Source of Meta-Igneous Blocks and Structure of the Colebrooke Schist in the Snowcamp Peak Area, Pickett Peak Terrane, Southwestern Oregon

Abstract of a thesis presented
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Master of Science
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Abstract

The Colebrooke Schist of the Pickett Peak terrane, southwestern Oregon, is the easternmost, structurally highest unit of the Late Mesozoic-Cenozoic Franciscan Accretionary Complex. The Colebrooke Schist consists of mostly transitional greenschist-blueschist-facies meta-sedimentary rocks with common blocks of meta-volcanics and serpentinites, rare talc-schists and meta-plutonic rocks. The Colebrooke Schist meta-volcanic blocks are greenstones, in many cases with visible relict pillow structures and relict igneous textures.

Fifteen meta-volcanic samples and one meta-plutonic sample were analyzed by XRF and ICP-MS and were plotted with analyses from Plake (1989) and Coleman (1972). The Colebrooke Schist meta-volcanic rocks plot in mid-ocean ridge basalt (MORB), island arc tholeiite (IAT) and transitional MORB/IAT fields on V-Ti, Th/Yb-Ta/Yb and Cr-Y diagrams. The range of magma types suggests that the Colebrooke Schist meta-volcanic blocks are derived from a back-arc basin basalt source. The Colebrooke Schist contains unusually high iron and titanium (Fe-Ti) MORB. The Colebrooke Schist analyses were separated into five individual large blocks. The Quosatana Butte, Skookumhouse

Butte and Copper Canyon blocks have MORB affinities, whereas blocks, in a serpentinite mélange underlying the Colebrooke Schist, from Mineral Hill and Saddle Mountain are transitional MORB/IAT. The geochemical similarity of Colebrooke Schist samples with Coast Range ophiolite and Josephine ophiolite, the similar age of a block in the Colebrooke to the Josephine ophiolite, as well as geochemical similarities and probable pebbly mudstone matrix all suggest that some of the Colebrooke Schist meta-igneous blocks may be sedimentary blocks derived from the Josephine and possibly also Coast Range ophiolites, deposited as olistostromes in the Early Cretaceous trench off western North America. Very large, MORB affinity blocks allows the possibility that at least some of the Colebrooke Schist blocks are dismembered remains of the ocean floor basement.

The Colebrooke Schist has undergone three deformation events. D_1 consists of foliation first observed by Coleman (1972) and later described by Plake (1989) as alignment of platy minerals and the flattening of relict pillow structures. D_2 consists of crenulation cleavage, S_2, and folds, F_2 (Coleman, 1972 and Plake, 1989). Plake (1989) described D_3 features as an S_3 crenulation cleavages and F_3

folds without axial planar cleavage. Foliations, equivalent to S_1 from Plake (1989), measured throughout the field area generally vary in strike from northwest to northeast and dip to the east and define a broad girdle on an equal area projection. The orientations of stretching lineations (equivalent to L_1 of Plake, 1989) are scattered with no clear average value, although most plunge gently to moderately southeast or northwest. These shallow plunges and variable trends are consistent with rotation about a vertical axis, which supports Plake's (1989) proposal that the Colebrooke Schist has undergone rigid block rotation. The variation in foliation and lineation measurements is likely the result of one or a combination of three possibilities: 1) post-metamorphic folding following D_3, 2) drag folding along the late north- to northeast-striking strike-slip faults, or 3) extensive shearing associated with veining throughout the Colebrooke Schist.

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Introduction

The Colebrooke Schist of the Pickett Peak terrane, in the Franciscan accretionary complex, forms the boundary between the Franciscan and the overlying Snow Camp terrane. The Colebrooke Schist, covering ~150 km^2 in southwestern Oregon, probably correlates (Brown and Blake, 1987) with the Shuksan Metamorphic Suite (Misch, 1966) in Washington, and the Condrey Mountain Schist, South Fork Mountain Schist and Redwood Creek Schist (Kelsey and Hagans, 1982) to the south. Sparse outcrop exposure and the poorly constrained age of the Colebrooke as well as the Shuksan, Condrey Mountain, South Fork Mountain and Redwood Creek Schists make reconstructing the tectonic history of the western North American Coast difficult. It would be beneficial to know in more detail the origins of these units.

The Colebrooke Schist contains numerous greenstone blocks. Similar greenstone blocks have been studied elsewhere in the Franciscan accretionary complex (Shervais and Kimbrough, 1987; Huot and Maury, 2002; Macpherson et al., 1990). These studies suggest a range of origins for these blocks, derived perhaps from both the downgoing slab and the hanging wall. The purpose of this study is to constrain the origin for the greenstone blocks of the Colebrooke Schist, and also to compare these to the greenstones of the overlying ophiolitic Snow Camp terrane and Josephine ophiolite to add insight to the accretion of the western North American terranes. In addition, the structural geology of the area was studied and is compared to previous work by Plake (1989).

Regional Geology

The Colebrooke Schist and a serpentinite mélange are part of the Pickett Peak terrane (Figure 1; Roure and Blanchet, 1983; Blake et al., 1982; 1985a). The Pickett Peak terrane is one of six fault-bounded, accreted terranes in southwestern Oregon (Blake et al., 1985a). From west to east, these six terranes are the following: Gold Beach terrane, Yolla Bolly terrane, Sixes River terrane, Pickett Peak terrane, Snow Camp terrane and Western Klamath terrane (Figure 2; Blake et al., 1985a).

The Gold Beach terrane consists of an Upper Jurassic sedimentary unit—the Otter Point Formation—with sedimentary rocks derived from an island arc (Figure 2; Blake et al., 1985a). The Otter Point Formation is unconformably overlain by Cretaceous quartzofeldspathic strata (Figure 2; Blake et al., 1985a).

The Yolla Bolly terrane (Blake and Jones, 1974; 1977) is composed of the Upper Jurassic to Lower Cretaceous Dothan Formation. Widmier (1962) divided the sedimentary and igneous rocks of the Dothan into two members: a predominately volcanic coastal member and a predominately sandstone inland member. Based on these

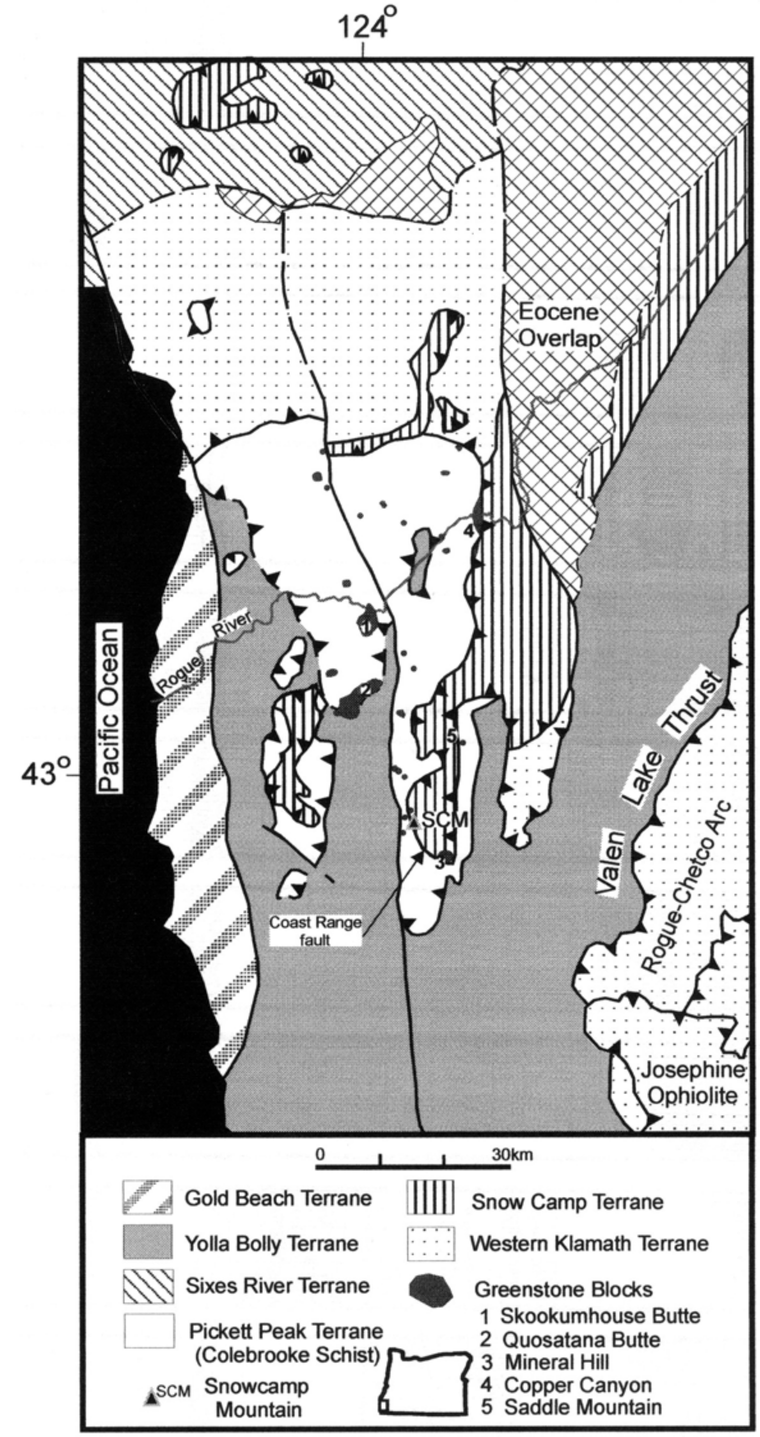


Figure 1. Regional map from Roure and Blanchet (1983), Blake et al. (1982, 1985a), and G. Harper and M. Giaramita (unpublished mapping). Mineral Hill and Saddle Mountain greenstone blocks are blocks in the serpentinite melange underlying the Colebrooke Schist.

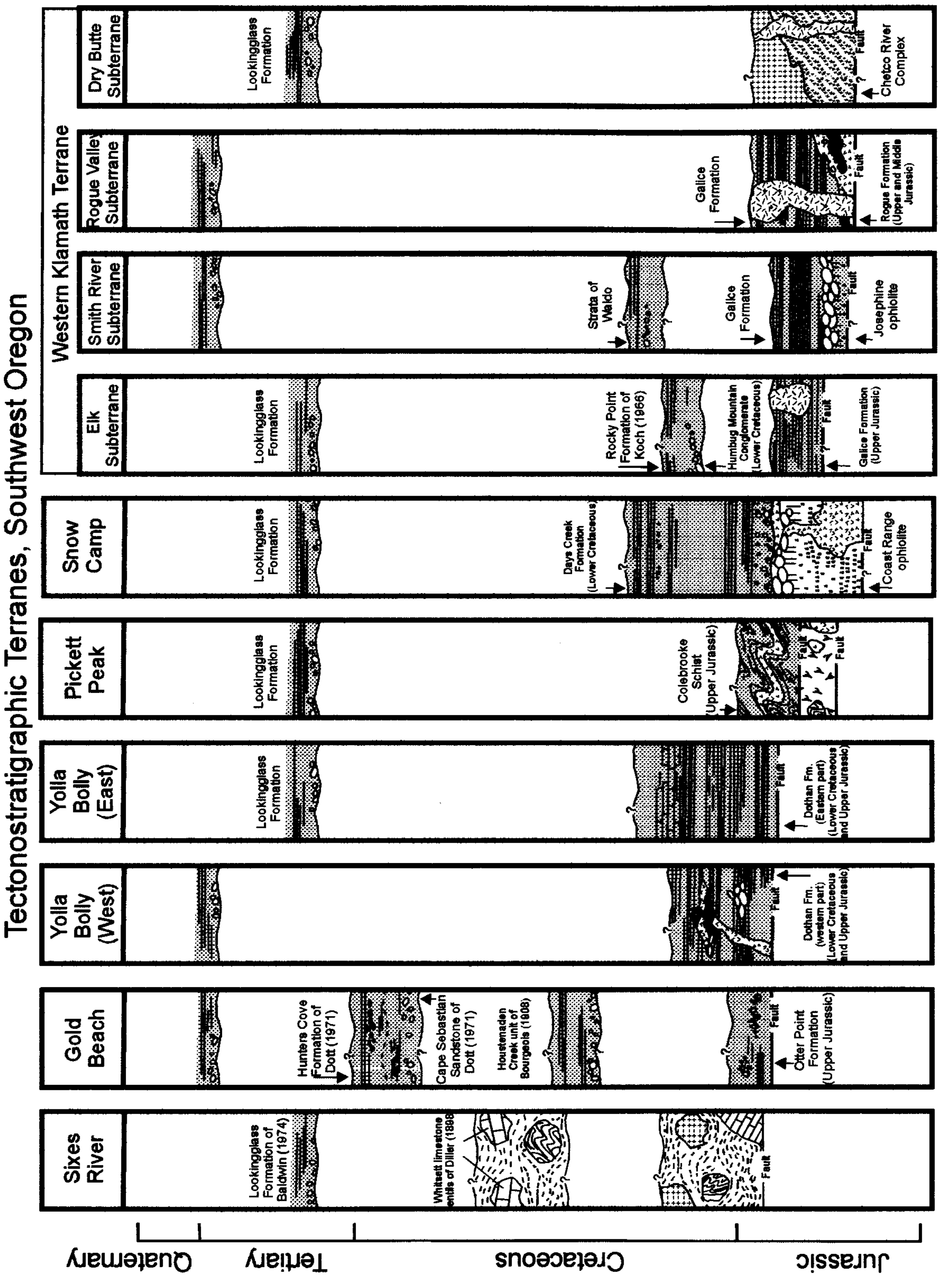


Figure 2: Tectonostratigraphic columns for terranes in southwestern Oregon (Figure 2 of Blake et al., 1985a).

lithologic differences, as well as textural and geochemical differences, Blake et al. (1985a) divided the Yolla Bolly terrane into eastern and western subterranes (Figure 2).

The Sixes River terrane is the only one of these terranes that contains abundant mélange, most of which has a sheared graywacke and shale matrix (Coleman and Lanphere, 1971). Blueschist and eclogite are common as tectonic blocks (Coleman and Lanphere, 1971), and a few limestone blocks have been found (Diller, 1898; Blake et al., 1985a).

The Pickett Peak terrane is the structurally highest and highest-grade unit of the Franciscan accretionary complex in northern California and southwestern Oregon. The Pickett Peak terrane in Oregon consists of the Colebrooke Schist; in addition, Blake et al. (1985a) include a serpentinite mélange, mapped by Roure and Blanchet (1982), that underlies the Colebrooke Schist (Figure 2), although in the Snowcamp Mountain area a serpentinite mélange overlies the Colebrooke (G. Harper and M. Giaramita, unpublished mapping). The Colebrooke Schist, as discussed below, is a transitional greenschist- and blueschist-facies metapelite and metagraywacke with common mafic metavolcanic units and rare metachert (Coleman, 1972). The serpentinite mélange mapped by Roure and Blanchet (1983) contains blueschist (Roure and Blanchet, 1983) and greenstone knockers (Blake et al., 1982). Coleman (1972) suggests that this mélange was a slab of oceanic crust and mantle that was serpentinized during accretion.

Two large greenstone blocks in this study are from a serpentinite mélange between the Colebrooke Schist and the Snow Camp terrane that is likely part of the Pickett Peak terrane. These blocks are Saddle Mountain (samples SM-10b, SM-10c, SM-10d; Figure 1) and Mineral Hill (samples SM-13a, SM-13b, SM-13c, SM-110, SM-116; Figure 1). The Saddle Mountain block is located on the eastern flank of Saddle Mountain, 540 m east of the peak (N 124 7' 21" latitude, W 42 24' 9" longitude). Blake et al. (1985a) included this serpentinite mélange in the eastern part of the Snow Camp terrane, but it is situated above the Colebrooke Schist and beneath ophiolitic rocks of the Snow Camp terrane (G. Harper and M. Giaramita, unpublished mapping). There are slivers of Colebrooke Schist in both the Saddle Mountain block and the Mineral Hill block (G. Harper, unpublished field data), so the serpentinite mélange could be part of the Colebrooke Schist even though it is here at the top, rather than at the base of the schist as reported by Roure and Blanchet (1983). Alternatively, the serpentinite mélange beneath the Snow Camp terrane might be younger than the Colebrooke Schist, having formed during juxtaposition of the Snow Camp terrane with the Colebrooke Schist along the Coast Range fault. Such an origin is suggested by the presence of blocks unlike those in the Colebrooke Schist (e.g., undeformed ultramafic cumulates, hornblende diorite, and peridotite; G. Harper, unpublished field data). This is also suggested by the geochemistry of the two pillow lava blocks analyzed for this study (presented below), which is more like that of ophiolitic rocks of the Snowcamp terrane and Josephine Ophiolite than that of blocks that are clearly part of the Colebrooke Schist.

The Snow Camp terrane is a dismembered ophiolite with overlying sedimentary rocks (Blake et al., 1985a). The ophiolitic rocks of the Snow Camp terrane were correlated with the Coast Range ophiolite of California by Blake et al. (1985b), but it may instead be an outlier of the Josephine Ophiolite (Schoonmaker et al., in press). The Coast Range and Josephine Ophiolite are similar in age, however, and may have formed in the same suprasubduction zone spreading system (e.g., Saleeby, 1992; Dickinson et al. 1996). The Coast Range ophiolite in California is variable and generally dismembered, consisting of faulted serpentinized peridotite, gabbro, rare sheeted dikes, pillow basalts, and/or (locally) ophiolitic breccias (Gullixson et al., 1980; Blake et al., 1985a; Dickinson et al., 1996; Shervais et al., in press), as well as local overlying andesitic and dacitic volcaniclastic rocks and rare later hypabyssal intrusions (Dott, 1971; Dickinson et al., 1996). A U-Pb zircon age for the sheeted dike complex in the Snow Camp terrane included in the Snowcamp Mountain area is 169 ± 1 Ma (Saleeby, 1984), and several ages from the Wild Rogue Wilderness ophiolitic rocks are 164 ± 1 Ma, similar to ages for the Coast Range and Josephine Ophiolites (Harper et al., 1994; Dickinson et al., 1996; Shervais et al., in press).

The ophiolitic rocks in the Wild Rogue Wilderness area of the Snow Camp Terrane are overlain by a thick sequence of intermediate to felsic volcaniclastic rocks that are locally interbedded with chert (Kosanke, 2000; Harper, 2002). A dacite flow (or sill) within the upper part of the volcaniclastic unit gave an Ar/Ar hornblende age of 153 ± 1 Ma, but otherwise the unit is undated (Kosanke, 2000). Marine clastic sedimentary rocks of the Myrtle Group overlie the volcaniclastic unit. The Myrtle Group contains index fossils of the bivalve *Buchia* (Imlay et al., 1959) that indicate an Upper Jurassic (Tithonian) to Lower Cretaceous age (Dott, 1971; Blake et al., 1985a). No volcaniclastic unit was found overlying the ophiolitic rocks in the Snowcamp Mountain area; a basal conglomerate-rich unit of the Myrtle Group overlies pillow lavas of the ophiolite in a road cut on the south flank of Saddle Mountain, although the contact itself is covered and may be a fault (G. Harper and M. Giaramita, unpublished data). A fault bounded outcrop in the upper part of Lawson Creek consists of massive green chert, some beds of which contains sand-size clasts of mafic volcanic rock similar in texture to boninitic pillow lavas at the top of the pillow lavas of the ophiolite (G. Harper, unpublished field data); these rocks are likely part of the pelagic sequence deposited on top of the pillow lavas. The Snow Camp terrane is intruded by ~149 Ma small plutons and dikes in the Snowcamp area (Harper et al., 2000).

The Myrtle Group has been correlated to the Great Valley Sequence that overlies the Coast Range ophiolite and its volcanopelagic sequence in California (Jones, 1973; Blake et al., 1985b; Dickinson et al., 1996). The Lower Cretaceous Myrtle Group unconformably (angular) overlies the Josephine ophiolite and overlying Galice Formation of the Western Klamath terrane (Harper et al., 1994; Dott, 1966), whereas Blake et al. (1985b) reports that the Upper Jurassic and Lower Cretaceous Myrtle Group depositionally overlie the ophiolite in the Snow Camp terrane (Blake et al., 1985b). Because of a lack of age data for sedimentary and volcaniclastic rocks between the ophiolite and the Myrtle Group, however, the contact could be a disconformity (Kosanke, 2000). Kosanke (2000) found that the bedding in the Myrtle Group and underlying volcaniclastic unit were similar, but that some shearing was present at the actual contact.

The Western Klamath terrane consists of the Josephine ophiolite and the overlying Galice Formation (Harper, 1984; Harper et al., 1994). It also includes the Late Jurassic volcanic Rogue Formation and the Chetco intrusive complex, a Late Jurassic island arc complex (e.g. Harper and Wright, 1984; Harper et al. 1994; Yule,

1996. Blake et al. (1985a) subdivided the Western Klamath terrane in Oregon into four subterranes (Figure 2). The Upper Jurassic Galice Formation consists of turbidites (flysch) that were metamorphosed to low grade and deformed during the Late Jurassic Nevadan Orogeny (Harper, 1984; MacDonald and Harper, in press). In the "Smith River subterrane" (Figure 2) of Blake et al. (1985a), the ~162 Ma Josephine Ophiolite, a complete ophiolite, is overlain by a hemipelagic sequence which is in turn overlain by flysch of the Galice Formation (Harper et al., 1994; MacDonald and Harper, in press). The Josephine Ophiolite is interpreted to have formed in a suprasubduction zone setting (Harper, 1984; Harper and Wright, 1984; Harper et al., 1994, Harper, 2003a, 2004). Rare, late stage highly fractionated Fe-Ti basalts have been found in the Josephine ophiolite (Harper, 2003a), suggesting formation at a propagating spreading center.

The Rogue-Chetco island arc complex of the western Klamath terrane consists of both the Rogue Formation and the Chetco Intrusive Complex (Dick, 1976; 1977; Garcia, 1982; Harper and Wright, 1984; Harper et al., 1994; Yule, 1996). In what Blake et al. (1985a) called the Rogue River subterrane (Figure 2), the Rogue Formation is depositionally overlain by the Galice Formation (Harper et al., 1994) and is comprised of submarine volcanic breccias, tuffs and volcaniclastic rocks metamorphosed to low grade. The ~157 to 153 Ma Rogue Formation is deposited on a basement of Triassic disrupted ophiolitic rocks (Yule, 1996), which may include amphibolite of the Briggs Creek subterrane (Figure 2) of Blake et al. (1985a). The Dry Butte subterrane of Blake et al. (1985a) consists of the 160 to 157 Ma Chetco Intrusive Complex, also known as the Illinois River plutonic complex (Yule, 1996), and is interpreted as the core of the Rogue-Chetco island arc complex (Dick, 1976; Garcia, 1982; Harper et al., 1994; Yule, 1996).

Franciscan Accretionary Complex

In Oregon, the Gold Beach terrane, Yolla Bolly terrane, Sixes River terrane and Pickett Peak terrane are part of the Franciscan Accretionary Complex. The Franciscan accretionary complex extends from California northward to Washington. The Franciscan accretionary complex in California has been extensively studied. Irwin (1960) divides the Franciscan into three belts—(from west to east) the Coastal belt of Bailey and Irwin

(1959), the Central belt and the Eastern belt (Figure 3). Blake et al. (1985b) further subdivided these belts into six terranes (Figure 3): the Yager, Coastal and King Range terranes are part of the Coastal belt; the Central terrane is now the Central belt, and the Yolla Bolly and Pickett Peak terranes comprise the Eastern belt (Figure 3).

The Coastal Belt of the Franciscan Complex is the most western, least metamorphosed of the Franciscan (Blake and Jones, 1981). The Coastal terrane contains Late Cretaceous to Late Eocene arkosic sediments and is highly fractured and sheared (Blake et al., 1985b). The Yager terrane is comprised of the Paleocene to Late Eocene Yager Formation, which contains mudstone-rich turbidites and interbedded sandstones and conglomerates (Blake et al., 1985b). The King Range terrane of McLaughlin et al. (1982) is composed of the Point Delgada and King Peak subterranes. The Late Cretaceous Point Delgada subterrane contains pillow lavas and diabase, overlain by arkosic sandstone and argillite (Blake et al., 1985b). The Paleogene to Middle Miocene King Peak subterrane is comprised of calcareous argillite with

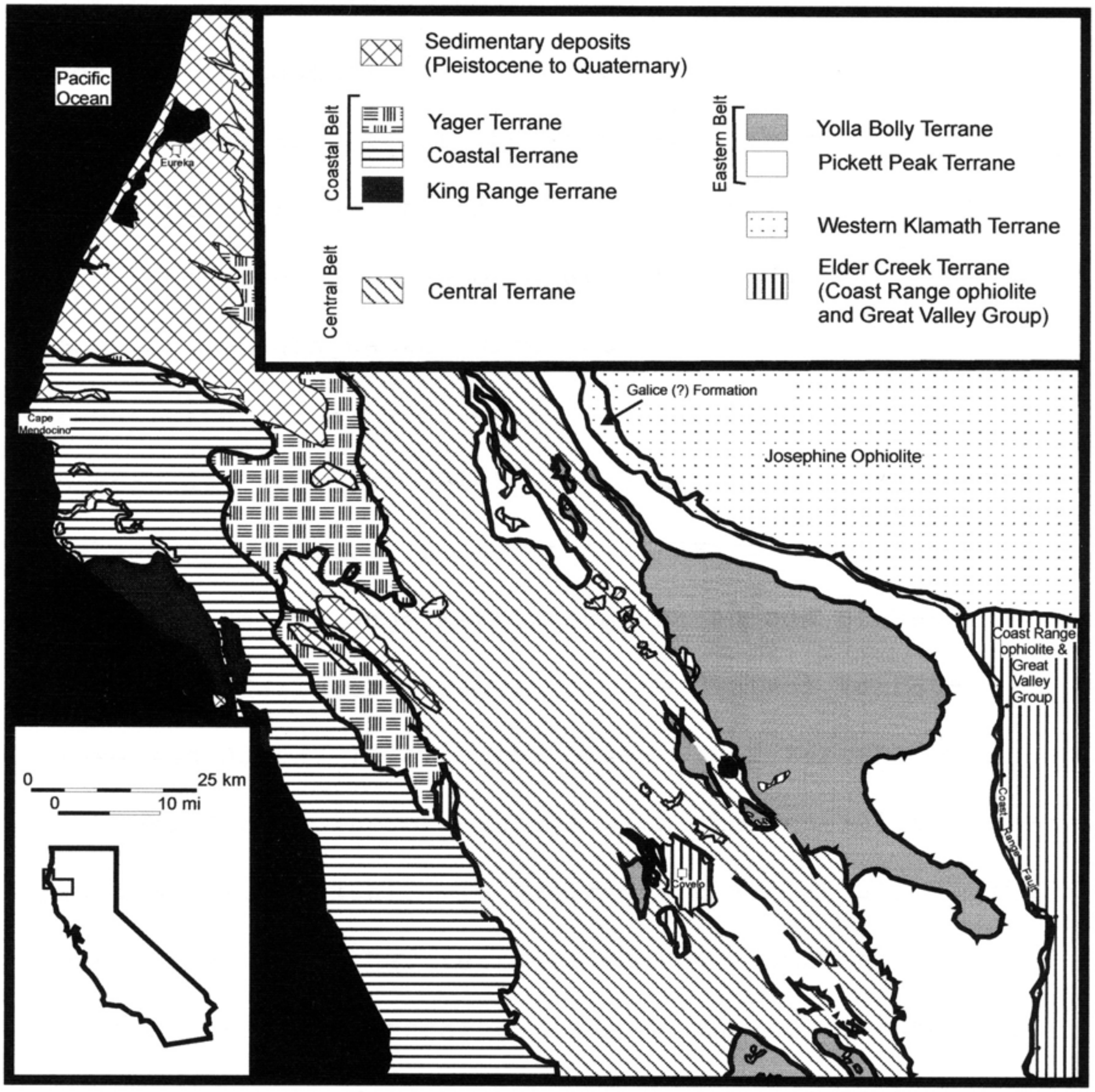


Figure 3. Terrane map of northwestern California, modified after Figures 2a and 2b in Blake et al. (1985b).

interbeds of quartzofeldspathic to volcaniclastic sandstone (McLaughlin et al., 1983).

The Central Belt of the Franciscan is comprised of the Central terrane of Blake et al. (1982; 1985b). The Central terrane is a mud or graywacke matrix mélange with blocks of metagraywacke, greenstone, chert and serpentinite (Blake and Jones, 1981). Blueschist knockers are abundant (Blake and Jones, 1981) in a matrix of sheared argillite (Blake et al., 1985b). *Buchia* fossils in the mélange matrix suggest an age of Late Jurassic to Early Cretaceous for the Central terrane (Blake and Jones, 1974). The Sixes River terrane of southwest Oregon is correlative with the Central terrane (Blake et al., 1985b). In addition, Blake et al. (1985b) suggest that the other terranes of the Franciscan accreted into the Central terrane on the continental margin, since the Central terrane is similar in protolith to the basal rocks of the Great Valley sequence (Blake and Jones, 1974).

The Eastern Belt is comprised of the Yolla Bolly and Pickett Peak terranes (Blake et al., 1985b). The Late Jurassic to Middle Cretaceous (Blake and Jayko, 1983) Yolla Bolly terrane contains units of graywacke and chert with intrusions of basalt and gabbro (Blake et al., 1985b). Lawsonite and sodic amphibole have been found in the Yolla Bolly terrane (Blake et al., 1981; Blake and Jayko, 1983). The Pickett Peak terrane is composed of the South Fork Mountain Schist and Valentine Spring Formation (Worrall, 1981). The South Fork Mountain Schist is quartz-mica-lawsonite schist with greenschist- and blueschist-facies metavolcanic rocks (Blake et al., 1967). The Valentine Spring Formation is schistose to gneissic metagraywacke (Worrall, 1981). In southwest Oregon, the Pickett Peak terrane consists of the Colebrooke Schist.

Colebrooke Schist

The Colebrooke Schist is part of the Pickett Peak terrane in Oregon (Figure 1; Roure and Blanchet, 1983; Blake et al., 1982; 1985a) and crops out over an ~150 km^2 area. The Colebrooke Schist consists largely of fine-grained metasedimentary rocks (phyllites and semischists) of transitional greenschist-blueschist facies. These metasedimentary rocks are strongly foliated. In addition to metasedimentary rocks, the Colebrooke Schist also contains minor tuff, metachert

(Coleman, 1972) rare talc-schists and common meter- to kilometers-scale meta-igneous blocks, nearly all of which are metabasalt. The meta-igneous rocks are greenstones. Many of the metabasalts have pillow structures. Most of the metabasalts observed show no foliation; in the few that do have foliation it appears to be similar in orientation to the foliation of the surrounding metasedimentary rocks. The Colebrooke Schist also contains rare metaplutonic rocks. The general metamorphic mineral assemblage for the metasedimentary rocks is quartz + chlorite + phengitic mica + albite + epidote ± lawsonite (lawsonite observed by Coleman, 1972; and Plake, 1989). The metamorphic assemblage for the meta-igneous blocks is generally actinolite + epidote + albite + chlorite ± pumpellyite ± crossite (crossite observed by Coleman, 1972). Inferred protoliths for the metasedimentary rocks are shale and sandstone (Coleman, 1972).

The age of the Colebrooke Schist is poorly constrained. A Rb-Sr isochron age for metasedimentary rocks of 128 ± 18 Ma is possibly the age of metamorphism (Coleman 1972). Walker et al. (1987) reported a concordant U-Pb age of 162 ± 1 Ma for a meta-quartz diorite block in the Colebrooke. This is perhaps the maximum age of the Colebrooke Schist, if the meta-quartz diorite block is sedimentary (Plake, 1989). If the meta-quartz diorite originally intruded the Colebrooke as suggested by Walker et al. (1987), this age would be a minimum age of the Colebrooke metasedimentary protolith.

Coleman (1972) inferred the Colebrooke Schist was deposited off a continental margin (the west coast of North America) as deep ocean sediments. In addition, Coleman (1972) suggests that the metabasalts in the Colebrooke Schist are derived from ocean basement.

Brown and Blake (1987) correlated the Colebrooke Schist with other units of western North America containing blueschists, including the following: the Shuksan metamorphic suite (Misch, 1966) in northwestern Washington, the South Fork Mountain Schist and Redwood Creek Schist (Kelsey and Hagans, 1982) of the Pickett Peak terrane in northern California, and the Condrey Mountain Schist of the central Klamath Mountains (Figure 4). These units are similar in lithology, were metamorphosed under high P/T conditions, have similar apparent ~125 to 135 Ma metamorphic ages, and are fault-bounded. Furthermore, the Shuksan and Colebrooke Schist

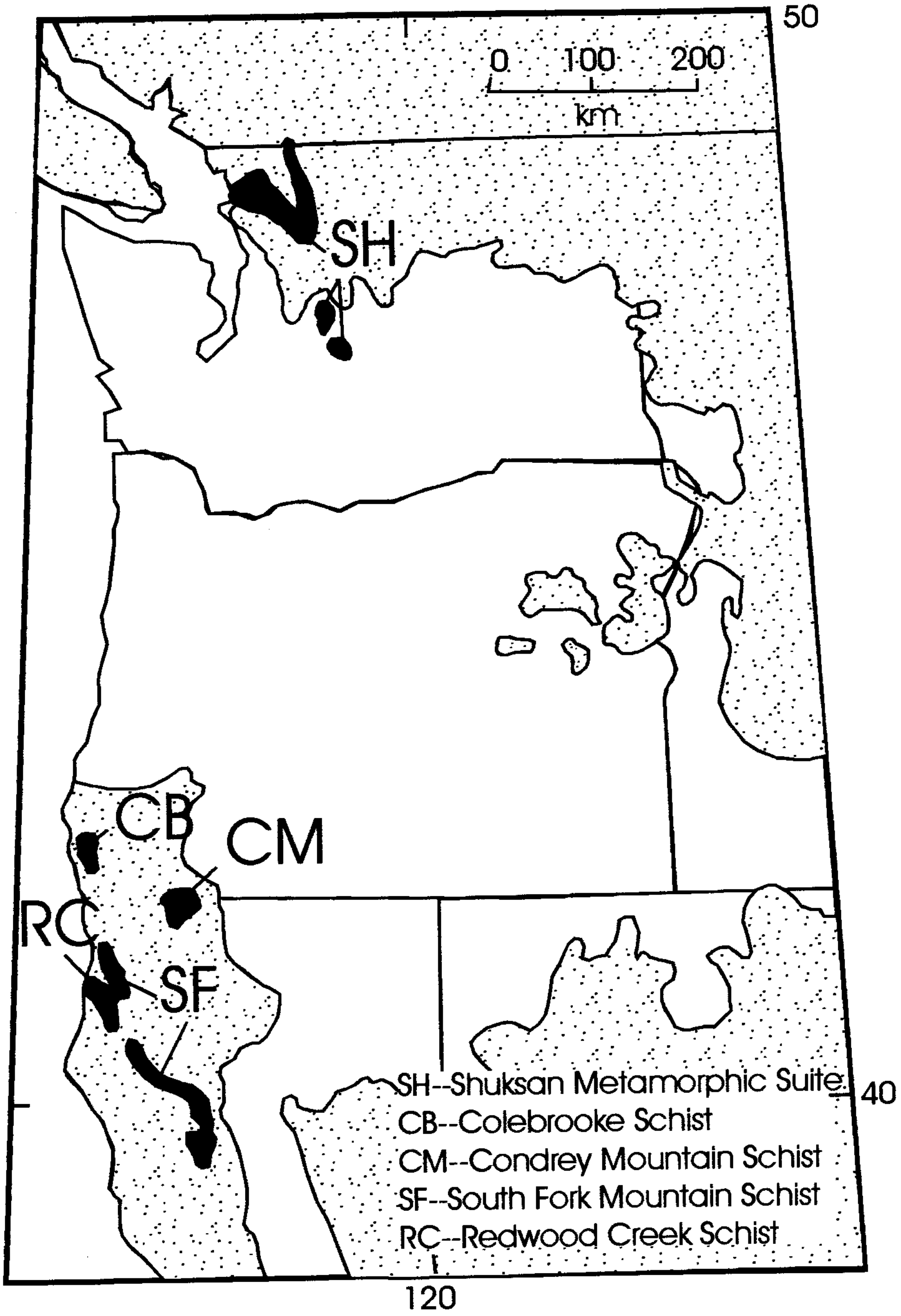


Figure 4: Location of blueschist units correlative with the Colebrooke Schist, from Figure 1 of Brown and Blake (1987). Dotted pattern is pre-Tertiary rock.

units contain ~163 Ma metaplutonic rocks (Walker et al., 1987). These blueschist units were perhaps at one time a continuous unit that was dismembered and dispersed northward after metamorphism (Brown and Blake, 1987). Another possibility is that each of these units formed independently in similar settings (Brown and Blake, 1987).

Coast Range fault

In Oregon, the eastward dipping Coast Range fault places the structurally highest unit of the Franciscan complex, the Pickett Peak terrane (Colebrooke Schist), in fault contact with the structurally overlying dismembered ophiolite of the Snow Camp terrane (Blake et al., 1985a). In California, the Coast Range fault separates the Pickett Peak terrane from either the Coast Range ophiolite or, in northernmost California, the Western Klamath terrane (Blake et al., 1984).

Previous Work

Colebrooke Schist

Diller (1903) first mapped and named the Colebrooke Schist. Coleman (1972) followed with a much more complete study of the Colebrooke Schist. In addition to publishing a comprehensive map of the Colebrooke Schist, Coleman (1972) did semiquantitative geochemical analyses on the Colebrooke Schist metasedimentary and metavolcanic rocks. According to Coleman (1972), the Colebrooke Schist metasedimentary rocks are geochemically similar to Galice Formation metasedimentary rocks (MacDonald and Harper, in press), but not geochemically similar to metasedimentary rocks in the Dothan or Otter Point Formations. Coleman (1972) interpreted this to mean that the Galice Formation and Colebrooke Schist formed in similar environments. Conversely, Coleman (1972) interpreted that the Colebrooke Schist and the Dothan and Otter Point either had different source areas or that their chemical differences resulted from metasomatism during metamorphism.

Both Coleman (1972) and Plake (1989) studied the geochemistry of the Colebrooke Schist meta-igneous rocks. Coleman (1972) quantitatively analyzed major elements for

11 metabasalts and semiquantitatively analyzed for trace elements. These metabasalts plot as tholeiitic on the AFM plot (Coleman, 1972), but Coleman did not consider the possibility of element mobility during metamorphism. Plake (1989) analyzed nine metavolcanic rocks and one metaplutonic rock by XRF. These meta-igneous rocks plot as mid-ocean ridge basalt (MORB) on discriminant diagrams, except for the one metaplutonic rock sample (Plake, 1989). Plake (1989) suggested that the Colebrooke Schist protolith formed in a marginal basin behind a volcanic arc.

Structure of the Colebrooke Schist

Coleman (1972) describes foliation, S_1, that is parallel to bedding and interpreted to have formed during regional metamorphism. This foliation is overprinted by strain-slip cleavage (S_2) and folds (F_2) the axes of which trend N-S and axial planes dip to the west at a low angle (Coleman, 1972). Coleman (1972) interprets that S_2 and F_2 formed during east directed thrusting. Plake (1989) further describes these same structures and interprets two deformation events, D_1 and D_2, as well as identifying crenulation cleavage (S_3) and folding (F_3) she ascribes to a third deformation event, D_3. Alignment of platy minerals and the flattening of relict pillow structures define S_1 (Plake, 1989). S_2 foliation is a crenulation cleavage associated with F_2 fold axes; these structures are the most dominant in outcrop (Plake, 1989). Plake (1989) observed the crenulation cleavage to be axial planar to F_2 folds. Plake (1989) also identifies subtle D_3 features as an S_3 crenulation cleavages and F_3 folds without axial planar cleavage.

Coast Range Fault

Blake et al. (1967) described unusual "upside-down metamorphic zonation," where the metamorphic grade increases upward toward the Coast Range fault, which he interpreted as a thrust. This is based on data from rocks in California, which are correlative with the Colebrooke Schist. Bailey et al. (1970) originally named this fault the Coast Range thrust. It was originally interpreted to be a fossil subduction fault (Hamilton, 1969; Ernst, 1970). Ernst (1970), however, interpreted normal fault motion of Neogene age between the Great Valley Group and the Franciscan Complex. Later, Platt (1986) and Jayko et al. (1987) suggested that normal faulting was responsible for the juxtaposition of the high P/T Pickett Peak rocks, formed at depths of > 25-30 km (Blake et al., 1988; Brown and Ghent, 1983; Ernst, 1993), with the unmetamorphosed rocks of the Coast Range ophiolite and Great Valley Group. Jayko et al. (1987) then suggested that the name be changed from Coast Range thrust to Coast Range fault.

Field Observations

The Snowcamp Mountain area has extensive vegetation cover. With the exception of the west side of Snowcamp Mountain, outcrop exposures are largely confined to road cuts and stream channels, and are sparse elsewhere. The heavy vegetation makes it very difficult to assess the nature of contacts between different metasedimentary rocks and blocks, as well as fault contacts.

Metasedimentary Rocks

The Colebrooke Schist metasedimentary rocks consist of mostly phyllite and semischist (Figure 5). The phyllite is black in color and very fine grained. It is extensively foliated and folded, with abundant quartz veins and rare prehnite veins both parallel and perpendicular to foliation (Figure 6).

The Colebrooke semischist is light to medium gray in color and ranges from very fine to coarse grained. It is foliated, with folds and crenulation cleavage visible in some outcrops. This foliation is visible in thin section (Figure 7). Bedding is not well preserved, but graded

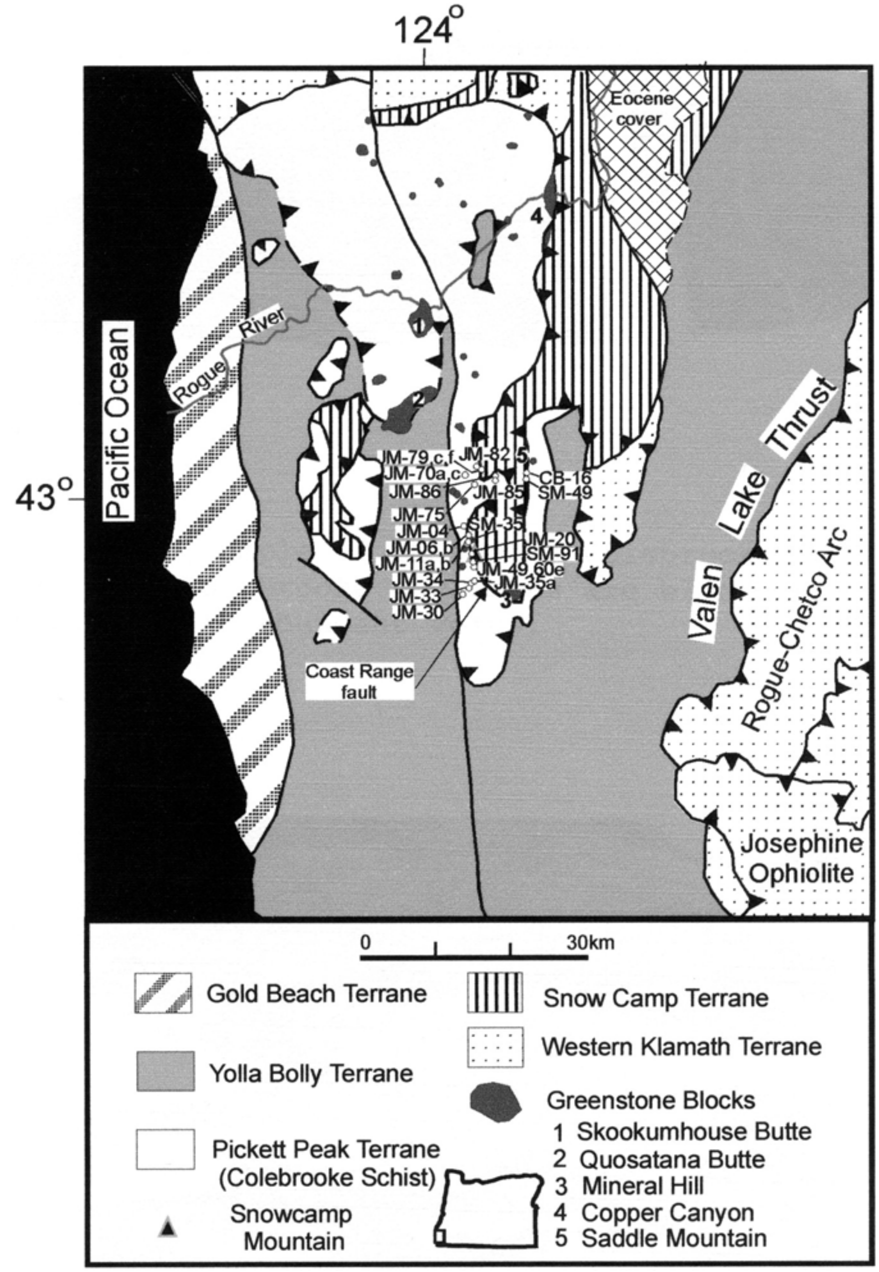


Figure 5. Regional map from Roure and Blanchet (1983), Blake et al. (1982, 1985a), and G. Harper and M. Giaramita (unpublished mapping), showing the locations of Colebrooke Schist metasedimentary rock samples and other types of rock samples. Mineral Hill and Saddle Mountain greenstone blocks are blocks in the serpentinite melange underlying the Colebrooke Schist.

Figure 6. Hand sample of JM-79c, a Colebrooke Schist phyllite. The Colebrooke phyllites are black and very fine grained, with abundant veins.

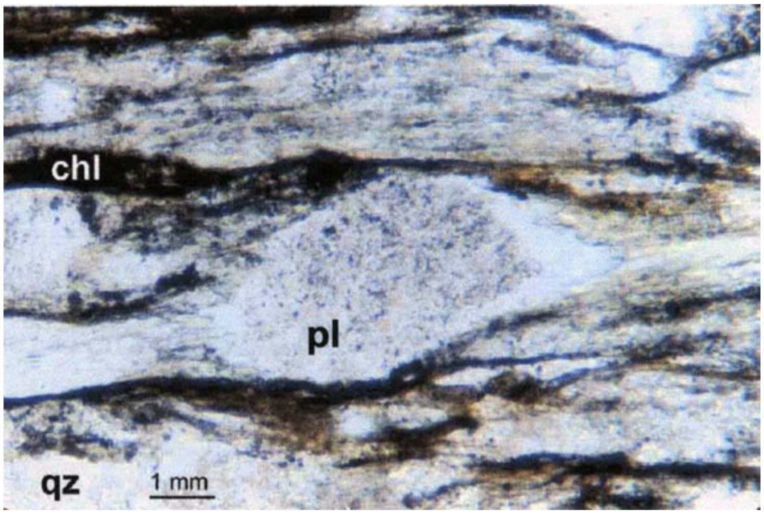


Figure 7. Photomicrograph, under plane polarized light, of metagreywacke sample SM-49 showing foliation. Quartz (qz) and plagioclase (pl) grains are flattened and chlorite (chl) grains are aligned.

bedding was observed at one outcrop, and rip-up clasts were seen at another outcrop (Figure 8).

Meta-igneous Blocks

The smaller, meters-scale meta-igneous blocks in the Colebrooke Schist are visible as bumps on the sides of mountains and in valleys, since they are more resistant to weathering than the surrounding metasedimentary rocks (Figure 9). The largest blocks, such as Quosatana Butte and Skookumhouse Butte (Figure 5), comprise entire mountain peaks. The contacts between the meta-igneous blocks and the metasediments are all obscured by vegetation. Relict pillow structures are well-preserved and common within the greenstone blocks (Figure 10).

Most of the meta-igneous rocks are not foliated, but foliation was observed at one outcrop of metabasalt (Figure 11). In addition, foliation is evident in thin section in samples JM-29 and SM-116 (Mineral Hill), which is a block within the serpentinite mélange underlying the Colebrooke Schist (Figure 12).

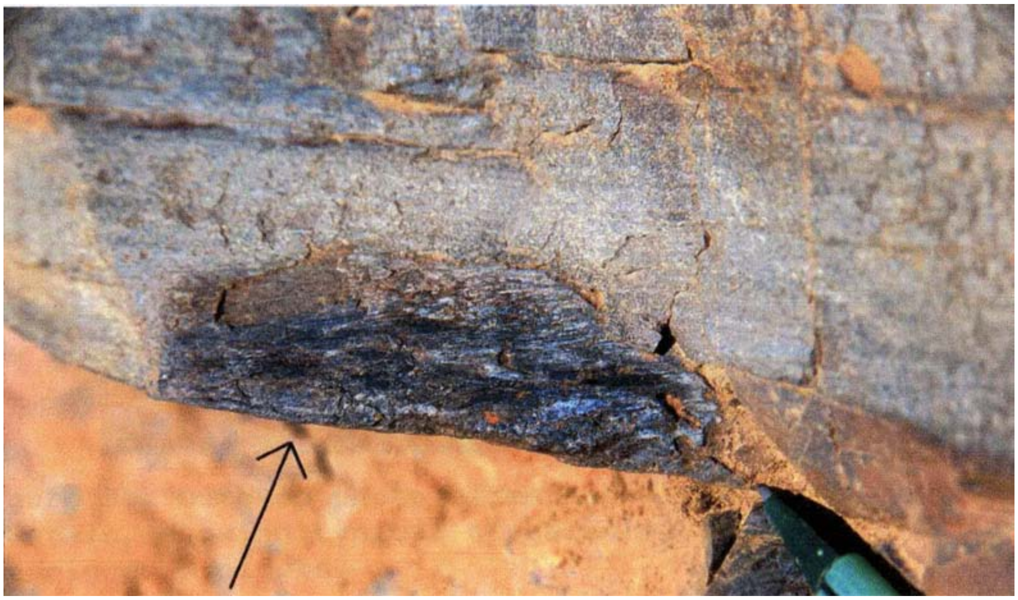


Figure 8. Outcrop of coarse-grained Colebrooke semischist with mud rip-up clast (arrow). Depositional features such as this and bedding surfaces were rarely observed, largely because of heavy vegetation and deformation.

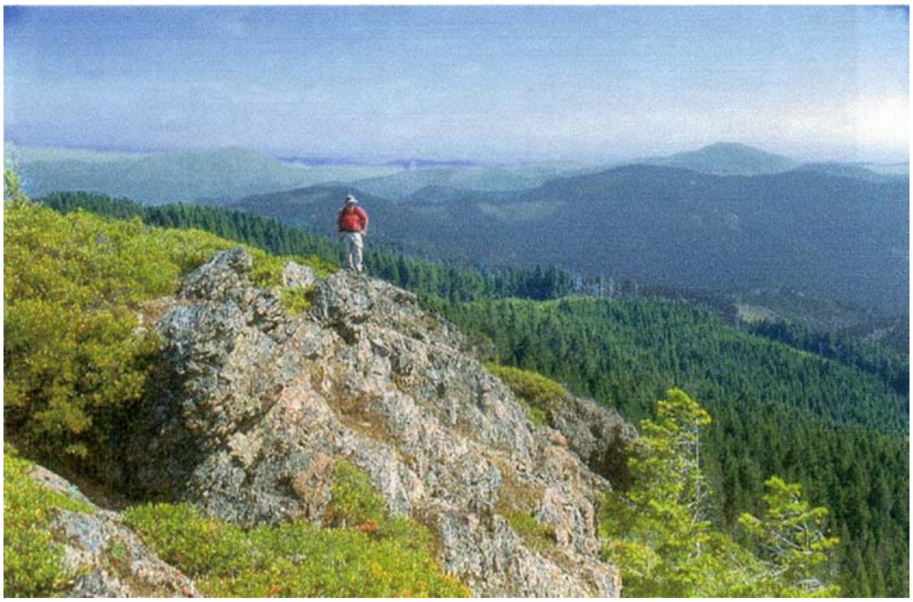


Figure 9. Outcrop photo of metabasalt block on Snowcamp Mountain, showing typical appearance of small Colebrooke meta-igneous blocks.

Figure 10. Outcrop of metabasalt sample JM-67 showing preserved pillow structures.

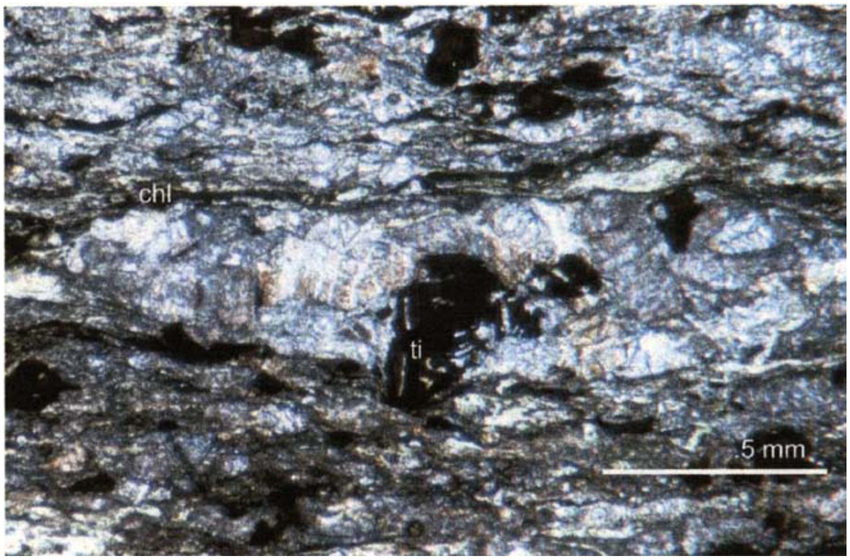


Figure 11. Photomicrograph, under crossed nicols, of metabasalt sample JM-29 showing foliation. Foliation is evident by flattening of grains and by alignment of chlorite (chl) grains. ti = titanite

Figure 12. Outcrop of metabasalt sample JM-86 showing foliation. White lines parallel foliation. Photo from G. Harper (unpublished data).

Other Rock Types

The Colebrooke Schist also contains minor blocks of talc schist and serpentinite. Both the talc schist and the serpentinite are foliated, and where visible appears to be similar in orientation to the foliation in the surrounding Colebrooke metasedimentary rocks.

Sedimentary Textures

A foliated serpentinite on the eastern side of Snowcamp Mountain (Table 1; samples 01-JM-06 and 01-JM-6b; Appendix I), in contact with phyllite (Figure 13), appears to have a clastic sedimentary texture (Figure 14).

Figure 15 is a sample from a mélange outcrop in the Colebrooke Schist. This mélange is adjacent to a greenstone block and contains clasts of greenstone. The mélange appears to have a sedimentary texture. It is deformed, however, as evident from the broken and strung-out clasts. Alternatively, the mélange might be entirely tectonic in origin and "healed" during the regional metamorphism so that it no longer has the scaly appearance characteristic of mudstone-matrix mélange.

A large, extensively brecciated metatonalite block, which locally contains clasts of rhyolite dikes (Figure

Figure 13. Exposure of a fault on the north side of Snowcamp Mountain between Colebrooke phyllite (black rock on right) and serpentinite (red weathering rock on left). If the serpentinite is part of the Snow Camp terrane, this fault is the Coast Range Fault; however, it is possible that the serpentinite is part of the Colebrooke. The serpentinite appears to have a clastic texture (Figure 14). Foliation in both rock types dips to the east (left side of photo), but is not evident in the phyllite in this photo.

Figure 14. Sample JM-06b, a probably detrital serpentinite (see Figure 13) This sample has sedimentary texture (note white and green clasts). This sample also has foliation and flattened grains. The sample pictured on bottom was cut parallel to lineation and perpendicular to foliation.

Figure 15. Hand sample from Colebrooke melange outcrop. This sample has sedimentary texture, as evidenced by the presence of clasts (green material). Clasts also appear to be deformed.

16), was observed on Snowcamp Mountain peak. Figure 17 is a sample from the metatonalite unit that has what appears to be a small amount of black pelitic matrix encompassing several clasts. X-ray diffraction confirmed the presence of quartz, albite, chlorite and muscovite, consistent with a pelitic matrix (Appendix 2). It is unclear whether this metatonalite unit is an intrusion that has undergone cataclasis, or whether it is a deformed sedimentary block. The presence of this pelitic matrix suggests that the metatonalite is a sedimentary block.

Coast Range Fault

There are no previously known exposures of the Coast Range fault in Oregon. However, outcrops of the Colebrooke Schist in close proximity to outcrops of the Snow Camp terrane help to constrain its location. In Figure 13, phyllite (black rock) of the Colebrooke Schist is visible on the right, with serpentinite (red rock) on the left. If this serpentinite is part of the Coast Range ophiolite, then this is indeed the only exposure of the Coast Range fault. However, the presence of possibly sedimentary serpentinite (JM-06 and JM-06b) close to the fault suggests that the serpentinite in fault contact with the phyllite is

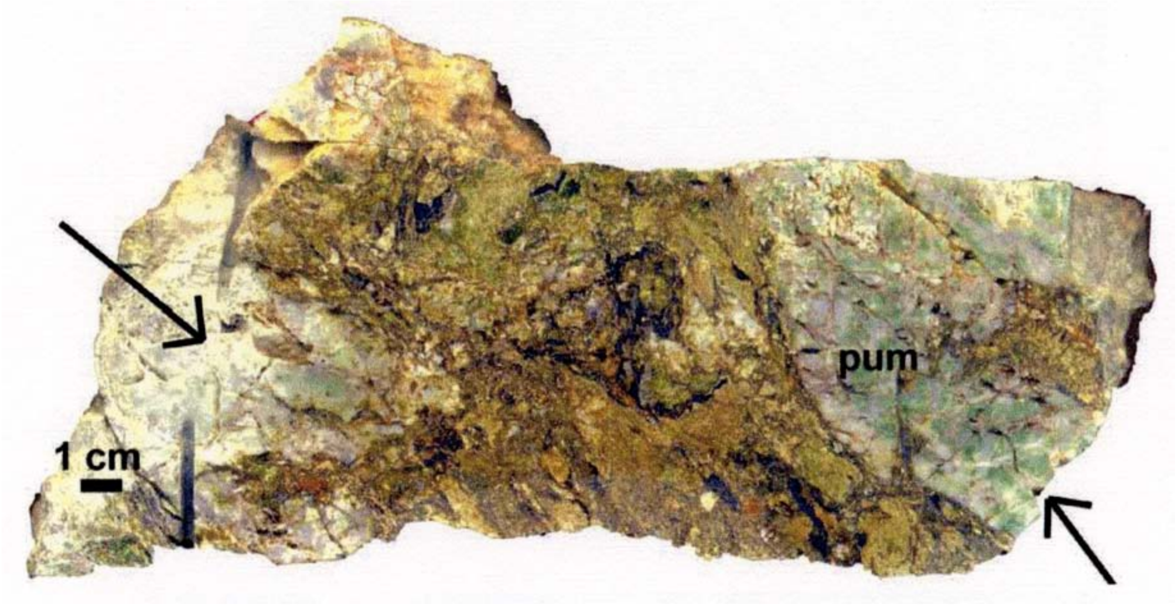


Figure 16. Hand sample of the brecciated metatonalite block from the peak of Snowcamp Mountain. Arrows point to metarhyolite dike clasts.
pum – pumpelleyite (blue-green color)

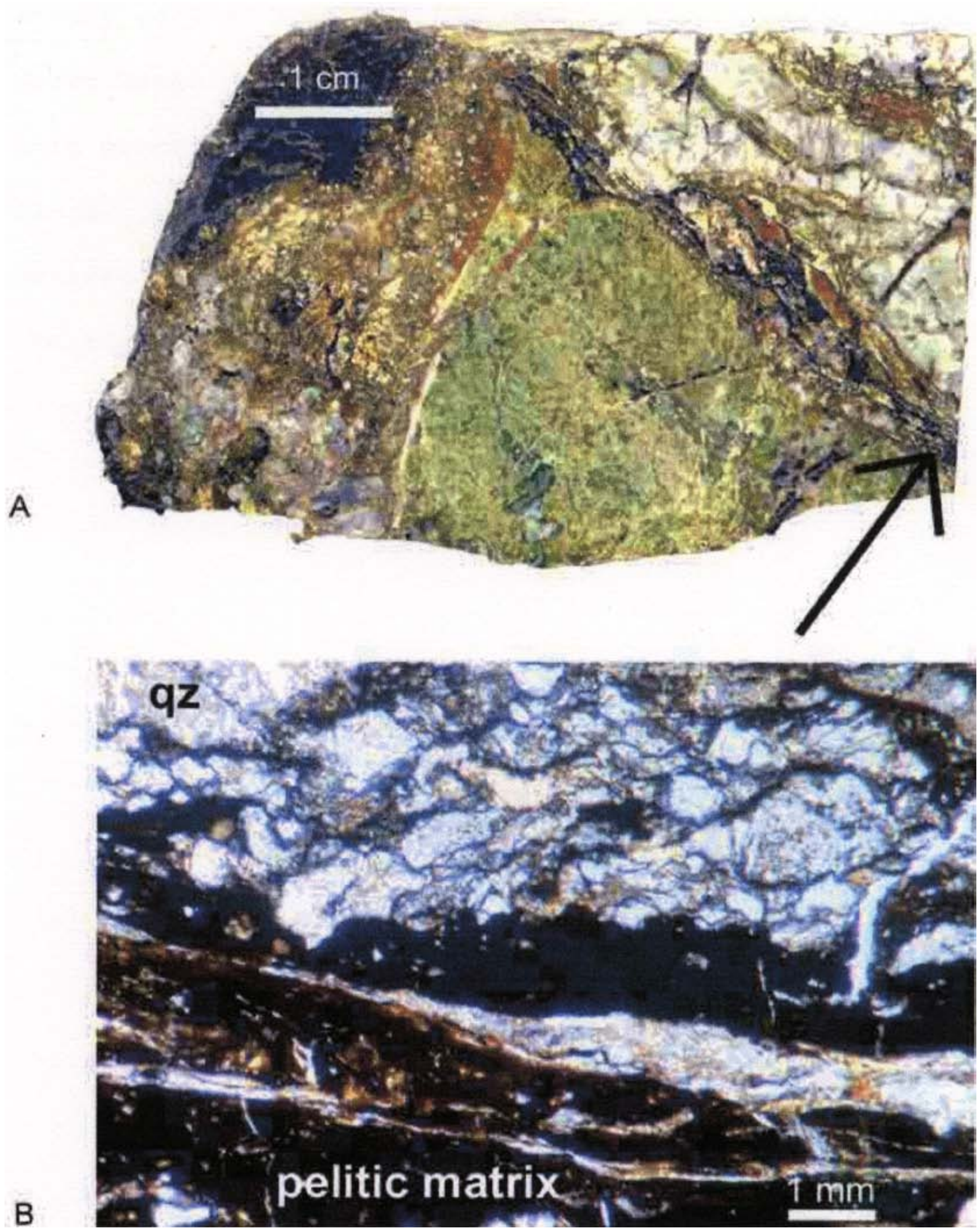


Figure 17. Hand sample (A) and photomicrograph (B), under plane polarized light, of metatonalite block showing pelitic matrix. Arrow points to pelitic matrix in hand sample (A), and dark areas are pelitic matrix in photomicrograph (B).

likely part of the Colebrooke. Since peridotite of the Coast Range ophiolite is within 5 meters of this location, this outcrop is useful since it is very close to the actual fault. Exposures further north show a few meters of highly sheared, gouge-like serpentine, which presumably post-dates the foliated serpentinite (JM-06 and JM-06b).

Petrography

The Colebrooke Schist is largely composed of phyllite and semischist. Commonly mixed in with the metasedimentary rocks are blocks ranging in size from several meters to several kilometers. Most of these blocks are greenstones, with some serpentinite blocks and rare talc schist blocks.

Metasedimentary Rocks

The petrography of the Colebrooke metasedimentary rocks is summarized in Tables 1a and 1b. Figure 5 shows the locations of the metasedimentary rock samples. The Colebrooke Schist metasedimentary rocks include phyllite and semischist. Colebrooke phyllite typically contains relict quartz, with the metamorphic minerals muscovite, graphite, chlorite and epidote/clinozoisite. Coleman (1972) and Plake (1989) identified lawsonite in the Colebrooke phyllite, but it was not observed in these samples. The metamorphic grade of the phyllite is transitional greenschist/blueschist.

The representative relict mineral assemblage for the Colebrooke semischist is quartz and plagioclase. The semischist also contains various rock fragments.

TABLE 1a. PETROGRAPHY OF COLEBROOKE METASEDIMENTARY ROCKS

Sample	Rock Type	Location	Mineralogy		Grain Size (mm)	Veins	Comments
			Relict	Metamorphic			
01-JM-04	semischist	N42.34948 W124.16691	qz	mus,ep,act,hem	0.2	qz	foliated
01-JM-06	metagraywacke	N42.34518 W124.16496	rf,sp,cpx	sep,pum,ox,hem	0.2-1	sep	sheared, foliated
01-JM-6b	metagraywacke	N42.34518 W124.16496	rf,sp,cpx	sep,ep,cz,chl,pum,ox	0.3-1	sep	sheared, foliated
01-JM-11a	phyllite	N42.34502 W124.16519	qz,ab	mus,gr,chl,pum,ep	<0.1	qz,unknown	foliated
01-JM-11b	phyllite	N42.34502 W124.16519	qz,ab,cpx	mus,gr,chl,pr	<0.2	qz,pr	foliated
01-JM-30	phyllite	N42.30972 W124.17505	qz,ab	mus,gr,chl	<0.1	qz,ab	foliated
01-JM-33	semischist	N42.31332 W124.17076	qz,ab,sp	mus,ep,act,hem	<0.2		foliated,folded
01-JM-34	semischist	N42.31332 W124.17076	qz,ab,rf,ox	mus	<0.3		foliated
SM-49*	semischist		qz,pl,rf	mus,ab,chl,ep,cz	<.1-2		sheared, foliated
01-JM-49	semischist	N42.32584 W124.16434	qz,pl,rf	mus,ab,chl,ep,cz,ti	<.1-1	qz	foliated
01-JM-60e	semischist	N42.32584 W124.16434	qz,pl,rf	mus,ab,chl	<0.1		sheared, foliated
01-JM-70a	semischist	N42.37281 W124.18260	qz,ab	mus,chl,ep	<0.1	qz	foliated
01-JM-70c	semischist	N42.37281 W124.18260	qz,ab	mus,chl,pum	<0.1	qz	foliated
01-JM-75	semischist	N42.36820 W124.16892	qz,ab,rf	mus,chl,ep	<0.1		foliated,crenulations
01-JM-79	semischist	N42.38345 W124.16171	cpx,ox	mus,ep,cz,hem	<0.1	qz	sheared, foliated
SM-79c*	phyllite		qz,ab	mus,gr,chl,ep,cz,pr	<0.1	qz,pr,unknown	foliated
SM-79f*	phyllite		qz,ab	mus,gr,chl,ep,cz	<0.1	qz,unknown	foliated
01-JM-82	semischist	N42.38363 W124.16196	qz,pl,rf,sp	mus,ab,chl,ep,cz,hem	<0.1	chl	foliated
SM-85*	semischist		qz,pl,rf	mus,ab,chl,ep,cz,sep	<3	qz	foliated
SM-85b*	semischist		qz,pl,rf,sp	mus,ab,chl,ep,cz,sep	<0.3	qz	foliated
01-JM-85	phyllite	N42.37520 W124.15371	qz,ab	mus,gr,chl,ep,cz,act,ti,hem	<0.1	qz	foliated
01-JM-86	semischist	N42.37546 W124.15368	qz,pl,cpx,ox	mus,ab,act,ep,cz	<0.1	cal	foliated

*Samples from Harper (unpublished data)
ab-albite, ep-epidote, cz-clinozoisite, act-actinolite, chl-chlorite, qz-quartz, cal-calcite, pum-pumpellyite, pr-prehnite, hem-hematite, pl-plagioclase, cpx-clinopyroxene, sp-spinel, ox-oxides, ti-titanite,mus-muscovite, gr-graphite, sep-serpentine, rf-rock fragments

TABLE 1b. MINERAL ASSEMBLAGES OF COLEBROOKE METASEDIMENTARY ROCKS

Sample	qz	mus	ab	chl	ep	cz	gr	act	pum	pr	hem	pl	cpx	sp	ox	ti	sep	rf
01-JM-04	X	X			X			X			X							
01-JM-06									X		X			X	X		X	X
01-JM-6b				X	X	X			X				X	X	X		X	X
01-JM-11a	X	X	X	X	X		X		X									
01-JM-11b	X	X	X	X			X			X			X					
01-JM-30	X	X	X	X			X											
01-JM-33	X	X	X		X			X			X			X				
01-JM-34	X	X	X												X			X
SM-49*	X	X	X	X	X	X						X						X
01-JM-49	X	X	X	X	X	X						X				X		X
01-JM-60e	X	X	X	X								X						X
01-JM-70a	X	X	X	X	X													
01-JM-70c	X	X	X	X					X									
01-JM-75	X	X	X	X	X													X
01-JM-79		X			X	X					X		X		X			
SM-79c*	X	X	X	X	X	X	X			X								
SM-79f*	X	X	X	X	X	X	X											
01-JM-82	X	X	X	X	X	X					X	X		X				X
SM-85*	X	X	X	X	X	X						X					X	X
SM-85b*	X	X	X	X	X	X						X		X			X	X
01-JM-85	X	X	X	X	X	X	X	X			X					X		
01-JM-86	X	X	X		X	X		X				X	X		X			

*Samples from Harper (unpublished data)

ab-albite, ep-epidote, cz-clinozoisite, act-actinolite, chl-chlorite, qz-quartz, cal-calcite, pum-pumpellyite, pr-prehnite, hem-hematite, pl-plagioclase, cpx-clinopyroxene, sp-spinel, ox-oxides, ti-titanite,mus-muscovite, gr-graphite, sep-serpentine, rf-rock fragments

Metamorphic minerals include muscovite, albite, chlorite, epidote/clinozoisite (Tables 1a and 1b), and lawsonite (lawsonite observed by Coleman, 1972; and Plake, 1989).

Samples 01-JM-06 and 01-JM-06b are from a foliated serpentinite on the east side of Snowcamp Mountain (Tables 1a and 1b). This serpentinite has clastic sedimentary texture (Figure 14). Serpentine was observed optically in thin section and confirmed via X-Ray diffraction at Union College (Appendix I). Relict detrital grains include clinopyroxene, chromian spinel and rock fragments. Metamorphic minerals in this sedimentary serpentinite include serpentine, and possibly epidote/clinozoisite, chlorite and pumpellyite.

Meta-igneous Rocks

The petrography of the Colebrooke meta-igneous samples in this study is summarized in Tables 2a and 2b. Figure 18 shows the locations of the meta-igneous samples. All of the Colebrooke meta-igneous samples are almost completely recrystallized to metamorphic minerals, although relict igneous textures are evident in many samples (Figure 19). All but one sample contains relict clinopyroxene and albite pseudomorphs after plagioclase. Some samples have relict

TABLE 2a. PETROGRAPHY OF COLEBROOKE GREENSTONES

	Sample	Rock Type	Location	Mineralogy		Alteration	Texture	Grain Size	Veins	Comments
				Igneous	Metamorphic					
Colebrooke Schist	01-JM-13a	metabasalt	N42.344,W124.166	pl,cpx	ab,ep,cz,sph,sp,chl,qz,hem	90%	porphyritic (5%)	<1mm	qz,chl,hem	
	01-JM-27	metadiabase	N42.339,W124.173	pl,cpx	ab,ep,cz,sph,pu,chl,cal	90%	spherulitic	<1mm	cal	diabasic texture
	01-JM-29	metabasalt	N42.327,W124.177	pl,cpx	ab,act,ep,cz,ti,pu,chl,qz	90%	foliated, subophitic	<1mm	qz	
	01-JM-50c	metabasalt	N42.505,W124.105	pl,cpx,sp	ab,ep,cz,pr,act,chl	90%	porphyritic (5%)	<1mm	pr	
	01-JM-61	metabasalt	N42.329,W124.166	pl,ox	ab,ep,cz,chl,qz,sp	90%		<1mm	qz,chl,ox	
	01-JM-66b	metabasalt	N42.556,W124.101	pl	ab,pu,chl,ep,cz,cal,qz	90%	porphyritic (5%)	<1mm	qz,cal	
	01-JM-67	metabasalt	N42.488,W124.202	pl,cpx	ab,ep,cz,chl,qz,hem	90%	subophitic,foliated	<1mm	chl,qz,hem	
	01-JM-68	metabasalt	N42.488,W124.208	pl	ab,ep,cz,act,lim,sph,chl,qz	90%	amygdaloidal	<1mm	chl,qz,act,lim	
	01-JM-69b	metabasalt	N42.371,W124.182	pl,cpx,sp	ab,ep,cz,act,pu,chl,qz,hem	90%			pu,chl,qz,hem	stretched pillow
	01-JM-70d	metabasalt	N42.373,W124.183	pl,cpx,sp,ol (ps)	ab,ep,cz,act,pu,chl,qz	90%	porphyritic (5%)	<1mm	qz,act,ep,chl	
	01-JM-200	metarhyolite	N42.344,W124.165	qz	ep,cz,pu,chl	90%	porphyritic (15%)	<1 - 2mm		
Blocks in Serpentinite Melange--Mineral Hill	SM-110*	metabasalt	N42.305,W124.125	pl,cpx	ab,ep,cz,chl,pu,qz	90%	subophitic,porphyritic (5%)	<1mm	qz,chl,pu	
	SM-116*	metabasalt	N42.310,W124.134	pl,cpx,ol (ps), sp	ab,ep,cz,cal,pu,qz,hem	90%	porphyritic (5%), amygdaloidal, subophitic	<1mm		sheared
	SM-96-13a*	metabasalt	N42.310,W124.130	pl,cpx,sp	ab,ep,cz,chl,pu,hem	90%	subophitic, porphyritic (5%), vesicular	<1mm	chl,hem	
	SM-96-13b*	metabasalt	N42.310,W124.130	pl,cpx,sp,ol (ps)	ab,ep,cz,chl,sph,pu,hem	90%	subophitic, porphyritic (5%)	<1mm	chl,ep,hem	
	SM-96-13c*	metabasalt	N42.310,W124.130	pl,cpx,sp,ol (ps)	ab,ep,cz,pu,chl,hem	90%	subophitic, porphyritic (5%), igneous foliation	<1mm	chl,hem	chert, rads present
Blocks in Serpentinite Melange--Saddle Mtn.	SM-96-10b*	metabasalt	N42.402,W124.121	pl, cpx, sp	ab,ep,cz,ti,cal,pu,chl,hem	90%	subophitic	<1mm	pu,chl,hem	
	SM-96-10c*	metabasalt	N42.402,W124.121	pl,cpx,ol (ps)	ab,ep,cz,pu,chl,qz	90%	subophitic, porphyritic (5%), sheared, amygdaloidal	<1mm	pu,chl,qz	
	SM-96-10d*	metabasalt	N42.402,W124.121	pl,cpx,oz	ab,ep,cz,ti,pu,chl,cal,qz	90%	spherulitic, porphyritic (5%)	<1mm	chl,cal,qz	

*Samples from Harper (unpublished data)
ab-albite, ep-epidote, cz-clinozoisite, act-actinolite, lim-limonite, sph-sphene, chl-chlorite, qz-quartz, cal-calcite, pu-pumpellyite, pr-prehnite, hem-hematite, pl-plagioclase, cpx-clinopyroxene, sp-spinel, ol-olivine, ox-oxides, ps-pseudomorph

TABLE 2a. MINERAL ASSEMBLAGES OF COLEBROOKE GREENSTONES

	Sample	pl	cpx	ab	ep	cz	act	lim	sph	chl	qz	cal	pu	pr	hem	sp	ol	ti	ox
Colebrooke Schist	01-JM-13a	X	X	X	X	X			X	X	X				X	X			
	01-JM-27	X	X	X	X	X			X	X		X	X						
	01-JM-29	X	X	X	X	X	X			X	X		X					X	
	01-JM-50c	X	X	X	X	X	X			X				X		X			
	01-JM-61	X		X	X	X				X	X					X			X
	01-JM-66b	X		X	X	X				X	X	X	X						
	01-JM-67	X	X	X	X	X				X	X				X				
	01-JM-68	X		X	X	X	X	X	X	X	X								
	01-JM-69b	X	X	X	X	X	X			X	X		X		X	X			
	01-JM-70d	X	X	X	X	X	X			X	X		X			X	X		
	01-JM-200				X	X				X	X		X						
Blocks in Serpentinite Melange—Mineral Hill	SM-110*	X	X	X	X	X				X	X		X						
	SM-116*	X	X	X	X	X					X	X	X		X	X	X		
	SM-96-13a*	X	X	X	X	X				X			X		X	X			
	SM-96-13b*	X	X	X	X	X			X	X			X		X	X	X		
	SM-96-13c*	X	X	X	X	X				X			X		X	X	X		
Blocks in Serpentinite Melange—Saddle Mtn.	SM-96-10b*	X	X	X	X	X				X		X	X		X	X		X	
	SM-96-10c*	X	X	X	X	X				X	X		X				X		
	SM-96-10d*	X	X	X	X	X				X	X	X	X					X	X

*Samples from Harper (unpublished data)
ab-albite, ep-epidote, cz-clinozoisite, act-actinolite, lim-limonite, sph-sphene, chl-chlorite, qz-quartz, cal-calcite, pu-pumpellyite, pr-prehnite, hem-hematite, pl-plagioclase, cpx-clinopyroxene, sp-spinel, ti-titanite, ol-olivine, ox-oxides, ps-pseudomorph

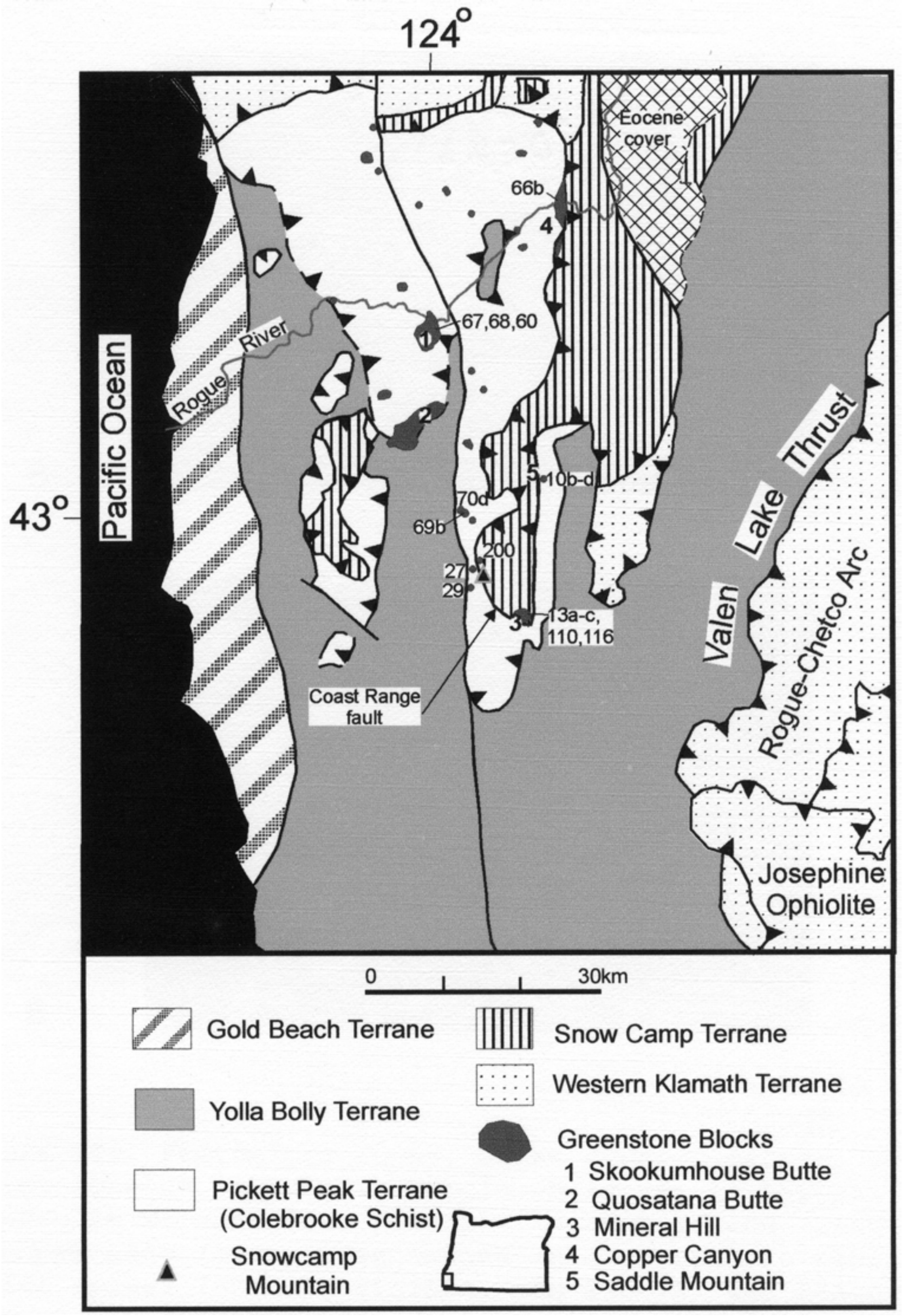


Figure 18. Regional map from Roure and Blanchet (1983), Blake et al. (1982, 1985a), and G. Harper and M. Giaramita (unpublished mapping), showing the locations of Colebrooke Schist meta-igneous rock samples. Mineral Hill and Saddle Mountain greenstone blocks are blocks in the serpentinite melange underlying the Colebrooke Schist.

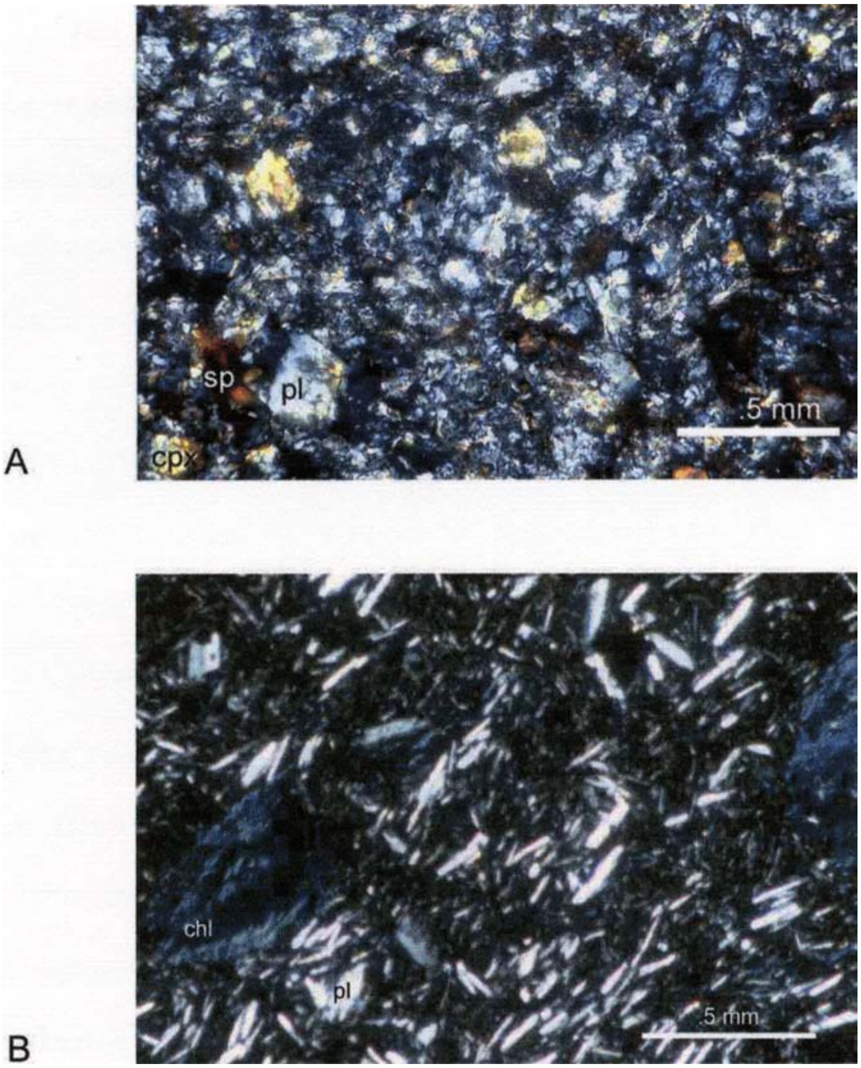


Figure 19. Photomicrographs, under crossed nicols, showing relict igneous textures. Sample JM-68 (A) is typical of Colebrooke metabasalts. Subophitic texture and relict clinopyroxene (cpx), plagioclase (pl) altered to albite and relict spinel (sp) are visible. SM-13c (B) has trachytic texture, evident by aligned plagioclase (pl) grains.
chl - chlorite

chromian spinel, and several contain olivine pseudomorphs, identified by their euhedral shape. Most of the samples are sparsely porphyritic (less than 5% phenocrysts), with phenocrysts of clinopyroxene (relict), plagioclase (pseudomorphs) and olivine (pseudomorphs). The groundmass generally varies from subophitic to intersertal, with some samples having spherulitic or variolitic groundmass as well (Figure 20). One sample (JM-27) contains relict diabasic texture. Sample JM-200 is a metarhyolite dike (Figure 21) within the metatonalite unit on Snowcamp Mountain (Figure 16). JM-200 contains phenocrysts of quartz; other relict igneous minerals, if any, in the groundmass are too small to be identified.

The metamorphic mineral assemblage observed in these meta-igneous rocks includes actinolite + epidote + albite + chlorite ± pumpellyite ± crossite (crossite observed by Coleman, 1972). In all meta-igneous samples, plagioclase, if present, has been replaced by albite. Additional common metamorphic minerals include epidote/clinozoisite, titanite, chlorite, quartz and calcite.

The Mineral Hill and Saddle Mountain greenstone blocks are blocks in the serpentinite mélange underlying the Snow Camp terrane (Figure 18 and Tables 2a and 2b). The mineral

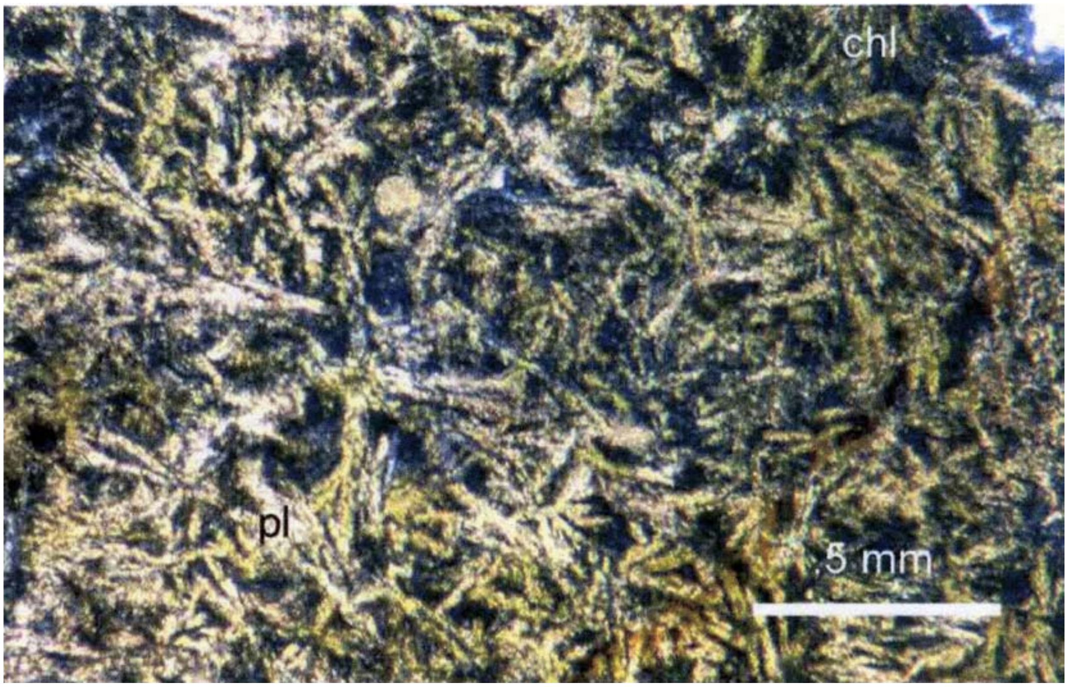


Figure 20. Photomicrograph, under plane polarized light, of sample JM-66a showing spherulitic texture.
pl - plagioclase (pl), chl - chlorite

Figure 21. Outcrop of metatonalite block with metarhyolite sample JM-200 in place. Arrow points to JM-200 (green).

assemblages and textures in the Mineral Hill and Saddle Mountain blocks are the same as the Colebrooke blocks, except they do not contain diabase units.

Other Rock Types

The Colebrooke Schist also contains minor blocks of talc schist and serpentinite. These rock types are summarized in Tables 3a and 3b.

TABLE 3a. PETROGRAPHY OF COLEBROOKE--OTHER TYPES OF ROCKS

Sample	Rock Type	Location	Mineralogy		Grain Size (mm)	Comments
			Relict	Metamorphic		
01-JM-20	serpentinite	N42.34090 W124.16518	ox	sep,hem	<.1	folded
01-JM-35a	serpentinite	N42.31642 W124.16867	sp	sep,chl,hem	<.1	phacoid
01-JM-37	serpentinite	N42.44168 W124.09038	ox	sep,chl,ep,cz	<.1	foliated
SM-88*	serpentinite		ox	sep,act	<1	
SM-91*	serpentinite	N42.33123 W124.16412		sep	<.1	foliated, relict minerals too small to identify
SM-35-98*	serpentinite	N42.34511 W124.16503	ox	sep,chl	<.1	foliated
CB-16 †	talc schist	N42.37565 W124.13717		talc	<.1	foliated, relict minerals too small to identify

* Samples from Harper (unpublished data)

† Samples from Ashcroft (unpublished data)

ep-epidote, cz-clinozoisite, act-actinolite, chl-chlorite, qz-quartz, hem-hematite, sp-spinel, ox-oxides, sep-serpentine

TABLE 3b. MINERAL ASSEMBLAGE OF COLEBROOKE–OTHER TYPES OF ROCKS

Sample	talc	ep	cz	act	chl	hem	sp	ox	sep
01-JM-20						X		X	X
01-JM-35a					X	X	X		X
01-JM-37		X	X		X			X	X
SM-88*				X				X	X
SM-91*									X
SM-35-98*					X			X	X
CB-16 †	X								

* Samples from Harper (unpublished data)
† Samples from T. Ashcroft (unpublished data)
ep-epidote, cz-clinozoisite, act-actinolite, chl-chlorite, qz-quartz,
hem-hematite, sp-spinel, ox-oxides, sep-serpentine

Geochemistry

Whole rock analyses of Colebrooke meta-igneous blocks include fourteen metabasalts, one metadiabase and one metarhyolite from this study, nine metabasalts and one meta-quartz diorite from Plake (1989) and ten metabasalts from Coleman (1972). Tables 4a and 4b list major element data and Tables 5a and 5b list trace and rare earth element data for Colebrooke meta-igneous blocks from this study. Figure 22 is a regional map showing the locations of the meta-igneous samples analyzed.

Sample Preparation Procedures

Samples of at least 10 cm in diameter were collected in the field. Care was taken to collect samples with fresh, nonweathered surfaces. Additional weathered surfaces were cut off in the laboratory with masonry saws. After cutting off weathered surfaces, a lap wheel was used to grind off saw marks. The sample was then cleaned to remove the grit residue. Then the sample was crushed with a jaw crusher into ~1 cm chips. The jaw crusher was thoroughly cleaned between each sample. The chips were then sorted to eliminate remaining weathered surfaces,

Table 4a: MAJOR (%) ELEMENT ANALYSES OF COLEBROOKE SCHIST GREENSTONES

Sample	JM 27	JM 29	JM 66A	JM 67	JM 68	JM 69B	JM 70D	SM 200
Magma type*	MORB	MORB	MORB	MORB	MORB	MORB	MORB	BON#
SiO_2	52.41	50.14	46.84	52.65	49.07	49.26	53.00	76.07
TiO_2	1.465	1.725	1.742	1.091	2.008	2.320	1.691	0.296
Al_2O_3	13.81	14.55	21.00	14.81	13.14	14.53	14.68	11.33
FeOT†	10.16	11.85	7.86	8.56	12.15	12.96	12.21	2.03
MnO	0.197	0.203	0.169	0.217	†0.28	0.130	0.198	0.065
MgO	8.84	9.82	17.00	11.34	12.85	11.67	6.12	7.23
CaO	8.20	7.93	2.99	6.65	7.11	5.93	7.15	1.12
Na_2O	0.09	0.02	0.08	0.05	0.11	1.30	0.12	0.02
K_2O	4.71	3.62	2.10	4.54	3.11	1.72	4.69	1.80
P_2O_5	0.117	0.140	0.219	0.083	0.175	0.166	0.141	0.043
LOI	3.18	3.27	5.23	2.58	3.09	3.17	2.75	3.81
Total§	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

*Magma type determined using immobile trace element discrimination diagrams. MORB = mid-ocean ridge basalt, IAT = island-arc tholeiite, IAT-MORB = transitional between IAT and MORB, BON = boninitic. Magma type does not equal rock type.

† FeOT= total iron as FeO.

§Analyzed at Washington State University where analyses are normalized to 100%.

#Source magma type

Table 4b. MAJOR (%) ELEMENT ANALYSES OF GREENSTONES FROM THE SERPENTINITE MELANGE BETWEEN THE COLEBROOKE SCHIST AND SNOW CAMP TERRANE

Sample	SM-10B	SM-10C	SM-10D	SM 110	SM 116	SM-13A	SM-13B	SM-13C
Magma type*	IAT	IAT-MORB	IAT-MORB	MORB	IAT-MORB	IAT-MORB	IAT	IAT-MORB
SiO_2	51.81	52.81	52.91	60.97	62.42	51.52	50.33	49.97
TiO_2	1.18	1.31	1.67	0.834	0.649	1.00	1.11	1.15
Al_2O_3	17.45	15.21	14.19	15.95	14.98	16.34	16.31	16.52
FeOT†	9.47	9.98	9.38	8.37	7.57	9.23	11.32	11.56
MnO	0.12	0.16	0.12	0.117	0.068	0.13	0.17	0.15
MgO	4.99	5.03	4.83	3.54	1.84	5.90	5.46	7.23
CaO	3.44	5.04	7.12	5.02	7.82	4.80	3.35	1.37
Na_2O	0.09	0.06	0.04	0.07	0.05	0.14	0.55	0.06
K_2O	6.06	5.47	3.29	5.02	4.50	5.91	5.63	5.27
P_2O_5	0.12	0.13	0.15	0.115	0.095	0.14	0.12	0.11
LOI	4.49	3.91	5.17	3.73	4.31	4.22	4.75	5.43
Total§	100.35	100.27	99.96	100.00	100.00	99.33	99.07	98.80

*Magma type determined using immobile trace element discrimination diagrams.

MORB = mid-ocean ridge basalt, IAT = island-arc tholeiite, IAT-MORB = transitional between IAT and MORB

† FeOT= total iron as FeO.

§Analyzed at Washington State University where analyses are normalized to 100%.

Table 5a. TRACE (ppm) ELEMENT ANALYSES OF COLEBROOKE SCHIST GREENSTONES

Sample Magma type*	JM 27 MORB	JM 29 MORB	JM 66A MORB	JM 67 MORB	JM 68 MORB	JM 69B MORB	JM 70D MORB	JM 200 BON#
Ba	35	68	67	28	90	124	68	11
Rb	1.2	0.2	1.1	0.7	1.9	31.9	3.1	0.2
Sr	139	96	166	77	129	325	69	23
Y	30.76	37.32	37.10	28.28	39.79	70.94	38.57	19.43
Zr	76	90	114	49	104	128	89	76
Nb	1.80	2.38	7.39	1.19	2.63	3.62	2.54	0.77
Th	0.17	0.16	0.59	0.11	0.17	0.26	0.21	0.85
Ni	54	67	70	71	36	41	26	7.00
V	316	350	268	287	367	458	350	42.00
Cr	288	225	305	364	97	127	36	0.00
Hf†	2.18	2.57	2.93	1.54	3.01	3.77	2.70	2.37
Sc	42.4	44.9	38.6	39.6	44.4	48.5	42.8	8.7
Ta	0.13	0.18	0.51	0.09	0.20	0.27	0.19	0.06
La	2.76	3.62	9.46	2.14	3.67	7.73	3.83	3.35
Ce	8.16	9.90	18.51	5.77	10.75	17.09	10.71	8.49
Pr	1.36	1.64	2.79	0.99	1.77	3.41	1.77	1.29
Nd	7.84	9.25	13.99	5.82	9.94	19.05	10.01	6.35
Sm	3.11	3.62	4.57	2.45	4.02	7.53	3.95	2.10
Eu	1.13	1.36	1.97	0.97	1.58	2.74	1.37	0.52
Gd	4.23	4.96	5.61	3.53	5.33	10.37	5.19	2.37
Tb	0.83	0.95	1.02	0.71	1.06	1.89	1.00	0.48
Dy	5.45	6.26	6.54	4.78	6.99	12.19	6.89	3.25
Ho	1.17	1.36	1.35	1.05	1.50	2.49	1.47	0.71
Er	3.24	3.75	3.69	2.97	4.12	6.83	4.05	2.08
Tm	0.47	0.54	0.51	0.42	0.60	0.97	0.60	0.32
Yb	2.91	3.35	3.13	2.68	3.73	5.88	3.73	2.16
Lu	0.45	0.52	0.47	0.42	0.57	0.89	0.58	0.37

*Magma type determined using immobile trace element discrimination diagrams. MORB = mid-ocean ridge basalt, IAT = island-arc tholeiite, IAT-MORB = transitional between IAT and MORB, BON = boninitic

†Analysis by ICP-MS at Washington State University

#Source magma type

Table 5b. TRACE (ppm) ELEMENT ANALYSES OF GREENSTONES FROM THE SERPENTINITE MELANGE BETWEEN THE COLEBROOKE SCHIST AND SNOW CAMP TERRANE

Sample	SM-10B	SM-10C	SM-10D	SM 110	SM 116	SM-13A	SM-13B	SM-13C
Magma type*	IAT	IAT-MORB	IAT-MORB	MORB	IAT-MORB	IAT-MORB	IAT	IAT-MORB
Ba	266	151	105	72	36	89	136	136
Rb	1	1	0	0.5	0.3	1	6	0
Sr	293	93	117	131	100	1	6	0
Y	24	31	36	22.17	17.80	30	23	23
Zr	66	84	110	60	36	78	63	70
Nb	1.9	2.5	3.3	1.37	1.03	2.1	1.8	2.0
Th	0.59	0.37	0.29	0.66	0.37	0.59	0.51	0.50
Ni	20	12	16	33	36	30	22	14
V	434	354	366	286	199	312	375	327
Cr	28	11	15	60	47	58	12	6
Hf†	2.00	2.40	2.89	1.93	1.17	2.17	1.90	1.95
Sc	46	27	33	34.4	35.4	36	31	28
Ta	0.10	0.14	0.20	0.09	0.07	0.13	0.11	0.12
La	5.40	4.03	3.61	5.41	3.48	5.03	3.67	2.60
Ce	12.03	11.77	10.75	10.17	7.59	12.67	9.55	7.11
Pr	1.83	1.99	1.84	1.75	1.19	2.06	1.61	1.31
Nd	9.02	10.35	9.95	8.95	6.07	10.37	8.06	7.01
Sm	2.77	3.34	3.49	3.00	2.01	3.25	2.64	2.43
Eu	1.00	1.05	1.22	0.99	0.68	1.01	0.90	0.76
Gd	3.47	4.29	4.74	3.63	2.53	4.12	3.54	3.12
Tb	0.61	0.77	0.86	0.64	0.46	0.70	0.62	0.57
Dy	3.97	5.04	5.74	3.98	3.00	4.57	4.00	3.78
Ho	0.84	1.08	1.21	0.83	0.65	0.99	0.86	0.80
Er	2.53	3.25	3.61	2.24	1.83	2.89	2.58	2.33
Tm	0.40	0.51	0.57	0.31	0.25	0.45	0.41	0.37
Yb	2.50	3.11	3.54	1.88	1.57	2.76	2.47	2.26
Lu	0.37	0.44	0.50	0.29	0.24	0.41	0.38	0.32

*Magma type determined using immobile trace element discrimination diagrams. MORB = mid-ocean ridge basalt, IAT = island-arc tholeiite, IAT-MORB = transitional between IAT and MORB

†Analysis by ICP-MS at Washington State University .

#Source magma type

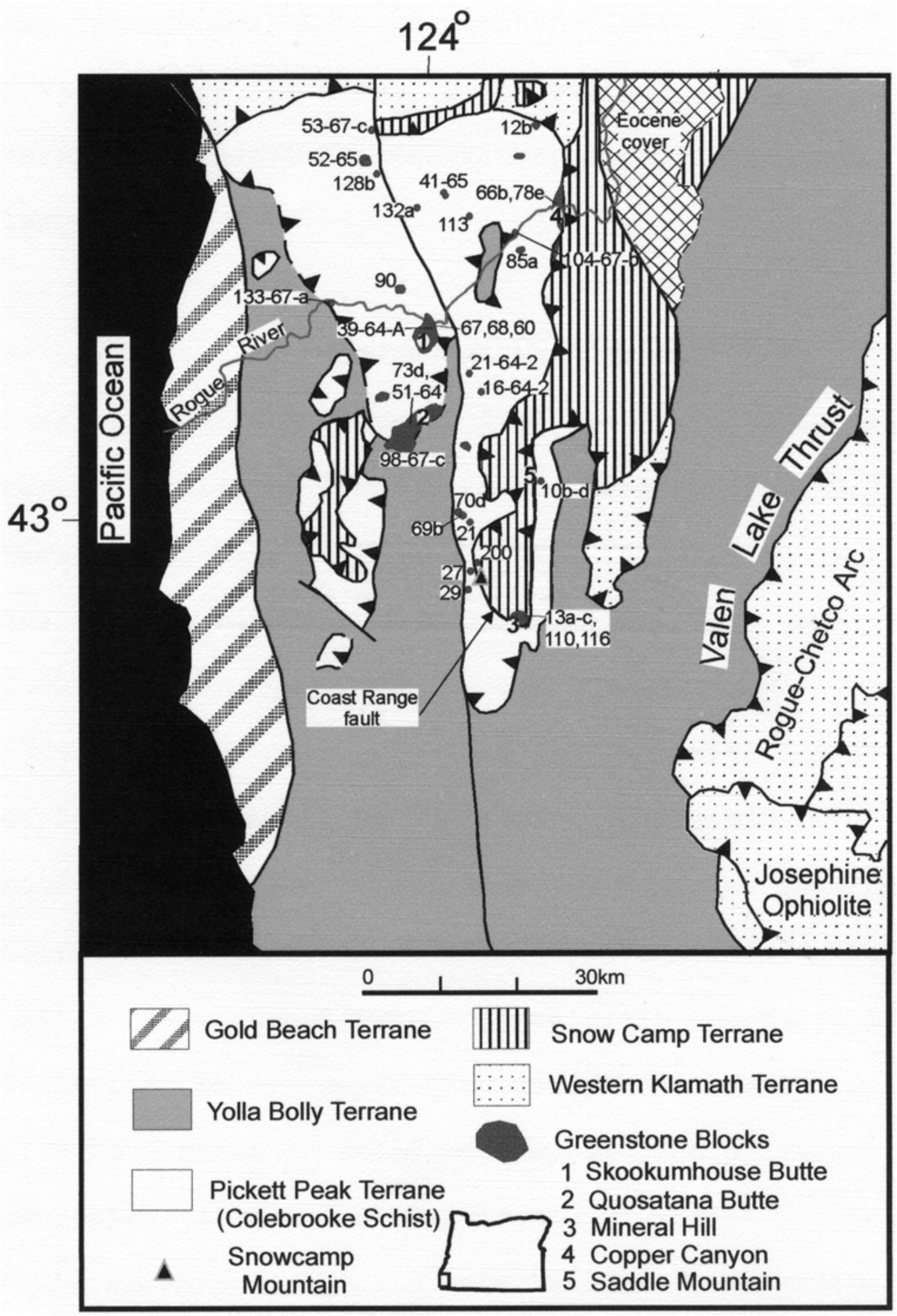


Figure 22. Regional map from Roure and Blanchet (1983), Blake et al. (1982, 1985a), and G. Harper and M. Giaramita (unpublished mapping), showing the locations of analysed Colebrooke Schist meta-igneous rock samples. Mineral Hill and Saddle Mountain greenstone blocks are blocks in the serpentinite melange underlying the Colebrooke Schist.

veins, jaw crusher marks or porphyroclasts. Over 600 g of each sample were then sent to the Washington State University GeoAnalytical Laboratory for crushing and analysis.

Analytical Methods

Major and trace elements of sixteen blocks in the Colebrooke Schist were analyzed at the Washington State University GeoAnalytical Laboratory. Abundances of the oxides SiO_2, TiO_2, Al_2O_3, FeO (total), MnO, MgO, CaO, Na2O, K2O, P_2O_5 were measured using x-ray fluorescence. All major and trace element data are listed in Tables 4a and 4b. To maintain precision in the XRF analysis, the WSU GeoAnalytical Laboratory utilizes two beads as internal standards (Johnson et al., 1999). These standard beads are run after every 28 unknowns. To maintain accuracy, WSU GeoAnalytical Laboratory continuously compares their results to a suite of standard samples from different laboratories (Johnson et al., 1999).

The Colebrooke samples were also analyzed at the Washington State University GeoAnalytical Laboratory for abundances of the elements Ba, Rb, Sr, Y, Zr, Nb, Th, Ni, V, Cr, Hf, Sc, Ta, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu by inductively coupled plasma mass spectrometry (ICP-MS). Trace and rare earth element data are listed in Tables 5a and 5b. The precision of ICP-MS analysis at WSU GeoAnalytical Laboratory is maintained by preparation of an internal standard 24 separate times, analyzed in 12 separate runs (Knaack et al., 1994). For accuracy, the scatter of the standards is calculated from a best-fit calibration line of all the standards (Knaack et al., 1994).

Major and trace element data from Plake (1989) were also obtained by XRF at Washington State University. Major element data from Coleman (1972) was analyzed by rapid rock analysis at the United States Geological Survey, and trace element data from Coleman (1972) are semi-quantitative.

Magmatic Affinities of Colebrooke Meta-igneous Blocks

Three discrimination diagrams are used to determine magmatic affinities of the 36 Colebrooke metavolcanic blocks. These magmatic affinities are summarized in Table 6. To minimize the effects of hydrothermal alteration, only diagrams utilizing generally immobile elements are considered.

TABLE 6. SUMMARY OF MAGMATIC AFFINITIES OF COLEBROOKE META-IGNEOUS ROCKS

	Skookumhouse Butte				Quosatana Butte			Snowcamp Mountain					Copper Canyon	
Sample	60*	39-64A†	JM 67	JM 68	51-64†	98-67-c†	73d*	JM 27	JM 29	JM 69B	JM 70D	JM 200	78e*	JM 66A
Ti-V	IAT-MORB	IAT-MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB (Fe-Ti)	MORB		MORB	MORB
Th/Yb-Ta/Yb			N-MORB	N-MORB				N-MORB	N-MORB	N-MORB	N-MORB	IAT#		E-MORB
Cr-Y	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB (Fe-Ti)	MORB (Fe-Ti)	BON#	MORB	MORB

	Blocks in Serpentinite Melange--Saddle Mountain			Blocks in Serpentinite Melange--Mineral Hill					Plake (1989)*	Coleman (1972)†
Sample	SM-10B	SM-10C	SM-10D	SM 110	SM 116	SM-13A	SM-13B	SM-13C	Misc.	Misc.
Ti-V	IAT	MORB	MORB	IAT	IAT-MORB	IAT-MORB	IAT	MORB	1 IAT-MORB,7 MORB (4 Fe-Ti)	10 MORB (4 Fe-Ti)
Th/Yb-Ta/Yb	IAT	IAT	MORB	IAT	IAT	IAT	IAT	IAT		
Cr-Y	IAT	IAT	IAT	IAT	IAT	MORB	IAT	IAT	2 BON, 8 MORB	10 MORB (5 Fe-Ti)

*Samples from Plake (1989)
†Samples from Coleman (1972)
#Source magma type

IAT-island arc tholeiite
MORB-mid-ocean ridge basalt
N-MORB-primitive mid-ocean ridge basalt
E-MORB-enriched mid-ocean ridge basalt
IAT-MORB-transitional island arc tholeiite and mid-ocean ridge basalt
BON-boninite

Colebrooke blocks consist of various magma types. Figure 23 is a mid-ocean ridge basalt-normalized spider diagram showing a representative suite of blocks from the Colebrooke Schist and the underlying serpentinite mélange. Quosatana Butte samples plot entirely in the mid-ocean ridge basalt (MORB) field on both the Ti-V (Figure 24) and Cr-Y (Figure 25a) discriminant diagrams. Copper Canyon and Skookumhouse Butte samples also consistently plot as MORB on both the Ti-V and Cr-Y diagrams. The smaller, unnamed Colebrooke blocks from this study, and those of Plake (1989) and Coleman (1972) also all plot in the MORB field on the Ti-V and Cr-Y diagrams. Mineral Hill samples plot in the island arc tholeiite (IAT) fields in the Ti-V and Cr-Y discriminant diagrams. One Mineral Hill sample plots MORB on the Cr-Y diagram and plots on the border of IAT and MORB on the Ti-V diagram, so it is transitional IAT/MORB. One Saddle Mountain sample is IAT in both diagrams, and the remaining two are transitional IAT/MORB since they plot as IAT on one diagram and as MORB on the other.

The Th/Yb versus Ta/Yb discriminant diagram (Figure 26) is useful for determining mantle source, since fractionation has little effect on these ratios (Pearce, 1982). For samples having arc affinities, the mantle

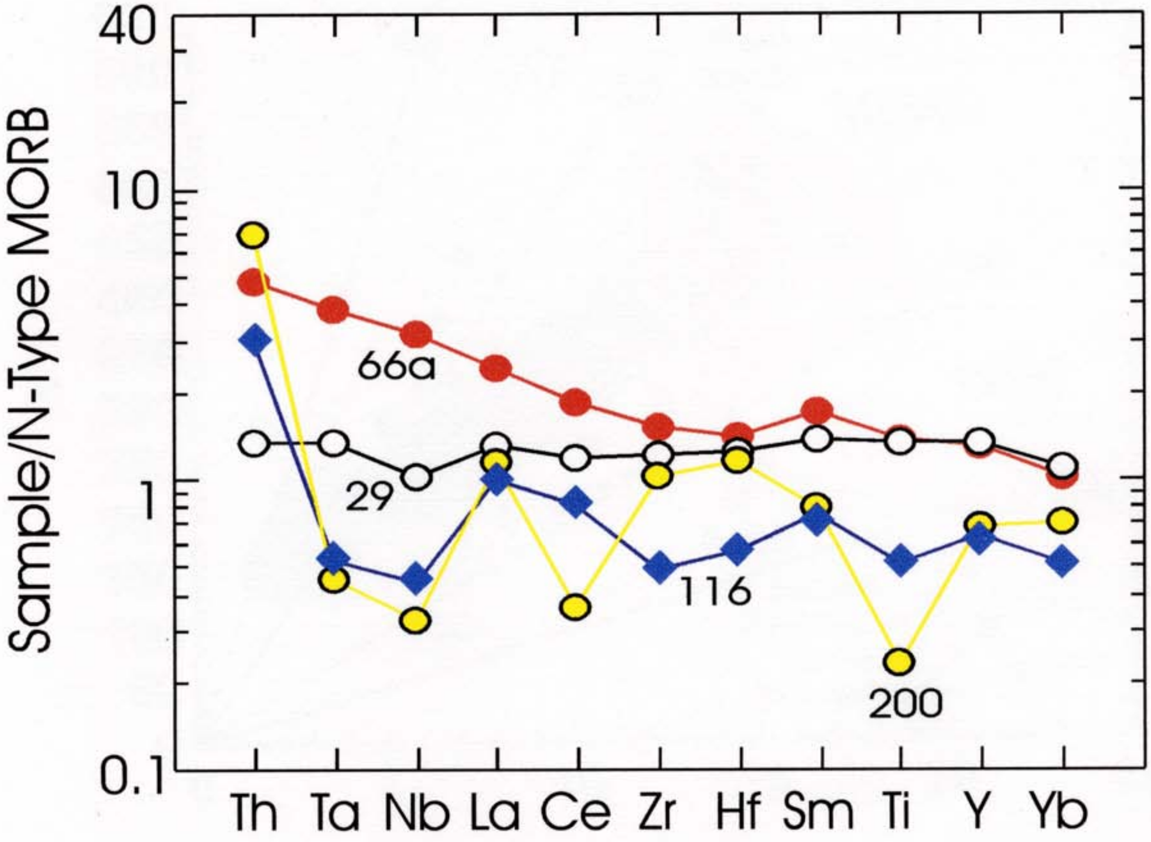


Figure 23: Representative samples of meta-igneous blocks from the Colebrooke Schist and the underlying serpentinite melange. Normalizing values are from Sun and McDonough (1989). MORB = mid-ocean ridge basalt

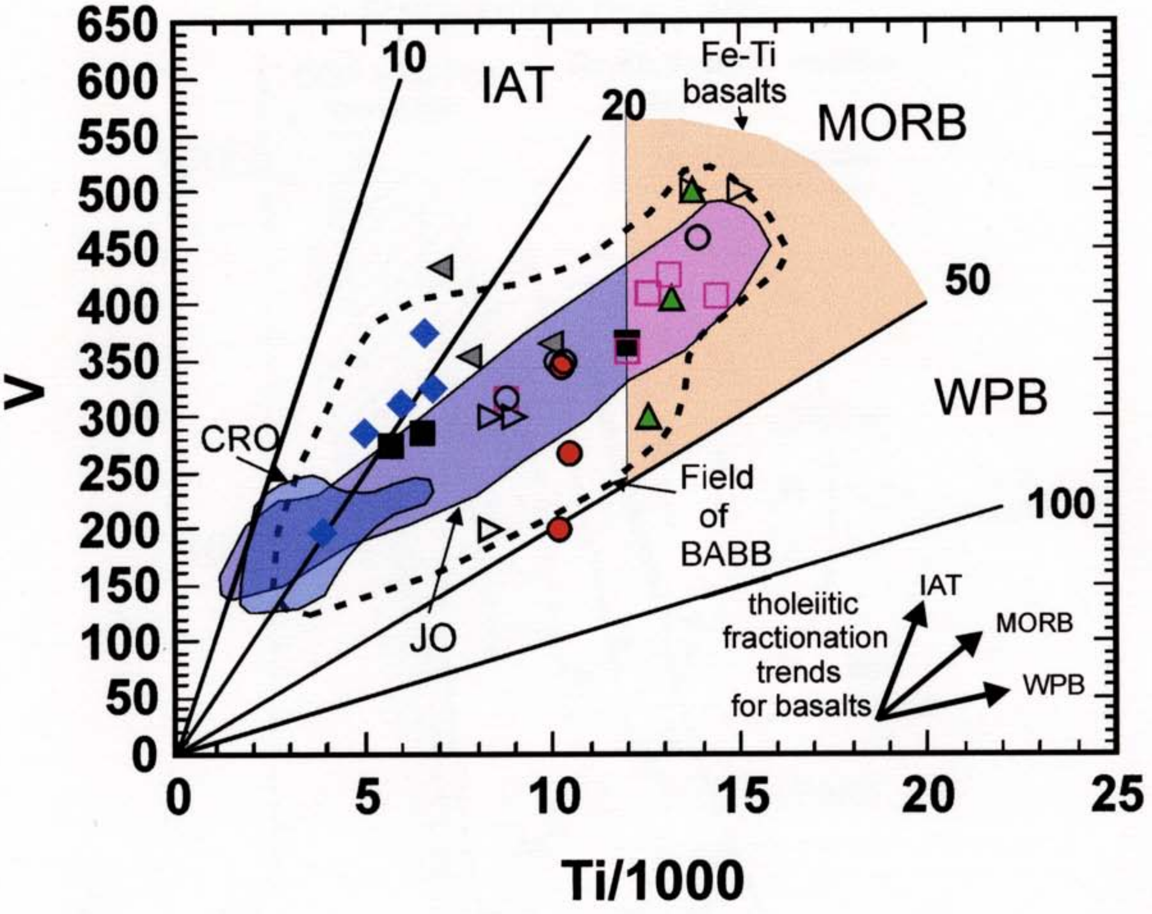


Figure 24: Ti versus V discrimination diagram (Shervais, 1982) including all Colebrooke basalts. CRO (from Snow Camp terrane in Snowcamp Mountain area) and JO fields from Harper (Harper, unpublished data; and Harper 2003a,2003b; respectively). Fe-Ti basalt field from Sinton et al. (1983). CRO-Coast Range ophiolite, JO-Josephine ophiolite, BABB-backarc basin basalt, IAT-island arc tholeiite, MORB-mid-ocean ridge basalt, WPB-within plate basalt.

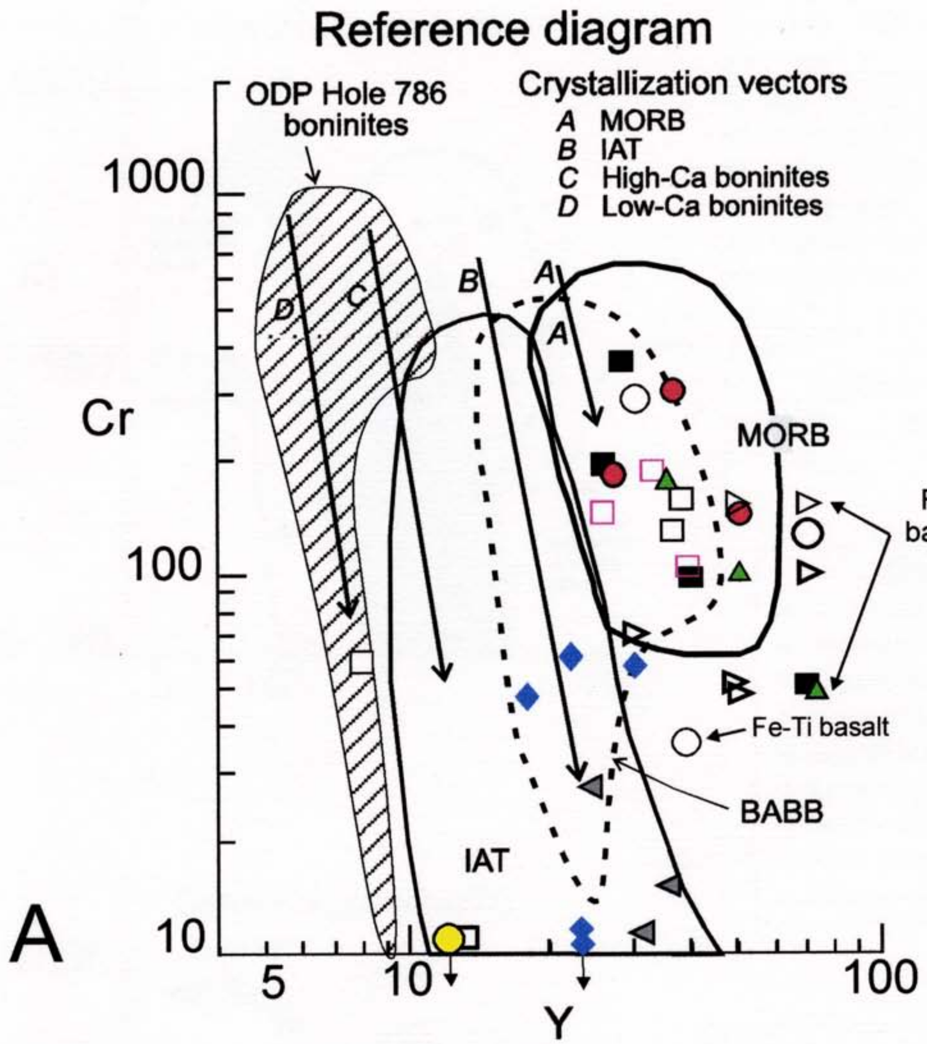


Figure 25a: Cr versus Y discrimination diagram of Pearce et al. (1984). Reference diagram in Metzger et al. (2002): field of BABB from Pearce et al. (1984 and references therein), Hawkins and Melchoir (1985) and Hawkins et al. (1990); field for boninites from ODP Hole 786, Izu-bonin forearc, from Murton et al. (1992). BABB-backarc basin basalt, IAT-island arc tholeiite, MORB-mid-ocean ridge basalt.

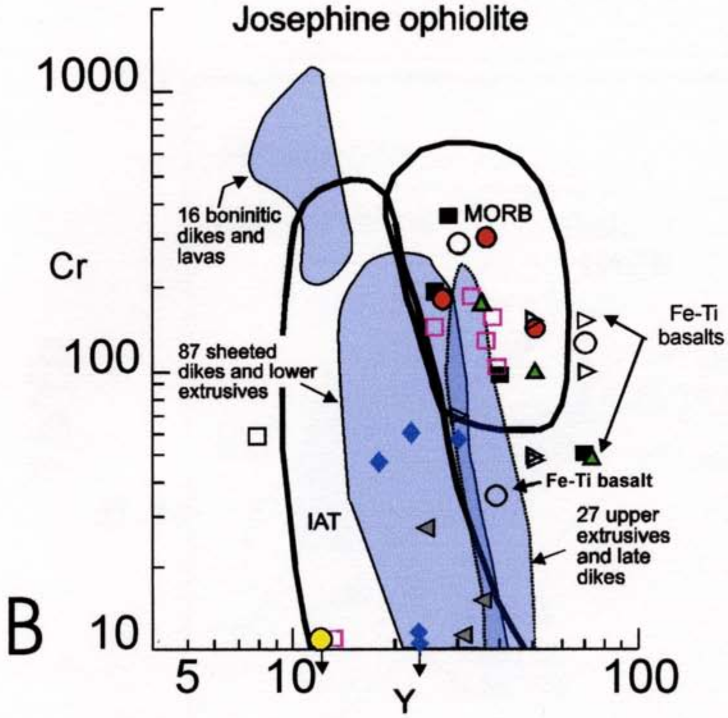


Figure 25b: Cr versus Y discrimination diagram from Pearce et al. (1984). Fields for JO (purple) are in Metzger et al. (2002), from Harper (1988), Coulton et al. (1995) and Harper (2003a, 2003b).

Legend

- ▲ Quosatana Butte
- ■ Skookumhouse Butte
- ● Copper Canyon
- ◆ Mineral Hill
- ◀ East of Saddle Mountain
- ○ Snowcamp Mountain
- ● JM-200 (Metarhyolite)
- □ Plake Miscellaneous
- ▷ Coleman Miscellaneous

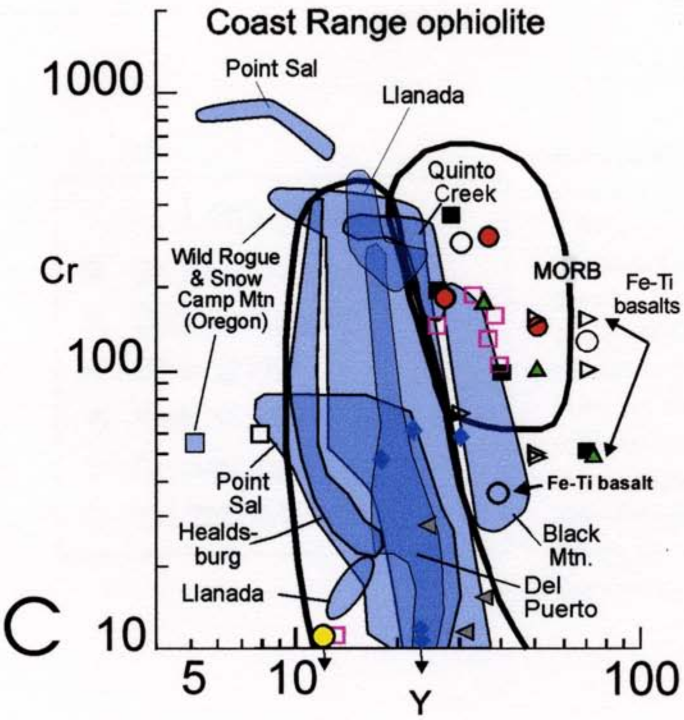


Figure 25c: Cr versus Y discrimination diagram from Pearce et al. (1984). Fields for CRO (blue; from Snow Camp terrane in Snowcamp Mountain area) are in Metzger et al. (2002) from Harper (unpublished data) and Kosanke (2000). IAT-island arc tholeiite, MORB-mid-ocean ridge basalt.

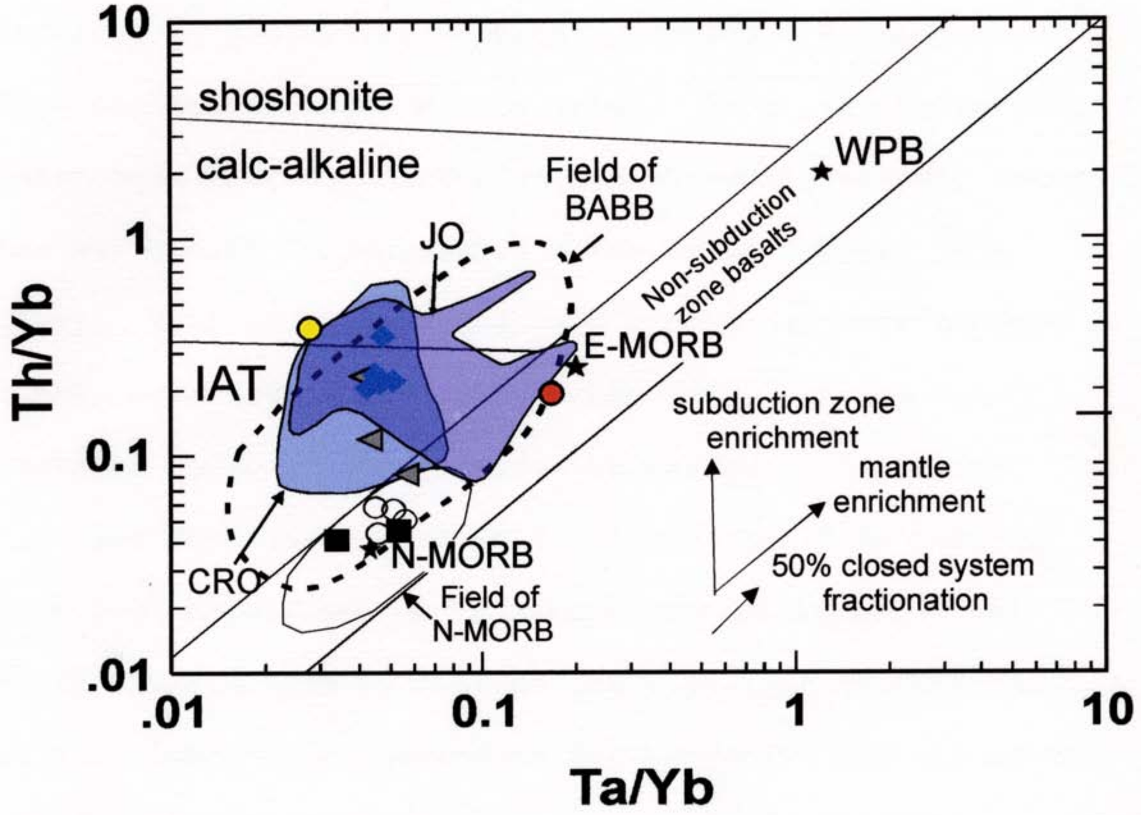


Figure 26: Th/Yb versus Ta/Yb discrimination diagram (Pearce, 1982). CRO (from Snowcamp Mountain area) and JO fields from Harper (unpublished data; and 2003a, 2003b; respectively). BABB-backarc basin basalt, IAT-island arc tholeiite, N-MORB-primitive mid-ocean ridge basalt, E-MORB-enriched mid-ocean ridge basalt, WPB-within plate basalt.

source prior to addition of a subduction component can be inferred by projecting vertically downward to the intersection with the mantle array. Ta/Yb ratios for all Colebrooke blocks indicate an N-MORB mantle source, except for one Copper Canyon sample which is an E-MORB. The Mineral Hill and Saddle Mountain blocks, and one unnamed block, also have a subduction component, denoted by elevated Th/Yb ratios relative to Ta/Yb.

Any MORB having > 2 wt.% (~12000 ppm) TiO_2 and > 12 wt.% FeO^T are called Fe-Ti basalt (Sinton et al., 1983). Fe-Ti basalts form by extreme fractionation of MORB (Sinton et al., 1983). All Quosatana Butte samples and six of the undifferentiated Colebrooke samples are Fe-Ti MORB. This is significant in that Fe-Ti MOR basalts are rare at mid-ocean ridges except near propagating rift tips (Sinton et al., 1983).

The Cr-Y diagram can also be used to single out rocks having boninitic affinity, because of their very low Y values. Two unnamed Colebrooke blocks from Plake (1989) fall along boninitic fractionation trends (Figure 25a). One of these (113b) is the meta-quartz diorite of Plake (1989). In addition, the Colebrooke metarhyolite (JM-200) from this study plots along a boninite trend. Since the Cr-Y diagram is better suited for basalts (Pearce, 1982), Figure 27 shows that this metarhyolite ocean ridge granite has the extreme depletion of high-field elements characteristic of boninitic (e.g. dashed line in Figure 27) felsic rocks.

Magmatic Affinities of Josephine and Coast Range Ophiolites

Fields for the Josephine ophiolite (Harper, 2003a; 2003b) pillow lavas and sheeted dikes of the Snow Camp terrane (Coast Range ophiolite; Harper, unpublished data) in the Snowcamp Mountain area are included in the three discrimination diagrams (Figures 24-26) for comparison with the Colebrooke meta-igneous blocks.

Most of the Josephine ophiolite samples plot as MORB on the Ti-V diagram, although some samples plot in the IAT field and along the IAT/MORB boundary (Figure 24). On the Cr-Y diagram (Figure 25b) the Josephine ophiolite samples plot in the fields for MORB, IAT and transitional IAT/MORB. Most of the Josephine ophiolite shows a subduction component on the Th/Yb versus Ta/Yb diagram, with deviation from a mantle enriched relative to N-MORB mantle (Figure 26). In addition, many of the Josephine ophiolite samples

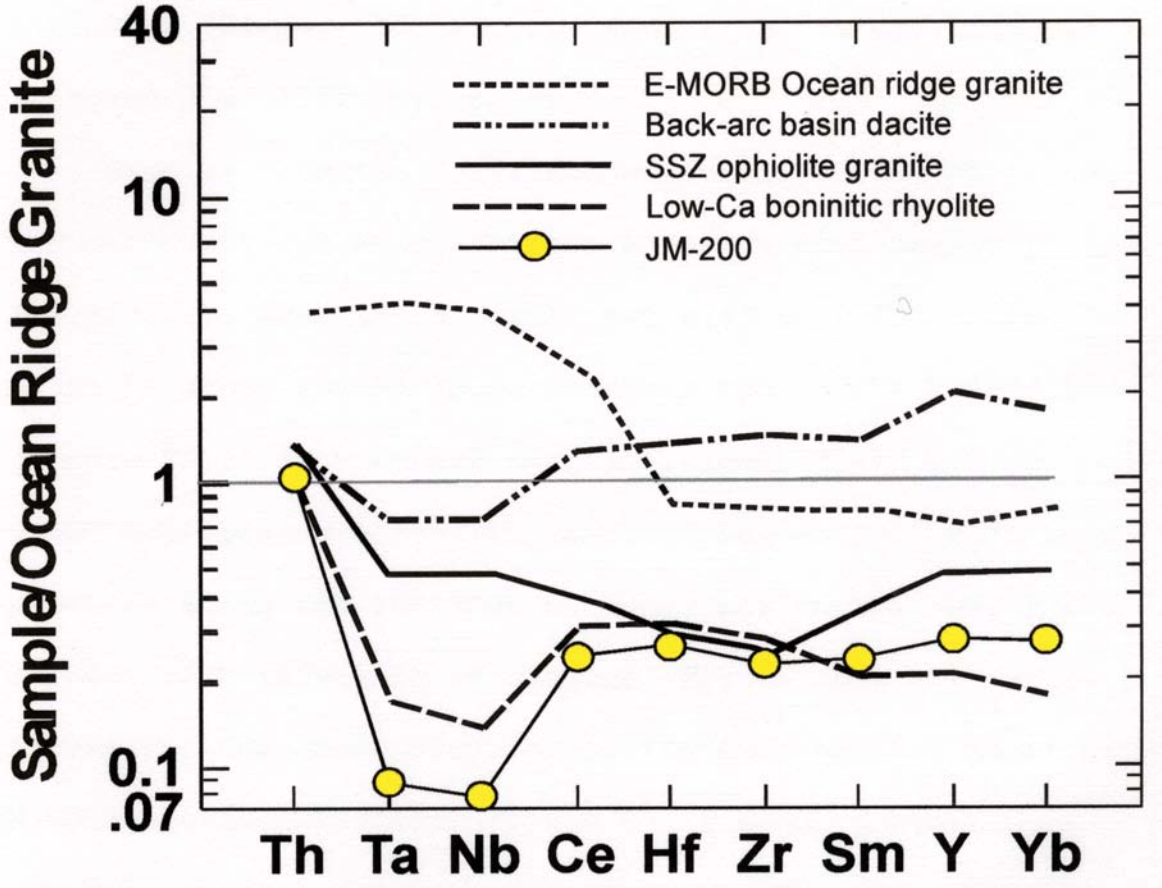


Figure 27. Ocean Ridge Granite normalized spider diagram with modern reference suite and Colebrooke metarhyolite sample JM-200 (yellow circle), modified from Pearce et al. (1984). Low-Ca boninitic rhyolite from Izu-Bonin forearc (sample 61R-4, hole 786B) (Murton et al. 1992), E-ORG (enriched ocean ridge granite) from Mid-Atlantic Ridge, 45N (Pearce et al. and references therein, 1984), backarc basin dacite from central Lau Srpeading Center, Lau Basin (ODP Leg 135) (Hawkins, 1995), SSZ (suprasubduction zone) ophiolite granite from Troodos Massif (Pearce et al. and references therein, 1984).

plot in the Fe-Ti MORB field on the Ti-V diagram (Figure 24; Harper, 2003a). The Josephine ophiolite also contains boninites (Harper, 2003b), as evident on the Cr-Y diagram (Figures 25a, 25b; Harper, 2004).

Samples from the Coast Range ophiolite remnant in the Snow Camp terrane near Snowcamp Mountain plot mostly in the IAT field on the Ti-V discriminant diagram, with some plotting along the IAT/MORB boundary and in the MORB field (Figure 24). In the Cr-Y diagram (Figure 25c), most of the Snow Camp terrane ophiolite samples plot as IAT, with some plotting along the IAT/MORB boundary and in the MORB field. On the Th/Yb versus Ta/Yb diagram (Figure 26), the mantle source for the Coast Range ophiolite samples is similar to N-MORB mantle, with most of the Coast Range ophiolite samples having a subduction component. The Snow Camp terrane ophiolite contains some boninitic rocks, which are apparent on the Cr-Y diagram (Figures 25a, 25c). Thus the Josephine ophiolite and Snow Camp terranes have broadly similar geochemistry, although the latter shows a more depleted mantle source and lacks Fe-Ti basalt.

Comparison of Colebrooke Meta-igneous Blocks to the Josephine and Coast Range Ophiolites

On the Ti-V and Th/Yb versus Ta/Yb diagrams (Figures 24 and 26) the Colebrooke Schist blocks, Josephine ophiolite and Snow Camp terrane ophiolite have affinities that range from MORB to IAT and plot within the field of back-arc basin basalts. On the Ti-V diagram (Figure 24) the Colebrooke Schist samples overlap much of the field defined by samples from the Josephine ophiolite, and there is some overlap of the IAT- and transitional-IAT/MORB-affinity Colebrooke Schist blocks with the Snow Camp terrane ophiolite samples. On the Cr-Y diagram (Figures 25a-c), the Colebrooke Schist blocks overlap fields defined by samples from the Josephine ophiolite and Snow Camp terrane ophiolite. The range of inferred mantle sources prior to addition of any subduction component for the Colebrooke Schist blocks is similar to that of modern N-MORB, although one is E-MORB. The Josephine ophiolite samples have similar sources, but some are similar to E-MORB mantle. The Snow Camp terrane ophiolite, like most of the Colebrooke Schist blocks, only has mantle sources similar to that for N-MORB. As evident from the Th/Yb versus Ta/Yb diagram (Figure 26), the Colebrooke Schist, Josephine ophiolite and Snow Camp terrane remnant of the Coast Range ophiolite all contain samples having a subduction component.

Both the Colebrooke Schist meta-igneous blocks and the Josephine ophiolite contain unusual highly fractionated Fe-Ti basalts having MORB affinities. Such rocks are relatively rare at modern spreading centers, occurring mostly at propagating rift tips [Sinton et al, 1983; Pearce et al., 1994]. In addition, the Colebrooke Schist blocks, Josephine ophiolite and Coast Range ophiolite all have rocks of boninitic magmatic affinities (Figure 25a-c; Harper, 2003b; Harper, unpublished data; Shervais, 1990 [Coast Range ophiolite]; Kosanke, 2000 (thesis); Kosanke et al., 2004), although the boninitic Colebrooke Schist blocks are metaplutonic rather than metavolcanic and are much more fractionated. The Colebrooke meta-igneous blocks show geochemical similarities to both the Josephine ophiolite and the structurally overlying ophiolite of the Snow Camp terrane, which has been correlated with the Coast Range ophiolite of California (Blake et al., 1985a). This ophiolite, however, may be an outlier of the Josephine ophiolite (Harper, unpublished data; Schoonmaker and Harper, in press), and the Coast Range ophiolite and

Josephine ophiolite may have originally formed a single ophiolite.

Structure of the Snowcamp Mountain Area

Summary of Structure

Plake (1989) recorded D_1 and D_2 features (Figure 28) and observed that orientations of D_2 features vary with geographic location. This is shown in Figure 29 from Plake (1989), whose study area is north of my study area. Plake (1989) suggests a model involving rigid block rotations about a vertical axis within the Colebrooke Schist to explain both the geographic variance in orientation of D_2 event structures and the subhorizontal girdle defined by F_2 and L_2 (Figure 29).

The Colebrooke Schist is cut by late, N-S trending normal faults first observed by Coleman (1972). In addition, Plake (1989) identifies late, NW-SE trending brittle shear zones containing sheared serpentinite. Slickensides showing a strike-slip sense have been observed on two of the late, NE-striking faults (G. Harper, personal communication).

Metasedimentary rocks of the Colebrooke Schist in my study area in the vicinity of Snowcamp Mountain are well foliated (Figure 7), and some pillow structures were observed to be flattened and foliated in several locations

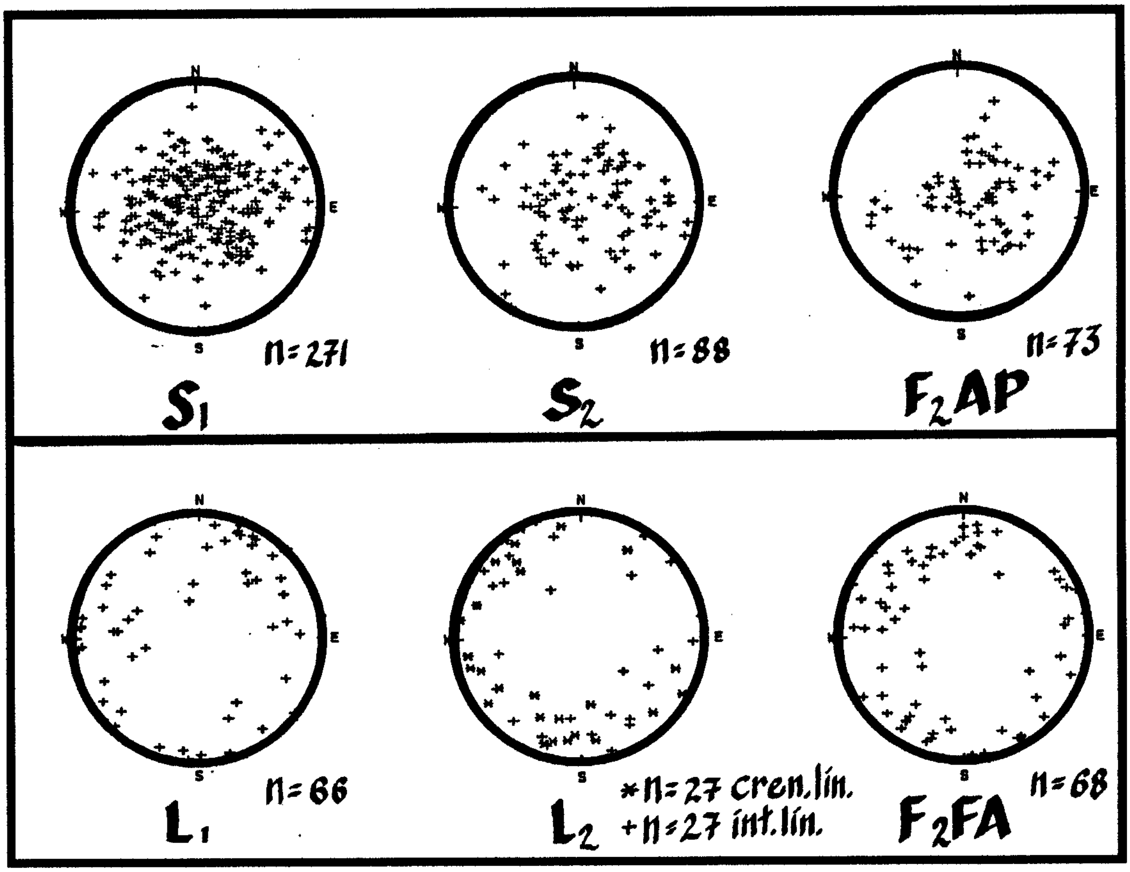


Figure 28: Equal-area stereonet projections of S_1, L_1, S_2, F_2 axial planes, L_2 crenulation lineations and F_2 fold axes. Figure from Plake (figure 33, 1989).
FA = fold axes, AP = axial planes

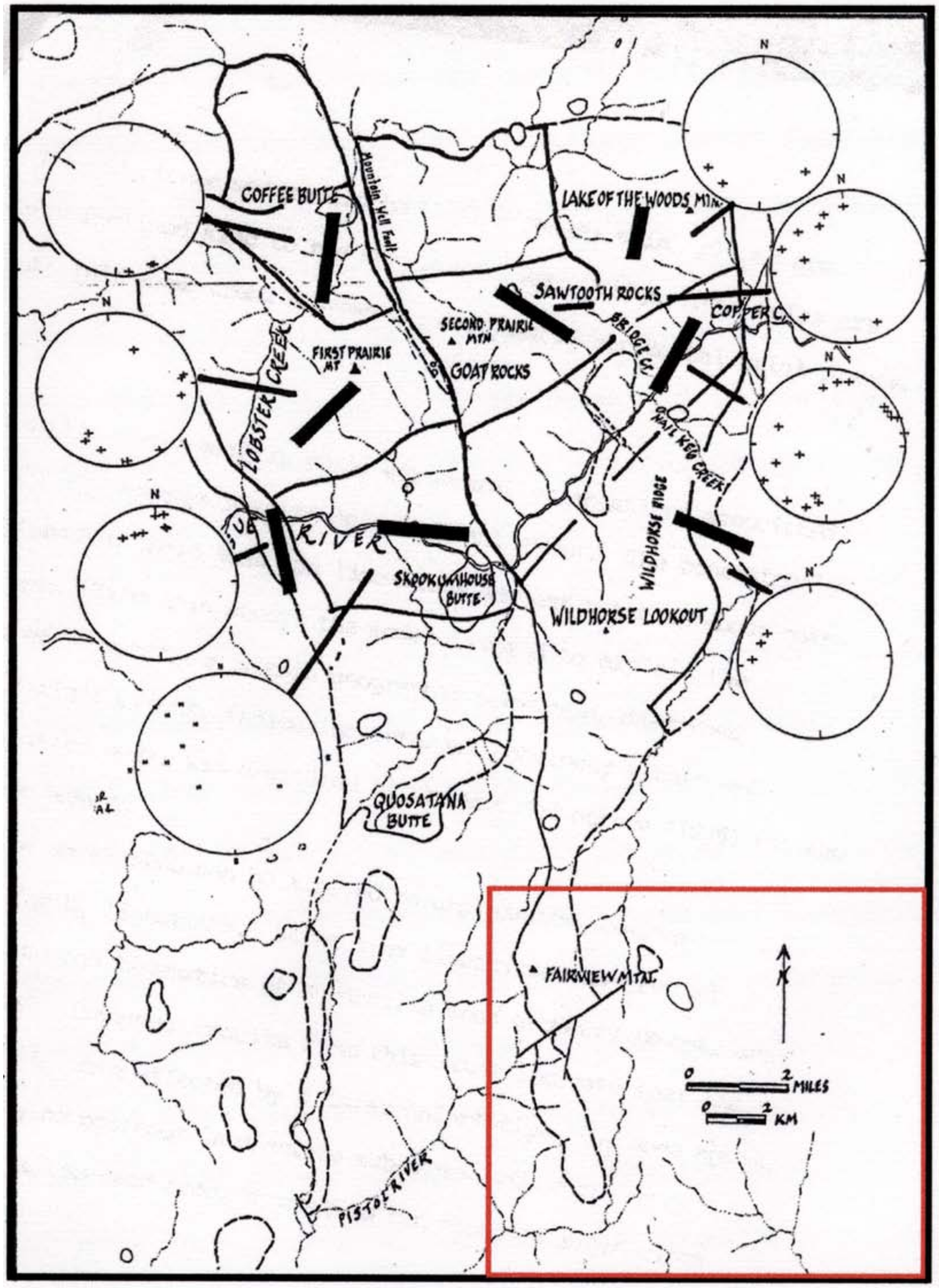


Figure 29. Stereonet projections of F2 fold axes. Plots are divided geographically. Figure from Plake (figure 34b, 1989). Red box indicates overlap with the field area from this study.

(Figure 10). This foliation and flattening of pillow structures are likely to be the same S_1 foliation described by Plake (1989). S_2 crenulation cleavage and F_2 fold axes as described by Plake (1989) were observed but not measured in my study. The Colebrooke Schist in this area is extensively veined with quartz and albite, and it is commonly sheared with polished slickensides on the shear surfaces. This shearing of the foliation indicates post-metamorphic faulting took place.

Field Data

Foliations, equivalent to S_1 from Plake (1989), measured throughout the field area generally vary in strike from northwest to northeast and dip to the east (Figures 30 and 31). Serpentinite foliations were measured throughout the Snowcamp Mountain area. Two measurements were made on coherent serpentinite (JM-06 and JM-06b) of possibly detrital origin (Figure 14). Foliation in one of these coherent serpentinites is parallel to that in pelitic phyllite in an exposure on the northwest side of Snowcamp Mountain (Figure 13), and were thus most likely formed in the same deformation event (D_1). Other measurements of serpentinite foliation were measured on incoherent sheared

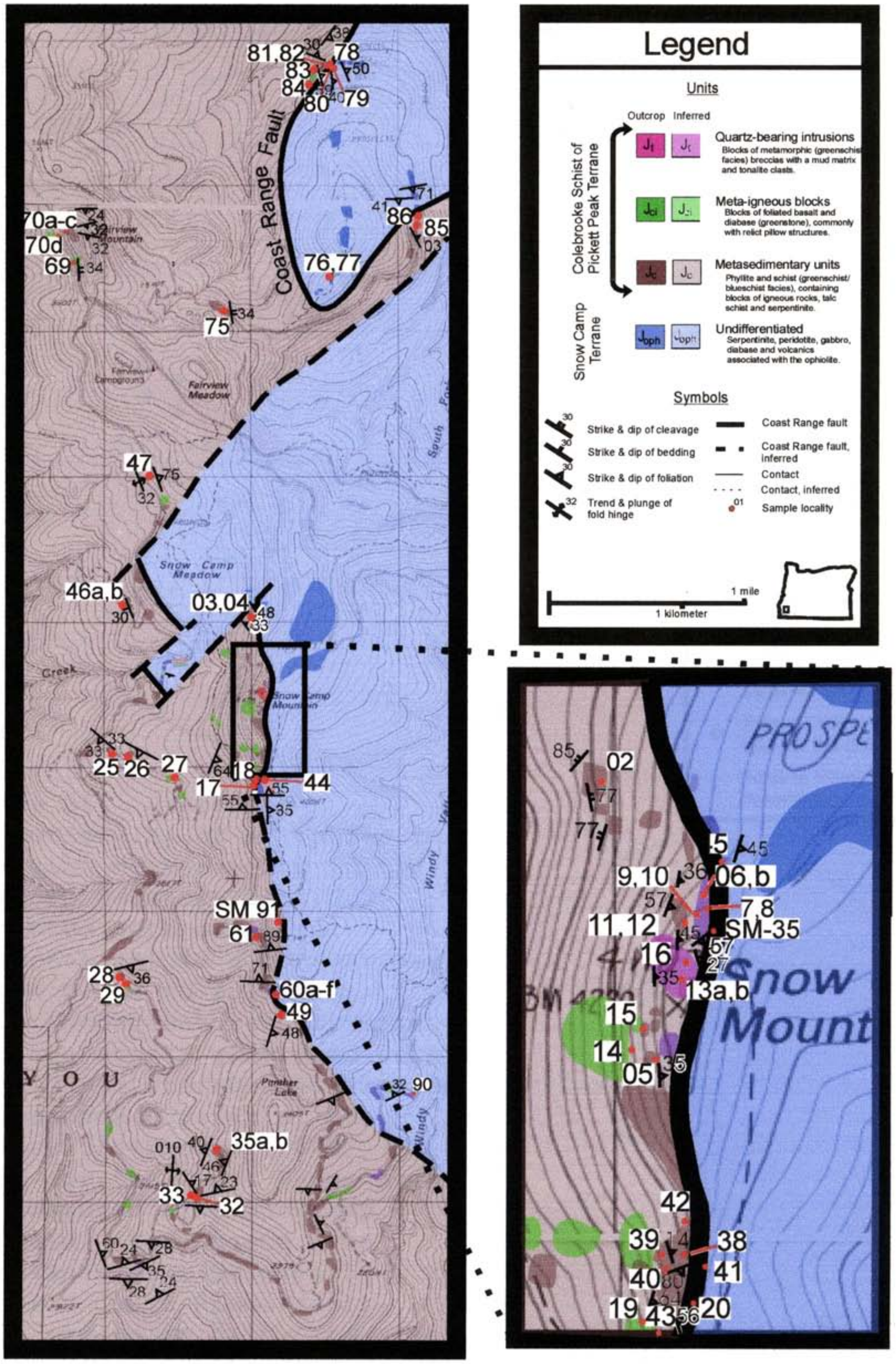


Figure 30: Field map of the Snowcamp Mountain area.

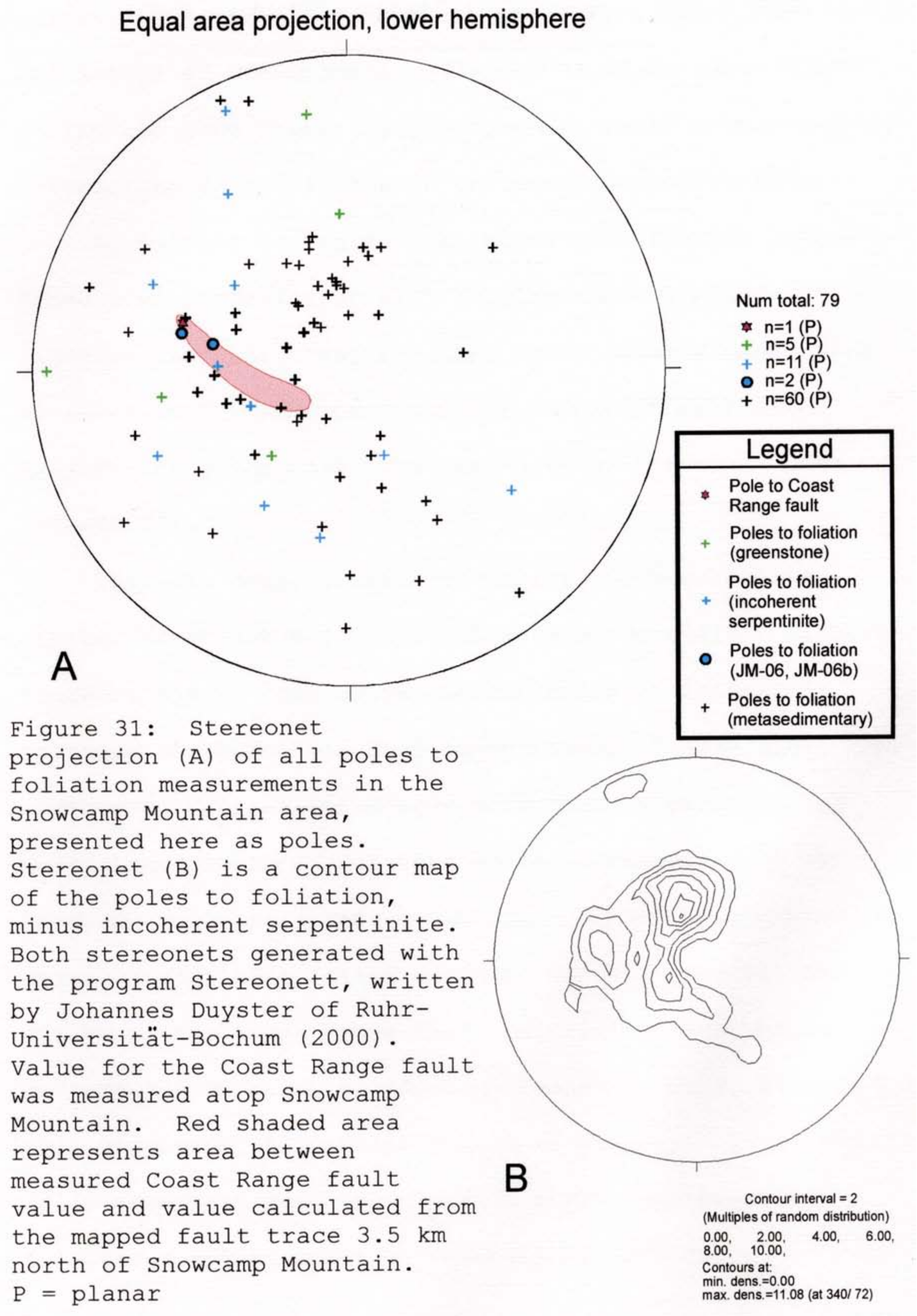


Figure 31: Stereonet projection (A) of all poles to foliation measurements in the Snowcamp Mountain area, presented here as poles. Stereonet (B) is a contour map of the poles to foliation, minus incoherent serpentinite. Both stereonets generated with the program Stereonett, written by Johannes Duyster of Ruhr-Universität-Bochum (2000). Value for the Coast Range fault was measured atop Snowcamp Mountain. Red shaded area represents area between measured Coast Range fault value and value calculated from the mapped fault trace 3.5 km north of Snowcamp Mountain. P = planar

serpentinite; this foliation is probably younger than the S_1 foliations of the D_1 event, although it might have formed during the late stages of the D_1 event since it has similar orientation to foliations in the metasedimentary rock.

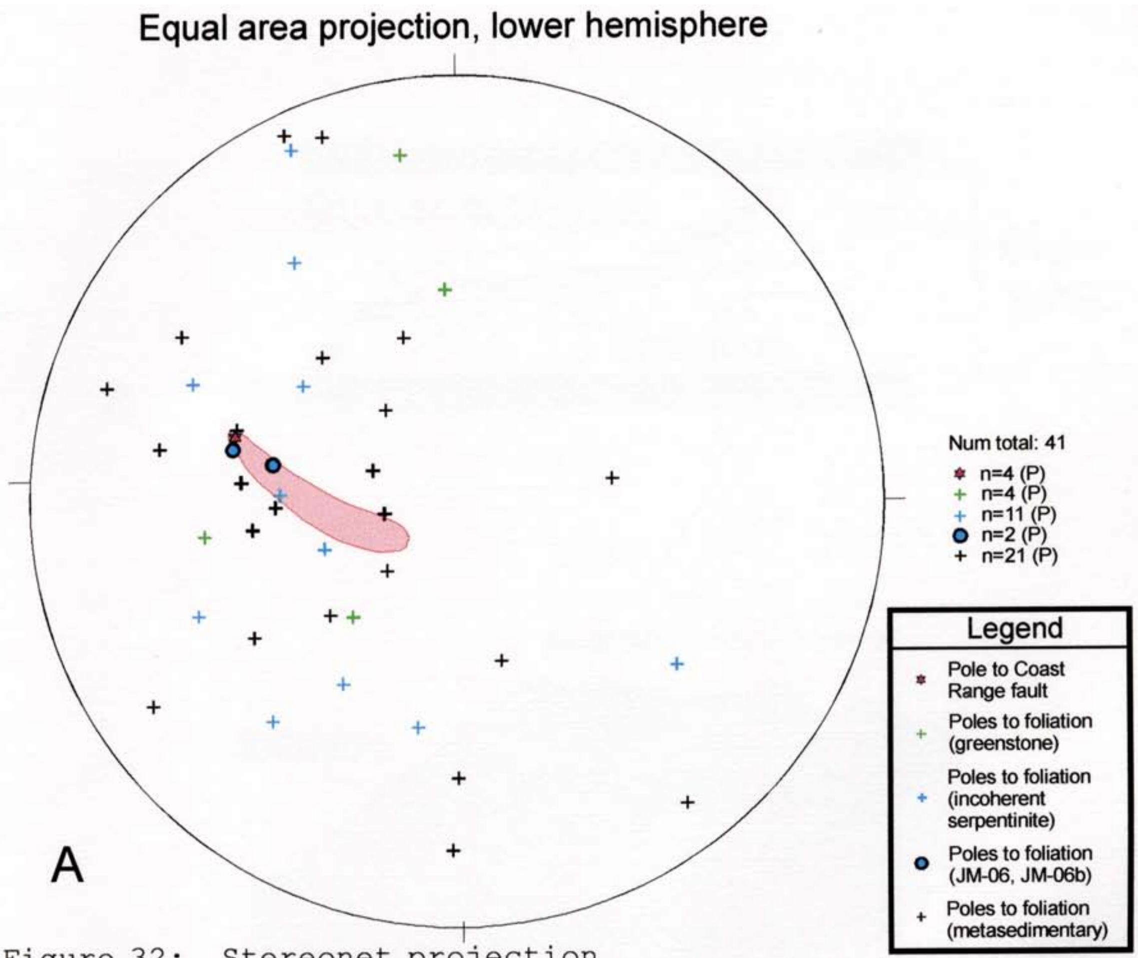
As evident in Figure 31A, poles to foliation define a broad girdle consistent with folding about a moderately plunging east-northeast trending axis. This distribution of poles to S_1 foliation is broadly similar to those measured by Plake (1989) to the north of the study area (Figure 29).

The most dense cluster of foliation measurements strikes northeast and dips southeast (Figure 31B), although there is also a less dense concentration of foliations striking northwest and dipping northeast (Figure 31A). The northeast striking foliations more closely parallel the Coast Range fault as measured on the northeast side of Snowcamp Mountain (N16E, 45°SE; locality of Figure 13). The northwest striking foliations more closely parallel the strike of the Coast Range fault calculated from the map pattern 3.5 km north of Snowcamp Mountain (N35W, 14°NE), but this cluster of foliations dips more steeply. In general, foliations near Snowcamp Mountain strike northeast and foliations 3.5 km north of Snowcamp are divided approximately equally between northeast- and northwest-striking.

When limited to measurements within 200 m to the Coast Range fault, the most dense concentration of foliation measurements strikes approximately north and dips east (Figure 32). Overall, however, there is no significant difference in orientation of foliations near or away from the fault; that is, poles to foliations define a broad girdle of similar orientation.

For ductile shear zones in general, foliation rotates toward parallelism with the shear zone boundary with increasing strain (Figure 33). Because of the wide variation in foliation orientation, as well as the similarity of the orientation of foliations both close to and farther from the Coast Range fault, it is unclear whether this geometry applies to the study area. If it once did, it has been obscured by later folding that is evident from the girdle defined by poles to foliation (Figure 31).

Lineation is a stretching lineation. It is measured on oriented hand samples, and is evident by the stretching or lining-up of resistant grains. The orientation of stretching lineations (equivalent to L_1 of Plake, 1989) is



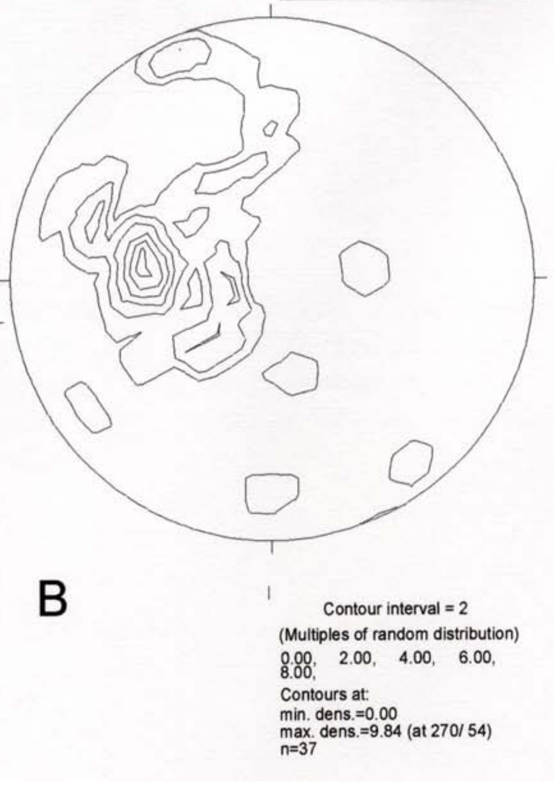


Figure 32: Stereonet projection (A) of foliation measurements close to the Coast Range fault, presented here as poles. Stereonet (B) is a contour map of the poles to foliation, minus incoherent serpentinite. Both stereonets generated with the program Stereonett, written by Johannes Duyster of Ruhr-Universität-Bochum (2000). Value for the Coast Range fault was measured atop Snowcamp Mountain. Red shaded area represents area between measured Coast Range fault value and value calculated from the mapped fault trace 3.5 km north of Snowcamp Mountain.
P = planar

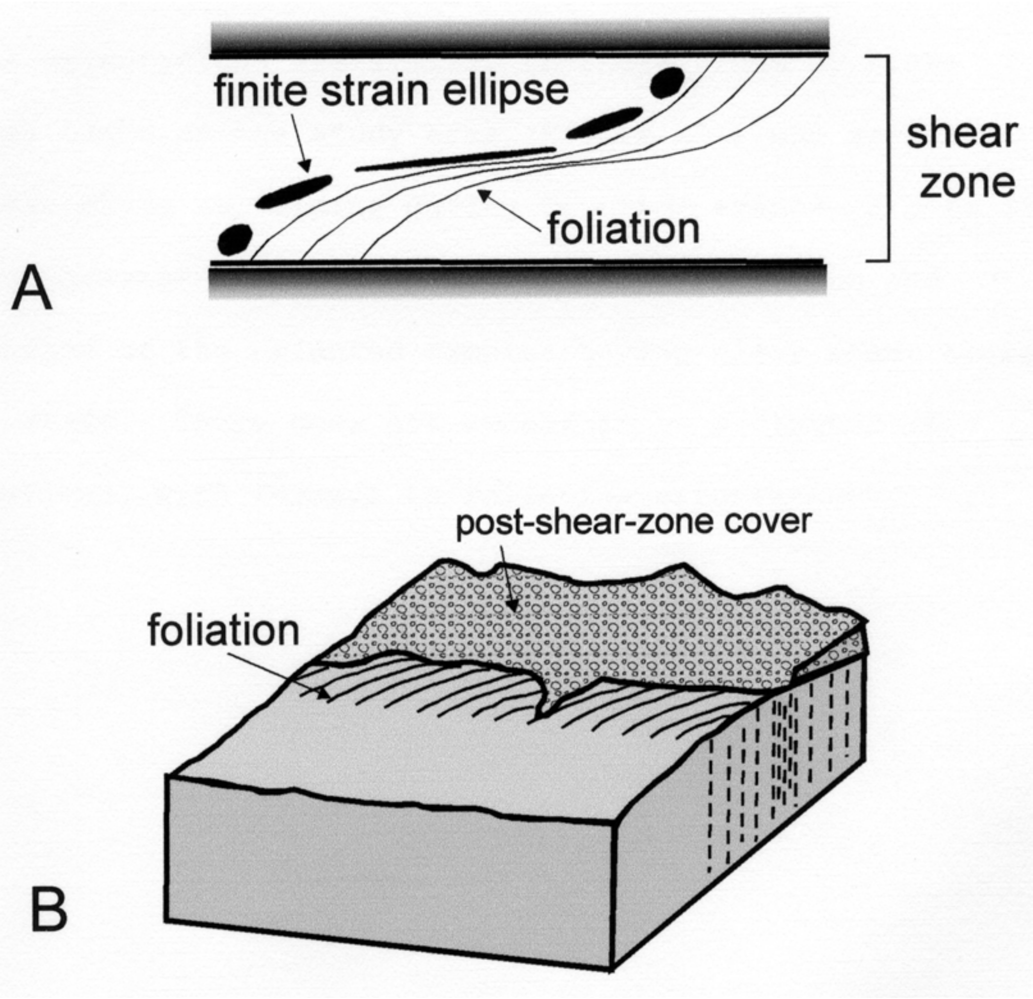


Figure 33. Illustrations from Davis and Reynolds (figures 9.37 and 9.38, 1996) showing the orientation of foliation in a shear zone. (A) is a cross section of a shear zone and (B) is a block diagram showing the surface trace of foliation as well as a cross section.

scattered with no clear average value, although most plunge gently to moderately southeast or northwest (Figure 34). These orientations are similar to those found by Plake (1989) north of the study area (Figure 29), who ascribed the variation to folding during D_2 and D_3 events. Figure 35 is an equal-area stereonet plot showing foliation and lineation of the oriented samples having clear shear sense indicators. There does not appear to be a cluster of lineations, with respect to foliation orientations.

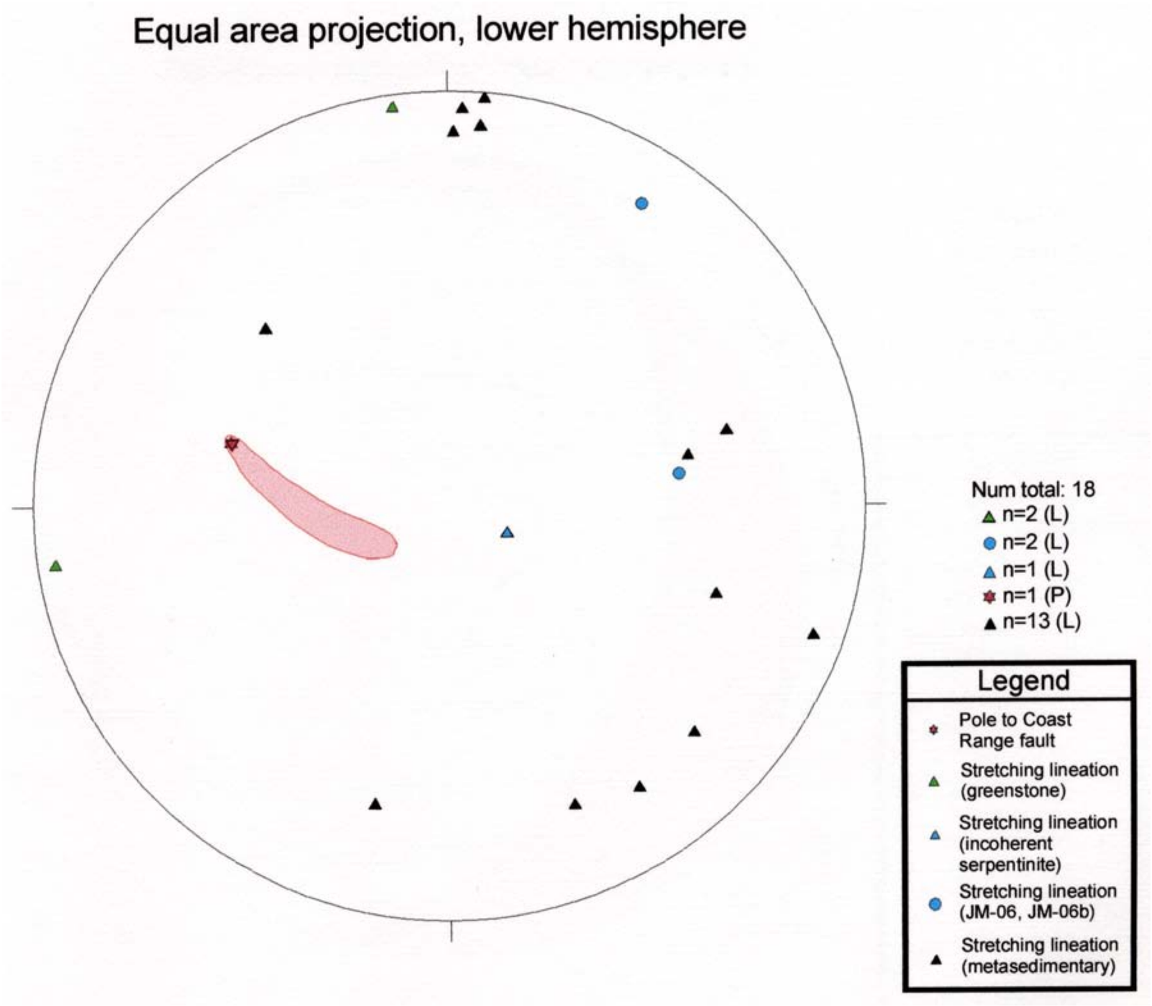


Figure 34. Stereonet projection of all stretching lineation measurements in the Snowcamp Mountain area. Stereonet generated with the program Stereonett, written by Johannes Duyster of Ruhr-Universitat-Bochum (2000). Value for the Coast Range fault was measured atop Snowcamp Mountain. Red shaded area represents area between measured Coast Range fault value and value calculated from the mapped fault trace 3.5 km north of Snowcamp Mountain.
L = linear, P = planar

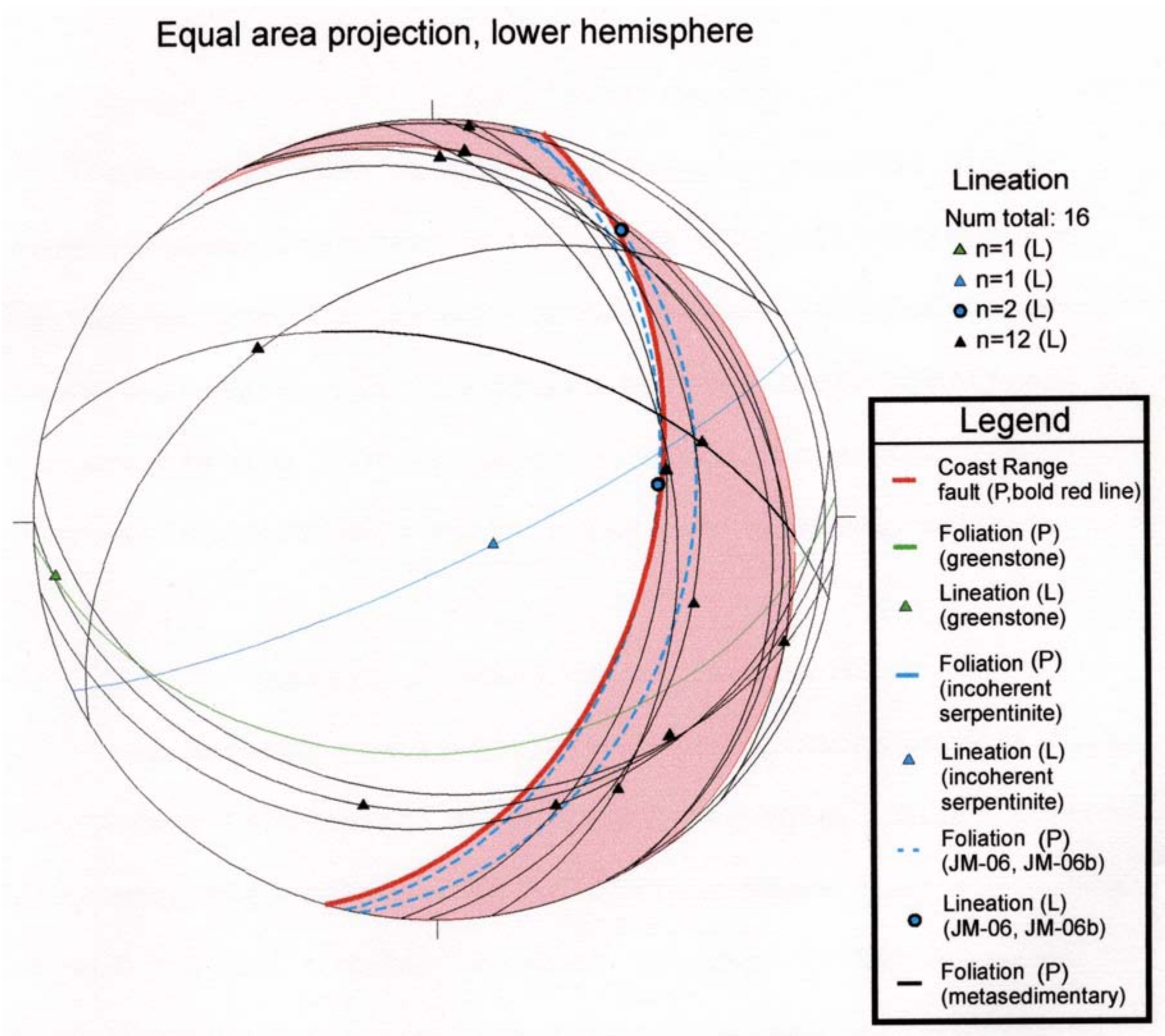


Figure 35. Stereonet projection of foliation and lineation measurements in the Snowcamp Mountain area. Only samples with clear shear sense indicators are included. Stereonet generated with the program Stereonett, written by Johannes Duyster of Ruhr-Universitat-Bochum (2000). Value for the Coast Range fault (bold red) was measured atop Snowcamp Mountain. Red shaded area represents area between measured Coast Range fault value and value calculated from the mapped fault trace 3.5 km north of Snowcamp Mountain.
L = linear, P = planar

Discussion

Geochemistry

The occurrence of the meta-igneous rocks as blocks suggests they represent either clasts in olistostromes or tectonic blocks in the Colebrooke Schist of dismembered ocean basement. Distinguishing between these hypotheses is hampered by the lack of exposure of contacts with the surrounding metasedimentary rocks due to heavy vegetation.

Summary of Geochemical Similarities

The largest blocks—Quosatana Butte, Skookumhouse Butte and Copper Canyon—show MORB affinities on all discriminant diagrams; the Th/Yb vs. Ta/Yb diagram shows they are N-MORB except for one E-MORB. Most of the smaller blocks also have N-MORB affinities. Many of these samples are unusual Fe-Ti MORB. Three other blocks have boninitic affinities, one of which is the latter is JM-200, a metarhyolite dike in a tonalite block from Snowcamp Peak, and the other two are meta-quartz diorites analyzed by Plake (1989). However, samples from the large Mineral Hill block have transitional IAT/MORB affinities (Figures 24 and 25a). The Colebrooke Schist meta-igneous blocks and Josephine ophiolite both cover a wide range of magmatic affinities, from Fe-Ti MORB to boninite.

In addition to geochemical similarities to the Josephine ophiolite, a U-Pb zircon age of a Colebrooke Schist meta-quartz diorite sampled by Plake (1989) and having boninitic affinities is 162 ± 1 Ma (Walker et al., 1987). This is similar to the 162 ± 1 and 164 ± 1 Ma zircon ages for the Josephine Ophiolite (Wyld and Wright, 1988; Harper et al., 1994). The Snowcamp remnant of the Coast Range ophiolite has a U-Pb zircon age of 169 ± 1 Ma (Saleeby, 1984), but somewhat younger ages are known from elsewhere in the Snow Camp terrane (Kosanke, 2000) and from the Coast Range ophiolite in California (e.g., Dickinson et al., 1996; Shervais et al., 2004).

If the Colebrooke Schist blocks are sedimentary, the Colebrooke Schist could be an ocean basin or trench deposit and the source of the meta-igneous blocks could be erosion of either the Josephine ophiolite or Coast Range ophiolite. Plake (1989) interprets the meta-quartz diorite as a sedimentary block because clastic textures were visible in one good outcrop (Plake, 1989). Brown and Blake (1987) interpret the meta-quartz diorite as a pre-metamorphic intrusion. If this latter interpretation is correct then the rest of the blocks, if sedimentary, are unlikely to have been derived from the Josephine ophiolite in that the minimum age of the Colebrooke Schist would be 162 Ma and thus probably older than the Josephine ophiolite. Also, Saleeby and Harper (1993) report ~170 Ma ages for an intrusion into the Condrey Mountain Schist: if the Colebrooke Schist indeed correlates with the Condrey Mountain Schist (Brown and Blake, 1987), then the protolith for the Colebrooke Schist is probably at least in part >170 Ma.

The Colebrooke Schist meta-igneous blocks could have been derived from the basement of the metasedimentary rocks, having been scraped off and incorporated into a mélange. This is consistent with the lack of any arc geochemical signature. For this possibility, there are several hypotheses.

(1) The similarity in the geochemistry of the Colebrooke Schist blocks to the Josephine ophiolite might imply that the Colebrooke Schist metasedimentary rocks and basement were originally part of the Josephine basin that was partially subducted. In this case, the metasediments are, at least in part, back-arc sediments and correlative to the Galice Formation overlying the Josephine ophiolite.

(2) All the blocks were derived from Colebrooke Schist basement, but the basement was part of another plate. The presence of MORB/IAT and BON implies that the basement was most likely formed in a back-arc basin, or an incipient arc that was built on true ocean crust. In this case, the similar geochemistry, including presence of both Fe-Ti MORB and boninitic rocks, and the ~162 Ma age of the quartz diorite (Walker et al., 1987) to the Josephine ophiolite would be coincidental. For this hypothesis, the Colebrooke Schist metasediments would be back-arc basin and/or trench deposits.

(3) The Colebrooke Schist greenstones formed at a mid-ocean ridge on another plate, probably with propagating rifts as evidenced by the presence of Fe-Ti basalt. However, in this case, the transitional MORB/IAT Mineral Hill, Saddle Mountain block and Snowcamp boninitic metatonalite might have been plucked from the Coast Range ophiolite/Josephine ophiolite and transported to their current setting during thrusting or low-angle normal faulting. This is consistent with their occurrence within serpentinite mélange near the fault with the overlying Snow Camp terrane, with the exception of the meta-quartz diorite of Plake (1989). The presence of this boninitic quartz

diorite of Plake (1989) suggests that these particular blocks are olistostromal. Testing of these models is dependent on constraining the depositional age of the Colebrooke Schist metasedimentary rocks.

Structure

The variation in foliation and lineation measurements of the Colebrooke Schist in the Snowcamp Mountain area is likely the result of post-metamorphic folding during D_2 and D_3 events of Plake (1989). Foliation and lineation formed during regional metamorphism generally have uniform orientations originally (Davis and Reynolds, 1996), and thus variation in these orientations most likely occurred post-metamorphism. Another possibility is that drag folding along the late northeast-striking faults affected the strike of the foliation, since some subhorizontal slickensides have been seen along these faults (G. Harper, personal communication). However, drag folding is unlikely to have caused D_2 folding or crenulation lineation, as observed by Plake (1989), to form, but it could be related to D_3. It is also possible that the extensive shearing and veining throughout the Colebrooke Schist changed the orientation of foliation and lineation.

Stereonet projections of Plake (1989) also show variation in foliation and lineation (Figure 28). One apparent difference in the stereonet projections from the Snowcamp area and in Plake's (1989) area is that foliation in the Snow Camp Mountain area is mostly east dipping, whereas foliation in Plake (1989) varies in dip from east to west (Figures 28 and 31). This could be an effect of proximity to the east dipping Coast Range fault. Plake (1989) suggests that, since there is less variation in foliation and lineation orientations when separated into geographic domains (Figure 29), later rigid block rotation about vertical axes could explain the wide variations seen (Figure 28). Lineations in the Snowcamp Mountain area do appear to have mostly shallow plunges but variable trends, which is consistent with rotation about a vertical axis (Figures 28 and 34; Plake, 1989).

Conclusions

The Colebrooke meta-igneous blocks range in magmatic affinity from N- and E-MORB to boninitic. Fe-Ti MORB are also present. The largest three blocks, Quosatana Butte, Skookumhouse Butte and Copper Canyon, are consistently MORB. The smaller blocks are mostly MORB, but three are boninitic. Two of the blocks with the serpentinite mélange unit between the Colebrooke Schist and Snow Camp ophiolite, Mineral Hill and Saddle Mountain, have transitional IAT/MORB affinities. Because of this diversity in magmatic affinity, the Colebrooke blocks may have a variety of origins, although all observed magma types can form in a back-arc basin setting (e.g., Harper, 2003b).

The Colebrooke blocks may be meta-igneous olistoliths in a metasedimentary matrix. Some evidence of clastic texture can be seen in the field and in cut slabs (Figures 11, 12, 14 and 17), although at least some of the texture is cataclastic in samples such as those in Figures 16 and 17. Similarities in magmatic affinity of the Colebrooke blocks to the Josephine ophiolite and/or Coast Range ophiolite suggest that these blocks may be derived from erosion of either one or both of these ophiolites.

Alternatively, the basement of the Colebrooke Schist may have been part of the Josephine basin or another back-arc basin. In addition, the diversity of magma types of the Colebrooke blocks is similar to the diversity of the Josephine ophiolite, such as the presence of boninitic rocks and Fe-Ti basalts. Also, the age of one boninitic Colebrooke blocks—162 ± 1 Ma (Walker et al., 1987)—matches the age of the Josephine ophiolite (Harper et al., 1994).

Since the largest of the blocks (>1 km across)—Quosatana Butte, Skookumhouse Butte and Copper Canyon—are MORB, it is possible they originated as ocean basement for the Colebrooke Schist. The ocean basement could have been disrupted during subduction and pieces of it incorporated into the accretionary complex.

In summary, the smaller Colebrooke meta-igneous blocks are likely clasts in olistostromes and may have been derived either from the Josephine ophiolite, Coast Range ophiolite or both. The largest MORB affinity blocks may be tectonic blocks derived from the ocean basement underlying the Colebrooke metasediments or from the roof of the thrust zone (forearc oceanic basement), although Moore et al. (1995) observed modern submarine landslide blocks that are as large as 10 km long and 500 m high.

Foliation and lineation measurements taken on the Colebrooke Schist in the Snowcamp Mountain area vary widely in orientation. Poles to foliation define a broad girdle consistent with folding about a moderately plunging east-northeast trending axis (Figure 31). Foliations near Snowcamp Mountain strike mostly northeast, and foliations 3.5 km north of Snowcamp strike between northeast and northwest. The variation in foliation and lineation in the Snowcamp area is likely a result of either D_3 overprinting or rigid block rotations about a vertical axis, as suggested by Plake (1989).

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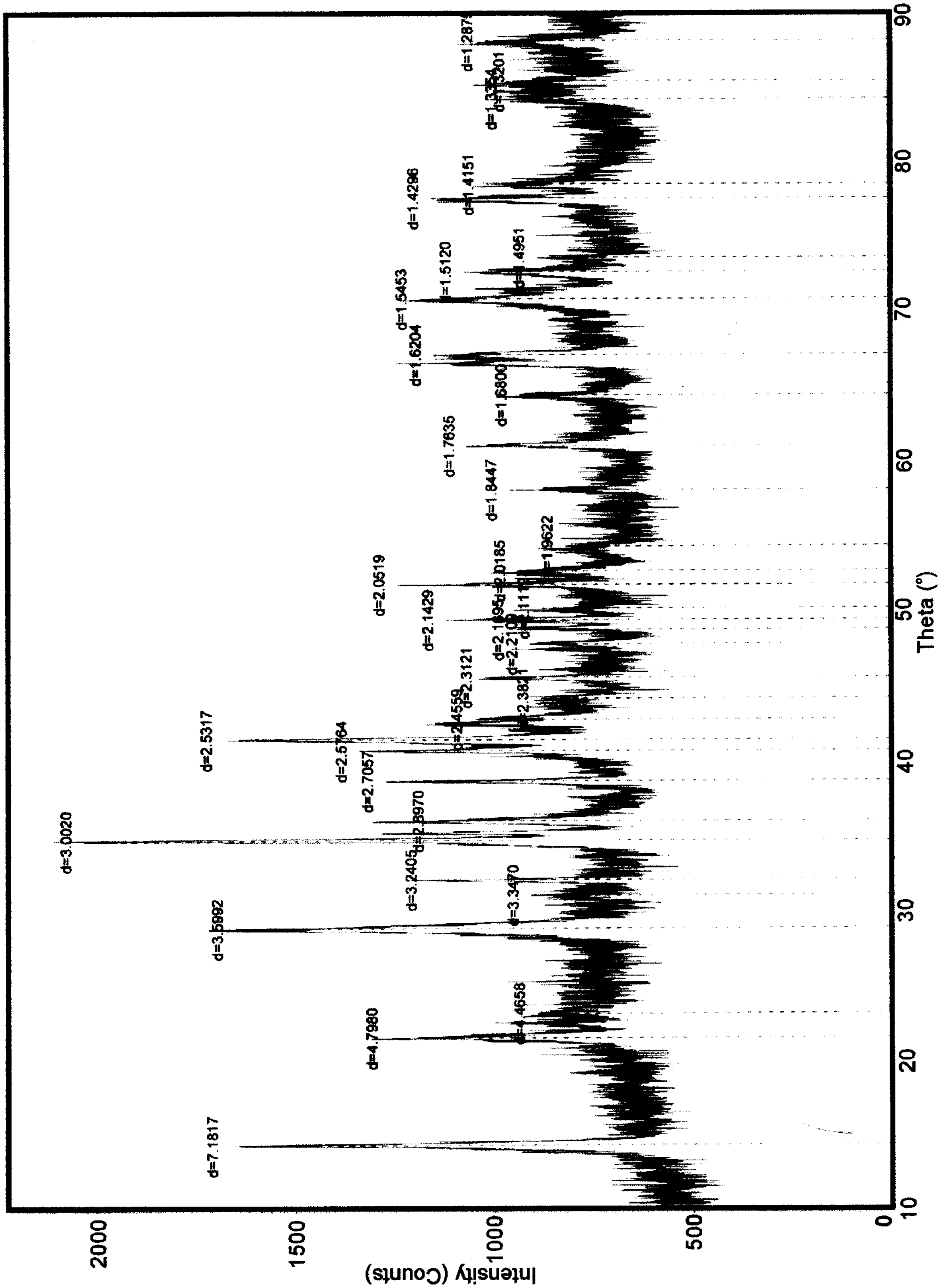
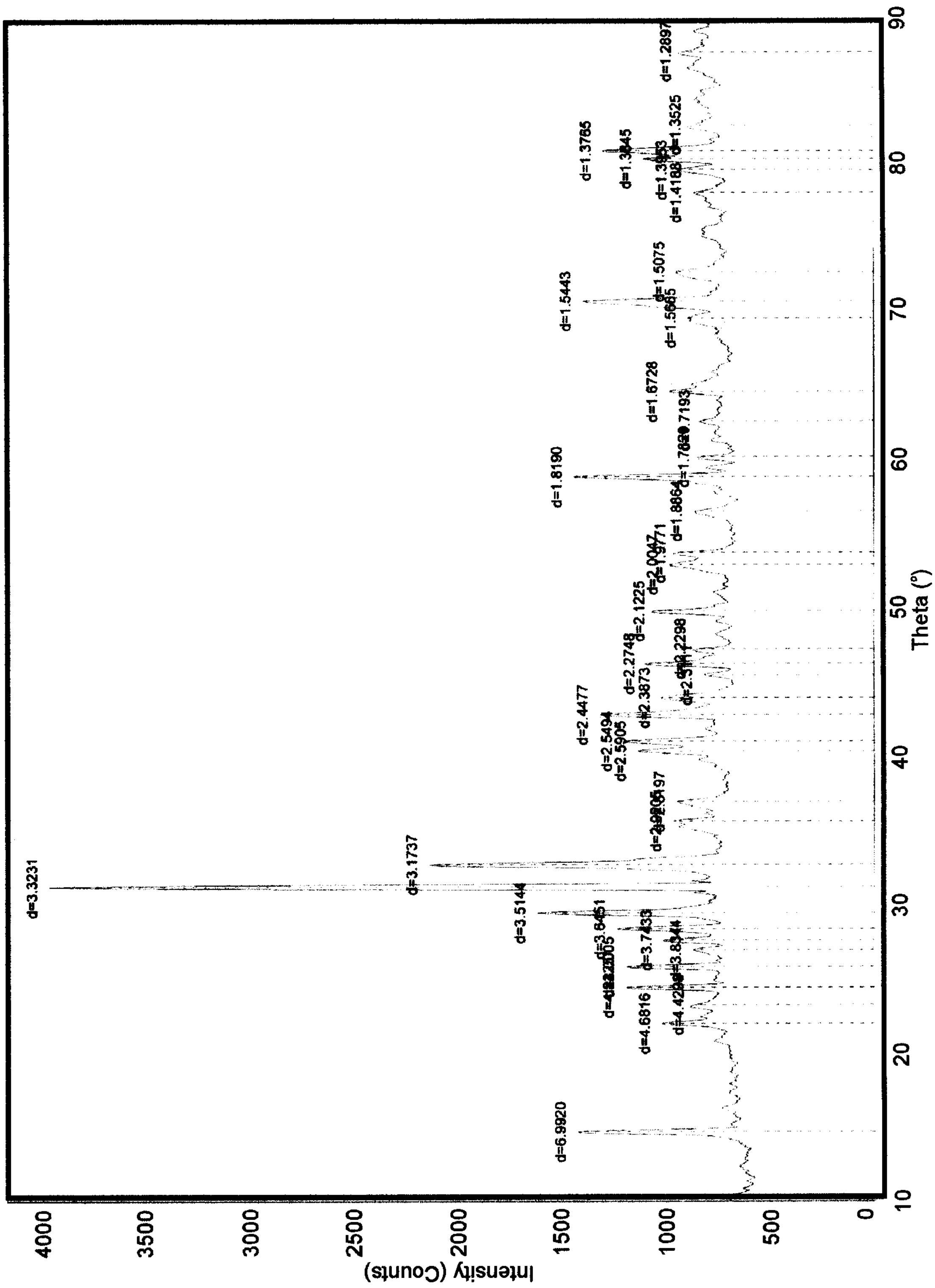


Appendix I: XRD data from JM-68 showing presence of serpentinite. XRD analysis performed at Union College.



Appendix II: XRD data from JM-200 showing presence of mud. XRD analysis performed at Union College.