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Significance of composite lineations in the mid- to deep crust: a case study from the North Cascades, Washington

Robert B. Miller [a,*], Scott R. Paterson [b], Hermann Lebit [c], Helge Alsleben [a,d], Catalina Lüneburg [c]

[a] Department of Geology, San Jose State University, San Jose, CA 95192-0102, USA
[b] Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089, USA
[c] Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148, USA
[d] Department of Geology, Texas Christian University, Fort Worth, TX 76129, USA

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Abstract

The origin of broadly orogen-parallel (NW–SE) mineral lineations in Cretaceous and Paleogene arc plutons and amphibolite–facies metamorphic rocks (paleodepths of <10–40 km) of the North Cascades (Cascades core) is controversial, particularly the kinematic significance of these lineations and their relationship to regional displacement fields. Outcrop- to map-scale structures are dominated by fold interference. Lineations are commonly parallel to the maximum finite strain axis, which is interpreted to result from nearly coaxial superposed folding and strain accumulation. This is compatible with the better development of kinematic indicators in lineation-normal sections rather than in lineation-parallel sections in much of the region. The fold-dominated strain pattern has been locally modified by steep SW-vergent, reverse shear zones with down-dip lineation that are localized next to plutons, and near the Windy Pass thrust where weak lineation is at a high angle to the inferred displacement direction. During Eocene exhumation, top-to-N to -NNE displacement on subhorizontal surfaces was superposed on fold-related fabrics in the deepest exposed levels of the orogen. The resultant lineation is subparallel to the inferred slip direction, compatible with widespread kinematic indicators in lineation-parallel surfaces. Mineral lineations in the Cascades core are thus composite, formed from pre-96 to $\sim$45 Ma, and are typically parallel to the direction of local maximum stretch and only locally to regional displacement. They formed by multiple mechanisms that were partitioned at a variety of scales, and under multiple boundary conditions, including: multi-scale folding, shear zone displacement, and flow in structural aureoles imposed by pluton emplacement. Local deformation, and not orogen-scale flow, dominated outcrop-scale structures, and pre-existing anisotropy and relative strengths of adjacent layers played an important role in development of final outcrop-scale structures.

Keywords: Lineations; Kinematics; Superimposed folding; North Cascades; Magmatic arcs

1. Introduction

Theoretical and experimental models predict the relationships between boundary conditions and expected regional strain patterns in orogens, which in turn are used to infer expected relationships between outcrop-scale structures and crustal-scale flow (e.g. Sanderson and Marchini, 1984; Robin and Cruden, 1994; Tikoff and Teyssier, 1994). These models, however, assume simplified boundary conditions and isotropic materials, whereas orogens consist of anisotropic, typically folded rocks, and may form in response to multiple, temporally and spatially variable boundary conditions and loads. It thus remains uncertain if outcrop-scale structures (e.g. lineation, foliation, and associated kinematic indicators) dominantly record boundary conditions that drive orogen-scale flow or reflect local heterogeneous deformation (e.g. Lüneburg and Lebit, 1998; Lebit et al., 2002; Piazolo and Passchier, 2002).

A comparable complication in many studies is that mineral lineations (lineations defined by aligned prismatic and acicular minerals, elongated grains, and/or polycrystalline aggregates) are assumed to have formed during a single deformation under constant boundary conditions over a relatively narrow time interval and are aligned parallel to the direction of regional displacement during this period. These assumptions have all been challenged, including the relationship between lineation and displacement direction in shear zones in regimes of

* Corresponding author. Tel.: +1 408 924 5025; fax: +1 408 924 5053.
E-mail address: rmiller@geosun.sjsu.edu (R.B. Miller).

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transpression or general shear (e.g. Tikoff and Teyssier, 1994; Lin et al., 1998) and the interpretation that outcrop-scale structures record strain during a single deformational event with constant boundary conditions (e.g. Tobisch and Paterson, 1988; Lüneburg and Lebit, 1998; Ramsay and Lisle, 2000).

The uncertainties about whether mineral lineations reflect single events or are a composite of multiple events, and the relative importance of homogeneous regional-scale flow versus heterogeneous flow controlled by local mechanics are among the reasons that the relationships between mineral fabrics, vorticity, and orogen-scale flow remain controversial in a number of mountain belts. Such belts include the North Cascades of Washington and British Columbia (e.g. Brandon et al., 1988; Brown and Talbot, 1989), Alps (Dietrich and Casey, 1989; Hubbard and Mancktelow, 1992), and Sierra Nevada (Tikoff and Teyssier, 1994; Greene and Schweickert, 1995). For example, in the crystalline core of the North Cascades (Cascades core), mineral lineation has been interpreted to reflect the regional displacement direction during distributed dextral strike slip by some workers (Brown and Talbot, 1989), whereas others interpreted the lineation to record the direction of maximum stretch but not direction of regional displacement during regional thrusting and folding (Miller and Paterson, 1992; Paterson and Miller, 1998a). The Cascades core is an excellent orogen to evaluate the implications of lineations because it contains well-exposed metamorphic and plutonic rocks that were deformed ductilely over a broad range of crustal levels (<10–>40 km paleodepth; Miller and Paterson, 2001a).

We demonstrate that lineation and other outcrop-scale structures in the Cascades core formed by several processes, originated under multiple boundary conditions, developed over a protracted time span, and are thus commonly composite. We conclude that over a wide range of structural levels it is difficult to determine orogen-scale flow, and thus inferred boundary conditions, from outcrop-scale structures.

2. Overview of the southern Cascades Core

The Cascades core exposes a Cretaceous to Paleogene continental magmatic arc and is the southern continuation of the Coast Plutonic Complex (Fig. 1). The Eocene, dextral Straight Creek fault separates the Cascades core from low-grade Paleozoic and Mesozoic oceanic and arc rocks to the west that were involved in the mid-Cretaceous Northwest Cascades thrust system (Figs. 1 and 2) (Misch, 1966; Brown, 1987; Brandon et al., 1988). To the south, the Cascades core is overlain along the Windy Pass thrust of the Northwest Cascades system by the low- to medium-grade, Jurassic Ingalls ophiolite (Miller, 1985). The high-angle Ross Lake fault zone separates the core from the Mesozoic Methow basin to the east (Misch, 1966), and the brittle, steep Eocene Entiat fault (Fig. 1) divides the Cascades core into the Wenatchee block to the SW and Chelan block to the NE (Tabor et al., 1989). These blocks are distinguished in part by their thermal histories; the Wenatchee block records arc magmatism from ca. 96 to 84 Ma, whereas magmatism continued to ∼45 Ma in the Chelan block (e.g. Tabor et al., 1989; Miller et al., 2003).

The Cascades core has been subdivided into several terranes (Tabor et al., 1989). The Nason terrane of the Wenatchee block consists of the metapelitic and metapsammitic Chiwaukum Schist and Nason Ridge Migmatitic Gneiss, which is probably an extensively injected variant of the schist (e.g. Plummer, 1980; Tabor et al., 1987, 2002; Stowell and Tinkham, 2003). Metamorphic pressures range from ∼0.3 to 0.9 GPa (e.g. Brown and Walker, 1993; Evans and Davidson, 1999), and paleodepths increase from SW to NE. The Nason terrane was rapidly loaded (by up to 20 km) at ∼90 Ma by thrusting and/or emplacement of magmas (e.g. Evans and Berti, 1986; Brown and Walker, 1993; Miller et al., 1993).

The NE boundary of the Nason terrane is the post-91 Ma, NE-dipping, reverse-sense White River shear zone that carries in its hanging wall high-P (0.8–1.2 GPa) amphibolite–facies rocks of the amphibolite- and quartzite (metachert)-dominated Napeequa Schist of the Chelan Mountains terrane (Figs. 2 and 3) (Van Diver, 1967; Tabor et al., 1987, 1989;

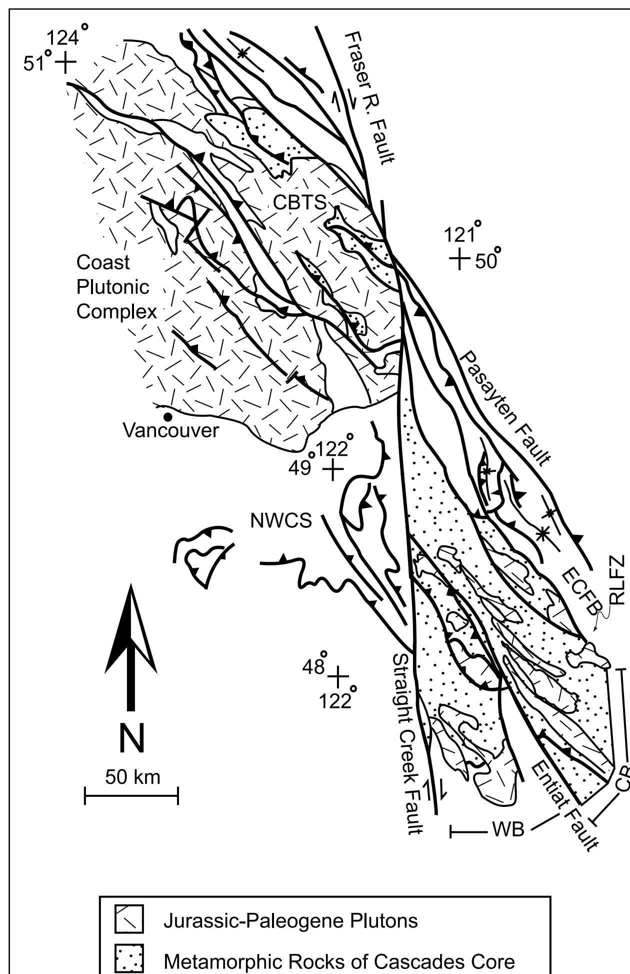


Fig. 1. Location of the crystalline core of the North Cascades (Cascades core) at the southern end of the Coast Plutonic Complex. Cretaceous thrusts are part of the Coast Belt thrust system (CBTS), Eastern Cascades fold-thrust belt (ECFB), and Northwest Cascades System (NWCS). CB—Chelan block, RLFZ—Ross Lake fault zone, WB—Wenatchee block.

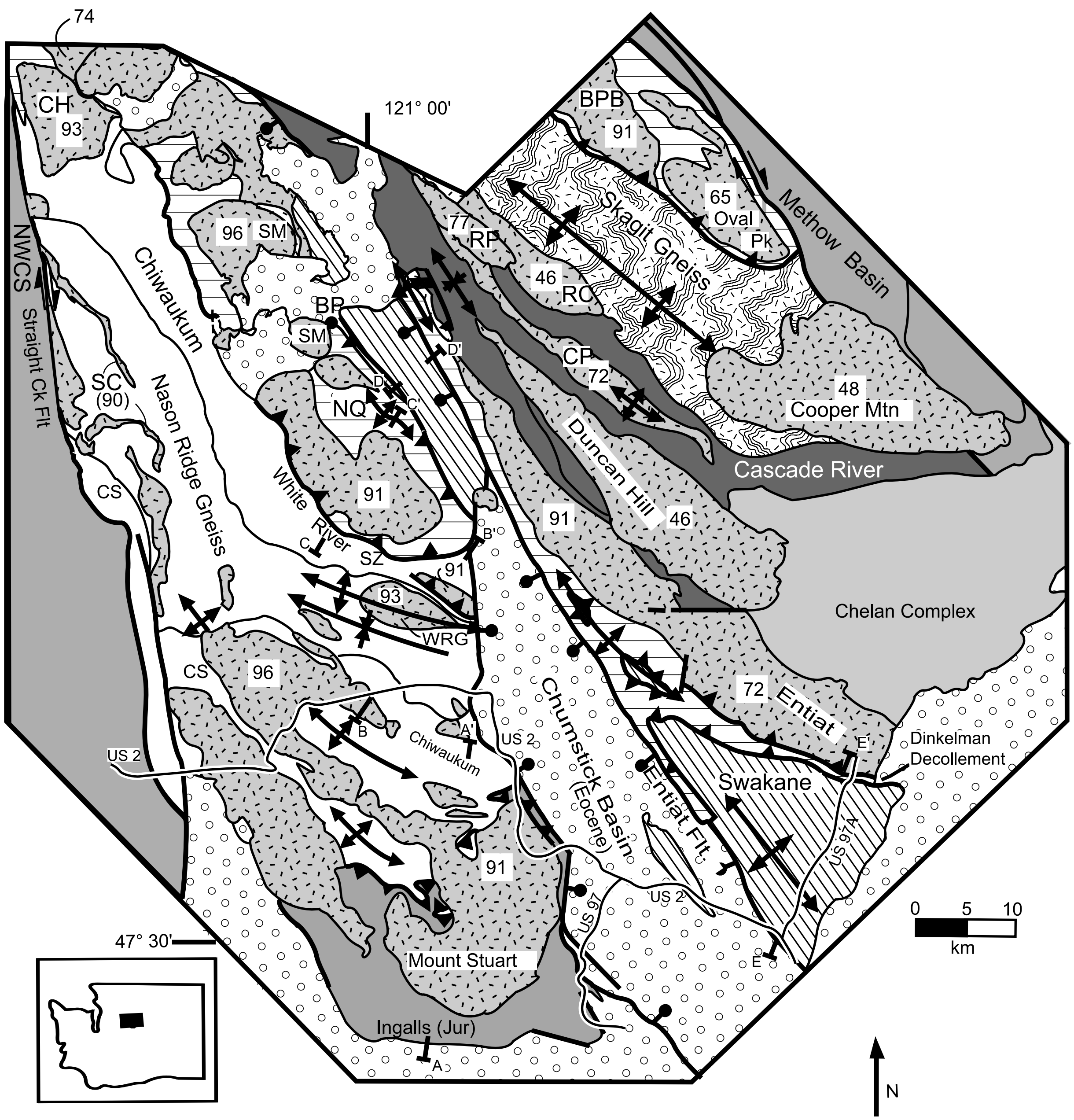


Fig. 2. Simplified geologic map emphasizing the southern and central Cascades core. Plutons are shaded with random dashes, and numbers are crystallization ages. BP—Buck Pass area (see Fig. 11), BPB = Black Peak batholith, CH = Chaval pluton, CP = Cardinal Peak pluton, CS = Chiwaukum Schist, DF = Dirtyface pluton, NQ = Napeequa unit, NWCS = Northwest Cascades system, RC = Railroad Creek pluton, RP = Riddle Peaks pluton, SC = Sloan Creek plutons, SM = Sulphur Mountain pluton, WRG = Wenatchee Ridge Gneiss. Open circle pattern = mid-Eocene and younger rocks. Also shown are the locations of major highways and lines of cross-sections in Fig. 3. Inset shows Washington State and location of the geologic map.

Magloughlin, 1993; Miller et al., 2003). The Nason terrane and Napeequa unit in the Wenatchee block have been extensively intruded by dominantly tonalitic 96–84 Ma plutons and thinner sheets that crystallized at pressures ranging from ∼0.3 to 1.0 GPa (e.g. Cater, 1982; Walker and Brown, 1991; Hurlow, 1992; Dawes, 1993). In the Chelan block, the Napeequa unit is intruded by 91–68 Ma sheets (e.g. Paterson and Miller, 1998b; Miller and Paterson, 2001b; Matzel, 2004). Regional reconstructions and barometric data indicate that the southeastern part of the Wenatchee block preserves a crustal section ranging from <10 to >35 km paleodepth and that the Chiwaukum Schist overlay the Napeequa unit before movement on the White River shear zone (Miller and Paterson, 2001a). The Napeequa unit, in turn, overlies biotite gneiss of the Swakane Gneiss along a younger folded, but probably originally gently dipping tectonic contact in both the Wenatchee and Chelan blocks (Figs. 2 and 3) (Tabor et al., 1987; Paterson et al., 2004). The Swakane Gneiss is the structurally deepest part of the Cascades core (Miller and Paterson, 2001a; Paterson et al., 2004). It has a Late Cretaceous protolith age, and was

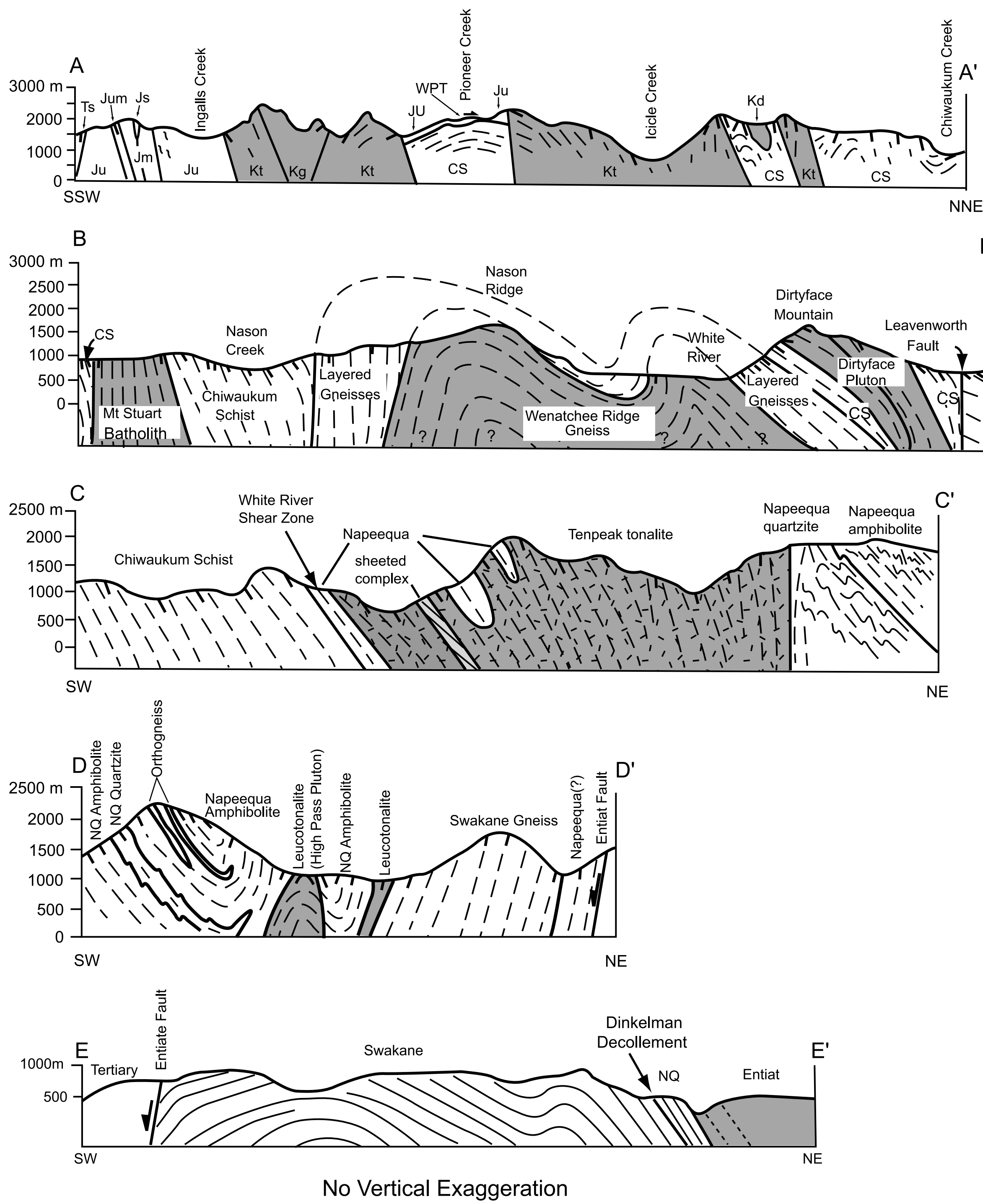


Fig. 3. Cross-sections through the Wenatchee block (arranged from SW and shallow levels (A–A′) to NE and deep levels (D–D′)) and southern part of Chelan block (E–E′). Tick marks at surface show dips of measured foliation, and dashes and thin lines (E–E′) are inferred foliation traces. Squiggles = foliation in sheared serpentinite. Note that foliation and some contacts define large, SW-vergent folds. CS = Chiwaukum Schist, Kd = Mount Stuart diorite and gabbro, Kg = Mount Stuart granodiorite, Kt = Mount Stuart tonalite, Jm = Ingalls Complex mafic rock, Js = Ingalls Complex sedimentary rock, Ju = Ingalls Complex ultramafic rock, Jum = Ingalls Complex serpentinite melange, NQ = Napeequa unit, Ts = Tertiary sandstone, WPT = Windy Pass thrust.

transported beneath the Napeequa unit subsequent to most of the magmatism and deformation in the structurally overlying units (Matzel et al., 2004; Paterson et al., 2004).

Two fundamentally different tectonic models have been proposed for the Cascades core. In one model, the core is pervasively deformed in a broad dextral strike-slip shear zone active from pre-96 to ∼45 Ma (Brown and Talbot, 1989). During much of this deformation (pre-96–∼58 Ma), the orogen is envisaged as transpressional with shortening taken up by thrusting and folding to the W and E of the Cascades core. NW- and SE-trending mineral lineation in the core records the regional displacement direction (Brown and Talbot, 1989), and thus outcrop-scale structures reflect orogen-scale flow under constant boundary conditions. In a second model, the Cascades core is dominated by SW–NE shortening, which is a deeper manifestation of SW-directed thrusts of the Northwest Cascades system and NE-vergent backthrusts in the Eastern Cascades fold belt (Fig. 1) (e.g. Brandon et al., 1988; McGroder, 1991). Mineral lineation in the Cascades core is interpreted to reflect the direction of maximum finite elongation, but not the direction of regional displacement (Miller and Paterson, 1992; Paterson and Miller, 1998a), whereas in the low-grade NW Cascades system lineation may record heterogeneous strain and volume loss, but neither the maximum elongation nor regional displacement (Brandon et al., 1994; Feehan and Brandon, 1999). A question for the second model is whether outcrop-scale structures in the core formed primarily by regional SW-directed, non-coaxial reverse shear or more local boundary conditions and processes such as folding of previously strained rocks (e.g. Lebit et al., 1998). A major problem for both models is that neither adequately addresses why only a single lineation formed in rocks repeatedly deformed over an interval of at least 50 m.y.

In the following, we evaluate the origin of outcrop-scale structures in the Cascades core by describing examples of structural patterns in amphibolite–facies rocks and plutons deformed at different crustal levels and ages. We focus in part on the development of kinematic indicators and relationship of these indicators to lineation, folds, and other outcrop-scale structures.

3. Structure of the Nason terrane and plutons that intrude the terrane

3.1. Chiwaukum Schist

The Chiwaukum Schist typically exhibits compositional layering, strong foliation and generally weak to moderately developed mineral lineation, although domains of L > S fabric are present. Layering is defined by variations in grain size, ratios of micas to quartz and plagioclase, and quartz segregations. In some places, this layering formed by metamorphic differentiation during folding, but in others it may be transposed bedding (Paterson et al., 1994).

Folds of layering and foliation are characteristic from the thin section to map scale. At least three cycles of regional folding are recognized in the Chiwaukum Schist. Two early cycles are characterized by coaxial, tight to isoclinal folds; these folds are apparently associated with an axial-planar foliation, which is the dominant fabric in the schist. Dips of foliation are variable; broad regions of moderate ($\sim 40°$) NNE dips probably reflect a younger cycle of larger, more upright folds (Figs. 2, 3 and 5). Qualitative restoration of the late folds suggests that early folds were initially recumbent or gently inclined. Folds of the latest generation range from outcrop to map scale, are open to tight, and generally lack new axial-planar fabric. They have mainly WNW- to NW-striking, moderately to steeply NE–SW dipping axial surfaces. Hinge lines of the various fold generations display some scatter in orientation, but their maxima are commonly gently WNW–NW or ESE–SE plunging and sub-parallel to the trend of the orogen (Paterson et al., 1994).

Mineral lineation in the schist is best defined by quartz and biotite aggregates, and records the local finite stretching direction, as indicated by parallelism to: fibrous overgrowths; elongate strain shadows and coronas on porphyroblasts; boudinaged and stretched porphyroblasts; and boudinaged quartz segregations, intrusive sheets, and other competent layers. On a regional scale, lineation in the Chiwaukum Schist has a subhorizontal, WNW–ESE- to NW–SE-trending maxima (Fig. 4) that is subparallel to hinge line maxima (Brown and Talbot, 1989; Paterson et al., 1994). Lineation varies in orientation within many outcrops, however, and commonly lies at a higher angle to hinge lines in limbs than in hinges. Lineation steepens in several other kilometer-scale domains, such as shear zones and pluton aureoles, and as a result of refolding, as discussed below.

Kinematic indicators are rare in the Chiwaukum Schist away from shear zones, which are localized next to plutons, and include shear bands, asymmetric boudins, and asymmetric tails around resistant objects. Outside of shear zones, we have observed roughly similar numbers of kinematic indicators in lineation-normal and lineation-parallel (and foliation-normal) sections. The lineation-parallel planes yield mixed results, arguing against simplistic dextral shear or SW-vergent thrust belt models where lineation is parallel to the internal transport direction. The lineation-normal sections primarily record flexural flow in fold limbs, which is illustrated by folds at a variety of scales. For example, on the SSW-dipping limb of a kilometer-wavelength fold directly north of the Mount Stuart batholith, the vergence of parasitic folds and shear-sense indicators in lineation-normal sections record NNE-directed shear, and mineral lineation intensity increases in the hinge zones of these folds. These features can be explained by fold superposition, as demonstrated by our detailed studies described in the ensuing two sections.

3.1.1. Larch Lake area

The Larch Lake area (Fig. 5) is dominated by sub-horizontal, NW- and SE-trending, upright minor folds that tend to verge SW (Fig. 6A). Larger-scale folds are delineated by M, S, or Z shapes of fold symmetry at individual outcrops. Outcrop-scale multi-layer folds have semi-planar limbs and localized, strongly curved hinges. Orthogonal thickness of compositional layers remains constant in limbs and increases slightly towards hinge zones indicating a significant flexural flow component during latest buckling. Earlier locally preserved isoclinal fold hinges are defined by compositional layers, and axial surfaces are sub-parallel to the local layer orientation (Fig. 7A). These axial surfaces are folded by the upright folds, which trend sub-parallel to the earlier folds, forming a type-III fold interference pattern (cf. Ramsay, 1967).

The young, upright folds are not associated with an axial-planar fabric, though they accommodated considerable shortening (Fig. 7A). Instead, the dominant foliation *mimics* the morphology of these folds by following the folded

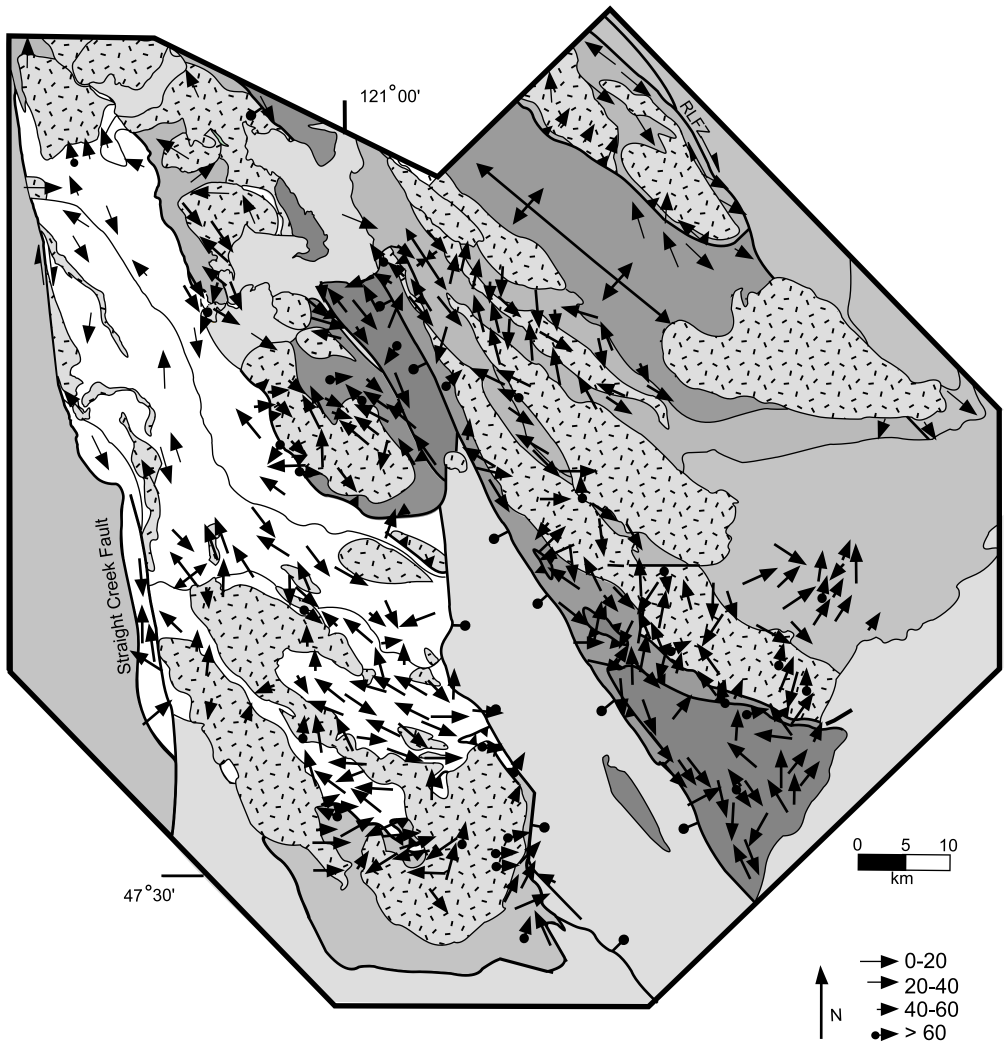


Fig. 4. Map illustrating mineral lineation orientations in the southern and central Cascades core. See Fig. 2 for rock units. Arrows indicate lineation plunge.

compositional layers (Fig. 7A), giving the impression that foliation is related to the earlier isoclinal folding and has been passively refolded by the upright folds. Detailed analysis of lineations, however, leads to a more complex interpretation, as discussed below. Mineral lineation is commonly parallel to hinge lines of upright folds, but a significant number of lineations are oriented clockwise from hinge lines (Fig. 6).

When following the trend of sub-horizontal folds over longer distances (>2 km), hinge lines of minor folds and mineral lineation gradually increase in plunge. In domains of steeper lineation plunges, mushroom-like, type-II fold interference patterns indicate significant change in angular arrangement of the component fold generations (Fig. 7B). These angular changes result from the development of the last generation of folds on curved, previously folded layers. Thus, the local type-II fold interference probably formed in hinge zones of large-scale, earlier folds, whereas their limbs were dominated by type-III fold superposition. The variation in interference patterns at a local scale also indicates imperfect coaxial, large-scale fold superposition, as coaxial fold generations form type-III patterns (Ramsay, 1967). We estimate a 15° clockwise angle between the axial trend of the last generation folds relative to the earlier folds by joining structurally similar points in the regional fold interference pattern (cf. Ramsay and Huber, 1987, p. 496).

The variability in small-scale fold interference relative to position in regionally oblique type-III fold superposition affects the geometry of other structures in such systems. Lineations are well preserved in hinges, but are weak in limbs. An illustrative example comes from the Wenatchee Ridge Gneiss, a well-foliated orthogneiss at the base of the Chiwaukum Schist (Fig. 3) (Miller and Paterson, 2001a). Fig. 8 summarizes orientations of mineral lineations measured across single sinusoidal folds (wavelength ~1 m) of foliation planes. Lineation lies at an acute angle clockwise to the fold axis in the hinge, whereas angles increase towards the inflexion line, forming in projection a partial complex locus (elliptical helix?) rather than a great or small circle. Such lineation distribution along a partial elliptical helix may result from flexural folding in combination with homogeneous background strain, which approximates mechanical buckling processes (e.g. Ramsay, 1967, p. 466; Ramsay and Huber, 1987, p. 481). In this scenario, however, foliation and lineation are pre-existing structures, passively deformed by the last folding. This, in turn, has important implications, as

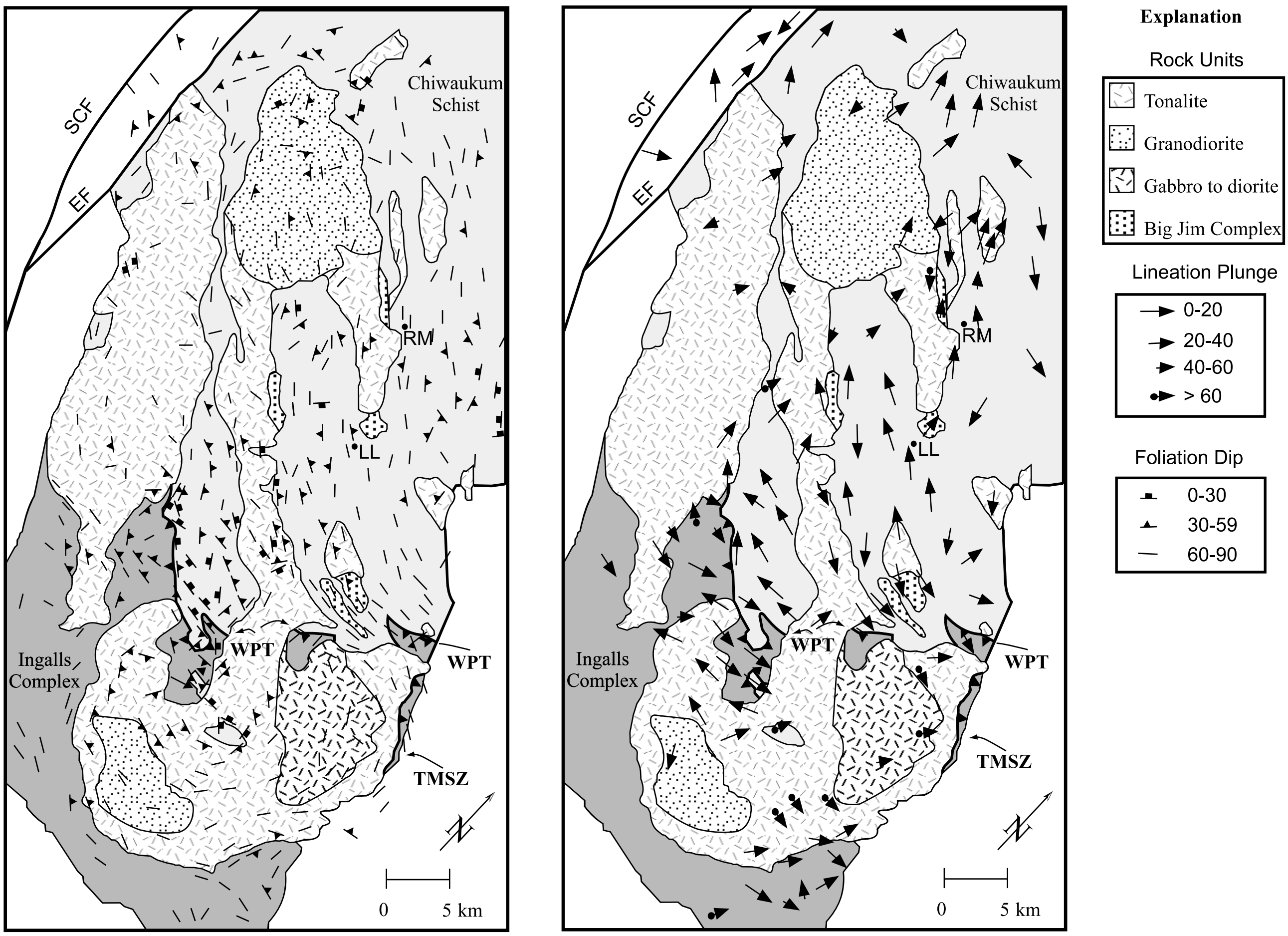


Fig. 5. Structural maps of Mount Stuart batholith and adjacent rocks. EF = Evergreen fault, LL = Larch Lakes detailed study area, RM = Rock Mountain/Rock Lake detailed study area, SCF = Straight Creek fault, TMSZ = Tumwater Mountain shear zone, WPT = Windy Pass thrust.

pre-existing, passively reoriented lineations are insignificant kinematic indicators for the last deformation.

Above, we have noted problems in the interpretation of the timing of the lineation and dominant foliation, and that the last fold generation lacks significant axial-planar fabric, but records considerable shortening. The sub-parallelism of lineations and hinge lines, however, implies some genetic correlation. The dominant foliation is thus likely to be related to this final ductile deformation, though foliation mimics fold morphology rather than possessing an axial-planar geometry.

3.1.2. Rock Mountain–Rock Lake area

The Rock Mountain–Rock Lake area is one of the few domains in the Chiwaukum Schist outside of structural

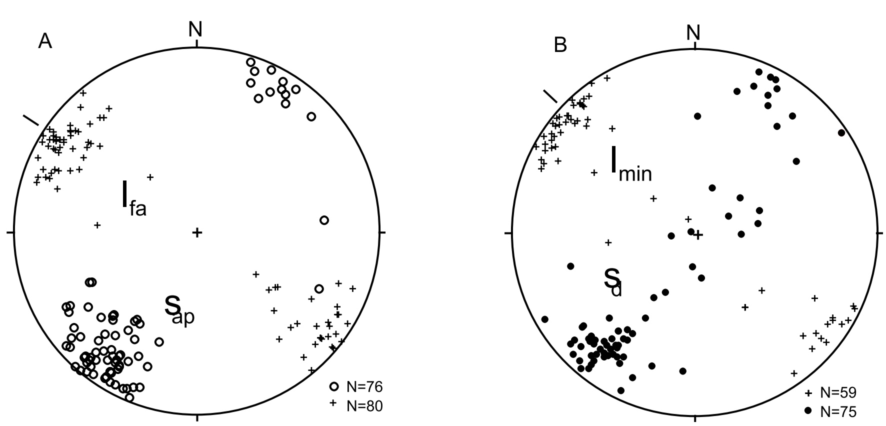
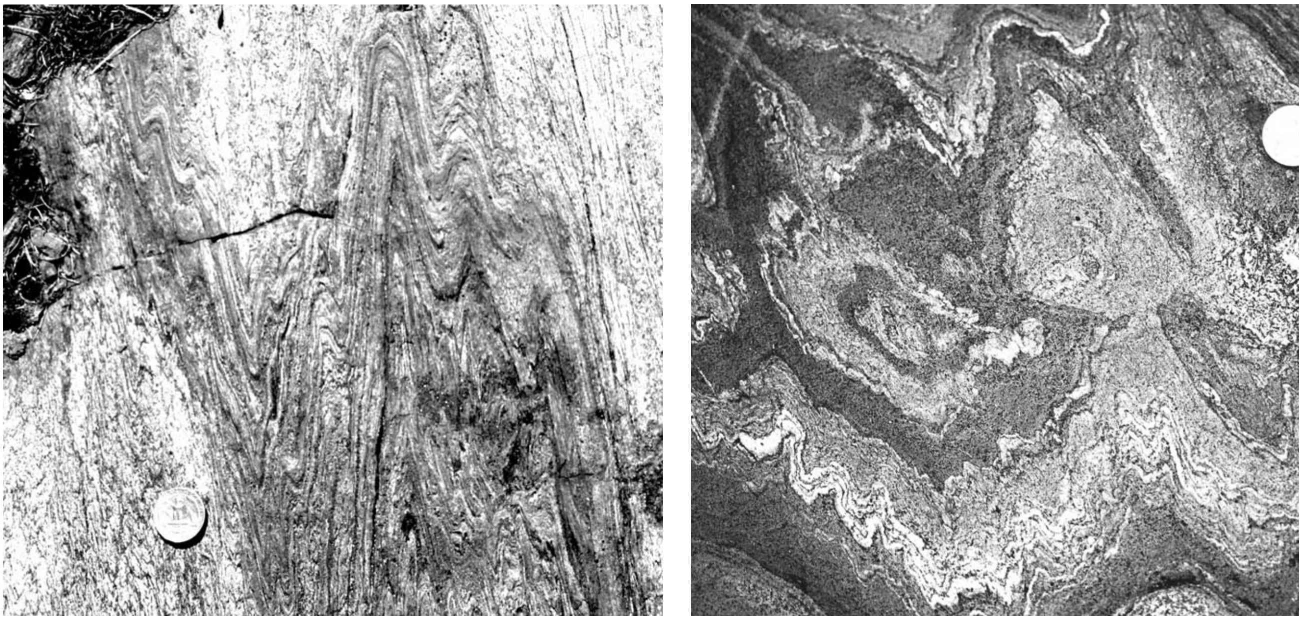


Fig. 6. Larch Lake study area, lower-hemisphere, equal-area projection of structures. (A) Hinge lines (l_{fa}) and axial planes (S_{ap}) of last generation upright folds, which predominantly trend ~305° and have slight SW vergence. (B) Mineral lineations (l_{min}) are typically parallel to the hinge lines, but with slight dextral offset of ~10° (average trend indicated by short line outside of circle), and the dominant foliation (S_d) mimics the morphology of the folds



A B

Fig. 7. (A) Last generation upright folds in Chiwaukum Schist near Larch Lake. Well-defined multilayer of differentiated composition and mineral fabrics records significant ductile flow between limbs and hinges. Layer curvature is concentrated near the fold hinges, but note lack of axial planar-fabrics although the folds experienced shortening of 62%. (B) Mushroom-like fold-interference pattern in Chiwaukum Schist. The local type-II fold superposition occurs in an almost coaxial (type III) regional interference pattern just where the hinges of the component folds intersect. This outcrop was found after evaluating the wavelength (∼5 and 2.5 km) and geometrical arrangement (axial angle ∼15°) by identical points of the regional interference pattern.

aureoles and reverse shear zones that is dominated by steeply plunging mineral lineation. This domain has been attributed to a late NW-striking, reverse shear zone (Rock Lake shear zone of Magloughlin (1993)), but detailed structural analysis indicates that local fold interference patterns control the structural morphology. The local type-II fold interference at Rock Lake comprises a subvertical southern limb and moderately NW-dipping northern limb forming an asymmetric antiform that is overprinted by NW-trending folds (Fig. 9A). In projection, minor last generation fold hinge lines scatter along a great circle that approximates the axial surface of the last folding event. Poles of axial surfaces of minor folds reveal an elongated distribution, which is due to fold initiation on variably oriented (pre-folded) layers. The same effect may explain the bimodal distribution of shallow NW-plunging, minor fold hinge lines (Fig. 9A). Each mode of the distribution pattern is formed by late minor folds developed on the opposing limbs of the pre-existing folds.

Axial surfaces of early folds form a great circle distribution near the perimeter indicating an originally steep dip of these surfaces (Fig. 9B). The pole to this great circle lies on the axial surface of the superimposed folds (compare Fig. 9A and B). The original orientation of the earlier axial surfaces remains unknown. Spatial distributions of early minor fold hinge lines are less organized (Fig. 9B), as individual hinge lines experienced varying reorientation, depending on their position relative to the larger-scale superimposed fold system. Passive reorientation of axial directions can be envisaged as refolding of lineations on differently inclined surfaces (cf. Ramsay, 1967, p. 461).

Lineations in the Rock Mountain–Rock Lake area are commonly sub-parallel to hinge lines of late minor folds and therefore form, in projection, similar distributions to corresponding hinge lines (Fig. 9C). A weak maximum lies close to the intersection of the component axial surfaces, which is the common direction for fold amplification of both systems in the study area. The dominant foliation also spreads along a great circle similar to those of the earlier fold axial surfaces. Coincidence in spatial distribution of both structural elements agrees with our observation that the dominant foliation follows the morphology of the last folds.

Small igneous bodies intrude the Chiwaukum Schist in this area and provide time constraints on deformation. Felsic dikes probably related to the Mount Stuart batholith are commonly folded and boudinaged by the last increments of ductile deformation. Mafic sheets, mapped as outliers of the 96 Ma Big Jim Complex of the batholith (Tabor et al., 1987), are folded with the Chiwaukum Schist. The contact between the mafic rocks and schists is marked by meter-scale cusps of strongly foliated igneous rock that are deflected into the schists and by lobes of opposite deflection. These relations indicate that the igneous rocks were less competent than the schist during folding. The folded interface invariably has Z-shape geometries, even at opposing sides of a mafic sheet (Fig. 10), implying that these folds formed before the igneous body reached its present shape. These folds presumably formed synchronously with early phase folds of the schist, as indicated by spatial coincidence of the respective fold axes. We also infer that this folding occurred during, or shortly after, emplacement

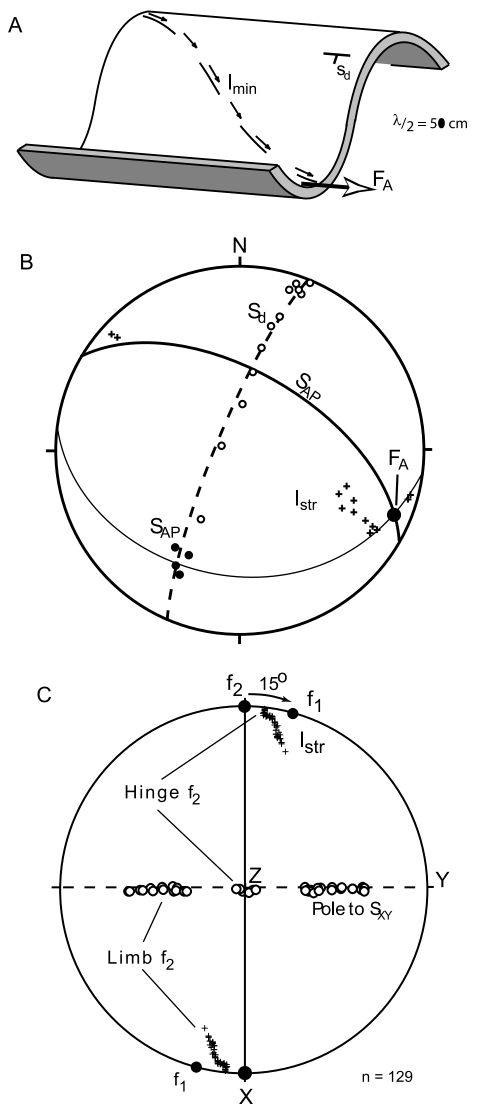


Fig. 8. Sigmoidal geometry of mineral lineation in a last generation fold, which refolded isoclinal folds. (A) Schematic outcrop sketch of fold in Wenatchee Ridge Gneiss. S_d is dominant foliation that carries the mineral lineation (l_{min}) and mimics the fold morphology. (B) Synoptic projection of detailed structural measurements reveals clockwise offset of mineral and stretching lineation (l_{str}) from the fold axis (F_A). Lineation forms a complex locus centered about the fold axial direction. S_{AP} = fold axial plane. (C) Finite strain orientations in a type-III fold interference pattern are derived from the cumulative (total) deformation of a similar fold with amplitude to wavelength ratio of 10 and a superposed buckle fold (infinite multi-layered stack, viscosity ratio 1:50). The axial direction of the pre-existing recumbent fold (f_1) is oriented 15° clockwise relative to the imposed upright folding (f_2). The calculated finite (total) elongations (l_{str}) are remarkably similar to the orientation pattern of measured mineral lineations, and suggest that the observed fabrics are a composite. This is strongly supported by the geometry of the *XY*-planes of the total strain that follow the morphology of the last generation fold, which is also analogous to the observed situation.

of the mafic igneous bodies when they were less competent than the host rock.

Subsequent refolding of the Z-shaped interface corresponds to the last generation of folding in the Chiwaukum Schist. This interpretation is supported by isolated bodies of gabbro that define open, upright and gently N-plunging synforms, similar in orientation to last generation folds in underlying schist (Fig. 10). At the folded interface, Chiwaukum Schist forms the cusps in contrast to the previously described folded interfaces, implying that the mafic intrusive rocks had gained significant strength relative to host rock. The isolated mafic body on Rock Mountain is cut discordantly by felsic dikes that experienced mild folding or boudinage, and were likely emplaced during late increments of the last generation of folding.

The bulk of both generations of folds likely formed over a cumulative time interval of <5.5 m.y., assuming that the mafic and felsic dikes were synchronous with the 96.5–91 Ma Mount Stuart batholith (Matzel, 2004). It further appears that both fold generations formed under amphibolite–facies conditions during emplacement of the batholith. These relatively constant thermal conditions may have enhanced continuous fabric development for the period of fold superposition, as documented by the single, dominant foliation and lineation.

3.2. Lineations in and near plutons intruding the Nason terrane

Magmatic to high-T subsolidus fabrics that are congruent with host rock fabrics and can be shown to record regional strains (cf. Paterson et al., 1998) presumably formed over a narrow time interval and are thus important in establishing the timing of formation of mineral lineations. Fabrics in structural aureoles of plutons are also likely to reflect, in part, local boundary conditions during emplacement. In the following, we describe structures in several of the dominantly tonalitic plutons (and their structural aureoles) that intrude the Chiwaukum Schist. We emphasize the Mount Stuart batholith, but also briefly describe the deeper Dirtyface and Tenpeak plutons.

The 91–96 Ma Mount Stuart batholith was emplaced at ca. 6–12 km depth and forms two major bodies (e.g. Tabor et al., 1987; Paterson and Miller, 1998a). The much larger (>500 km^2) northeastern body has a mushroom-shaped southeastern end, sheet-like central area, and hook-shaped northwestern end (Fig. 5). We have described the structure of this body elsewhere (Miller and Paterson, 1994; Paterson and Miller, 1998a), and emphasize findings that are most relevant for the significance of mineral lineation in the batholith and host rocks.

Magmatic foliation and weak lineation in the mushroom-shaped region largely reflect internal magma chamber processes (Paterson and Miller, 1998a). Host rock in the structural aureole to the batholith was largely transported downward in response to intrusion. This response to local boundary conditions imposed by magma emplacement is modified in four domains where fabrics are inferred to record regional shortening strains during and shortly after emplacement (Paterson and Miller, 1998a).

One domain is located near the Windy Pass thrust, which places the Jurassic Ingalls ophiolite onto the Chiwaukum Schist (Figs. 2 and 3). This structure is a N-vergent backthrust (Miller, 1985), which may have late SSW-directed motion (Paterson and Miller, 1998a). Strong, gently dipping magmatic foliation in the batholith near the Windy Pass thrust is

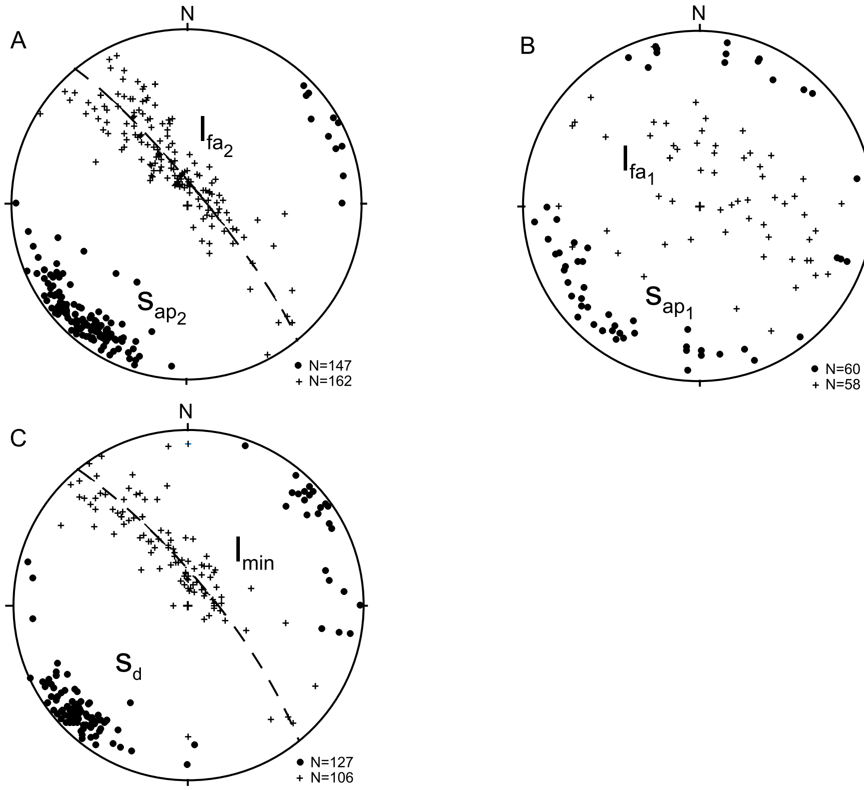


Fig. 9. Projections of structural measurements in the Rock Lake area (see text for explanation). The dashed great circle approximates the bulk axial plane of last generation folds. (A) l_{fa2}- and s_{ap2}-axes and axial planes, respectively, of late upright folds. (B) l_{fa1}- and s_{ap1}-axes and axial planes, respectively, of early folds. (C) l_{min}—mineral and elongation lineation, S_d—dominant foliation.

semi-continuous with thrust-related ductile fabrics in the Ingalls ophiolite and Chiwaukum Schist. Weak lineation in the batholith and host rocks plunges gently E or W, highly oblique to the probable thrust transport direction (Figs. 4 and 5). Miller and Paterson (1992, 1994) inferred from these patterns that the batholith was deformed by thrusting while melt dominated, but upon reaching its solidus locked up displacement on the thrust.

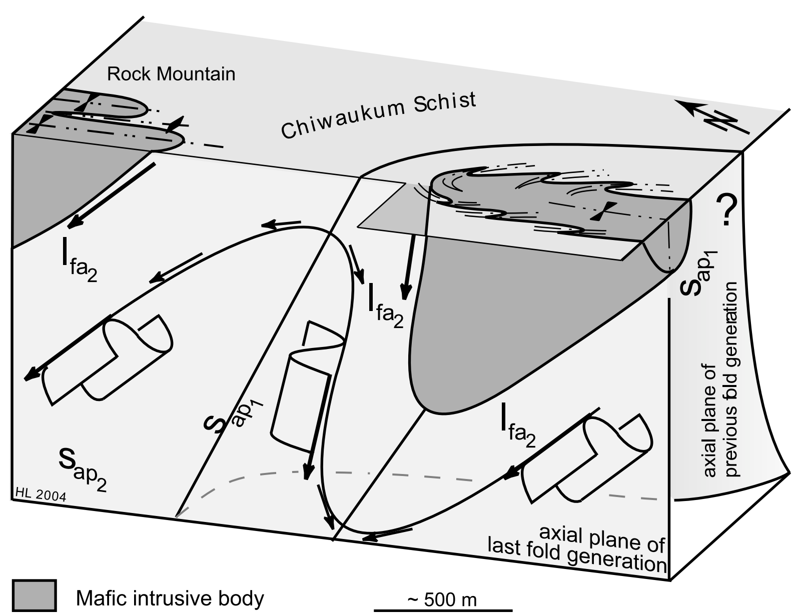


Fig. 10. Block diagram of the Rock Lake area where steeply dipping axial planes of an older fold generation (S_{ap1}) are refolded by younger folds (S_{ap2}) forming a type-II interference pattern. The cuspate–lobate morphology of minor folds at the interface of the southern magmatic body indicates it is less competent than the host rock during early generation folding, whereas reversed interfacial morphology at the contact of the northern body indicates that this body was more competent during last generation folding. Felsic dikes (not illustrated) truncate discordantly both rock units and are weakly deformed by the last folding event. Other abbreviations are same as in Figs. 8 and 9.

The moderately to steeply NE-dipping, >200-m-thick Tumwater Mountain shear zone was localized along part of the NE margin of the 'mushroom' (Fig. 5), and formed during the transition from magmatic to solid-state conditions (Miller and Paterson, 1994). Kinematic indicators in sections parallel to the down-dip mineral lineation, and normal to foliation, record reverse motion that carried Ingalls rocks upward and to the SW relative to the batholith.

In the sill-like region of the Mount Stuart batholith are magmatic folds (typically 10–50 cm wavelength) of foliation with steeply NNE-dipping axial planes and subhorizontal, WNW–ESE-trending hinge lines that are parallel to magmatic lineation (Figs. 4 and 5). These linear structures are subparallel to the regional orientation of mineral lineation and fold axes in Chiwaukum Schist. The WNW–ESE stretching directions indicated by syn-tectonic, contact-metamorphic porphyroblasts (andalusite, cordierite) (e.g. Plummer, 1980; Evans and Berti, 1986; Paterson et al., 1994) are compatible with that of boudinaged Mount Stuart sills in the schist and tension joints filled by aplite and pegmatite (Miller and Paterson, 1994). These relationships indicate that lineation in the schist formed during and after emplacement of the batholith.

Magmatic foliation similarly defines gently plunging, NW–SE-trending magmatic folds in the hook-shaped region of the batholith, and the hook-like shape may reflect a large fold (Paterson and Miller, 1998a; Benn et al., 2001). Weak mineral and AMS-defined magnetic lineations are subparallel to fold hinge lines, and these magmatic structures are subparallel to equivalent host rock structures. Mineral lineations in the hook- and sill-like regions of the batholith and host rock were thus controlled by folding and subhorizontal stretch parallel to the margin during shortening.

Evidence for complex boundary conditions is also found in Chiwaukum Schist adjacent to the 91 Ma Dirtyface pluton and 90–92 Ma Tenpeak pluton (Figs. 2 and 3). The moderately to steeply NE-dipping, sheeted Dirtyface pluton displays strong magmatic foliation and lineation that are locally overprinted by a parallel high-T subsolidus fabric. These fabrics are continuous with those in the surrounding schist where porphyroblasts of garnet, staurolite, and kyanite are wrapped by the dominant foliation. Regional structural patterns change near the pluton. In the SW margin of the pluton and adjacent schist, non-coaxial shearing and folding intensify in a 200-m-wide zone that extends a short distance beyond the NW end of the pluton (S.R. Paterson, unpub. mapping). In this zone, regional NW–SE-trending, shallowly plunging mineral lineation and fold hinge lines in the schist, swing to down-dip (NE-plunging) orientations. Lineation also plunges variably NE in the Dirtyface pluton, and down-dip lineation is found for another 1–2 km NE of the pluton in the Chiwaukum Schist. Local shear bands and asymmetric boudins in lineation-parallel surfaces in the schist and pluton indicate top-to-SW motion.

The Tenpeak pluton was emplaced at ~25–35 km depth (Dawes, 1993; Miller et al., 2000) into the Napeequa unit and along part of its SW margin into Chiwaukum Schist (Figs. 2 and 3). Magmatic foliation and mostly moderately to steeply plunging lineation (Fig. 4) are variably overprinted by margin-parallel, medium- to high-T subsolidus fabric. A 500 m–1 km wide structural aureole characterized by downward ductile flow of host rock dominated along much of the margin of the Tenpeak pluton (Miller and Paterson, 1999). The structural aureole next to the S and SW margin coincides in part with the moderately to steeply N- to NE-dipping White River shear zone where the pluton and a thin (0–500 m thick) rind of Napeequa unit structurally overlie Chiwaukum Schist (Figs. 2 and 3). The shear zone is marked by intense deformation and synkinematic greenschist–facies retrogression in the schist (Van Diver, 1967; Tabor et al., 1987; Magloughlin, 1993) and Napeequa unit, and by medium- and high-T S–C fabrics in Tenpeak tonalite that record S- to SW-vergent reverse shear parallel to down-dip lineation.

4. Structure of Napeequa Unit and Swakane Gneiss in the Wenatchee Block

The Napeequa unit and Swakane Gneiss are exposed in both the Wenatchee and Chelan blocks (Fig. 2). In the Wenatchee block, the Napeequa unit is intruded by 96–84 Ma plutons and numerous concordant tonalitic sheets (~10 cm–1 km thick) that crystallized at ca. 0.7–1.0 GPa (Fig. 2) (Walker and Brown, 1991; Dawes, 1993; Miller et al., 2000). In contrast, the Swakane Gneiss is only intruded by leucogranite sheets and Miocene plutons. Sparse thermobarometric data suggest peak metamorphic conditions of 565–675 °C at ~0.9–1.1 GPa for the Napeequa unit and 625–655 °C at ~0.9–1.0 GPa for the Swakane Gneiss (Brown and Walker, 1993; Valley et al., 2003).

Our structural mapping in the Wenatchee block has focused on a transect from the Napeequa unit into the Swakane Gneiss in the Buck Creek Pass area (Figs. 2, 3 and 11). This area lies in the SW-dipping limb of a regional SE-plunging (~30°), asymmetric synform that has a steeply NE-dipping axial surface and wavelength of >7 km (Fig. 3). In this transect, the Napeequa unit consists of amphibolite and less abundant quartzite that are intercalated on the meter to 100s of meters scale.

The dominant foliation in all units strikes NW and dips variably (mainly 35–70°), generally to the SW. In the Napeequa unit, foliation strike rotates progressively over ~3 km from ~285° in the south next to the High Pass pluton to ~330° next to the tectonic contact with Swakane Gneiss. Lineation trends are more complex, but similarly change from WNW and ESE to NNW and SSE near the Swakane Gneiss, and plunges are gentle to moderate (Fig. 11).

Folds are evident in most Napeequa outcrops. Early isoclinal folds and associated axial-planar foliation are refolded by the dominant cycle 2 folds, resulting in local type-1 interference patterns and causing cycle 1 hinges to curve through angles of 45°. Cycle 2 folds are open to more commonly tight to locally isoclinal, and wavelengths are typically 1–30 cm; sheets related to the 84 Ma Buck Creek pluton (Hurlow, 1992) are involved in these folds. Axial surfaces are on average subparallel to the regional orientation of the folded foliation. The gently to moderately NW- or

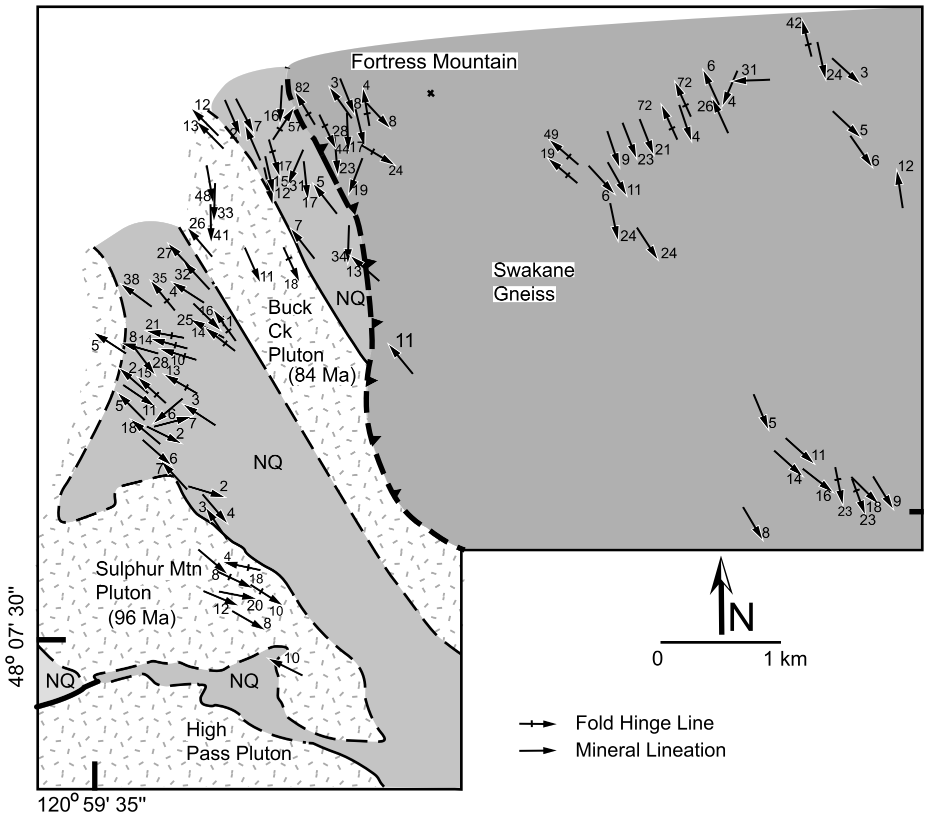


Fig. 11. Map of Buck Creek Pass area emphasizing orientations of mineral lineation and hinge lines of minor folds in the Napeequa and Swakane units. NQ= Napeequa unit.

SE-plunging cycle 2 hinge lines are subparallel to mineral lineation at the scale of the Buck Creek Pass domain, but angular discordances of $>30°$ are present in a number of outcrops, and lineation is at a higher angle to the hinge line in limbs than in the hinge of individual folds. Mineral lineation is folded by other cycle 2 folds where it is at an angle of $>45°$ in both the limbs and hinge. Local incipient axial-planar cleavage resulted in an intersection lineation that is subparallel to mineral lineation. Cycle 3 structures are sporadically developed and are mainly open to less commonly tight folds with wavelengths of 1–30 cm. Mushroom-type interference patterns resulted from refolding of cycle 2 folds, and cycle 2 hinge lines are bent through angles of $>30°$ over distances of less than a meter. Cycle 3 hinge lines commonly plunge moderately SW or NE, and axial surfaces strike ENE to NE with moderate to steep SE dips.

Kinematic indicators are sparse in the Napeequa unit. Shear bands and asymmetric strain shadows on garnets in amphibolites are found on only a few lineation-parallel and foliation-normal surfaces, and yield no consistent shear-sense pattern.

The oldest dated pluton that intrudes the Napeequa unit is the 96 Ma Sulphur Mountain pluton (Fig. 2). Brown and Walker (1993) stated that this intrusion cross-cuts fabrics in the Napeequa host rock, but Tabor et al. (2002) mentioned highly strained tonalite in the pluton margin, and our observations indicate that the eastern part of the Sulphur Mountain pluton has strong solid-state fabric continuous with foliation in the Napeequa unit. The pluton displays quartz- and biotite-defined mineral lineation, and inclusions of the Napeequa unit have long axes parallel to lineation. In Sulphur Mountain protomylonites, asymmetric plagioclase porphyroclasts, displaying core and mantle structure, and weakly oblique fabrics in coarse-grained quartz ribbons containing well-developed subgrains give contradictory kinematic results within individual thin sections, and outcrop-scale kinematic indicators are similarly rare. A few other samples display widespread, unrecovered strain that probably records deformation at lower (upper greenschist/lower amphibolite facies) temperatures. Stations with asymmetric fabrics in lineation-parallel and foliation-normal sections yield both top-to-NW and top-to-SE shear on gently N-dipping surfaces.

The felsic, ca. 88 Ma (J.P. Matzel, written commun.) High Pass pluton in the transect displays solid-state fabric defined by quartz and bioite, which is much weaker than that of the older Sulphur Mountain pluton. Numerous High Pass dikes intrude the Sulphur Mountain pluton (Cater, 1982). Most display solid-state fabric, and some are openly to tightly folded; hinge lines plunge gently NW or SE, subparallel to mineral lineation in the host pluton.

The sheeted, granodioritic to leucotonalitic Buck Creek pluton (Cater, 1982) displays solid-state fabrics parallel to those in the Napeequa unit, and the fabrics are qualitatively of equal intensity. Some Buck Creek-like sheets in the Napeequa unit are folded by cycle 2 and cycle 3 structures, and others are boudinaged. A few aplite dikes cut foliation in the sheets, and thus deformation was probably ongoing during emplacement.

The Swakane Gneiss structurally underlies the Napeequa unit in the NE limb of the regional synform across a major structure of the Cascades core, called the Dinkelman décollement in the Chelan block (Paterson et al., 2004) (Figs. 2 and 3). This biotite gneiss is the structurally lowest unit in the southern part of the Cascades core. Detrital zircons are as young as 72.5 Ma (Matzel et al., 2004) and the Swakane protolith thus postdates plutons in the overlying Napeequa unit. One of the thin (<10 m), leucogranitic sheets that intrude the unit (Boysun, 2004) is ~68.5 Ma (Matzel et al., 2004).

In the Swakane Gneiss of the Buck Creek Pass area, SW-dipping foliation is parallel to subtle layering, which ranges from <1 cm to meters scale and is defined by variations in mica content. Mineral lineation is marked by aggregates of biotite and quartz, and mainly plunges <25°SSE (Fig. 11). Folds are much less common than in other metamorphic units of the Cascades core and formed where compositional layering is most pronounced. Folds include rare tight to isoclinal structures that nearly completely transpose layering and an earlier foliation into the dominant foliation. Subsequent local tight folds of foliation, having wavelengths of 10 cm–>1 m, lack axial-planar fabric. The early folds plunge moderately to steeply NW or SE, more steeply than mineral lineation. Local, younger, gentle to open, commonly asymmetric folds have wavelengths of 15 cm–4 m. These folds may be parasitic to the regional synform and trend similarly to earlier folds, but plunge more gently. They have broadly similar trends to mineral lineation, but are more variably oriented and plunge to both the NW and SE in contrast to the dominant SSE plunge of lineation.

The leucogranitic sheets provide information on the age of Swakane deformation. Many sheets, including the 68.5 Ma granite, display prominent solid-state foliation and lineation defined by quartz aggregates and micas. Most concordant to mildly discordant sheets display pinch-and-swell or boudinage, whereas sheets intruded at higher angles to foliation are ptygmatically folded. Some of these folds are tight to isoclinal and transpose sheets. These relationships demonstrate substantial post-68.5 Ma foliation-normal shortening, but other features indicate that deformation overlapped sheet intrusion. Openly folded sheets with solid-state foliation parallel to axial planes are locally intruded along these planes by other sheets. Elsewhere, a pegmatite cutting foliation in biotite gneiss has strong subsolidus fabric, but another pegmatite in the same outcrop is only gently folded and apparently postdated most deformation.

The Swakane Gneiss displays pervasive non-coaxial shear in the Chelan block (Alsleben, 2000; Paterson et al., 2004), as discussed below, and evidence for non-coaxial shear is widespread in the Wenatchee block. Local outcrop-scale ductile shear zones that deflect foliation nucleated along contacts of granitic sheets, and other diffuse shear zones lie along limbs of folds of foliation. More pervasive shear is recorded by extensional shear bands of finely recrystallized biotite (±muscovite) and quartz that deflect the dominant foliation and grade into 5–10-mm-thick shear zones. This biotite contrasts with medium-sized, commonly bent biotite in the dominant foliation. Shear bands, 'biotite fish', oblique quartz-defined foliation, and asymmetric strain shadows on garnet yield a consistent sense-of-shear in lineation-parallel sections in 50% of the Swakane samples ($n=24$) examined in thin section. In the other samples, conjugate shear bands are in accord with symmetrical strain shadows on garnet. Dextral shear occurred in 76% of the stations where outcrop- and/or thin section-scale kinematic indicators were recognized. Comparison with the Chelan block suggests non-coaxial structures were steepened by late regional folding (Alsleben, 2000; Paterson et al., 2004). If foliation is restored to gentle orientations, then the dextral indicators record top-to-N shear.

Shear bands cut the granitic sheets and postdate peak metamorphic assemblages, as these structures and the dominant (reactivated?) foliation wrap garnet and kyanite porphyroblasts. Kyanite is strongly kinked, and some grains are pulled apart parallel to lineation with muscovite and biotite connecting the fragments. Variably recrystallized quartz displays deformation bands and much unrecovered strain, further suggesting deformation below peak temperatures.

5. Structure of Napeequa Unit and Swakane Gneiss in the Chelan Block

The Napeequa and Swakane units are also important components of the southern part of the Chelan block (Figs. 2 and 12). We have described the overall geology elsewhere (e.g. Paterson et al., 2004), and focus on fabric formation in this area.

The major structure of the southern Chelan block is the Dinkelman décollement, which may have initiated during rapid underthrusting of Swakane protolith sediments to depths of >40 km in <5 m.y. (Matzel et al., 2004). Latest motion led to substantial excision across the décollement (Paterson et al., 2004). The décollement is folded by a regional, gently NW–SE plunging antiform (Figs. 3 and 12). Peak metamorphic conditions in the Napeequa unit near the décollement are ~1.0–1.1 GPa at 640–740 °C and for the structurally underlying Swakane Gneiss are ~1.1–1.2 GPa at 660–730 °C (Valley et al., 2003).

In the Napeequa unit, structures are similar to those in the Wenatchee block. Early tight to isoclinal folds have hinge lines that vary in orientation depending upon proximity to the Dinkelman décollement and Entiat pluton (Paterson et al., 2004) (Fig. 12). Superposed on these folds are open to tight, upright to moderately N-plunging folds, including the regional antiform. These folds generally lack axial-planar foliation. Mineral lineation has variable orientations, and is statistically subparallel to the early fold hinge lines.

Symmetrical high-T fabrics are observed in the majority of Napeequa outcrops. A few top-to-W or -SW indicators are found near the Dinkelman décollement, but more commonly, asymmetrical fabrics in lineation-parallel sections indicate top-to-N shear near the décollement and top-to-NE shear at a greater distance (Paterson et al., 2004). In lineation-normal sections, local kinematic indicators change across nearby axial surfaces. Paterson et al. (2004) concluded that Napeequa

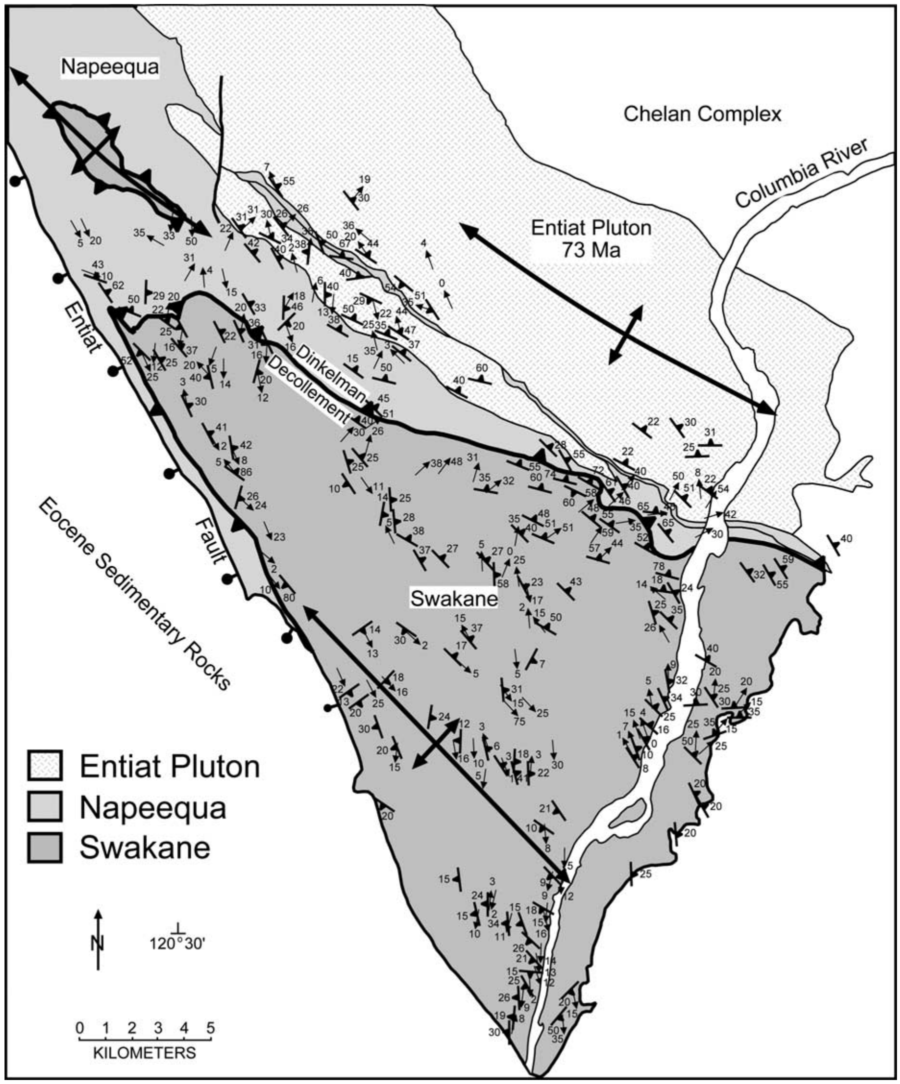


Fig. 12. Structural map of southern Chelan block. Chelan Complex consists of poorly dated plutons and migmatitic metaplutonic rocks.

structures reflect early W- to SW-directed thrusting, younger top-to-N or -NE shear, and flexural flow folding.

The largest body intruding the Napeequa unit is the >70-km-long, steeply dipping Entiat pluton. This tonalitic intrusive complex was emplaced at ca. 20–25 km depths (Dawes, 1993) and ranges from 91 Ma in the NW to 72 Ma in the SE (Matzel, 2004). Magmatic foliation defines outcrop- to map-scale, upright, NW-trending magmatic folds that are continuous with those in adjacent host rock (Paterson and Miller, 1998b; Paterson et al., 1998; Miller and Paterson, 2001b). The widespread magmatic folds and structural coupling between pluton and host rock suggest that magmatic foliation and lineation in the southern part of the Entiat pluton largely record regional shortening at ~72 Ma (Paterson and Miller, 1998b; Miller and Paterson, 2001b).

In the Swakane Gneiss, pervasive, medium- to high-T lineation in the gently to moderately dipping foliation is defined by stretched quartz, biotite, and locally hornblende. A second lineation formed at lower temperatures, as indicated by a streaky, striae-like appearance, less pervasive development, and presence of chlorite. The pervasive lineation commonly plunges gently N, whereas the lower-T lineation typically trends 10–30° counterclockwise to the earlier one (Paterson et al., 2004).

The gneiss displays two cycles of sporadically formed folds (Alsleben, 2000; Paterson et al., 2004), as in the Wenatchee block. Early mesoscopic, recumbent to gently inclined, tight to isoclinal folds, fold a foliation and have a foliation parallel to their axial surfaces. Axial trends range from N to NNE (locally SSW) to SE. These structures are refolded by the regional, upright antiform and local parasitic(?) folds, which generally lack axial-planar fabric, and also commonly plunge gently to the N.

The dominant foliation is cut and reactivated by extensional shear bands that pervade the Swakane Gneiss. Most shear bands are composed of the same minerals as the main foliation, but others incorporate recrystallized chlorite and formed at lower temperatures (Valley et al., 2003). Shear bands associated with both the pervasive and lower-T lineation, mica fish, asymmetric strain shadows, offset markers in shear

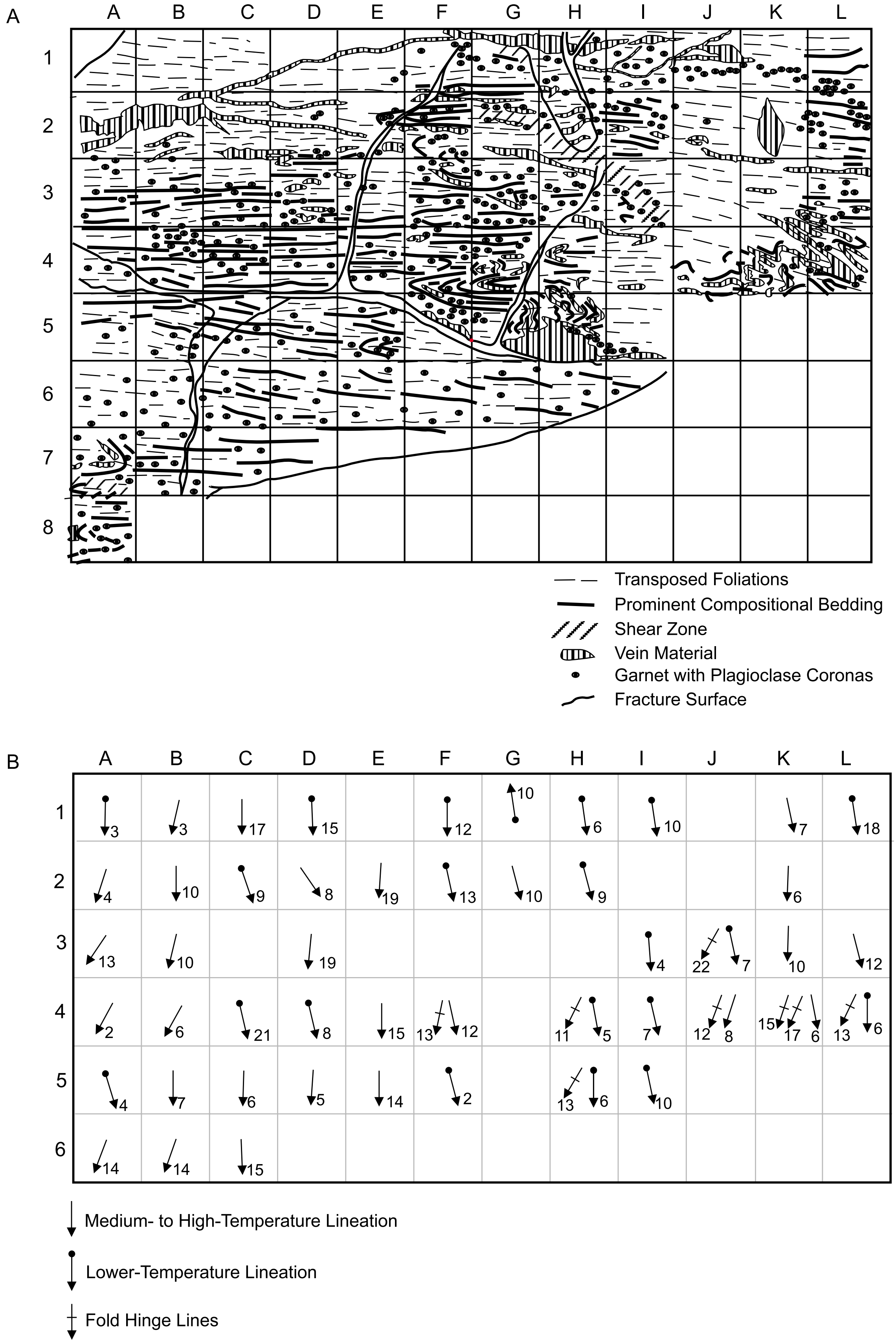


Fig. 13. (A) Detailed grid map of Swakane Gneiss in core of regional antiform. Grids are 25 cm by 25 cm. (B) Lineation and fold hinge line orientations from grid map in (A). Note that hinge lines of isoclinal, nearly recumbent folds plunge SSW (average = 11/220), ∼25° clockwise to the dominant mineral lineation, and the lower-T lineation is oriented counterclockwise to the medium- to high-T lineation.

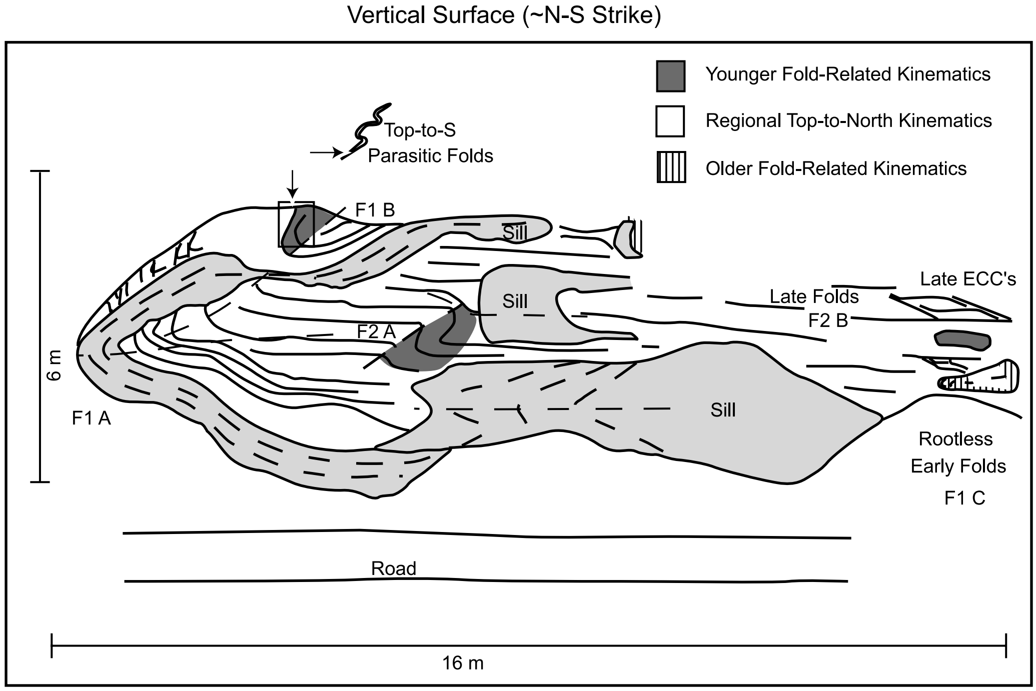


Fig. 14. Sketch emphasizing regional- and fold-related kinematics in a roadcut in the Swakane Gneiss. Older fold-related kinematics (F1) are overprinted by regional top-to-N structures, including an extensional crenulation cleavage (ECC). The youngest structures are parasitic, roughly upright, open folds (F2) and display fold-related kinematics.

zones, and asymmetric boudinage of meter-scale leucogranite sheets record top-to-N to top-to-NE, non-coaxial shear in lineation-parallel sections (Alsleben, 2000; Boysun, 2004; Paterson et al., 2004).

Kinematic indicators are best developed in mica-rich layers. These layers also focus non-coaxial shear in layer-parallel, millimeter- to centimeter-thick shear zones, which typically contain the lower-T lineation. This pattern probably reflects greater vorticity in these layers relative to the quartz-rich layers (e.g. Lister and Williams, 1983; Ridley, 1986). Although strain was apparently partitioned at the outcrop scale, no obvious strain gradient developed between the lowest levels of the Swakane Gneiss and the Dinkelman décollement, and the entire unit was deformed by non-coaxial shear.

The pervasive non-coaxial shear in the Swakane Gneiss is in stark contrast to the other units in the Cascades core. We have evaluated the consistency of this shear through grid mapping (25 cm by 25 cm grids) in the core of the regional antiform, > 700 m below the Dinkelman décollement, where 79% of the 95 grid points in surfaces parallel to lineation and normal to foliation record top-to-N shear, and none record top-to-S shear (Fig. 13). Symmetrical fabrics characterized all lineation-normal surfaces. In a second, structurally higher area in the core of the antiform, the results from 202 grid (1 m by 1 m) points in lineation-parallel surfaces were 80% top-to-N and 0.5% top-to-S. In lineation-normal surfaces, >95% of the grid points were symmetrical. The kinematics of these grid points were determined from field observations and thin sections (minimum of two per sample).

In many places (e.g. Fig. 13), top-to-N shear bands were superposed on recumbent folds and no earlier kinematics are preserved. More complex relationships are illustrated in another locality (Fig. 14) where foliation in gneiss and leucogranite sills is deformed by reclined to recumbent, tight to isoclinal folds. The dominant foliation is axial-planar to these folds. Foliation asymmetries in the lower limb of one isocline are incompatible with top-to-N shear, and may be related to fold formation or earlier non-coaxial shear of uncertain tectonic significance. Structures recording top-to-N shear overprinted the early folds and foliation in much of the outcrop. All of these structures were in turn folded by more open folds that may be parasitic to the regional antiform. The regional fold postdates most, if not all, of the top-to-N shear in the Swakane Gneiss and Napeequa unit.

The pervasive non-coaxial shear in the Swakane Gneiss and domainal shear in the Napeequa unit define a >2-km-thick, top-to-N to -NNE ductile shear zone. Structures associated with this shear record decreasing temperatures, changing from pervasive high-T fabric, to chlorite-grade fabrics in narrow shear zones, and finally to discrete slip surfaces that displaced leucogranite sheets by up to 2 m and were locally associated with pseudotachylite where slickenside striae are parallel to the lower-T lineation (Paterson et al., 2004). As temperatures decreased, the displacement direction changed by up to 30° in a counterclockwise sense.

6. Discussion

In the following, we address some of the general problems in interpreting mineral lineations raised in the introduction, as well as potential implications of lineations for models of the structural evolution of the Cascades core.

6.1. Mineral lineations and stretching directions

Mineral lineations in metamorphic rocks in the Cascades core can generally be shown to have formed parallel to the local stretching direction, as indicated by boudinage, fibrous overgrowths, and elongate mineral aggregates. In plutons, magmatic to high-T subsolidus mineral lineations that are subparallel to the regional lineation in host rocks also commonly formed parallel to the stretching direction. This relationship is best demonstrated where magmatic lineations are oriented perpendicular to late dikes and parallel to regional lineation. Magmatic lineations in the interiors of some plutons (e.g. Mount Stuart, Tenpeak) may largely reflect internal magmatic processes (cf. Paterson et al., 1998).

6.2. Summary of timing of deformation

Structural and geochronological data indicate protracted deformation in the region. We begin by interpreting age relations in the south (shallowest levels) and proceed to the NE.

The ages of outcrop-scale structures in the Nason terrane are best constrained near the Mount Stuart batholith. Early axial-surface fabrics in Chiwaukum Schist are truncated by a 96 Ma outlier of the batholith (Paterson et al., 1994). Magmatic lineation and subhorizontal stretching associated with folding in the hook-shaped and sill-like regions of the batholith and adjacent schist were synchronous with crystallization at ca. 96–93 Ma (Miller et al., 2003; Matzel, 2004). Intense magmatic foliation and weak lineation in the Mount Stuart batholith and schist resulted from motion on the Windy Pass thrust at ~94 Ma. Movement on the Tumwater Mountain shear zone initiated during crystallization of the 91 Ma part of the batholith, and K–Ar biotite dates from nearby rocks suggest that displacement ceased shortly after emplacement (Miller and Paterson, 1992; Matzel, 2004). These observations and biotite cooling ages (Ar/Ar, K–Ar) of 90–81 Ma in the batholith and southern part of the Chiwaukum Schist (Engels et al., 1976; Tabor et al., 1982, 1987; Evans and Davidson, 1999) indicate that metamorphism and deformation started before 96 Ma, continued from 96 to 91 Ma, and ended by 81 Ma.

Deformation of the Napeequa unit in the Wenatchee block initiated before emplacement of the 96 Ma Sulphur Mountain pluton NW of the Buck Creek Pass area (Brown and Walker, 1993) and continued until after 68 Ma. The much more pronounced solid-state deformation of the Sulphur Mountain pluton relative to the High Pass pluton supports deformation between 96 and 88 Ma. Solid-state fabrics, tight folds and boudinage of 84 Ma Buck Creek sheets imply significant deformation after this time. Reorientation of foliation strike from WNW to NNW as the contact with the Swakane Gneiss is approached suggests that deformation also coincided in part with that in the gneiss, a unit that was deposited after 73 Ma. Substantial strain of the gneiss occurred after intrusion of 68.5 Ma sheets, and the regional upright synform folds foliation in the Swakane Gneiss and thus also formed after 68.5 Ma. Sparse K–Ar biotite ages (Engels et al., 1976) in the Napeequa unit indicate significant cooling by 54–58 Ma and also provide a younger limit for medium- to high-T ductile deformation.

In the southern Chelan block, the earliest documented structures are foliation and lineation in the Napeequa unit that are reoriented in the aureole of the 91 Ma part of the Entiat pluton (Paterson and Miller, 1998b; Miller and Paterson, 2001b). Widespread top-to-N shear deformed 68 Ma sheets in the Napeequa and Swakane units. Hornblende (K–Ar, Ar/Ar), biotite (Ar/Ar), and fission track zircon ages suggest that ductile deformation terminated by ~57 Ma in the hanging wall and 48 Ma in the footwall of the Dinkelman décollement (Paterson et al., 2004). Eocene (~46–48 Ma) dikes intrude both plates of the décollement; they cut moderate- and low-T, top-to-N fabrics, but are cut by brittle slip surfaces. Thus, some, if not all, top-to-N shear occurred during exhumation.

The age data and field relations indicate that lineation in the Cascades core formed over an interval of ca. 50 m.y. (or more). Lineation formation was probably restricted to a narrower interval (<15 m.y.) in the Mount Stuart area, whereas in the Napeequa unit, ductile deformation persisted over at least 30 m.y., from before 96 Ma to after 68 Ma. In the structurally deepest rocks of the Swakane Gneiss, deformation probably lasted from ca. 70 to 48 Ma. The prolonged deformation of the Cascades core, and particularly the Napeequa unit, resulted in only a single lineation and foliation in most outcrops. The composite nature of the fabrics probably reflects relatively constant metamorphic temperatures during much of the deformation.

6.3. Boundary conditions of deformation

Multiple boundary conditions and processes controlled the formation and orientation of mineral lineation and other outcrop-scale structures in the Cascades core (Fig. 15), as discussed in the following.

6.3.1. Fold-dominated outcrop-scale structures

Much of the Nason terrane and Napeequa unit are dominated by folding in response to protracted SW–NE regional shortening, and outcrop-scale structures largely record flexural fold-dominated shear compatible with the mechanically active role of layering. Lineation patterns mainly reflect superposition of upright folds on early recumbent, tight to isoclinal folds, as best documented for the Chiwaukum Schist.

We briefly introduce a model that integrates the observed geometries of structures in the Chiwaukum Schist in the detailed study areas (e.g. Fig. 10), and is also probably compatible with fold-dominated parts of the Napeequa unit. This model is based on the common assumption that foliation and elongation lineation reflect principal orientations of finite strain. These finite strains are not related exclusively to a single deformation episode in multiply deformed rocks such as the Chiwaukum Schist where strain accumulated over the entire deformation path. Macroscopic fabrics and strain-related structures may reflect this *total* strain as long as metamorphic conditions remain approximately constant and deformation is

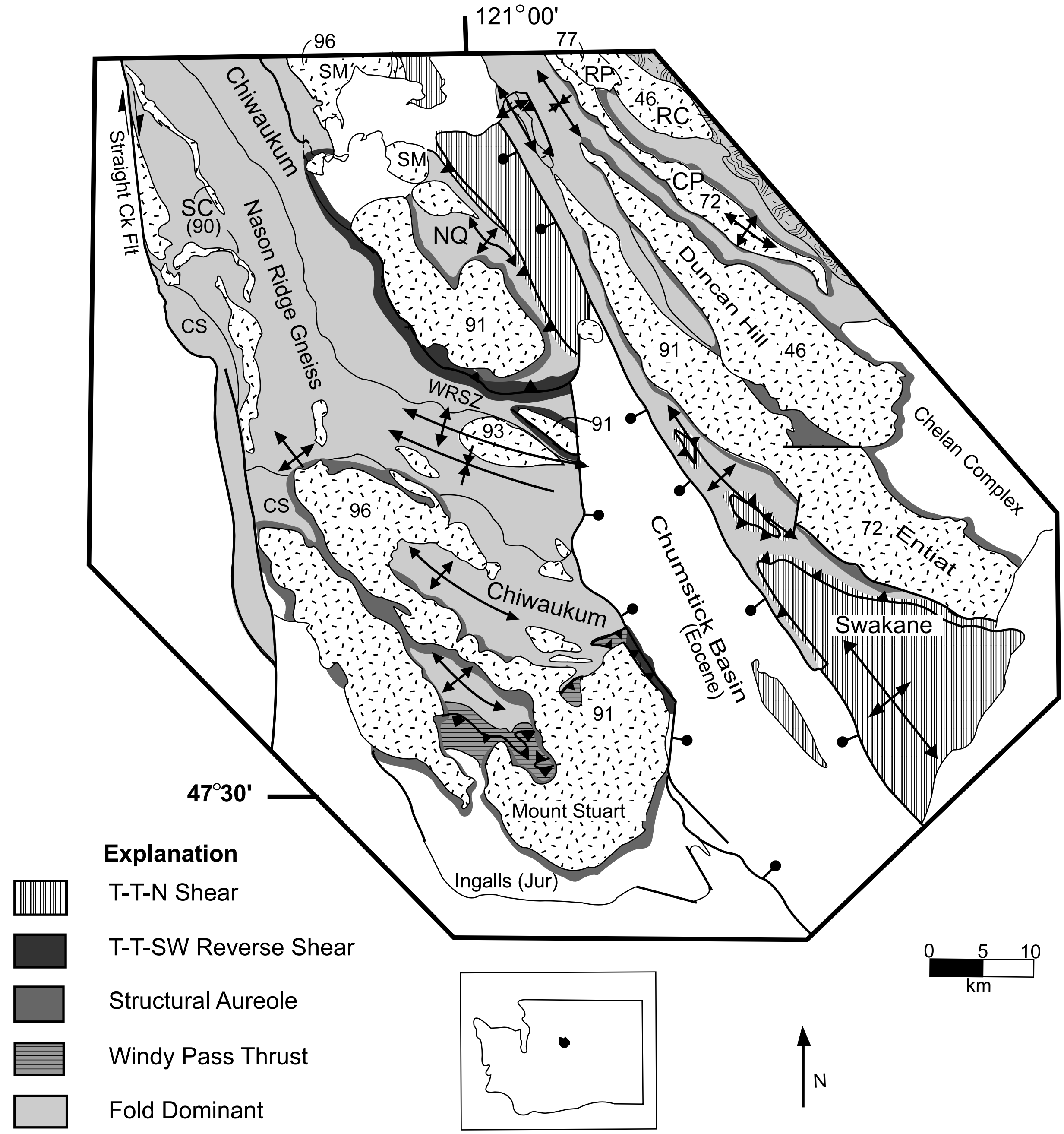


Fig. 15. Summary map of dominant boundary conditions for different parts of the Cascades core (see text for details). See Fig. 2 for geological units.

continuously accommodated on the granular scale (Lüneburg and Lebit, 1998; Ramsay and Lisle, 2000).

In our hypothesis, early tight to isoclinal folds were accompanied by development of axial-planar, S-fabrics. These fabrics were subsequently modified by heterogeneous deformation during formation of the upright buckle folds. Buckling took advantage of the sub-parallelism of isoclinally folded layers and axial-planar fabric anisotropy. In this respect, our approach is similar to classical fold models where layer-parallel mechanical anisotropy is responsible for buckling instabilities and subsequent fold amplification when a sufficient bulk shortening component acts within the layers (e.g. Hudleston, 1973; Cobbold, 1976; Cobbold and Watkinson, 1981; Johnson and Fletcher, 1994). The present model differs, however, in that we address the state of strain of the fabric anisotropy.

The subsequent buckling imposes heterogeneous deformation on the pre-existing layer/fabric system. Limb shear at the amplifying waveform is the major component of the local deformation field in buckle folds. This shear commonly contributes to an axial-planar fabric, but the first increments of limb shear are imposed on fabrics that are close to the local, limb-parallel, shear plane. This situation is comparable with simple shear zones, where foliation approaches the shear plane with increasing strain and further strain increments merely modify the foliation, and orientation changes only slightly; that is, the rotational component of strain decreases with progressive deformation. This concept applies to the limbs of the developing buckle folds where limb shear increments intensify fabrics already sub-parallel to the shear plane.

In the fold hinges a major component of the imposed incremental shortening persistently operates parallel to the pre-existing foliation and weakens the S-fabrics that may subsequently transform into L-fabrics. The resultant elongation is parallel to the hinge line because the bulk shortening component is close to normal to the axis of the amplifying folds. This situation is comparable with folding of compacted sediments, which develop pencil structures preferentially in fold hinges as a result of layer-parallel shortening superimposed on sedimentary fabrics recording volumetric strains during compaction (e.g. Ramsay and Wood, 1973; Ramsay and Huber, 1983). These patterns are also similar to those of the last generation folds in the Chiwaukum Schist and Napeequa unit where lineations are well developed in hinge zones, but are weaker in limbs. Whether the lineation parallels, or transects, fold hinge lines is contingent upon the irrotational or rotational nature of the applied bulk deformation and/or the prior orientation of the buckled layers. Thus, L-fabrics slightly oblique to last generation folds are common due to progressive rotation and migration of their hinge lines.

6.3.2. Shear zone dominated outcrop-scale structures

Deformation associated with the Windy Pass thrust (Fig. 15) reoriented and intensified foliation in the footwall of Chiwaukum Schist. Weak lineation in the schist and overriding ophiolite is at a high angle to the inferred displacement direction of the thrust and is probably composite, reflecting superposition of thrust-related shear on earlier folds. In the Mount Stuart batholith, this lineation primarily records non-coaxial shear during thrusting.

Pervasive shear in the Swakane Gneiss and top-to-N or -NNE domainal shear in the Napeequa unit in the Chelan block are associated with the Dinkelman décollement and document the significance of non-coaxial shear. In the Wenatchee block, reorientation of lineation in the Napeequa unit as the Swakane contact is approached is also compatible with non-coaxial shear along this boundary. Non-coaxial shear associated with the décollement was considerably younger (post-72 Ma to perhaps 45 Ma) than the other shear zones and at least in part related to exhumation of deep levels of the Cascades core, which overlapped with regional Eocene transtension (e.g. Johnson, 1984). This younger non-coaxial shear controlled lineation orientation over a sizable percentage of the deepest exposed levels of the core (Fig. 15), but affected an exposed structural thickness of <1.5 km.

Down-dip mineral lineation records SW-directed shear in moderately to steeply NE-dipping reverse shear zones that deform the Chiwaukum Schist, Napeequa unit, and Ingalls ophiolite, and are localized next to plutons (Mount Stuart, Dirtyface, Tenpeak). Mineral lineations are concordant to those in the adjacent plutonic rocks and reflect superposition of strong non-coaxial shear on previously folded rocks. These shear zones take up the same NE–SW shortening as fold-dominated tracts and deform a relatively small volume of rock (Fig. 15). Localization of the shear zones probably reflects the large rheological contrast across moderately to steeply dipping contacts between plutons and host rocks during regional shortening.

6.3.3. Pluton structural aureole dominated outcrop-scale structures

Ascent and emplacement of magma imposed another set of structural boundary conditions on metamorphic units in narrow structural aureoles of plutons (Fig. 15). Lineations are deflected, commonly intensify, and in most aureoles reflect vertical, typically downward, ductile flow. Vertical ductile flow is preserved in structural aureoles of plutons ranging from 96–90 (Mount Stuart, Tenpeak) to 72 (Entiat pluton) to 46 Ma (Duncan Hill pluton; Miller and Paterson, unpub. data). We have interpreted the ductile deformation as recording return flow of host rock during ascent of viscoelastic diapirs (Paterson and Miller, 1998b; Miller and Paterson, 1999).

6.4. Summary and regional implications

Some workers (e.g. Brown and Talbot, 1989) have utilized mineral lineation in the Cascades core to infer the regional displacement direction and proposed that the core was deformed by distributed dextral strike slip. Our data refute this hypothesis. In the large regions dominated by mid- to Late Cretaceous (pre-96–$\sim$72 Ma) folding, particularly in the Chiwaukum Schist and Napeequa unit, mineral lineation orientation is controlled by folds and may vary across individual folds. Lineation is thus not parallel to the regional displacement. In the steep, SW-vergent shear zones, mineral lineation probably more closely approximates the direction of non-coaxial shear. The orientation of these shear zones, and presumably the displacement direction, however, is in part controlled by the moderately to steeply dipping walls of plutons that localized the zones. The generally weak, E–W-trending mineral lineation in the domain deformed by the Windy Pass thrust is at a high angle to the inferred displacement direction. Collectively, these structures are compatible with regional NE–SW to NNE–SSW Cretaceous shortening, in agreement with metamorphic P–T–t data that indicate major crustal thickening between 91 and 75 Ma (cf. Whitney et al., 1999).

Folding continued to influence lineation orientation during ductile deformation in the deepest exposed levels of the Cascades core after 72 Ma, but top-to-N to -NNE non-coaxial shear dominated. NNW- to NNE-trending mineral lineation in the Swakane Gneiss and lowest levels of the structurally overlying Napeequa unit was probably subparallel to regional displacement during exhumation (ignoring spin from vertical thinning) in response to regional transtension. Counterclockwise rotation in lineation orientation also likely tracked changing displacement directions as temperatures decreased.

7. Conclusions

1. Ductile deformation and mineral lineation formation initiated before 96 Ma in the Chiwaukum Schist and

Napeequa unit of the Cascades core, and probably continued until nearly 48 Ma in the structurally deepest rocks of the Swakane Gneiss.

2. Outcrop-scale structures in the Cascades core record multiple boundary conditions. Mineral lineation in most of the Chiwaukum Schist and much of the Napeequa unit reflects strains resulting from superposition of multiple cycles of folds. Displacement in shear zones, which are commonly localized next to plutons, modified fold-related fabrics in several domains. Fabrics were also modified by flow in structural aureoles imposed by pluton emplacement.
3. Only a single mineral lineation and foliation developed in most places, implying that both are generally composite and record multiple deformation cycles. Formation of these composite fabrics was probably facilitated by deformation during prolonged amphibolite–facies conditions.
4. Mineral lineation orientations cannot be used to infer regional displacement in much of the Cascades core, as these are the end products of a complex history lasting for >45 m.y. at various crustal levels.
5. Mechanical anisotropy played a major role in controlling outcrop-scale structures in the Cascades core.

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