surfaces (Fig. 66). Only symmetric varieties are identified in surfaces oriented perpendicular to the lineation. These observations are supported by detailed grid mapping completed by R.B. Miller (1998, pers. comm.). He recorded north-directed shear in 79.7% of 202 stations in an $\sim 250 \text{ m}^2$ area.

For the microscopic analysis, a total of 50 thin sections [15 samples in both X-Z plane and Y-Z plane (30 total); 20 samples in X-Z plane only] were examined from samples collected in Area 1. All thin sections generally show strong transposition foliation (S_T) defined by biotite $\pm$ muscovite in both X-Z and Y-Z planes. In addition, 24

Fig. 65. Picture of curved transposition foliation (S_T) and meso-scale, spaced shear bands (S_{ec}) indicating top-to-the-north (right) shear. (Penny for scale).

Fig. 66. Asymmetric boudins in pegmatite sill in Swakane Biotite Gneiss indicating top-to-the-north (right) shear.

out of 35 samples (69%) cut parallel to either L_{m1} or L_{m2} and perpendicular to S_T show an extensional crenulation cleavage (S_{ec}), which records top-to-the-north shear (Fig. 67), thus confirming field observations. Only 1 section (sample 1-115-1) shows top-to-the-south shear.

Shear bands are better developed in mica-rich than in quartz-rich layers. The shear bands are mainly composed of strongly recrystallized, very fine-grained biotite and quartz (Fig. 68) and minor plagioclase and/or muscovite. Minerals in shear bands that are associated with L_{m1} resemble matrix minerals in appearance. This suggests that these shear bands formed at, or close to, peak metamorphic conditions. Shear bands parallel to L_{m2} incorporate recrystallized chlorite in addition to quartz and biotite, indicating lower metamorphic grade and temperatures. Thus, the formation of shear bands probably occurred over a protracted period of time.

The angle between S_T and S_{ec} generally reflects the amount of shear strain, and increasing shear should lead to subparallelism (e.g., Ramsay, 1980; Lister and Snoke, 1984). This is not observed in the Swakane terrane of Area 1, where S_{ec} is on average 26° from S_T .

Shear along S_{ec} also led to kinking and recrystallization of biotite and/or muscovite and formation of asymmetric mica fish. These fish range in length from 0.5 to 5 mm. Intensity of deformation and recrystallization of individual biotite and muscovite fish ranges from weak (Fig. 69) to strong (Fig. 70).

Tails of fine-grained biotite and quartz and in some places muscovite and plagioclase are common on garnet porphyroblasts. Both asymmetric (Fig. 71) and symmetric tails are present, but generally not in the same sample. Asymmetric σ -type

Fig. 67. Photomicrograph of shear bands (S_{ec}) and biotite fish showing top-to-the-north (right) shear. Sample 2-264-1 (X-Z plane). Picture taken with plane light. Field of view is 6.6 mm in long dimension.

Fig. 68. Photomicrograph of shear bands containing recrystallized quartz and biotite. Sample 181-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 0.33 mm in long dimension.

Fig. 69. Photomicrograph of weakly recrystallized biotite fish showing top-to-the-north (left) shear. Sample 2-173-1b (X-Z plane). Picture taken with cross-polarized light. Field of view is 1.32 mm in long dimension.

Fig. 70. Photomicrograph of muscovite fish showing top-to-the-north (left) shear. Sample 2-199-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 6.6 mm in long dimension.

Fig. 71. Photomicrograph of asymmetric σ -type garnet porphyroblast tail showing top-to-the-north (left) shear. Tails are composed of fine-grained quartz, muscovite, and biotite. Sample 181-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 6.6 mm in long dimension.

tails (Passchier and Simpson, 1986) record top-to-the-north shear in sections parallel to the mineral lineation. Decompression during metamorphism is locally shown by plagioclase coronas on garnet (e.g., Dirks and Sithole, 1999), and by plagioclase porphyroblasts that overgrew garnet (Fig. 72). These observations support the isothermal decompression model of Whitney et al. (1999).

The mineral assemblage observed in tails (biotite, quartz, muscovite, and plagioclase) is also observed locally in the strain shadows. This composition is indicative of granitic melts, and it is possible that incipient melting occurred in the Swakane terrane and melts migrated into lower strain areas (D.L. Whitney, pers. comm., 1999).

Two samples from the same outcrop (157-1, 157-2; Fig. 8) show consistent, although weakly developed, top-to-the-east shear in the Y-Z plane, indicating shearing at high angles to the mineral lineation. In all other (13) Y-Z sections from Area 1, curvature of S_T was inconsistent and shear bands were not observed.

Area 2 (Northeast Limb of the Regional Antiform).

Swakane Terrane. Mineral lineations and outcrop-scale kinematic indicators are less distinct in the medium- to coarse-grained rocks of Area 2. S.R. Paterson (1999, pers. comm.) made similar observations along strike to the northwest, and inferred increased temperatures and stronger recrystallization and annihilation of fabrics in structurally higher parts of the Swakane terrane close to the Dinkelman decollement.

In the Swakane terrane of Area 2, 29 of 113 stations (26%) display mesoscopic shear-sense indicators that record non-coaxial shear. Microscopic analysis of 30 thin

Fig. 72. Photomicrograph of garnet porphyroblast overgrown by plagioclase porphyroblast. Quartz inclusion trails are subparallel to external foliation. Sample shows top-to-the-north (right) shear. Sample 2-213-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 6.6 mm in long dimension.

sections [10 in both X-Z plane and Y-Z plane (Total 20); 10 X-Z plane only] reveals the same, but less well-developed, kinematic indicators as in Area 1 (shear bands, mica fish, porphyroblast tails). Shear bands are present in 14 of 20 sections (70%) cut parallel to lineation and perpendicular to S_T . Mineral assemblages are the same as in Area 1, and although shear bands are less distinct, the average angle between S_T and S_{ec} (29°) is similar to that in Area 1 (26°). The mineral lineation shows greater scatter in Area 2 than in Area 1 (compare Fig. 30-33 and Fig. 23, respectively), and thus the shear direction varies from top-to-the-northwest to top-to-the-northeast (Fig. 7). Of the 10 Y-Z sections, two samples indicate non-coaxial shear. Sample 2-180-1 gives top-to-the-northwest shear, whereas sample 2-213-1 shows top-to-the-southeast shear (Fig. 73).

In one sample (2-135-4; Plate 1), which is composed of quartz, plagioclase, hornblende, biotite, and chlorite, hornblende was sheared brittlely but did not recrystallize, and the shear bands are composed of quartz, biotite, and chlorite (Fig. 74). The lack of recrystallization of hornblende provides a maximum temperature of $\sim 500^\circ\text{C}$ for shearing in this sample. The presence of recrystallized chlorite in cataclastic-looking shear bands also indicates relatively low temperatures.

Napeequa Complex. Kinematic indicators are very scarce in the Napeequa Complex. Mixed top-to-the-northeast and top-to-the-southwest shear sense indicators were observed in the field. Top-to-the-southwest shear indicators are generally weakly developed; the best examples are asymmetric boudins in marbles (Fig. 75), which are

Fig. 73. Photomicrograph of biotite-defined shear bands at high angle to the mineral lineation showing top-to-the-southeast (right) shear. Sample 2-213-1 (Y-Z plane). Picture taken with cross-polarized light. Field of view is 6.6 mm in long dimension.

Fig. 74. Photomicrograph of sheared hornblende; shear bands are composed of biotite, quartz, and chlorite. Sample 2-135-4 (X-Z plane). Picture taken with cross-polarized light. Field of view is 0.33 mm in long dimension.

Fig. 75. Picture of asymmetric tails around calc-silicate boudin in marble matrix at station 2-86 (Plate 1) indicating top-to-the-southwest (right) shear.

best seen in surfaces at high angles to the rare, steeply plunging mineral lineation. Top-to-the-northeast kinematic indicators are most commonly present in quartz-mica schist.

Ten samples [8 in both X-Z plane and Y-Z plane (16 total); 2 X-Z plane only] were examined in thin section. Two of three quartz-mica schists (2-188-1 and 2-154-1) contain weak shear bands and mica fish that indicate top-to-the-northeast shear (Fig. 76). Six orthogneiss samples, one hornblende schist, and sections cut along the Y-Z plane did not show conclusive kinematic indicators.

Southwest-directed shear has been recorded along strike in the Napeequa Complex to the northwest by S.R. Paterson (pers. comm., 1999) and may be related to postulated early southwest-directed thrusting along the Swakane terrane – Napeequa Complex contact or emplacement of the Entiat pluton.

Entiat Pluton. Weak indications for non-coaxial shear are only observed in outcrop at three stations (4-19, 4-20, 4-42; Plate 1). Here the rocks contain plagioclase with weakly developed asymmetric tails that record top-to-the-southwest shear. These tails may be evidence for reverse shear along the Entiat pluton – Napeequa Complex contact (Hurlow, 1992) or downward flow in the structural aureole of the pluton (Paterson and Miller, 1998b). These observations, however, could not be unequivocally confirmed during thin section analysis, which did not show conclusive kinematic indicators.

Fig. 76. Photomicrograph of muscovite fish showing top-to-the-northeast (left) shear. Sample 2-188-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 6.6 mm in long dimension.

Area 3 (Southwest Limb of the Regional Antiform). In Area 3, shear bands indicating top-to-the-north shear were recognized in outcrop at 10 of 40 stations (25%). Ten thin sections of 7 samples [3 in both X-Z plane and Y-Z plane (total 6); 4 X-Z plane only] were examined in detail. Five of the samples (71%) cut along the X-Z plane have weak shear bands that record top-to-the-north shear. Y-Z sections did not show any consistent sense of shear.

Summary

1) Lineation parallel (X-Z plane) shear-sense indicators are developed throughout the Swakane terrane. They record top-to-the-north shear in the hinge and the southwest limb of the regional antiform. On the northeast limb, the direction of shear varies with the orientation of the mineral lineation from top-to-the-northwest to top-to-the-northeast (Fig. 7).

2) Shearing occurred over an unknown period of time as indicated by shear bands that formed at low and medium to high temperatures.

3) Thin sections from 4 of 15 samples in the Swakane terrane cut in the Y-Z plane show local weakly developed kinematic indicators. These record top-to-the-east, top-to-the-northwest, and top-to-the-southeast shear.

4) In the Napeequa Complex, shear-sense indicators are scarce, and mixed top-to-the-northeast and top-to-the-southwest shear is deduced in the field. In thin section, only two samples show top-to-the-northeast shear. Samples examined in the Y-Z plane did not contain kinematic indicators.

5) The Entiat pluton in the field area shows weak mesoscopic top-to-the-southwest kinematic indicators at three stations; these were not observed in thin section.

Relationships between Folding and Kinematic Indicators

The relative timing of folding and top-to-the-north shearing was evaluated by examining shear-sense indicators on the opposing limbs of individual folds. The limbs of tight to isoclinal recumbent folds consistently record top-to-the-north shear, rather than opposing directions of shear. Thus, shearing postdates these folds.

Kinematic indicators record sinistral and dextral directions of shear on opposing limbs of the open, upright folds and the mineral lineation is folded across the hinge, which strongly implies that these folds postdate shearing. To the northwest along strike, however, domains of contemporaneous shearing and upright folding are reported by S.R. Paterson (1999, pers. comm.), who argues that open, upright folds mostly predate top-to-the-north shear. If correct, folding predates shearing in one domain in the Swakane terrane and postdates it in another, and in other places they overlap in time. This suggests that different domains record different successions of events (cf. Tobisch and Paterson, 1988).

Porphyroblast – Matrix Relationships in the Swakane Terrane

Introduction. A total of 27 samples from the Swakane terrane contain biotite, plagioclase, garnet, and/or muscovite porphyroblasts (Table 1) with well-preserved

Table 1. Summary of porphyroblast observations.

Sample #	Mineral	Size (mm)	Internal fabric (S_i) to external fabric (S_e)	Inclusion fabric	Inclusion mineral
60-1	Biotite	1 - 1.75	Ranges from subparallel to perpendicular	Straight	Graphite
68-1	Biotite	1.25	Mostly subparallel	Straight	Graphite
77-1	Biotite	2.5	S_e at angle to axial plane of folds of S_i	Folded	Graphite
2-128-3	Biotite		Commonly random		Graphite
2-153-1	Biotite	0.5 - 3	Ranges from subparallel to perpendicular	Straight	Graphite
2-157-1	Biotite	2.5	Mostly subparallel or random	Straight	Graphite
2-173-1	Biotite	0.5	Mostly subparallel or random	Straight	Graphite
2-213-1	Biotite	0.5 - 1	Ranges from subparallel to perpendicular	Straight	Graphite
3-2-2	Biotite	0.5	Mostly subparallel	Straight	Graphite
3-34-1	Biotite	0.5 - 1	Mostly subparallel	Straight	Graphite
181-1	Biotite/ muscovite	0.5 - 1.0	Mostly subparallel	Straight	Graphite
56-1	Plagioclase	1 - 3.5	S_e is axial planar to folds of S_i	Folded	Graphite
56-1	Plagioclase	1 - 3.5	Ranges from subparallel to perpendicular	Straight	Quartz
60-1	Plagioclase	2 - 3	Mostly perpendicular or oblique	Straight	Quartz
68-1	Plagioclase	0.5 - 2.5	Mostly subparallel, S_e is axial planar or at angle to folds of S_i	Folded	Graphite
77-1	Plagioclase	1.25 - 2.5	S_e at angle to axial plane of folds of S_i , straight inclusions range from subparallel to perpendicular to S_e	Folded	Graphite
106-1	Plagioclase	1.75	Mostly oblique	Straight	Quartz
123-1	Plagioclase	1 - 1.5	Mostly perpendicular or oblique, S_e is axial planar to folds of S_i	Curved/ wavy	Graphite
134-1	Plagioclase	2.5 - 3.5	Ranges from subparallel to perpendicular	Straight	Quartz/ Biotite
157-1	Plagioclase	2.5	Mostly perpendicular or oblique	Straight	Quartz

Table 1 (continued)

Sample #	Mineral	Size (mm)	Internal fabric (S_i) to external fabric (S_e)	Inclusion fabric	Inclusion mineral
157-1	Plagioclase	2.75	Mostly subparallel	Straight	Quartz/ Biotite
163-1	Plagioclase	1 - 2.5	S_e is axial planar and at angle to folds of S_i	Folded	Graphite
163-1	Plagioclase	3.5	Ranges from subparallel to oblique	Straight	Graphite
181-1	Plagioclase	1.25	Mostly perpendicular or oblique	Straight	Graphite
181-1	Plagioclase	3	S_e is axial planar or at angle to folds of S_i	Folded	Graphite
201-2a	Plagioclase	1-2	Ranges from subparallel to perpendicular	Straight	Quartz
2-135-3	Plagioclase	1 - 2	Mostly perpendicular or oblique	Straight	Graphite
2-135-4	Plagioclase	2.5	Mostly oblique	Straight	Quartz
2-153-1	Plagioclase	2.5	S_e is axial planar to folds of S_i	Folded	Graphite
2-153-1	Plagioclase	1.5 - 3.5	Mostly subparallel, S_e at angle to axial plane of folds of S_i	Straight	Quartz/ Biotite
2-173-1	Plagioclase	2 - 3	Ranges from subparallel to perpendicular	Straight	Quartz
2-180-1	Plagioclase	2	Mostly perpendicular or oblique	Straight	Quartz
2-213-1	Plagioclase	2.5 - 4	Mostly subparallel, 2 S_i fabrics	Straight	Graphite
2-238-1	Plagioclase	3	Mostly subparallel	Straight	Quartz
2-27-1	Plagioclase	1.75	Mostly subparallel	Straight	Quartz
2-273-1	Plagioclase	1.5 - 5	Ranges from subparallel to oblique, 2 S_i fabrics	Straight	Graphite
2-273-1	Plagioclase	5	S_e at angle to axial plane of folds of S_i	Folded	Graphite
3-2-2	Plagioclase	0.5 - 1	Mostly subparallel	Straight	Graphite
68-1	Garnet	0.5 - 3	Mostly perpendicular or oblique	Straight	Graphite
77-1	Garnet	1	Ranges from subparallel to oblique	Straight	Graphite
134-1	Garnet	3	Ranges from subparallel to perpendicular	Straight	Graphite
134-1	Garnet	2.5 - 3	S_e is axial planar and at angle to S_i folds	Folded	Graphite
163-1	Garnet	1.0	Slightly oblique	Straight	Graphite

Table 1 (continued)

Sample #	Mineral	Size (mm)	Internal fabric (S _i) to external fabric (S _e)	Inclusion fabric	Inclusion mineral
181-1	Garnet	1.5 - 1.75	Sigmoidal S _i	Curved	Graphite
181-1	Garnet	2 - 2.5	Ranges from subparallel to perpendicular	Straight	Graphite
181-1	Garnet	1.5 - 2.75	S _e is axial planar to folds of S _i	Folded	Graphite
201-2a	Garnet	2.0	Mostly perpendicular or oblique	Straight	Graphite
2-128-3	Garnet	2.25	Mostly subparallel	Straight	Graphite
2-128-3	Garnet	4	Snowball S _i	Curved	Quartz
2-128-3	Garnet	4	Center oblique, rim subparallel	Curved	Quartz
2-153-1	Garnet	1 - 3	Mostly subparallel	Straight	Graphite
3-2-2	Garnet	2	Mostly subparallel	Straight	Graphite
56-1	Muscovite	0.5	Mostly subparallel	Straight	Graphite
181-1	Muscovite	0.5	Subparallel	Straight	Graphite

inclusion trails of opaque minerals (graphite, magnetite?). Other common inclusions are quartz, biotite, and muscovite in plagioclase and/or garnet. Inclusion trails defined by quartz and biotite are always confined to a single plagioclase or garnet porphyroblast, whereas those defined by opaque minerals are in some places overgrown by two or more grains (Fig. 77). The inclusion trails define a foliation (S_i) that was almost completely obliterated during succeeding deformational events.

Biotite. In the Swakane terrane of the study area, biotite commonly (1) is recrystallized and defines the dominant transposition foliation (S_T), (2) is strongly reduced in grain size and partly constitutes shear bands (S_{ec}), (3) is dynamically recrystallized and forms mica fish, and (4) occurs as porphyroblasts. These porphyroblasts show weak to strong undulose extinction and incipient recrystallization of their rims. They range in size from 0.5 to 3 mm and average about 1 mm. In an individual sample, porphyroblasts commonly overgrew S_T , but in places porphyroblasts started to recrystallize and be incorporated in S_T . Strain shadows were not developed. Twelve samples contain biotite that overgrew mostly well-preserved straight or slightly curved inclusion trails defined by opaque minerals, which are observed throughout the mineral. In other samples, inclusions are either randomly oriented or absent. Inclusion trails in X-Z and Y-Z planes range from continuous with (Fig. 78) to highly oblique to (Fig. 79) S_T , and all variations can be found within a single sample. The majority of inclusion trails, however, are subparallel to S_T .

Fig. 77. Photomicrograph of opaque mineral inclusion trails continuously overgrown by garnet (upper left) and plagioclase (right center). Inclusion trails are subparallel to external foliation and are weakly folded in the rim of the garnet. Sample 77-1 (X-Z plane). Picture taken with plane light. Field of view is 1.32 mm in long dimension.

Fig. 78. Photomicrograph of straight opaque inclusion trails subparallel to external, biotite-defined foliation. Sample 60-1 (X-Z plane). Picture taken with plane light. Field of view is 3.3 mm in long dimension.

Fig. 79. Photomicrograph of straight opaque inclusion trails in biotite at high angle to external foliation. Note that inclusion trails differ in orientation from one porphyroblast (A) to another (B). Sample 2-153-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 1.32 mm in long dimension.

These patterns have several possible explanations. The weak deformation of biotite and the dominant orientation of inclusion trails subparallel to S_T suggest that biotite grew after or late during formation of S_T . However, this explanation does not account for the variable orientations of inclusion trails or their slight curvature. These relationships could be explained if the porphyroblasts overgrew S_i during early stages of folding of an earlier foliation (Fig. 80) and the development of S_T . During later stages of this folding, subsequent folding of S_T , and top-to-the-north shearing, biotite porphyroblasts were located in lower strain areas and did not become strongly deformed. A third hypothesis is that biotite grew continuously or periodically during folding of an earlier foliation and formation of S_T and now preserves various stages of this deformation. This hypothesis accounts nicely for the variable orientations of inclusion trails. The second and third hypotheses are most likely, but it is difficult to choose between them.

Plagioclase. Plagioclase porphyroblasts are very common throughout the study area. Mostly symmetric, elongate strain shadows of quartz, plagioclase, and locally biotite are commonly developed on porphyroblasts in the hinge of the regional antiform (Area 1). Strain shadows are typically absent on the limbs (Area 2, 3). S_T wraps around porphyroblasts in the hinge of the antiform, whereas plagioclase mostly overgrew the biotite-defined S_T on the limbs (Area 2, 3), although exceptions exist. Inclusion trails (S_i) are defined by biotite, opaque minerals, quartz, and/or muscovite; one or more minerals can be present in a single porphyroblast. Some porphyroblasts contain more than one

Fig. 80. Photomicrograph of opaque inclusion trails overgrown by biotite and plagioclase. Note that inclusions define a fold with an axial plane from upper right to lower left. External foliation is oblique to the postulated fold. See text for discussion. Sample 68-1 (X-Z plane). Picture taken with plane light. Field of view is 3.3 mm in long dimension.

fabric (Fig. 81). S_i ranges from subparallel to highly oblique to S_T , and folds of trails of opaque minerals range from open to isoclinal in individual samples. Axial planes are mostly subparallel (Fig. 82, 83) to S_T , but samples with axial planes at high angles to S_T exist (Fig. 84). Quartz-defined S_i is generally at a high angle or perpendicular to S_T in Area 1 (Fig. 85) and at small angles or subparallel to S_T in Area 2 (Fig. 86).

The complexity of the inclusion trails implies that plagioclase crystallized over a protracted period of time and during different stages of deformation. Porphyroblasts overgrowing S_i that is continuous with S_T on the limbs of the regional antiform (Area 2, Area 3) indicate that some porphyroblasts grew during or after formation of S_T , whereas the wrapping of porphyroblasts by S_T and the folding of S_i implies growth before and during formation of S_T . In the hinge of the antiform (Area 1), S_i is at higher angles to S_T ; thus, it probably formed largely before S_T , or S_T and/or the porphyroblasts rotated during subsequent deformation. Thus, porphyroblasts grew at different times and/or S_T did not form at the same time throughout the study area.

Garnet. Xenoblastic and idioblastic garnet porphyroblasts are common in the Swakane terrane and have symmetric and asymmetric tails (see above). These porphyroblasts are generally wrapped by S_T , indicating that S_T at least in part postdates garnet growth. Nine samples contain garnet, which ranges in size from 0.5 to 4 mm (average ~ 2 mm), with well-preserved inclusion trails of opaque minerals, quartz [2 samples (RO-32-1 at station 27; 2-128-3)], and muscovite [1 sample (201-2a)]. Inclusion trails range from straight to isoclinally folded, and all variations can be present in a single

Fig. 81. Photomicrograph of 2 fabrics of quartz and biotite inclusion trails in plagioclase porphyroblast. One fabric is subparallel to the external, biotite-defined foliation. The second (2nd) fabric is oriented at a 25° angle to the first and the external fabric. Sample 2-273-1 (Y-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension. Red dot is mark on thin section.

Fig. 82. Photomicrograph of openly folded inclusion trails in plagioclase (A). The external foliation is axial planar to the fold. Inclusion trails in the center top plagioclase (B) are subparallel to the external foliation. Sample 2-153-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension.

Fig. 83. Photomicrograph of tightly folded inclusion trails in plagioclase. The axial plane is subparallel to external foliation. Sample 2-153-1 (X-Z plane). Picture taken with plane light. Field of view is 3.3 mm in long dimension.

Fig. 84. Photomicrograph of openly to tightly folded inclusion trails in plagioclase (center). The axial plane is at a high angle to the external foliation. Sample 181-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension.

Fig. 85. Photomicrograph of straight, slightly deflected quartz and openly folded opaque inclusion trails in a plagioclase porphyroblast. Both are at a high angle to the external, biotite-defined foliation. Sample 2-153-1 (X-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension.

Fig. 86. Photomicrograph of quartz and biotite inclusion trails in a plagioclase porphyroblast. Inclusion trails are subparallel to the external, muscovite- and biotite-defined foliation. Sample 2-173-1b (X-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension. (Red dots are marks on thin section).

thin section. Straight inclusion trails in the hinge of the regional antiform (Area 1) range from parallel to perpendicular to S_T , whereas on the northeast limb (Area 2), they are more commonly subparallel to S_T or S_{ec} . Folds of inclusion trails preserved in two samples from Area 1 (134-1, 181-1; Fig. 8) range from open (Fig. 87) to isoclinal (Fig. 88) and have axial planes that are dominantly subparallel to S_T , although oblique examples exist. These patterns strongly suggest that the porphyroblasts in these samples grew during folding.

Inclusion trails with sigmoidal (Sample 181-1, Fig. 89) and spiral shapes (Sample 2-128-3, Fig. 90) are observed in the Swakane garnets and are common in garnets in general (e.g., Williams and Jiang, 1999). The origins of these shapes are strongly debated and have been assigned to rotation of the porphyroblast during deformation (e.g., Powell and Vernon, 1979; Lister and Williams, 1983; Williams and Jiang, 1999) or rotation of the external foliation (e.g., Bell, 1985; Bell and Johnson, 1992; Bell et al., 1992). Williams and Jiang (1999) differentiate between sigmoidal trails, where the curvature of inclusions is less than 90° with respect to the external foliation, and spiral trails, where the curvature is greater than 90° with respect to the external foliation (snowball garnets). One possible explanation for sigmoidal inclusion trails is that they form during folding. Another hypothesis is that sigmoidal and/or spiral fabrics form when garnet grows slowly while rotating; thus, the inclusions in the core are at a higher angle to the external foliation than those in the rims. The same rim-core pattern would form if garnet growth was episodic or was slow enough that the foliation in the matrix rotated during progressive deformation, presumably during folding (e.g., Bell, 1985; Bell and Johnson, 1992). Garnets with inclusion trails in their cores, but inclusion-free rims,

Fig. 87. Photomicrograph of open to tight folds of inclusion trails in garnet porphyroblast. Inclusion trails could (1) be overgrown fold with axial planes subparallel to shear bands and at high angle to external foliation, or (2) indicate rotation of the porphyroblast (see text for discussion). Sample 181-1 (X-Z plane). Picture taken with plane light. Field of view is 3.3 mm in long dimension.

Fig. 88. Photomicrograph of tightly to isoclinally folded inclusion trails in garnet with axial plane sub-parallel to external foliation. Axial plane is gently refolded. Sample 134-1 (X-Z plane). Picture taken with plane light. Field of view is 1.32 mm in long dimension.

Fig. 89. Photomicrograph of curved (sigmoidal) inclusion trails in garnet porphyroblast. Shear is to the north (left). Note that orientation of inclusion trails changes. Inclusion trails are subparallel to S_T in the rim and at an angle to S_T in the center (see text for discussion). Sample 181-1 (X-Z plane). Picture taken with plane light. Field of view is 3.3 mm in long dimension.

Fig. 90. Photomicrograph of quartz inclusion trails in garnet porphyroblast. Inclusions have an apparent spiral form, which may indicate contemporaneous rotation and growth of the grain (see text for discussion). Sample 2-128-3 (X-Z plane). Picture taken with cross-polarized light. Field of view is 3.3 mm in long dimension.

support multiple periods of growth, which is compatible with Sawkyo's (1994) petrologic analysis of garnets in the Swakane terrane.

In summary, the presence of straight and folded inclusion trails, rim-core relationships, and possible rotation to form sigmoidal and spiral inclusion trails implies that garnet growth occurred over a protracted period of time during one or more deformational stages, or that deformation was very heterogeneous at the thin-section scale.

Muscovite. Two samples from Area 1 (181-1, 56-1) contain straight inclusion trails of opaque minerals in muscovite that are subparallel to S_T or S_{ec} . The muscovite is about 0.5 mm long and is weakly strained. These relationships imply that muscovite grew after the formation of S_T and probably after S_{ec} .

Microscopic Folds. The folds preserved in porphyroblasts range from open to tight to isoclinal, and interlimb angles range from 10° to 140° . The axial planes are oriented perpendicular to parallel to S_T . Presumed correlative folds are only rarely (3 samples) recognized in the matrix, where recumbent, isoclinal folds deform a muscovite-defined foliation (S_i ; Fig. 91). These structures are interpreted as the earliest preserved cycle of folding in the Swakane terrane. They are overprinted and almost completely obliterated by the now dominant transposition foliation, which is parallel to their axial

Fig. 91. Photomicrograph of isoclinal F_T fold of muscovite-defined S_i foliation. The transposition foliation (S_T) is axial planar to the fold. Sample 201-2a (Y-Z plane). Picture taken with cross-polarized light. Field of view is 1.32 mm in long dimension.

planes. S_T is itself tightly to isoclinally folded (see above), thus, there must be at least two generations of tight to isoclinal folds.

Summary and Conclusions on Porphyroblast – Matrix Relationships. Most garnet, plagioclase, and biotite porphyroblasts in the hinge of the regional antiform (Area 1) and some on the limbs (Area 2, 3) grew during tight to isoclinal folding of inclusion trails (S_i) and are pre- to syn- S_T . S_T mostly wraps around those porphyroblasts and is deformed and probably predates S_{cc} ; thus, most porphyroblasts, with the exception of muscovite, which grew later, are older than top-to-the-north shearing in the Swakane terrane. On the limbs of the regional antiform (Area 2, 3) closer to the decollement, many plagioclase and garnet porphyroblasts are synchronous with, or postdate, S_T . This observation, combined with the coarsening of grain size in structurally higher areas closer to the decollement, and the lack of well-developed outcrop-scale kinematic indicators (see p. 45), suggest that areas closer to the decollement stayed at elevated temperatures for a longer period of time than structurally lower regions, where porphyroblast growth ceased earlier.

Shear Zones and Faults

Dinkelman Decollement

The contact between the Swakane terrane and the Napeequa Complex is an inferred mid-crustal decollement (Dinkelman decollement; Miller et al., 1996).

Differences between these units in types of intrusive rocks, folding styles, orientations of fold axes, and Ar cooling ages provide strong evidence that the decollement is a significant structure. The Swakane terrane, which forms the ~ 1-km-thick footwall, is deformed by north-directed non-coaxial shear, and no obvious strain gradient developed between the lowest levels of the terrane and the decollement. In the hanging-wall rocks of the Entiat pluton and the Napeequa Complex, kinematic indicators are absent or only locally present and show mixed senses of shear.

Throughout the study area, and along strike to the northwest, the Napeequa Complex contains abundant (~ 60% of total outcrop) tonalitic to granodioritic intrusive sheets probably related to the Entiat pluton (Tabor et al., 1987a; R.B. Miller and S.R. Paterson, unpublished). These sheets range from a few centimeters to several meters in thickness in the study area. In the Swakane terrane, however, pegmatites are main (sole?) pre-decollement intrusive rocks. These observations strongly suggest that the Swakane and Napeequa units were not in their present positions at the time of emplacement of the youngest pre-decollement intrusions, and that their contact records significant displacement. If the decollement has only minor displacement, the magmatic sheets that intrude the Napeequa Complex must have ascended through the Swakane terrane without leaving any sign of their passage.

Different styles of folding and orientations of fold axes are further evidence for the Dinkelman decollement. In the heterogeneous Napeequa Complex, folds are abundant and observations in other parts of the Napeequa Complex (Miller and Paterson, 2000) reveal early isoclinal folds that are refolded during one and probably more cycles of folding. In the more homogeneous Swakane terrane, folds are much less common, but

the same sequence of early isoclinal folds refolded by open, upright folds is present. In the Swakane terrane, axes of recumbent folds trend north-south to north-northeast – south-southwest (Fig. 52-54), whereas axes in the Napeequa Complex show maxima that trend east-northeast – west-southwest and north-south (Fig. 58). Thus, structures are broadly similar, but the differences in styles, abundance, and orientations of folds imply that the units became detached during folding.

Further evidence for significant displacement on the decollement comes from distinctly different Ar-Ar and K-Ar ages from the upper and lower plates (Tabor et al., 1987b; R.B. Miller, unpublished data, 1999). Rocks at shallower crustal levels should reach their blocking temperatures for Ar loss ($\sim 500^{\circ}\text{C}$ for hornblende, $\sim 300^{\circ}\text{C}$ for biotite) earlier than at deeper levels. In the upper plate, K-Ar ages for hornblende range from 60.0 to 73.2 Ma in the Entiat pluton (Tabor et al., 1987b) and from 67.1 to 71.5 Ma in the Napeequa Complex (Tabor et al., 1987b). These ages are significantly older than a 50.8 ± 1.4 Ma age on hornblende in one sample from the Swakane terrane (Tabor et al., 1987b). Similar differences are observed for biotite ages. The ages range from 56.2 to 62.8 Ma in the Entiat pluton (Tabor et al., 1987b), and one sample from the Napeequa Complex is 59.8 ± 1.2 Ma (R.B. Miller, unpublished data). These are also significantly older than those in the Swakane terrane [49.1 ± 1.2 , 46.2 ± 1.5 , and 44 ± 2 Ma; R.B. Miller (unpublished data)]. Fission-track zircon ages have greater uncertainties, but show comparable differences (average ~ 57 Ma for Entiat pluton, average ~ 43 Ma for Swakane terrane; Tabor et al., 1987b). These significant age gaps probably do not reflect very slow exhumation rates, based on metamorphic studies, which show a P-T-t path with isothermal decompression (e.g., Whitney et al., 1999), and the apparent lack of a

continuous gradient in ages in the hanging-wall and footwall units. Instead, the data support significant excision of rock along the Dinkelman decollement, which would have juxtaposed the considerably cooler Napeequa Complex against much deeper Swakane gneisses and produced the age gap between the units.

Relationships between Non-Coaxial Shearing and Orientation of Fold Axes and Mineral Lineations

Displacement on the Dinkelman decollement and non-coaxial shear may explain the difference between the orientation of the axes of early recumbent folds and the medium- to high-temperature mineral lineation in Area 1 and their near subparallelism in Areas 2 and 3 of the Swakane terrane. If a strain gradient, which was not noticed during field work, developed, top-to-the-north shear presumably had a stronger influence on structurally higher rocks closer to the decollement (Area 2, 3), causing the fold axes to rotate close to subparallelism with the mineral lineation (e.g., Escher and Watterson, 1974; Ramsay, 1980), whereas fold axes in structurally lower parts rotated less and are now oriented $\sim 25^\circ$ clockwise from the lineation. The southwesterly trend of fold axes in areas of lower strain (Area 1) supports an original northeast-southwest maximum of fold axes, which may have originated from southwest-directed ductile folding and thrusting during the mid-Cretaceous (Miller and Paterson, 1992). In this fold and thrust system, fold axes would have rotated into northeast-southwest trending orientations during progressive deformation and been oriented subparallel to the shear direction (e.g., Escher and Watterson, 1974; Ramsay, 1980).

Relationships between the two fold axes maxima, mineral lineations (Fig. 64), and associated weak kinematic indicators in the Napeequa Complex of the study area are ambiguous, making interpretation difficult.

Ductile Shear Zones

Ductile to brittle-ductile shear zones are common throughout the Swakane terrane in the study area. These zones are usually only a few millimeters thick, but ten thicker (~50 cm), northwest-southeast- to north-south-striking, low-angle brittle-ductile shear zones (Fig. 92) were mapped. Thin shear zones tend to be oriented subparallel to foliation and compositional layering and record top-to-the-north shear parallel to the medium- to high-temperature mineral lineation (L_{m1}). Displacements of steep, ductilely deformed pegmatite dikes oriented at high angles to the shear zones range from a few centimeters to 50 cm. Larger displacements are likely in the thicker shear zones. Whether these low-angle structures are “thrust faults” or ductile shear zones with reverse motion as suggested by Waters (1932) or zones with normal displacement cannot be determined because of gentle dips and generally missing offset markers. Local small, open to tight upright folds of transposition foliation, compositional layering, and L_{m1} occur in the shear zones and do not extend outside of these zones, which suggests that these folds formed during shearing. These folds are typically asymmetric and have wavelengths ranging from a few centimeters to about 50 cm. Axes have no preferred orientation (Fig. 93), but fold asymmetry suggests north to northeast displacement of the hanging wall. In some places, brittle deformation overprints the ductile fabrics in the

Fig. 92. Stereonet plot of poles to ductile shear zones in the Swakane terrane (all areas). Average orientation is 156° , 11° (n=10 data).

Fig. 93. Stereonet plot of orientation of fold axes in ductile shear zones (n=12 data).

shear zones. Rocks are strongly brecciated, and veins of pseudotachylite, which range in length from <1 to ~ 3 cm and reach a thickness of ~ 5 mm, are present locally. In places, pseudotachylite cuts chlorite, which overprints biotite. This shows that movement on the shear zones occurred as temperatures decreased.

Brittle Faults

Moderately to steeply dipping brittle faults are abundant throughout the Swakane terrane. Subvertical and subhorizontal slickenside striae provide information about displacement directions across these faults. Magnitudes of offset are similar to those of the ductile shear zones and probably do not exceed a few meters.

Fourteen northeast-southwest–striking normal faults (Fig. 94) were identified from offset of subhorizontal pegmatite sheets and quartz veins and deflected foliation. Offsets and slickenside striae on seven of these faults (Fig. 94) indicate down-to-the-northeast movement of the hanging wall. Although the cumulative magnitude of offset is difficult to determine, it is probably insignificant because large offsets would lead to exposure of shallower structural levels in the southern part of the Swakane terrane, which has not been documented.

Five east-west–striking high-angle faults have shallowly east-plunging slickenside striae (Fig. 95). This suggests strike-slip motion, but the magnitude and sense of offset could not be determined. The shear sense could also not be determined on five other high-angle, oblique-slip faults. These faults strike northwest-southeast or approximately east-west, and slickenside striae have intermediate pitches (Fig. 96).

Fig. 94. Stereonet plot of orientations of normal faults (great circles) and associated slickenside striae (■) in the Swakane terrane (all areas). Average orientation of faults is 222° , 75° ($n=14$ data). Maximum of slickenside striae is 62° , 066° ($n=7$ data).

Fig. 95. Stereonet plot of orientations of faults with a strike-slip component (great circles) and associated slickenside striae (■) in the Swakane terrane (all areas). Average orientation of faults is 275° , 85° ($n=5$ data). Maximum of slickenside lineation is 22° , 097° ($n=5$ data).

Fig. 96. Stereonet plot of high-angle faults (great circles) where displacement direction could not be determined (n=5 data) and associated slickenside striae (■) (n=4 data) in the Swakane terrane (all areas).

DISCUSSION

Timing of Deformational Events in the Study Area

Introduction

Interpretations of the timing of deformational events in the Swakane terrane and adjacent units are based on field and microscopic observations, structural data collected for this project, and observations by R.B. Miller and S.R. Paterson. As stated previously, assigning numbers to deformational events (D_x) should be done cautiously (e.g., Williams, 1985; Tobisch and Paterson, 1988). It is possible, however, to make generalizations about the relative timing of deformational events. Thus, instead of numeric subscripts, character subscripts are mainly used to describe the deformational stages in the study area (Table 2). In the following, four hypotheses for the structural history of the area are described (Table 3) and strong and weak points of each hypothesis are summarized.

Scenario 1 (Fig. 97):

Stage A:

The earliest deformational event is marked by a foliation (S_i) defined by inclusion trails in porphyroblasts and locally by muscovite in the matrix.

Stage B:

S_i is folded. These folds (F_P) are preserved in porphyroblasts and as rare, small folds of muscovite in the matrix.

Table 2. Explanation of symbols for structural features and events.

D_N	North- to northeast directed shear along the Dinkelman decollement (Scenarios 1 through 3)
D_{NE}	Northeast-directed shear along the Dinkelman decollement (Scenario 4)
D_{NS}	North-directed shear in the Swakane terrane (Scenario 4)
D_{SW}	Southwest-directed shear along the Napeequa Complex -- Entiat pluton contact and/or downward flow in the structural aureole
F_O	Open, upright folding
F_P	Tight to isoclinal folding recognized by folded inclusion trails in porphyroblasts
F_T	Tight to isoclinal, recumbent, outcrop-scale folding
S_{CL}	Compositional layering in the Swakane terrane
S_{cc}	Extensional crenulation cleavage throughout the Swakane terrane
S_i	Internal foliation preserved in porphyroblasts and rare muscovite-defined foliation in the matrix of the Swakane terrane
S_T	Transposition foliation in Swakane terrane and Napeequa Complex

Table 3. Timing of Scenarios 1 through 4. See text for detailed explanation.

Scenario 1	
Muscovite-defined S_i	Muscovite-defined S_i
F_P of S_i	F_P of S_i
S_T and S_{CL} overprint F_P	S_T and S_{CL} overprint F_P
Emplacement of Entiat pluton and D_{SW}	All units folded by F_T
All units folded by F_T	D_N starts prior to emplacement of Entiat pluton and D_{SW}
D_N along decollement that continues during initial exhumation	D_N continues after pluton emplacement and during exhumation
F_O outlasts shearing and produces broad regional antiform	F_O outlasts shearing and produces broad regional antiform
Scenario 2	
Muscovite-defined S_i	Muscovite-defined S_i
F_P of S_i	F_P of S_i
S_T and S_{CL} overprint F_P	S_T and S_{CL} overprint F_P
All units folded by F_T	All units folded by F_T
Emplacement of the Entiat pluton and D_{SW}	Emplacement of the Entiat pluton and D_{SW}
D_N along decollement that continues during initial exhumation	D_{NS} in Swakane terrane
F_O starts during D_N but outlasts it	D_{NE} along the decollement during exhumation
	F_O starts during D_{NE} but outlasts it
Scenario 3	
Muscovite-defined S_i	Muscovite-defined S_i
F_P of S_i	F_P of S_i
S_T and S_{CL} overprint F_P	S_T and S_{CL} overprint F_P
All units folded by F_T	All units folded by F_T
F_T continues during early stages of Entiat pluton emplacement and D_{SW}	Emplacement of the Entiat pluton and D_{SW}
D_N along decollement that continues during initial exhumation	D_{NS} in Swakane terrane
F_O starts during D_N but outlasts it	D_{NE} along the decollement during exhumation
	F_O starts during D_{NE} but outlasts it
Scenario 4	
Muscovite-defined S_i	Muscovite-defined S_i
F_P of S_i	F_P of S_i
S_T and S_{CL} overprint F_P	S_T and S_{CL} overprint F_P
All units folded by F_T	All units folded by F_T
F_T continues during early stages of Entiat pluton emplacement and D_{SW}	Emplacement of the Entiat pluton and D_{SW}
D_N along decollement that continues during initial exhumation	D_{NS} in Swakane terrane
F_O starts during D_N but outlasts it	D_{NE} along the decollement during exhumation
	F_O starts during D_{NE} but outlasts it

Fig. 97. Cartoon depicting Scenario 1. A) S_1 foliation develops throughout the Swakane terrane. B) S_1 is tightly folded during F_p and C) related S_T develops. D) Emplacement of Entiat pluton with possible SW-directed shear and/or downward flow of host rock in the structural aureole of the pluton (D_{SW}). E) Formation of locally abundant tight to isoclinal, recumbent outcrop-scale folds (F_T). F) N-directed shear (D_N) along the gently dipping Dinkelman decollement. G) Juxtaposition of all units to present day outcrop pattern concludes N-directed shear and H) subsequent F_O folding deforms the area into a broad regional antiform. See text for discussion.

Stage C:

F_P folds are almost completely obliterated during formation of the associated, gently dipping transposition foliation (S_T) and parallel compositional layering (S_{CL}); this stage is recorded throughout the Swakane terrane and Napeequa Complex.

Stage D:

Emplacement of the Entiat pluton follows at 73 Ma. Syn-emplacement southwest-directed shear (Hurlow, 1992) or downward flow in the structural aureole of the pluton (D_{SW}) (Paterson and Miller, 1998b) leads to steepening of S_T in the Napeequa Complex and the Swakane terrane and of the Swakane terrane – Napeequa Complex contact. Sheets in the margin of the Entiat pluton develop a moderately northeast-dipping magmatic foliation that is subparallel to host rock structures. In the interior of the pluton, the magmatic foliation is gently northeast dipping.

Stage E:

Subsequent folding (F_T) produces tight to isoclinal, recumbent, outcrop-scale folds in the Swakane terrane and the Napeequa Complex.

Stage F:

Pervasive non-coaxial shear occurs in the Swakane terrane and movement takes place on the Dinkelman decollement. Divergent non-coaxial shear (D_N) is north-directed along the gently-dipping part of the Dinkelman decollement and northeast-directed along the more steeply-dipping part.

Stage G:

Non-coaxial shear continues during exhumation and open, upright folding (F_O), which outlast shearing.

Stage H:

F_O deforms the units into a broad, regional antiform to produce the present outcrop pattern.

This scenario accounts for the generally gently dipping pattern of S_T in all units. Steepening of this foliation and the decollement to the northeast in the structural aureole of the Entiat pluton is caused by pluton emplacement. The timing of formation of mineral lineations and kinematic indicators relative to the recumbent (F_T) and open, upright folds (F_O) is also appropriate. Strong deformation and tight to isoclinal folding in some of the orthogneiss sheets in the Napeequa Complex that are coeval with the Entiat pluton is accounted for. This scenario also explains evidence for coeval F_O and shearing (S.R. Paterson, 1999, pers. comm.), and F_O correctly outlasted shearing.

This scenario involves complex flow along the decollement, including synchronous top-to-the-north and top-to-the-northeast non-coaxial shear. The mechanics of the diverging displacement directions are uncertain and pose a problem for this scenario. The northeast trends of the mineral lineation cannot be explained by the late folding (F_O), because only minor reorientation of north-south-trending structures is expected by folding them around an axis that trends northwest-southeast (Tabor et al., 1987b) or west-northwest – east-southeast (this study; see Fig. 48). A lesser problem in

this scenario is the absence of widespread tight to isoclinal folds in the Entiat pluton.

Perhaps the pluton was simply too rigid to undergo such folding.

Scenario 2 (Fig. 98):

The deformational events of Scenario 1 and 2 are identical for stages A through C. In Scenario 2, however, recumbent folding (F_T) (Stage E in Scenario 1) and north-directed shear (D_N) (Stage F) predate the emplacement of the Entiat pluton (Stage D). North-directed shear may have continued during, or resumed temporarily after, pluton emplacement. This is shown by kinematic indicators in pluton-related orthogneiss sheets, in the Napeequa Complex (Miller, pers. comm., 1998) and in low-temperature fabrics in the Swakane terrane. The final stages are again identical to Scenario 1.

This scenario accounts adequately for the observed foliation and mineral lineation patterns, including the steepening of dips and deflection of trends to the northeast. It also correctly puts north-directed shear between the tight to isoclinal and open, upright folding events. The main problem is that F_T folding ceases prior to the emplacement of the Entiat pluton. Orthogneiss sheets in the Napeequa Complex, which are related to the Entiat pluton, are in places strongly deformed and locally tightly to isoclinally folded, which is difficult to account for in this scenario. In addition, small amounts of shear after pluton emplacement are not supported by significantly different age data, which suggest that excision of rock was considerable (see above). Further, steepening of the Dinkelman decollement and S_T requires late top-to-the-north shear to occur on a highly curved surface, which is probably mechanically difficult.

Fig. 98. Cartoon depicting Scenario 2. A) S_1 foliation develops throughout the Swakane terrane. B) S_1 is tightly folded by F_p and C) related S_T develops. D) Folding of Napeequa Complex and Swakane terrane into local, tight to isoclinal, recumbent, outcrop-scale folds (F_T). E) N-directed shear (D_N) starts along the gently dipping Dinkelman decollement. F) Emplacement of Entiat pluton with SW-directed shear or downward flow of host rock in the structural aureole of pluton (D_{SW}). Continued or resumed shearing leads to G) present day juxtaposition of all units and H) subsequent F_O folding deforms the area into a broad regional antiform. See text for discussion.

Scenario 3 (Fig. 99):

Scenario 3 differs from Scenario 2 in two respects. First, top-to-the-north shear (D_N) starts after pluton emplacement and occurs along the gently dipping part of the decollement, while top-to-the-northeast shear occurs on the moderately dipping part closer to the Entiat pluton. Second, recumbent folding (F_T) continues during early stages of emplacement of the Entiat pluton.

This scenario best explains the present outcrop pattern. It accounts for foliation- and mineral lineation patterns and shear directions and also accounts for folds in orthogneiss sheets in the Napeequa Complex. This scenario has the same mechanical problems as Scenario 1 regarding synchronous top-to-the-north and top-to-the-northeast displacement.

Scenario 4 (Fig. 100):

One of the main assumptions of the first three scenarios is that the medium- to high-temperature lineation and associated kinematic indicators in the Swakane terrane and Napeequa Complex are synchronous with movement on the decollement. If, however, kinematic indicators close to the Dinkelman decollement did not form at the same time as those in other parts of the Swakane terrane, then at least one other scenario can be envisioned. This scenario is identical to Scenario 3, except that north-directed shear affects only the Swakane terrane (D_{NS}). This shear is followed by movement along the moderately northeast-dipping Dinkelman decollement (D_{NE}), which produces northeast-plunging mineral lineations and top-to-the-northeast kinematic indicators

Fig. 99. Cartoon depicting Scenario 3. A) S_1 foliation develops. B) Tight F_p folding of S_1 . C) S_T develops. D) Folding of Napeequa Complex and Swakane terrane into recumbent, folds (F_T), which continues during E) pluton emplacement (D_{SW}). F) N-directed shear (D_N) leads to G) juxtaposition of all units and H) F_O folding deforms the area into a broad regional antiform. See text for discussion.

Fig. 100. Continued on next page.

Fig. 100 continued. Simple cartoon depicting Scenario 4. A) S_i foliation develops. B) S_i is folded by F_p and C) related S_T develops. D) Folding of Napeequa Complex and Swakane terrane into recumbent folds (F_T) continues during E) pluton emplacement (D_{SW}). F) N-directed shear (D_{NS}) occurs in the Swakane terrane G) NE-directed shear (D_{NE}) along the Dinkelman decollement leads to H) juxtaposition of all units and I) subsequent F_0 folding deforms the area into a broad regional antiform. See text for discussion.

(D_{NE}). These fabrics obliterate earlier D_{NS} fabrics in the contact zone between the Swakane terrane and Napeequa Complex.

This scenario explains the outcrop pattern, but the main problem is that kinematic indicators associated with the low-temperature lineation in the hinge of the regional antiform (Area 1) record top-to-the-north shear (D_{NS}). Thus, north-directed shear occurred at lower temperatures and is unlikely to have been succeeded by medium- to high-temperature top-to-the-northeast shear (D_{NE}) at higher structural levels, unless D_{NS} started again after D_{NE} ceased. Another problem is the lack of evidence for overprinting relationships, which would probably be preserved locally in a transition zone.

In summary, all scenarios have strong and weak points that need further investigation, but Scenario 3 seems to best fit the observed relationships and is favored as the most likely hypothesis.

Implications for Significance of Lineations and Kinematic Indicators

Current research on the relationships of stretching lineations to regional displacement directions has focused on transpressional shear zones. Transpression for the Cascades core in the Late Cretaceous to Early Eocene is suggested by the plate motion reconstruction of Engebretson et al. (1985) and is also favored by Brown and Talbot (1989). Models for these shear zones predict that, under some boundary conditions, lineations will be oriented at a significant angle to the displacement direction (e.g., Sanderson and Marchini, 1984; Robin and Cruden, 1994; Tikoff and Teyssier,

1994; Lin et al., 1998). These models divide the deformation across the zone into pure and simple shear components; different ratios of pure shear to simple shear lead to distinct lineation and foliation patterns. Sanderson and Marchini (1984) use a monoclinic deformation path in their geometric model of a transpressional zone in which one end-member produces stretching lineations that are subparallel to the direction of shear and kinematic indicators that are parallel to the lineation. More recent and realistic models (Robin and Cruden, 1994; Lin et al., 1998) produce very complex fabrics recording generally triclinic deformation paths and stretching lineations that are oriented anywhere from parallel to perpendicular to the direction of shear. The likelihood of changing rock rheologies and heterogeneous deformation during progressive shear led Jiang and Williams (1999) to conclude that non-steady flow histories dominate in nature, and to suggest caution when interpreting shear-sense indicators.

Outcrop-scale observations in the Swakane terrane and thin-section analysis suggest that kinematic indicators are best developed parallel, or at least close, to the mineral lineation and perpendicular to the foliation and record the displacement direction. However, only sections parallel and perpendicular to the foliation have been examined, and if deformation was triclinic, kinematic indicators could be best developed at an acute angle to the mineral lineation. One way to evaluate this possibility is to cut serial sections at different angles (e.g., 10° increments) to the mineral lineation and assess the development of kinematic indicators.

Distribution of Shear (Coaxial versus Non-Coaxial) in the Swakane Terrane

Meso- and micro-scale observations throughout the Swakane terrane reveal that most rocks record non-coaxial shear. Kinematic indicators probably formed over a prolonged period of time (see above) and are better developed in mica-rich layers, which are associated with millimeter- to centimeter-thick ductile shear zones (see above). This probably reflects greater vorticity (larger component of non-coaxial shear) in these layers. Shear-sense indicators are less well-developed in quartz-rich layers; this may indicate that deformation was closer to coaxial shear (e.g., Lister and Williams, 1983; Bell, 1985) but has not been unequivocally documented. These observations suggest that non-coaxial shear was unevenly distributed at a scale of hand sample and thin section, and support partitioning of coaxial and non-coaxial strain (Lister and Williams, 1983; Platt and Behrmann, 1986). The small competence contrast between layers may have been sufficient to create such partitioning (e.g., Bell, 1985; Ridley, 1986).

The above observations in the Swakane terrane suggest that strain is localized in distinct shear bands and that heterogeneous ductile deformation occurs at deep crustal levels at an outcrop- to thin section-scale. Biotite best shows localization of strain. It ranges from coarse, relict flakes, which presumably lie in lower strain domains, to medium-size, recrystallized grains that define the transposition foliation, to very small, recrystallized grains in shear bands. The development of weak kinematic indicators in surfaces perpendicular to, and strong kinematic indicators in surfaces parallel to, the mineral lineation in the same sample also indicates, at least local, heterogeneous flow. This supports models that predict that small mineralogical differences may strongly influence the rheology of the deep crust (e.g., Cosgrove, 1997).

Rheological models that predict dominantly homogeneous deformation at deep crustal levels at a regional scale (e.g., Dewey, 1986; Rannali, 1997) have recently been challenged (e.g., Cosgrove, 1997; Miller and Paterson, 2000). Lithological heterogeneity, mechanical anisotropy, and melts are important variables in vertical strength profiles of the crust (e.g., Kohlstedt et al., 1995; Cosgrove, 1997; Hollister and Crawford, 1986; Davidson et al., 1994). In the Swakane terrane, domains of tight to isoclinal recumbent folds of S_T and S_{ec} suggest that mechanical heterogeneity still played a role in the deep crust and that deformation was not homogeneous. In contrast, the entire terrane is deformed by non-coaxial shear, which indicates that this terrane behaved as a single entity and responded broadly similar to stress throughout its thickness.

Implications for Regional Tectonics

The regional importance of north-directed shear in the Swakane terrane and on the Dinkelman decollement is enigmatic. To date, no analogous decollement has been described in the Cascades core, possibly because deep structural levels are exposed only in the study area. The decollement may underlie much (all?) of the Cascades core and be covered by mid- to upper-crustal rocks. However, north-directed shear does not fit simply either of the current models for the Cascades core (e.g., Brown and Talbot, 1989; Miller and Paterson, 1992; Paterson and Miller, 1998a).

Miller and Paterson (1992) report southwest-directed ductile thrusting in the Mount Stuart batholith and its host rocks (e.g., Chiwaukum Schist) at ~ 96 to ~ 81 Ma. This correlates with the well-documented thrusting of the offset continuation of the

Cascades core in the Coast Belt of British Columbia (e.g., Journeay and Friedman, 1993; Fig. 2). Brown and Talbot (1989) interpret the abundance of gently plunging, northwest-southeast-trending stretching lineations to reflect dextral strike-slip throughout the core. Dextral motion is estimated to have occurred between 85 to 45 Ma. Based on cooling ages and relationships between the Swakane terrane, Napeequa Complex, and the Entiat pluton, north-directed shear in the Swakane terrane and on the decollement is probably younger (between 72 Ma and 48 Ma) than the mid- to Late Cretaceous contractional structures (e.g., Windy Pass thrust, White River shear zone; Fig. 2) in the Cascades core (e.g., Miller and Paterson, 1992) and coeval with fabrics interpreted to reflect dextral shear (Brown and Talbot, 1989). Mineral lineations in the study area are at an angle to the stretching lineations of Brown and Talbot (1989), and dextral strike-slip on the nearly subhorizontal foliations that characterized the Swakane terrane before late, upright folding seems implausible.

Haugerud et al. (1991) describe middle Eocene (47-44 Ma) northwest-southeast-directed ductile extensional structures (e.g., stretching lineations, mylonitic fabrics) from the Skagit Gneiss Complex in the Chelan block (Fig. 2) northwest of the study area. In addition, brittle northwest-southeast extension is shown by a northeast-southwest-trending dike swarm associated with the ~ 46 Ma Duncan Hill pluton (Fig. 2) (Tabor et al., 1987b; Haugerud et al., 1991).

North-directed shear in the Swakane terrane is oblique to the extension direction in the Skagit Gneiss Complex and the extensional events may not be closely related. However, top-to-the-north shear may represent the displacement direction in the Chelan

block and perhaps the entire Cascades core during the Late Cretaceous to Early Eocene. More data from other terranes are needed to evaluate this hypothesis.

Remaining Kinematic Problems

Several kinematic problems remain ambiguous or unanswered.

(1) The northwest-trending mineral lineation in the Northern Highway 97 domain is not explained adequately.

(2) The counterclockwise orientation of the low-temperature lineation relative to the high-temperature one throughout the Swakane terrane is not understood. Whether this reflects rotation of the local stress field during progressive deformation or two separate deformational events is equivocal. It is perhaps noteworthy that the orientation of the low-temperature lineation is closer to the direction of regional northwest-southeast extension (e.g., Tabor et al., 1987b; Haugerud et al., 1991).

(3) Grain size coarsens upwards in the Swakane terrane and kinematic indicators are less well-developed nearer the Dinkelman decollement. This may indicate higher temperatures and obliteration of kinematic indicators during dynamic recrystallization closer to the decollement (S.R. Paterson, 1999, pers. comm.). However, an explanation is needed to account for the elevated temperatures.

(4) Scenarios 1 through 3 pose the mechanical problem of contemporaneous top-to-the-north and top-to-the-northeast shear on highly curved surfaces.

CONCLUSIONS

- (1) The oldest structures in the Swakane terrane are preserved only on a micro-scale. Inclusion trails in biotite, garnet, and plagioclase porphyroblasts delineate a foliation (S_i) that is folded (F_P).
- (2) A strong, generally gently dipping transposition foliation (S_T) is developed throughout the field area. Foliation steepens in the Swakane terrane and the Napeequa Complex near the Entiat pluton, reflecting downward flow in the structural aureole of the pluton (Paterson and Miller, 1998b) or southwest-directed shear (Hurlow, 1992).
- (3) Tight to isoclinal, recumbent, outcrop-scale folds (F_T) of compositional layering (S_{CL}) and S_T predate north-directed shear, which is in places contemporaneous, but mostly predates, late, open, upright folds.
- (4) F_T folds are probably related to mid- to Late Cretaceous thrusting. Southwest-trending fold axes are reoriented by north-directed shear to north-south trends on the limbs of the regional antiform and to south-southwest orientations in the hinge of the regional antiform.
- (5) Kinematic indicators are best developed in surfaces parallel to mineral lineation and perpendicular to foliation.
- (6) North-directed shear is the dominant displacement direction in the Swakane terrane and probably occurred between 72 and 48 Ma; it began during or after emplacement of the Entiat pluton and continued during exhumation.

- (7) Shear sense indicators in the Napaequa Complex are weakly developed and record both top-to-the-northeast and top-to-the-southwest shear.**
- (8) The Dinkelman decollement has major, but poorly quantified displacement.**
- (9) Kinematic indicators in the Swakane terrane and movement on the decollement are probably coeval. If not, then north-directed shear predates northeast movement on the decollement.**
- (10) Strain partitioning into coaxial and non-coaxial shear can not be documented. However, the vorticity is probably larger in mica-rich than in quartz-rich layers.**

REFERENCES CITED

- Alsleben, H., Miller, R.B., and Paterson, S. R., 1998. Kinematic and folding history of the mid- to deep-crustal levels of an arc: Swakane terrane, North Cascades, Washington: Geological Association of Canada NUNA Conference, Canadian Tectonic Studies Group, 18th Annual Meeting, Abstracts with Programs.
- Alsleben, H., Miller, R.B., and Paterson, S.R., 1999. Kinematic significance of mineral lineations and strain partitioning in Mid- to Deep-crustal Rocks, Swakane Terrane, North Cascades, WA: Geological Society of America Cordilleran Section Meeting Abstracts with Programs, v. 31, no. 6, p. A-34.
- Bell, T.H., 1985, Deformation partitioning and porphyroblast rotation in metamorphic rocks: a radical reinterpretation: *Journal of Metamorphic Geology*, v. 3, p. 109-118.
- Bell, T.H., and Johnson, S.E., 1992, Shear sense: a new approach that resolves conflicts between criteria in metamorphic rocks: *Journal of Metamorphic Geology*, 10, p. 99-124.
- Bell, T.H., Forde, A., and Hayward, N., 1992, Do smoothly curved, spiral-shaped inclusion trails signify porphyroblast rotation? *Geology*, v. 20, p.59-62.
- Berthé, D., Choukroune, P., and Jegouzo, P., 1979, Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South American Shear-Zone: *Journal of Structural Geology*, v. 1, p. 31-42.
- Brown, E.H., and Talbot, J.L., 1989, Orogen-parallel extension in the North Cascades crystalline core, Washington: *Tectonics*, v. 8, p. 1105-1114.
- Brown, E.H., and Walker, N.W., 1993, A magma loading model for Barrovian metamorphism in the SE Coast Plutonic Complex, British Columbia and Washington: *Geological Society of America Bulletin*, v. 105, p. 479-500.
- Cater, F.W., and Crowder D.F., 1967, Geologic map of the Holden quadrangle, Snohomish and Chelan Counties, Washington: United States Geological Survey, Map GQ-646, scale 1:62,500.
- Cosgrove, J.W., 1997, The influence of mechanical anisotropy on the behaviour of the lower crust: *Tectonophysics* 280, p. 1-14.
- Davidson, C., Schmid, S.M., and Hollister, L.S., 1994, Role of melt during deformation in the deep crust. *Terra Nova*, v. 6, p. 133-142.

- Dawes, R. L., 1993, Mid-crustal, Late Cretaceous plutons of the North Cascades: petrogenesis and implications for the growth of continental crust [Ph.D. thesis]: Seattle, University of Washington.
- Dewey, J.F. 1986, Diversity in the lower continental crust, *in* Dawson, J.B., Carswell, D.A., Hall, J., Wedepohl, K.H. (Eds.). *The Nature of the Lower Continental Crust*. Geological Society of America Special Publication 24, p. 71-78.
- Dirks, P.H.G.M., and Sithole, T.A., 1999, Eclogites in the Mabuti Gneisses of Zimbabwe: implications for the tectonic evolution of the Zambezi Belt in southern Africa: *Journal of Metamorphic Geology*, v. 19, p. 593-612.
- Engelbreton, D.C., Cox, A., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Boulder, Colorado, Geological Society of America, Special Paper 206, 54p.
- Escher, A., and Watterson, J., 1974, Stretching fabrics, folds, and crustal shortening: *Tectonophysics*, v. 22, p. 223-231.
- Evans, J.E., 1994, Depositional history of the Eocene Chumstick Formation: Implications of tectonic partitioning for the history of the Leavenworth and Entiat-Eagle Creek faults systems, Washington: *Tectonics*, v. 13, p. 1425-1444.
- Haugerud, R.A., Van der Heyden, P., Tabor, R.W., Stacey, J.S., and Zartman, R.E., 1991, Late Cretaceous and early Tertiary plutonism and deformation in the Skagit Gneiss Complex, North Cascade Range, Washington and British Columbia: *Geological Society of America Bulletin*, v. 103, p. 1297-1307.
- Hollister, L.S., and Crawford, M.L., 1986, Melt-enhanced deformation: A major tectonic process. *Geology*, v. 14, p. 558-561.
- Hubbard, M., and Mancktelow, N.S., 1992, Lateral displacement during Neogene convergence in the western and central Alps: *Geology*, v. 20, p. 943-946.
- Hurlow, H.A., 1992, Structural and U-Pb Geochronologic Studies of the Pasayten Fault, Okanogan Range Batholith, and Southeastern Cascades Crystalline Core, Washington [Ph.D. thesis]: Seattle, University of Washington, 168p.
- Jiang, D., and Williams, P.F., 1999, A fundamental problem with kinematic interpretation of geological structures: *Journal of Structural Geology*, v. 21, p. 933-937.
- Journeay, J.M., and Friedman, R.M., 1993, Structural setting and geochronology of the Lilloet River fault system, south-western British Columbia: *Tectonics*, v. 12, p. 756-775.

- Kohlstedt, D.L., Evans, B., and Mackwell, S.J., 1995, Strength of the lithosphere: Constraints imposed by laboratory experiments. *Journal of Geophysical Research*, v. 100, p. 17,587-17,602.
- Lin, S., Jiang, D., and Williams, P.F., 1998, Transpression (or transtension) zones or triclinic symmetry: natural example and theoretical modeling, *in* Holdsworth, R.E., Strachan, R.A., and Dewey, J.F. (Eds.), *Continental Transpressional and Transtensional Tectonics*, Geological Society of London, Special Publications, v. 135, p. 41-57.
- Lister, G.S., and Snoke, A.W., 1984, S-C Mylonites: *Journal of Structural Geology*, v. 6, p. 617-638.
- Lister, G.S., and Williams, P.F., 1983, The partitioning of deformation in flowing rock masses: *Tectonophysics*, v. 92, p. 1-33.
- Mattinson, J.M., 1972, Ages of zircons from the northern Cascade Mountains, Washington: *Geological Society of America Bulletin*, v. 83, p. 3769-3783.
- McGroder, M.F., 1991, Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia: *Geological Society of America Bulletin*, v. 103, p. 189-209.
- Miller, R.B., 1985, The ophiolitic Ingalls Complex, North Cascades, Washington: *Geological Society of America Bulletin*, v. 96, p. 27-42.
- Miller, R.B., and Paterson, S.R., 1992, Tectonic implications of syn- and post-emplacement deformation of the Mount Stuart batholith for mid-Cretaceous orogenesis in the North Cascades: *Canadian Journal of Earth Sciences*, v. 29, p. 479-485.
- Miller, R.B., and Paterson, S.R., 2000, Influence of lithological heterogeneity, mechanical anisotropy, and magmatism on the rheology of an arc, North Cascades, Washington: *Tectonophysics in press*.
- Miller, R.B., Bowring, S.A., and Hoppe, W.J., 1989, Paleocene plutonism and its tectonic implications, North Cascades, Washington: *Geology*, v. 17, p. 846-849.
- Miller, R.B., Brown, E.H., McShane, D.P., and Whitney, D.L., 1993a, Intra-arc crustal loading and its tectonic implications, North Cascades crystalline core, Washington and British Columbia: *Geology*, v. 21, p. 255-258.

- Miller, R.B., Whitney, D.L., and Geary, E.E., 1993b, Tectono-stratigraphic terranes and the metamorphic history of the northeastern part of the crystalline core of the North Cascades: evidence from the Twisp Valley Schist: *Canadian Journal of Earth Sciences*, v. 30, p. 1306-1323.
- Miller, R.B., Haugerud, R.H., Murphy, F., and Nicholson, L.S., 1994, Tectonostratigraphic framework of the northeastern Cascades: Washington Division of Geology and Earth Resources, Bulletin 80, p.73-92.
- Miller, R.B., Paterson, S.R., and Hurlow, H.A., 1996, Mid-crustal detachment in the crystalline core of the North Cascades: *Geological Society of America Abstracts with Programs*, v. 28, no. 5, p. 92.
- Misch, P., 1966, Tectonic evolution of the northern Cascades of Washington State -- a west Cordilleran case history: *Canadian Institute of Mining and Metallurgy, Special Volume 8*, p. 101-148.
- Monger, J.W.H., Price, R.A., and Templeman-Kluit, D.J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera: *Geology*, v. 10, p. 70-75.
- Monger, J.W.H., Van der Heyden, P., Journeay, J.M., Evenchick, C.A., and Mahoney, J.B., 1994, Jurassic-Cretaceous basins along the Canadian Coast Belt: Their bearing on pre-mid-Cretaceous sinistral displacements: *Geology*, v. 22, p. 175-178.
- Passchier, C.W., and Simpson, C., 1986, Porphyroclast systems as kinematic indicators: *Journal of Structural Geology*, v. 8, p. 831-843.
- Paterson, S.R., and Miller, R.B., 1998a, Magma emplacement during arc-perpendicular shortening: An example from the Cascades crystalline core, Washington: *Tectonics* v. 17, p. 571-586.
- Paterson, S.R., and Miller, R.B., 1998b, Mid-crustal magmatic sheets in the Cascades Mountains, Washington: implications for magma ascent: *Journal of Structural Geology*, v. 20, p. 1345-1363.
- Paterson, S. R., and Miller, R.B., 1998c, Rheological controls on meso-scale structures and kinematics near a mid-crustal detachment: an example from the Napeequa Complex, Cascades core, Washington: Geological Association of Canada NUNA Conference, Canadian Tectonic Studies Group, 18th Annual Meeting, Abstracts with Programs.

- Paterson, S.R., Miller, R.B., Anderson, J.L., Lund, S., Bendixen, J., Taylor, N., and Fink, T., 1994, Emplacement and evolution of the Mt. Stuart batholith, *in* Swanson, D.A., Haugerud, R.A., (Eds.), *Geologic field trips in the Pacific Northwest*, Geological Society of America Annual Meeting, p 2F-1- 2F-47.
- Paterson, S.R., Fowler Jr., T.K., and Miller, R.B., 1996a, Pluton emplacement in arcs: a crustal-scale exchange process: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 87, p. 115-123.
- Paterson, S.R., Lund, S., Miller, R.B., and Teruya, L., 1996b, Tertiary rotations in the Cascades core, Washington: *Geological Society of America Abstracts with Programs*, v. 28, no. 5, p. 99.
- Paterson, S.R., Fowler Jr., T.K., Schmidt, K.L., Yoshinobu, A.S., Yuan, E.S., and Miller, R.B., 1998a, Interpreting magmatic fabric patterns in plutons: *Lithos*, v. 44, p. 53-82.
- Paterson, S. R., Miller, R.B., Lebit, H., Alsleben, H., and Luneburg, C., 1998b, Variable mechanical controls on meso-scale kinematics in the mid-crust, Cascades core, Washington: *Geological Association of Canada NUNA Conference, Canadian Tectonic Studies Group, 18th Annual Meeting, Abstracts with Programs*.
- Platt, J.P., and Behrmann, J.H., 1986, Structures and fabrics in a crustal-scale shear zone Betic Cordillera, SE Spain: *Journal of Structural Geology*, v. 8, p. 15-33.
- Powell, C.McA, and Vernon, R.H., 1979, Growth and rotation history of garnet porphyroblasts with inclusion spirals in a Karakoram schist: *Tectonophysics*, v. 54, p. 25-43.
- Ramsay, J.G., 1980, Shear zone geometry: a review: *Journal of Structural Geology*, v. 2, p. 83-99.
- Ramsay, J.G., and Huber, M.I., 1983, *The Techniques of Modern Structural Geology: Volume 1: Strain Analysis*: San Diego, CA, Academic Press, Inc., 307p.
- Ramsay, J.G., and Huber, M.I., 1987, *The Techniques of Modern Structural Geology: Volume 2: Folds and Fractures*: Orlando, FL, Academic Press, Inc., 462p.
- Ranalli, G., 1997, Rheology of the lithosphere in space and time, *in* Burg, J.P., Ford, M. (Eds.), *Orogeny through time*: Geological Society of London Special Publications, 121, p. 19-37.

- Rasbury, E.T., and Walker, N.W., 1992, Implications of Sm-Nd model ages and single grain U-Pb zircon geochronology for the age and heritage of the Swakane Gneiss, Yellow Aster Complex, and Skagit Gneiss: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A65.
- Ridley, J., 1986, Parallel stretching lineations and fold axes oblique to a shear displacement direction - a model and observations: *Journal of Structural Geology*, v. 8, p. 647-653.
- Robin, P.Y.F., and Cruden, A.R., 1994, Strain and vorticity patterns in ideally ductile transpression zones: *Journal of Structural Geology*, v. 16, p. 447-466.
- Rubin, C.M., Saleeby, J.B., Cowan, D.S., Brandon, M.T., and McGroder, M.F., 1990, Regionally extensive mid-Cretaceous west-vergent thrust system in the Northwestern Cordillera: Implications for continent-margin tectonism: *Geology*, v. 18, p. 276-280.
- Sanderson, D.J., and Marchini, W.R.D., 1984, Transpression: *Journal of Structural Geology*, v. 16, p. 449-458.
- Sawkyo, L.T., 1994, The geology and petrology of the Swakane Biotite Gneiss, North Cascades, Washington [M.S. thesis]: Seattle, University of Washington, 130p.
- Shackleton, R.M., and Ries, A.C., 1984, The relation between regionally consistent stretching lineations and plate motions: *Journal of Structural Geology*, v. 6, p. 111-117.
- Simpson, C., 1986, Determination of Movement Sense in Mylonites: *Journal of Geological Education*, v.34, p. 246-261.
- Simpson, C., and Schmid, S.M., 1983, An evaluation of criteria to deduce the sense of movement in sheared rocks: *Geological Society of America Bulletin*, v. 94, p. 1281-1288.
- Tabor, R.W., Zartman, R.E., and Fritzell, V.A., 1987a, Possible tectonostratigraphic terranes in the North Cascades Crystalline Core, Washington, *in* Schuster, J.E. (Ed.), *Selected papers on the geology of Washington: Washington Division of Geology and Geology, Bulletin 77*, p.107-127.
- Tabor, R.W., Fritzell, V.A., Jr., Whetten, J.T., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Zartman, R.E., 1987b, Geological map of the Chelan 30-minute by 60-minute quadrangle, Washington: United States Geological Survey, Map I-1661, scale 1:100 000.

- Tabor, R.W., Haugerud, R.A., and Miller, R.B., 1989, Overview of the geology of the North Cascades, *in* Tabor, R.W., Haugerud, R.A., Brown, E.H., Babcock, R.S., Miller, R.B. (Eds.), *Accreted terranes of the North Cascades range, Washington - Spokane to Seattle, Washington July 21-29, 1989: International Geological Congress, 28th, Field Trip Guidebook T307*, p. 1-33.
- Tikoff, B., and Teyssier, C., 1992, Crustal-scale, en echelon "P-shear" tensional bridges: a possible solution to the batholithic room problem: *Geology*, v. 20, p. 927-930.
- Tikoff, B., and Teyssier, C., 1994, Strain modeling of displacement-field partitioning in transpressional orogens: *Journal of Structural Geology*, v. 16, p. 1575-1588.
- Tobisch, O.T., and Paterson, S.R., 1988, Analysis and interpretation of composite foliations in areas of progressive deformation: *Journal of Structural Geology*, v. 10, p. 745-754.
- Twiss, R.J., and Moores, E.M., 1992, *Structural Geology*: New York, W.H. Freeman and Company, 532p.
- Umhoefer, P.J., and Miller, R.B., 1996, Mid-Cretaceous thrusting in the southern Coast Belt, British Columbia and Washington, after strike-slip fault reconstruction: *Tectonics*, v. 15, p. 545-565.
- Valley, P.M., Whitney, D.L., Paterson, S.R., Miller, R.B., and Terrien, J., 2000, Pressure – temperature history of deepest exposed units of the North Cascades arc: thermobarometric results across the Swakane – Napeequa contact: *Geological Society of America Cordilleran Section Meeting Abstracts with Programs*, v. 32.
- Van der Heyden, 1992, A middle Jurassic to early Tertiary Andean-Sierran arc model for the coast belt of British Columbia: *Tectonics*, v. 11, p. 82-97.
- Waters, A.C., 1932, A petrologic and structural study of the Swakane gneiss, Entiat Mountains, Washington: *Journal of Geology*, v. 40, no. 6, p. 604-633.
- Whitney, D.L., Miller, R.B., and Paterson, S.R., 1999, P-T-t constraints for mechanisms of vertical tectonic motion in a contractional orogen: north-western US and Canadian Cordillera: *Journal of Metamorphic Geology*, v. 17, p. 75-90.
- Williams, P.F., 1985, Multiply deformed terrains-problems of correlation: *Journal of Structural Geology*, v. 7, p. 269-280.
- Williams, P.F., and Jiang, D., 1999, Rotating garnets: *Journal of Metamorphic Geology*, v. 17, p. 367-378.

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH
SMALL OVERLAPS**

UMI

120°15' W

47°37'30" N

Plate 1. Station map of Area 2.

Swakane
terrane

Sw

Napeequa Complex
(undifferentiated)

Nq

Entiat pluton

Ep

Dinkelman
decollement

DD

500 m

Contour interval = 200 ft.

● Station with number (bold and
enlarged mentioned in text)

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH
SMALL OVERLAPS**

UMI

120°15' W

Thick dashes show measured foliations, whereas thin d

measured foliations, whereas thin dashes indicate the inferred foliation pattern.

Plate 2. Foliation data from Area 2.

47°37'30" N

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH
SMALL OVERLAPS**

UMI

Plate 3. Lineation data from Area 2.

Swakane terrane Sw	Napeequa Complex (undifferentiated) Nq	Napeequa orthogneiss Nqo	Napeequa schist Nqs
Napeequa marble + calc-silicate rock Nqm	Napeequa ultramafic Nqum	Entiat pluton with Napeequa 'rafts' Epr	Entiat pluton Ep
Contact domain C	Mills Canyon domain MC	Northern Highway 97 domain N-HW 97	Southern Highway 97 domain
			Dinkelman decollement DD

0 1 km

47°40'

47°37' 30"

120°10'