TECTONIC ELEMENTS AND EVOLUTION OF NORTHWEST WASHINGTON

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WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-52
December 2003

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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Published in the United States of America

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INTRODUCTION

This report is a companion document to the recently published "Geologic Map of Washington—Northwest Quadrant" (Washington Division of Geology and Earth Resources publication GM-50, Dragovich and others, 2002b). That map, published at a scale of 1:250,000, portrays Washington geology on the basis of units defined by age and lithology. The map of this report (Fig. 1, scale=1:625,000) mostly follows the geologic contacts and structures of GM-50. The map differs from GM-50 in that we have attempted to group rocks that have experienced the same tectonic evolution, aspects of which are described under each unit listed below. Many units so defined are allochthonous and fault bounded and thus fit the definition of 'terranes'. However, the degree to which units of different regional map areas or of slightly different tectonic setting and age are related or were once contiguous is poorly known. Thus we have referred to these units as 'tectonic assemblages' rather than terranes so as to invite efforts to understand correlations and pre-orogenic connections. Units given the same color in this report have enough lithologic and tectonic features in common that they are considered to be directly related to each other.

Two terranes of regional extent long recognized as defining a tectonic context for northwest Washington are Wrangellia, underlying Vancouver Island, and Quesnellia, lying east of the Methow Valley and comprising part of the North American continent since the Middle Jurassic (for example, Monger and others, 1982). The tectonic map of this report nudges into the edge of Quesnellia (QN) at the northeast corner, but does not reach Wrangellia. The relation of Wrangellia and Quesnellia to northwest tectonics is portrayed in the cartoon drawings of Figure 4.

A difficult problem in assessing the tectonic evolution of the region is a paucity of radiometric ages for blueschist facies rocks of the Northwest Cascades and San Juan Islands thrust systems. Because Early Cretaceous mineral ages are known for the Easton Metamorphic Suite and Lopez Structural Complex, we tentatively consider blueschist minerals in other units of these thrust systems to be of similar age.

TECTONIC ASSEMBLAGES

(Arranged approximately from younger to older)

Volcanic rocks of the Cascade arc (CA)

Protolith: Basalt to rhyolite volcanic rocks and volcanic derived sediments. *Tectonic setting:* Andean arc. *Protolith age:* Oligocene to present. *References:* Ford, 1959; Tabor and others, 2000, in press; Hildreth and others, 2003.

Volcanic rocks of the Challis arc (CL)

Protolith: Basalt to rhyolite volcanic rocks and volcanic-lithic clastic sedimentary rocks. *Tectonic setting:* Igneous rocks of this age range are widely distributed across the Pacific Northwest. Typical calc-alkaline compositions in western Washington are the basis for assigning these rocks an arc origin. *Protolith age:* Eocene to Early Oligocene. *Tectonite fabric:* Absent except in fault zones. *References:* Vance, 1957, 1982; Tabor and others, 2000, 2002.

Plutons (P1, P2, P3, P4, P5)

Cascade plutons are mostly diorite, quartz diorite, and tonalite. These rocks are derived from calc-alkaline magmas interpreted to be generated by subduction-related processes. Separation of plutons based on age (P1–P5) is somewhat arbitrary, but reflects natural breaks in clusters of radiometric ages. Fabrics of P1 through P4 plutons range in different places from being entirely igneous, commonly showing magmatic foliation, to completely metamorphic, exhibited as orthogneiss. Large plutons are composites of multiple injections, dominantly sheets. The depth geometry of some P1 through P3 plutons can be inferred (as shown in cross sections of Fig. 2) from down-plunge views of the country-rock structure with which they are concordant. For other plutons, there is no direct evidence of the depth structure. Relatively shallow floors are tentatively inferred for P5 batholiths shown on the cross sections, based on comparison with the known depth-geometry of similar batholiths elsewhere on earth (for example, Benn and others, 1999; Brown and Tryggvason, 2001). Pluton fabrics serve as useful markers of strain and age of deformation. Pluton aureoles bear pressure sensitive metamorphic minerals that coupled with pluton ages give a depth-time relation for the orogen. *References:* Tabor and others, 1987, 2002, in press; Haugerud and others, 1991; Brown and Walker, 1993; Paterson and Miller, 1998; Brown and McClelland, 2000; Miller and others, 2000; Miller and Paterson, 2001a.

Olympic Subduction Complex (OS)

Protolith: Deep marine lithic sandstone, siltstone, and shale. Turbidites are common. *Tectonic setting:* Accretionary prism. *Protolith age:* Lower Eocene to Pliocene, based on fossils and fission track ages. *Metamorphic facies:* Ranges from zeolite facies in the western part to prehnite-pumpellyite and locally greenschist facies in the east. *Metamorphic age:* Eocene to Miocene. *Tectonite fabric:* Diapiric mélange and broken formation are notable in the western part, slaty cleavage and imbricate thrust structure in the eastern part. *References:* Stewart, 1974; Tabor and Cady, 1978a,b; Brandon and Vance, 1992.

Olympic Peripheral Rocks (OP)

Protolith: Tholeiitic basalt (Crescent basalts) and continent-derived marine sediments. *Tectonic setting:* Forearc rift zone in a forearc sliver translated north relative to the continent. *Protolith age:* Lower Eocene to Pliocene, based on Ar-Ar ages in basalt and fossils in sedimentary units. *Metamorphic facies:* Mostly unmetamorphosed, local prehnite-pumpellyite facies.

Tectonite fabric: Minimal. *References:* Rau, 1981; Tabor and Cady, 1978a; Babcock and others, 1992, 1994.

Chuckanut and Swauk Formations, Puget Group (CN)

Includes other related units. *Protolith:* Arkosic and lithic sandstone, siltstone, conglomerate, and coal. Mostly fluvial deposition, locally marine near Seattle. *Tectonic setting:* Intracontinental rift zones, likely strike-slip pull-apart basins. This unit is transitional to and partly overlaps OP across the Coast Range Boundary and Southern Whidbey Island faults. *Protolith age:* Early Eocene to Oligocene from fossils and fission-track ages of zircons. *Metamorphic facies:* Zeolites occur locally. *Tectonite fabric:* Absent except in fault zones. *References:* Gresens and others, 1981; Tabor and others, 1984; Johnson, 1984, 1985; Evans and Ristow, 1994.

Nanaimo Group (NA)

Protolith: Mostly marine, deep-water sandstone, siltstone and mudstone; local conglomerate, coal. *Tectonic setting:* Intracontinental basin near the edge of North America. Possibilities for basin formation include strike-slip pull-apart, forearc in front of the Coast plutonic complex, or (less likely) foreland depression in front of west-vergent thrusts emanating from the Cascade core. *Protolith age:* Late Cretaceous (90–65 Ma), based on fossils. *Metamorphic facies:* Insignificant to very low-grade burial metamorphism. *Tectonite fabric:* Slaty cleavage related to Cowichan fold and thrust system is broadly developed along the southwestern flank of the Nanaimo belt in Canada, but is generally absent except in fault zones in Washington. *References:* Pacht, 1984; England and Calon, 1991; Mustard, 1994.

Methow Stratigraphic Sequence (MT)

Protolith: Jurassic and Early Cretaceous rocks are dominantly marine volcanic-lithic clastic sedimentary rocks and lesser andesitic-dacitic volcanic rocks. Provenance of sediments is east of the basin. The mid-Cretaceous part of the sequence is marked by the appearance of chert-lithic clastic rocks with a western provenance. *Tectonic setting:* During the Jurassic and Early Cretaceous, the Methow sequence is interpreted to have formed along the continental margin outboard of an Andean arc to the east and with open ocean to the west. Sedimentary facies beginning late in the Early Cretaceous (~110 Ma) indicate development of a foreland basin setting caused by thrust loading in the Cascade core on the western flank of the Methow sequence. The depositional basin changes from marine to subaerial in the early Late Cretaceous (100–90 m.y.a.). *Protolith age:* Middle Jurassic to Late Cretaceous, based on fossils in sedimentary rocks and U-Pb ages of 87–100 Ma for igneous components of the sequence and 88–90 Ma for cross-cutting plutons. *Metamorphic facies:* Zeolite to prehnite-pumpellyite facies in the Methow Valley, increasing to amphibolite facies at the margin of the Cascade crystalline core. *Metamorphic age:* Cretaceous. *Tectonite fabric:* No pervasive tectonite fabric through the Methow Valley area. Rocks are phyllitic to schistose along the flank of the crystalline core. *References:* Tabor and others, 1968; Barksdale, 1975; Tennyson and Cole, 1978; Dragovich and Norman, 1995; Haugerud and others, 1993, 2002.

Chiwaukum Schist (CS)

Includes Tonga Formation, banded gneiss, and Nason Ridge migmatitic gneiss. *Protolith:* Mostly sandstone and mudstone with volcanic-arc provenance; turbidite bedding is preserved in lower grades. Limestones, oceanic basalts, cherts, and ultramafic rocks comprise lesser components, presumed to be structurally intercalated with the clastic rocks. A broad zone of migmatite of dominantly injection origin is developed through the central part of the Chiwaukum unit (see migmatite on map). *Tectonic setting:* Accretionary wedge. *Protolith age:* No reliable direct information on the protolith age is available. Indirectly and with considerable uncertainty, the age of the Chiwaukum Schist protolith is suggested to be Late Jurassic to Early Cretaceous. This interpretation is based on: 1) correlation with the Settler Schist in British Columbia and 2) inference by Monger and Journeay (1994) that the Settler Schist is the metamorphic equivalent of the Late Jurassic to Early Cretaceous Cayoosh Formation. *Metamorphic facies:* Greenschist to upper amphibolite facies. *Metamorphic age:* Mid-Late Cretaceous, based on radiometric analysis of metamorphic minerals. *Tectonite fabric:* Pervasive recrystallization and development of phyllitic, schistose, and gneissic fabrics. *References:* Getsinger, 1978; Plummer, 1980; Evans and Berti, 1986; Magloughlin, 1986; Tabor and others, 1987; Duggan and Brown, 1994; Miller and Paterson, 2001b.

Constitution Formation (CO)

Protolith: Mostly massive siltstone and volcanic-lithic sandstone. Interlayered rocks include conglomerate, mudstone, oceanic pillow basalt, and dacitic tuff. Lithic clasts include metamorphic detritus and fossiliferous rocks that resemble older units in the San Juan Islands. *Tectonic setting:* Trench marginal to arc and North America. *Protolith age:* Radiolaria in cherts give approximate ages of Late Jurassic to Early Cretaceous. *Metamorphic index minerals:* Prehnite, lawsonite, and aragonite. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Fine-grained rocks show slaty cleavage; metagraywackes lack penetrative foliation except in fault zones. *References:* Vance, 1975; Brandon and others, 1988; M. C. Blake, Western Wash. Univ., written commun., 2003.

Helena–Haystack Mélange (HH)

The Helena–Haystack mélange of Tabor (1994) is a complex structural zone consisting in part of rocks derived from other nearby tectonic units, but also of rocks not known elsewhere in the region. *Protolith:* This mélange is characterized by a voluminous serpentinite matrix. Tectonic blocks embedded in the matrix range up to several kilometers in extent and are of many types, including: 1) abundant metamorphosed oceanic basalt, gabbro, and diabase, 2) minor tonalite, 3) moderate amounts of metamorphosed graywacke, mudstone, and chert, 4) a significant tract of metamorphosed volcanic rocks ranging from basalt to rhyolite, and 5) minor amphibolite. *Protolith age:* U-Pb zircon ages of blocks are 150 to 170 Ma in tonalite and 168 Ma in dacite of the Deer Peak unit. *Metamorphic facies:* Metamorphic grade varies from epidote-blueschist to amphibolite in different blocks. Metamorphism associated with the cataclastic mélange fabric is not well described but reported to be of low grade, lower than in the blocks. *Metamorphic age:* K-Ar dates representing metamorphic ages of blocks are 90 Ma for muscovite from meta-rhyolite and 141, 128, and 114 Ma for hornblende in amphibolites. *Tectonite fabric:* Fabric of the matrix is brittle-ductile. Textures of the blocks range from unfoliated to phyllitic and schistose. *Tectonic setting:* Basalts and gabbros of oceanic affinity make up a large component of the HH. Significant amounts of chert also indicate an oceanic setting. Sedimentary clastic rocks likely represent a trench setting. The Deer Peak basalt-rhyolite suite is of arc origin. Juxtaposition of these tectonic elements suggests an accretionary wedge, but the hetero-

geneity of rock types and disparity in metamorphic grade among blocks and between blocks and matrix indicates that at least part of the mélange assembly represents tectonic mixing after terrane accretion. Tabor (1994) suggests that the HH formed as a zone of deformation along the contact between the Easton suite and Western and Eastern mélange belts. Age brackets for development of the mélange are provided by 90 Ma metamorphic mica in a mélange block, and Eocene sedimentary and volcanic rocks deposited across mélange structure. The abundant serpentinite matrix invites correlations with the ultramafic-rich Fidalgo or Ingalls ophiolite complexes, but other lithologies and metamorphic grade present difficulties for making such connections. *References:* Whetten and others, 1980; Cruver, 1983; Reller, 1986; Miller and others, 1993; Tabor, 1994; Dragovich and others, 1998, 2002a.

Lopez Structural Complex (LS)

Protolith: This unit is a tectonically mixed rock assemblage consisting of sheets, blocks, and phacoids of mostly of graywacke sandstone and mudstone, but also oceanic pillow basalt, chert, gabbro, tonalite, and other rocks. *Tectonic setting:* Ocean floor and trench. *Protolith age:* Jurassic to mid-Cretaceous based on fossils. *Metamorphic index minerals:* Aragonite, lawsonite, pumpellyite. *Metamorphic and deformational age:* Ar ages of metamorphic mica derived from volcanic glass and defining foliation are 125 Ma. *Tectonite fabric:* Imbricate structure with elongate tectonic lenses of more competent rocks; penetrative foliation in less competent rocks. *References:* Cowan and Miller, 1981; Brandon and others, 1988; Bergh, 2002; Brown and Lapen, in press.

Lummi Formation (LM)

Protolith: Mostly mudstone and lithic sandstone, lesser chert and oceanic basalt. Outcrop relations suggest a stratigraphic succession, now disrupted, of pillow basalt overlain by chert that is in turn overlain by clastic rocks. *Tectonic setting:* Ocean floor and trench. *Protolith age:* Middle to Upper Jurassic radiolaria occur in older parts of the stratigraphic succession. *Metamorphic index minerals:* Aragonite, lawsonite, pumpellyite. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Pervasive slaty to phyllitic cleavage in metasediments, but relict clastic textures visible. Metabasalts lack internal fabric. *References:* Vance, 1975; Carroll, 1980; Garver, 1988a; Blake and others, 2000; Burmester and others, 2000.

Easton Metamorphic Suite (EA)

Protolith: The Easton Metamorphic Suite includes a variety of rock types grouped on the basis of structural continuity and degree and age of metamorphism, parameters that in this region are not perfectly definitive. The map pattern shown in this report is more inclusive than that preferred by some workers (for example, see below). The eastern part of the EA is dominated by large tracts of metabasite with MORB chemical composition and by siliceous carbonaceous phyllites derived from muds; metagraywacke and metaperidotite occur locally. The western part north of the Skagit River contains much carbonaceous phyllite similar to that in the east, but metagraywacke is more abundant, metabasalt is less abundant, and gabbro-tonalite plutons and metatuffs occur locally. *Tectonic setting:* Ocean ridge, trench, transitional area to island arc. *Protolith age:* Intrusive age of metaplutonic rocks in the western part is 163 Ma determined from U-Pb in zircons. *Metamorphic facies:* Regional epidote-blueschist facies, local amphibolite and eclogite facies associated with ultramafic rock. *Metamorphic age:* Metamorphic age measured by Rb-Sr and K-Ar in micas and amphiboles is 144 to 160 Ma in local amphibolite/eclogite and 120 to 130 Ma in regional blueschists. *Tectonite fabric:* Throughout most of the eastern part of the EA meta-igneous and metasedimentary lithologies are thoroughly recrystallized to phyllite and schist. An exception is a band of slate and semischist south of the Skagit River, termed the "Slate of Rinker Ridge" by Tabor and others (2002), who suggest that this rock is not part of the EA but correlates with the Chilliwack Group. In the western part of the EA, recrystallization and development of foliation are generally less intense than in the east. Phyllites, greywacke semischists, and weakly deformed to undeformed pillow basalts and gabbro-tonalite plutons are the prevalent rocks. Some of this rock was considered to be part of the Haystack assemblage by Dragovich and others (1998, 1999). *References:* Misch, 1966; Haugerud and others, 1981; Dungan and others, 1983; Brown, 1986; Armstrong and Misch, 1987; Gallagher and others, 1988; Dragovich and others, 1998, 1999; Tabor and others, 2002.

Ingalls Tectonic Complex (ING)

Protolith: This unit is a metamorphosed dismembered ophiolite, the structure in part characterized as mélange. The dominant protolith rock is peridotite. Also in the complex are lesser amounts of gabbro, diabase, pillow basalts, mudstone, chert, and graywacke. *Tectonic setting:* The Ingalls complex is interpreted to be a composite of rocks formed in part as Lower Jurassic ocean floor and in part in an Upper Jurassic supra-subduction zone setting. *Protolith age:* A discordant U-Pb zircon from gabbro gives an age in the range of 164 to 155 Ma. Radiolaria range from Early to Late Jurassic. *Metamorphic facies:* Prehnite-pumpellyite to amphibolite facies. *Metamorphic age:* Amphibolite facies metamorphism is Mid- to Late Cretaceous. Prehnite-pumpellyite facies age is bracketed by the Jurassic protolith age and the overprinting amphibolite facies. *Tectonite fabric:* Penetrative foliation in the complex is associated with mélange structure. This fabric predates juxtaposition of the Ingalls complex with the Chiwaukum Schist along the Windy Pass thrust. Fabric is also developed in the Ingalls complex in the vicinity of the Windy Pass thrust. *References:* Miller and others, 1993; Miller and Paterson, 2001b; Metzger and others, 2002.

Western Mélange Belt (WM)

Protolith: Mostly lithic sandstone, siltstone, and mudstone; lesser gabbro, tonalite, diabase, and chert; sparse limestone and ultramafic rock. *Tectonic setting:* Rock components bear lithologies suggestive of trench and island arc settings. Origin of the mélange structure is uncertain, but is most likely related to post-accretionary displacements. *Protolith age:* U-Pb zircon ages from tonalite are in the range of 150 to 160 Ma. Fossils in metasedimentary rocks are mostly Late Jurassic to earliest Cretaceous in age, but some limestone blocks are Permian. *Metamorphic facies:* Prehnite-pumpellyite. *Metamorphic age:* No direct evidence. Metamorphism post-dates Early Cretaceous fossils and pre-dates Eocene intrusive rock. *Tectonite fabric:* Pervasive foliation, foliated sandstone, phyllite, and semischist. Mélange structure may be in part olistostromal, in part tectonic. *References:* Frizzell and others, 1987; Tabor and others, 2002.

Fidalgo Complex (FC)

Protolith: Ophiolite occurring as a partially disrupted stratigraphic sequence that from older to younger parts consists of peridotite, gabbro, quartz diorite-tonalite intrusive complex, coarse sedimentary breccia, radiolarian argillite, and volcanic-

lithic sandstone. *Tectonic setting:* Island arc or forearc. *Protolith age:* U-Pb zircon ages from tonalite are 160 to 170 Ma. Ages of radiolaria are Late Jurassic. *Metamorphic facies:* Slight recrystallization to prehnite, pumpellyite facies; rare aragonite identified with uncertainty. *Metamorphic age:* Broadly bracketed as Late Jurassic to mid-Cretaceous. *Tectonite fabric:* Penetrative fabric is absent through much of the complex, but clastic sedimentary rocks are foliated near fault zones. *References:* Whetten and others, 1978; Gusey, 1978; Brown and others, 1979; Dragovich and others, 2000.

Nooksack Formation (NK)

Protolith: Marine volcanic-lithic sandstone, siltstone, and local conglomerate. Local andesitic-dacitic volcanic member. *Tectonic setting:* Island arc. *Protolith age:* Middle Jurassic to Early Cretaceous, from Oxfordian to Valanginian fossils and a discordant U-Pb age of zircon from dacite interpreted to represent formation between 174 to 180 Ma. *Metamorphic facies:* Prehnite-pumpellyite, possible lawsonite. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Variably developed pervasive slaty cleavage. Rock relatively undeformed compared to overlying nappes. *References:* Misch, 1966; Sondergaard, 1979; Brown and others, 1981; Franklin, 1985; Tabor and others, in press.

Haro Formation and Spieden Group (HS)

The Haro Formation and Spieden Group are lumped together here because they appear to have a similar tectonic history, and for simplicity, although the units are not contiguous and it is unknown whether they represent a single tectonic element. *Protolith:* Andesitic to dacitic sedimentary clastic and pyroclastic rocks. *Tectonic setting:* Island arc. *Protolith age:* The Haro Formation has Upper Triassic fossils. The Spieden Group bears Upper Jurassic to Lower Cretaceous fossils and yields K-Ar ages of volcanic rocks in that same time span. *Metamorphic facies:* Zeolite. *Tectonite fabric:* Minimal. *References:* Vance, 1975; Johnson, 1978, 1981; Brandon and others, 1988.

Deadman Bay Volcanics (DB)

Protolith: Interbedded ocean-island pillow basalts, pelagic limestones with Tethyan fusulinids, and radiolarian ribbon cherts. *Tectonic setting:* Ocean floor. *Protolith age:* Fossils indicate Permian through Triassic depositional ages. *Metamorphic index minerals:* Lawsonite, aragonite. *Metamorphic age:* Likely Early Cretaceous. *Tectonite fabric:* In local shear zones. *References:* Danner, 1966; Vance, 1975; Brandon and others, 1988.

Orcas Chert (OC)

Protolith: Mostly ribbon chert, with lesser mudstone, pillow basalt, and limestone. *Tectonic setting:* Ocean floor. *Protolith age:* Fossils indicate Triassic to Early Jurassic age. *Metamorphic index mineral:* Aragonite. *Metamorphic age:* Likely Early Cretaceous. *Tectonite fabric:* Pervasive slaty cleavage in metamudstone. Chert layers are stretched and broken. *References:* Vance, 1975; Brandon and others, 1988.

Bell Pass Mélange (BP)

Protolith: The Bell Pass mélange of Tabor and others (in press) represents a tectonic assemblage of a number of unrelated rock units. A major component is the Elbow Lake formation of Blackwell (1983), a highly disrupted assemblage of chert, oceanic basalt, and volcanic lithic clastic rocks. Less competent sedimentary rocks of the Elbow Lake formation, as well as exotic serpentinite, serve as a high-strain matrix in which more competent blocks of Elbow Lake rock and exotic rocks are embedded. The competent blocks occur as lenses up to many kilometers across aligned in the fabric of the matrix. Exotic blocks include the Yellow Aster Complex (YA), the Vedder Complex (VC), and the Twin Sisters Dunite (TS), the larger fragments of which appear as separate map units. The structurally overlying Easton suite and underlying Chilliwack Group are also imbricated within this complex. *Tectonic setting:* The Elbow Lake Formation bears ocean floor and trench lithologies. The exotic blocks include previously accreted oceanic rocks (Vedder Complex) and rocks of probable continental origin (Yellow Aster Complex). A two-stage process is envisaged for development of the mélange: 1) tectonic mixing of Elbow Lake components in an accretionary wedge, then 2) subsequent mixing of the Elbow Lake structural complex with exotic rocks picked up by transport along the continental margin to the final emplacement site. *Protolith age:* The Elbow Lake Formation has yielded radiolaria ranging in age from Triassic to Middle Jurassic. *Metamorphic index minerals:* The mélange matrix fabric contains pumpellyite, lawsonite, aragonite, and rare Na-amphibole. *Metamorphic age:* Not directly dated. *Tectonite fabric:* The mélange matrix fabric is a brittle-ductile flow fabric wherein pre-tectonic grains occur in various stages of flattening, elongation, and size reduction. Also defining the fabric are aligned, newly crystallized minerals, mostly chlorite and muscovite. This fabric is penetrative through less competent metasedimentary rocks and is developed in the margins of, but absent inside, more competent blocks. *References:* Misch, 1966; Haugerud, 1980; Blackwell, 1983; Brown, 1987; Brown and others, 1987; Smith, 1988; Tabor and others, in press.

Hozameen Group (HZ)

Protolith: Predominantly basalt and chert and lesser argillite, graywacke, limestone, and gabbro. *Tectonic setting:* Ocean floor, distal fan. *Protolith age:* Pennsylvanian to Early Jurassic based on fossils. *Metamorphic facies:* Partial development of prehnite-pumpellyite facies. *Tectonite fabric:* Phyllitic cleavage in meta-argillites, other rocks have only spaced cleavage or lack fabric. *References:* Haugerud, 1985; Tabor and others, in press.

Eastern Mélange Belt and Trafton Mélange (EM)

Protolith: Tectonic blocks, up to several kilometers long, consist predominantly of metamorphosed basalt and chert; also occurring are blocks of ultramafic rock, gabbro, tonalite, migmatitic gneiss, graywacke, argillite, and limestones with Tethyan fusulinids. *Tectonic setting:* Tectonic fragments are of dominantly oceanic materials. *Protolith age:* U-Pb zircon ages of two gabbro and tonalite blocks are 165 and 190 Ma respectively. Fossils range from Devonian to Middle Jurassic. *Metamorphic facies:* Mostly prehnite-pumpellyite facies; amphibolite facies in some blocks. *Metamorphic age:* K-Ar age of hornblende from an amphibolite block is 121 Ma. *Tectonite fabric:* Texture is static in some blocks, phyllitic and schistose in others. *References:* Danner, 1977; Frizzell and others, 1987; Tabor and others, 1993, 2002.

Napeequa Schist (NP)

Protolith: Ocean island and ocean ridge basalt, chert, abundant siliceous argillite, gabbro, ultramafic rock, limestone, and rare granitic intrusive bodies. *Tectonic setting:* Ocean floor and distal fan. *Protolith age:* Broadly known as pre-middle Cretaceous. Beyond that, correlation with the Cogburn rock unit in British

Columbia, which is intruded by a 225 Ma pluton, suggests that at least part of the Napeequa Schist may pre-date that age. *Metamorphic facies:* Greenschist to upper amphibolite facies. *Metamorphic age:* Mid-Cretaceous. *Tectonite fabric:* Well recrystallized, schistose to gneissic foliation. *References:* Bryant, 1955; Cater and Crowder, 1967; Dragovich, 1989; Brown and others, 1994; Brown and others, 2000; Miller and Paterson, 2001b; Tabor and others, 2002; Valley and others, 2003.

Chilliwack Group and Cultus Formation (CH)

Protolith: Volcanic lithic sandstone and siltstone, basaltic to dacitic volcanic rocks, fossiliferous reefoidal limestones. *Tectonic setting:* Island arc. *Protolith age:* The Chilliwack Group is Devonian to Permian. The Cultus Formation is Triassic to Early Jurassic and lies unconformably over the Chilliwack. *Metamorphic index minerals:* Aragonite, lawsonite, pumpellyite, and rare crossite. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Strong phyllitic foliation in metasediments near fault zones, elsewhere slaty foliation. Volcanic rocks are massive to somewhat flattened. *References:* Danner, 1966; Monger, 1966; Misch, 1966; Smith, 1988; Christianson, 1981; Sevigny, 1983; Sevigny and Brown, 1989; Tabor and others, in press.

Cascade River Complex (CR)

Includes Marblemount–Dumbell plutonic belt and Holden assemblage. *Protolith:* An intact but strained stratigraphic section in the Cascade River area displays, from older to younger—a plutonic complex ranging from gabbro to tonalite, andesitic to dacitic volcanic rocks, a conglomerate/sandstone clastic facies, and a mudstone-siltstone facies. Marbles occur locally in the sedimentary section. The map unit as a whole contains similar rocks, but the stratigraphy is obscured by deformation. *Tectonic setting:* Island arc. *Protolith age:* Concordant U-Pb zircon ages of 220 Ma have been obtained from the plutonic and volcanic rocks. *Metamorphic facies:* Greenschist, albite-epidote-amphibolite, and amphibolite facies. *Metamorphic age:* Mid- to Late Cretaceous, based on sparse isotopic mineral ages and relation to plutons of known age. *Tectonite fabric:* Pervasive phyllitic, schistose, and gneissic foliation. *References:* Misch, 1966; Cater and Crowder, 1967; Mattinson, 1972; Dragovich, 1989; Cary, 1990; Brown and others, 1994; Miller and others, 1994; Tabor and others, 2002, in press.

East Sound Group (ES)

Protolith: Mostly andesitic to dacitic pyroclastic rocks, with lesser limestone lenses, shale, argillite, graywacke, and conglomerate. *Tectonic setting:* Island arc. *Protolith age:* Devonian to Early Permian based on fossils. *Metamorphic index minerals:* Aragonite and lawsonite. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Foliated rocks restricted to fault zones. *References:* Danner, 1966, 1977; Vance, 1975; Brandon and others, 1988.

Vedder Complex (VC)

Protolith: Basalt and siliceous mudstone. *Tectonic setting:* Ocean floor. *Protolith age:* No direct evidence. Age is probably not much greater than that of the Permian subduction zone metamorphism that has affected the unit. *Metamorphic facies:* Albite-epidote amphibolite with barroisitic amphibole; partial blueschist overprint. *Metamorphic age:* Ages determined by Rb-Sr of minerals and whole rocks and K-Ar of minerals span a range of 196 to 285 Ma, but a preponderance of ages are in the range 260 to 285 Ma. *Tectonite fabric:* Schistose, completely recrystallized. *References:* Bernardi, 1977; Rady, 1980; Armstrong and others, 1983; Armstrong and Misch, 1987.

Garrison Schist (GA)

Protolith: Oceanic basalt and chert, minor limestone. *Tectonic setting:* Ocean floor. *Protolith age:* Pre-dates Permian metamorphism, see Vedder Complex. *Metamorphic facies:* Albite-epidote amphibolite (barroisite) partially overprinted by blueschist; late veins of aragonite. *Metamorphic age:* K-Ar mineral ages are 167, 242, and 286 Ma. The two older ages are regarded as best representing peak metamorphism. *Tectonite fabric:* Well recrystallized, phyllitic, and schistose, but fine-grained. *References:* Danner, 1966; Vance, 1975; Armstrong and others, 1983; Brandon and others, 1988.

Yellow Aster Complex (YA)

This unit consists of an older gneissic part and a younger intrusive complex. It occurs as tectonic blocks a few meters to kilometers in breadth. *Protolith:* The older part consists of siliceous garnet-pyroxene gneiss (possibly metasandstone), calc-silicate rock, and marble (metalimestone). The younger part, intrusive into the older part, is a suite of gabbro-tonalite plutonic rocks and basalt-andesite hypabyssal rocks. Tectonic fragments of ultramafic rock are commonly associated with this assemblage. *Tectonic setting:* The older part likely formed in a passive continental margin rift zone, based on protolith materials of limestone and possibly quartz sandstone. The younger plutonic suite is interpreted to be roots of an arc, possibly the Chilliwack volcanic arc. *Protolith age:* Discordant U-Pb analyses of zircons from the older part suggest a Proterozoic protolith, but with uncertainty about whether the zircons are detrital. Zircons from the younger intrusive suite give middle Paleozoic ages (mostly in the range 410–320 Ma) but are also discordant and therefore not definitive. *Metamorphic facies:* Foliated rocks have amphibolite facies metamorphism. Static greenschist facies metamorphism and a sparsely developed subsequent prehnite-pumpellyite facies metamorphism partially overprint rocks of the Yellow Aster Complex. *Metamorphic age:* A concordant U-Pb sphene age of 415 Ma represents the metamorphic age of a gneissic rock. The lower grade metamorphic assemblages are undated. *Tectonite fabric:* The older part has a strong mylonitic to gneissic foliation. The younger rock is part foliated, part not foliated. *References:* Misch, 1966; Mattinson, 1972; Sevigny, 1983; Rasbury and Walker, 1992; Tabor and others, in press.

Turtleback Complex (TB)

Protolith: This unit is dominated by a gabbro-diorite-tonalite suite. Intrusive into the plutonic rocks are dikes ranging from basalt to dacite. *Tectonic setting:* Arc roots, possibly basement to the East Sound Group volcanic arc. *Protolith age:* K-Ar hornblende ages and discordant U-Pb zircon ages are interpreted to indicate intrusive ages of 550 to 400 Ma. *Metamorphic facies:* Static greenschist facies minerals are partially overprinted by prehnite-pumpellyite facies assemblages associated with shear zones. *Metamorphic age:* No direct evidence. *Tectonite fabric:* Localized in fault zones. *References:* Mattinson, 1972; Vance, 1975; Whetten and others, 1978; Brandon and others, 1988.

Swakane Biotite Gneiss (SW)

Protolith: Most of this unit is homogeneous quartzo-feldspathic gneiss, variously interpreted to have been derived from arkose or silicic volcanic rock. Rare intercalated amphibolite, marble, quartzite, and ultramafic rock also occur. *Tectonic setting:* Not well constrained. *Protolith age:* Work in progress by Matzel

and others (2002) finds U-Pb ages of zircons considered to be detrital ranging from Proterozoic to 73 Ma. An intrusive granitic body yielded a 68 Ma zircon. Thus, the protolith age would be between 73 and 68 Ma. Previous workers have suggested a Proterozoic protolith age. Confirmation of this anomalously young age of Cascade core protolith material awaits completion of the Matzel study. *Metamorphic facies:* Middle to upper amphibolite facies. *Tectonite fabric:* Pervasive gneissic and schistose fabric. *References:* Waters, 1932; Mattinson, 1972; Rasbury and Walker, 1992; Sawyko, 1994; Tabor and others, 1987; Miller and Paterson, 2001b; Valley and others, 2003.

Twin Sisters Dunite (TS)

This unit consists primarily of unaltered dunite, with lesser amounts of harzburgite. Serpentinite is marginal to the body. The rock is a metamorphic tectonite lens within the Bell Pass mélange. It contains a penetrative fabric apparently inherited from the mantle. *References:* Ragan, 1963; Christensen, 1971; Thompson and Robinson, 1975; Onyeagocha, 1978.

ACKNOWLEDGMENTS

We are indebted to Steve Boyer (Charles Wright Academy) and Bill Lingley (Wash. Dept. of Natural Resources) for contributing a cross section of the Olympic Peninsula prepared in the early 1990s, based on mapping by Tabor and others (1978a) and following principles of balanced sections. Discussions with Clark Blake, Russ Burmester, Dave Engebretson, Liz Schermer, and Chris Suczek (all of Western Wash. Univ.) and reviews of the document by Sam Johnson and Rowland Tabor (U.S. Geological Survey), Bob Miller (San Jose State Univ.), Bill Lingley, and Liz Schermer have considerably improved this analysis. We thank Jari Roloff and Dave Norman (Wash. Dept. of Natural Resources) for editorial guidance and facilitation of this project.

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