Northwest Geological Society

Society Publications in Pacific Northwest Geology

FIELD TRIP GUIDEBOOK #054

EXOTIC TERRANES OF THE CASCADE RANGE: THE TWIN SISTERS DUNITE AND DARRINGTON PHYLLYTE, WHATCOM AND SKAGIT COUNTIES, WASHINGTON

June 1, 2019

Tom Bush, Professor, Pierce College Puyallup Earth and Space Sciences
Heather Vick, Washington State Department of Ecology
Corky Smith, Jr., Twin Sisters Olivine

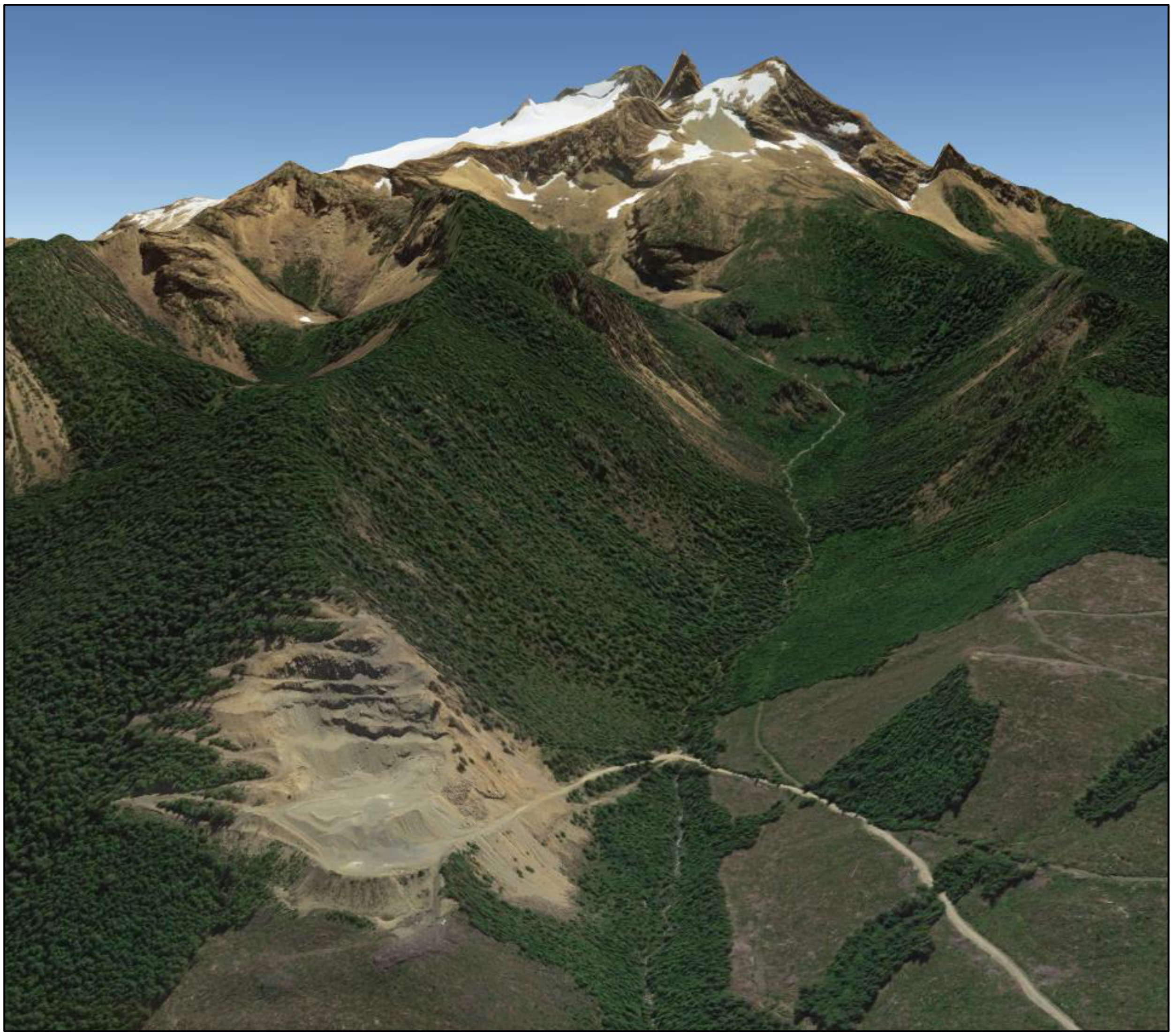
NWGS FIELD TRIP GUIDEBOOK SERIES

This field trip guide has been reformatted from the original document provided by the authors. All the original text and illustrations are reproduced here, and nothing has been added to the document in the process.

Of particular note, some stops on these trips may be located on private property. ***Publication of this guide does not imply that public access has been granted to private property.*** If there is a possibility that the site might be on private property, you should assume that this is the case. ***Always ask permission before entering private property.***

NORTHWEST GEOLOGICAL SOCIETY FIELD GUIDEBOOK SERIES
Field Trip Guidebook #054

Published by the Northwest Geological Society, Seattle, WA.



***Cover photo**: Oblique aerial view of the Swen Larsen Quarry (lower left) on the north end of the Twin Sisters Range. North Twin Peak forms the skyline. View is looking south-southeast. Google Earth image on 7/15/18.*

TABLE OF CONTENTS

EXOTIC TERRANES OF THE CASCADE RANGE: THE TWIN SISTERS DUNITE AND DARRINGTON PHYLLITE, WHATCOM AND SKAGIT COUNTIES, WASHINGTON

Tom Bush, Professor, Pierce College Puyallup Earth and Space Sciences
Heather Vick, Washington Department of Ecology
Corky Smith, Twin Sisters Olivine

I. INTRODUCTION

An examination of the major geologic elements of the North American Cordillera reveals that it comprises roughly 200 displaced geologic terranes (Oldow and others, 1989), or crustal blocks that preserve geologic features (rock units, fossils, structures, and geophysical properties) that are distinctly different from adjacent blocks (Gabrielse and others, 1991). Such terranes are recognized because they contain rocks that have been together since they formed, and their geologic histories differ significantly from surrounding terranes (Monger and Brown, 2016). Although the boundaries between terranes may be concealed beneath younger rocks or sediments (cover sequences) or intruded by plutons (stitching plutons), the boundaries are consistently faults of various types.

The term 'terrane' does not necessarily imply large geographic displacement. Some are continental terranes, formed where they presently occur as part of North America, while others are peri-continental, formed near enough to North America to receive at least some sediment from it. Terranes can also be exotic, formed at some distant location and later accreted to North America (Cheney, 2016A). Most terranes of the Cordillera have been tectonically transported perhaps 100s or possibly 1,000s of kilometers (kms) before emplacement into their present position (Oldow and others, 1989; Gabrielse and others, 1991; Cowan and Bruhn, 1992; Saleeby and Busby-Spera, 1992; Cowan, 1994; Cheney, 2016A). These exotic terranes, those that have undergone significant transport relative to the stable craton (Klaus and others, 2005), are an important geologic component of the Pacific Northwest (PNW) **(Fig. 1**). In some cases, multiple terranes were assembled into a crustal block prior to accretion to the continental margin, forming a composite terrane or superterrane. Conversely, at least one PNW terrane, Wrangellia, was disassembled prior to its accretion, with portions now scattered along the Cordilleran margin from present day Alaska to Vancouver Island and even western Idaho.

Emplacement of the exotic and peri-continental terranes of the PNW took place throughout much of the Mesozoic and early Cenozoic, building the continental margin outward by processes broadly analogous to those that formed the craton during the Precambrian. In some cases, magnetic inclinations in some accreted rocks suggest significant continental margin-parallel northward (and perhaps southward) transport may have occurred along major strike-slip faults prior to reaching their present position (Cowan, 1994). A final conclusion has yet to be reached regarding this *Baja British Columbia* (or *Baja B.C.*) hypothesis because sound geologic evidence, including the identification of a potential fault system is lacking (Cheney and Figge, 2016). Furthermore, many of these terranes have undergone significant post-emplacement faulting, especially along

Figure 1. Map showing the primary exotic and peri-continental terranes of the PNW. Terrane boundaries are approximate. All but the Siletzia terrane boundaries are adapted from Monger and Brown (2016); Siletzia terrane boundary adapted from Phillips and others (2017). CPC = Coast Plutonic Complex. Cover sequences and stitching plutons (except the CPC) are omitted for simplicity. Box shows approximate area of Fig. 2.

right-lateral strike-slip faults or Cenozoic extensional faulting, and have received sediment and volcanic cover, complicating the delineation of their histories.

Five packages of exotic terranes and one peri-continental terrane occur in the PNW (**Fig. 1**). The Blue Mountains terranes comprise the Blue Mountains in northeastern Oregon, and the Klamath terranes comprise the Klamath Mountains of southwestern Oregon and northwestern California (**Fig. 1**). In the northern portion of the PNW, from east to west, are the Intermontane superterrane, terranes of the Cascade Range, and the Insular superterrane (**Fig. 1**). Finally, peri-continental Siletzia comprises a portion of southern Vancouver Island, the Olympic Mountains, and southward areas along the Washington and Oregon coasts (**Fig. 1**). This field trip will focus on two exotic rock units within the terranes of the Cascade Range, the Twin Sisters dunite and the Darrington phyllite, discussed in detail below.

Terranes of the Cascade Range

The terranes of the Cascade Range are sandwiched between the Intermontane superterrane on the east (Quenellia and Cache Creek terranes) and the Insular superterrane (Wrangellia) and Siletzia on the west (**Fig. 1**). Unlike the Intermontane and Insular superterranes, the terranes of the Cascade Range were only partially assembled into a composite terrane before accretion, although their accretionary histories are complex (Monger and Brown, 2016), with accretion to the continental margin having been completed by the middle Cretaceous (Cheney and Figge, 2016). The Pasayten and Straight Creek faults form the eastern boundary of the terranes of the Cascade Range (Miller and others, 1994; Monger and Brown, 2016) **(Fig. 2**). In Washington and southern British Columbia, the ~500-km-long Pasayten fault, a northwest-trending, high-angle fault, forms the boundary between the terranes of the Cascade Range and Quenellia (Cheney and Figge, 2016) of the Intermontane superterrane. At its northern end, it merges with the north-striking Fraser River-Straight Creek fault (Miller and others, 1994). North of there, the Fraser River-Straight Creek fault juxtaposes terranes of the Cascade Range against Quenellia and the Cache Creek terrane (Monger and Brown, 2016).

The western boundary of the terranes of the Cascade Range is formed along a basal thrust between them and Wrangellia of the Insular superterrane in the San Juan Islands (Cowan and Bruhn, 1992, Fig. 10), and mostly likely where they meet Siletzia further south beneath Puget Sound (Cheney and Figge, 2016).

The northern boundary of the terranes of the Cascade Range is complex and difficult to define. Tabor and Haugerud (1999) indicate that in British Columbia, the Intermontane and Insular superterranes are in direct contact with each other along the Insular suture zone. This belt widens southwestward in Washington into a system of thrust nappes (sheet-like rock units moved long distances along thrust faults, recumbent folds, or both) that form the western portion of the terranes of the North Cascades. The rather large Coast Range batholith obscures much of this zone in the Coast Range Mountains of British Columbia (**Fig. 1**).

The southern limit of the terranes of the Cascade Range lays buried in Washington beneath a wide variety of Cenozoic rocks and sediments of the Challis, Kittitas, Walpapi, and High Cascade synthems, in particular the Columbia River Basalt Group (Cheney, 2016A; Cheney, 1994) (**Figs. 1 and 2**). The most southerly limit of the

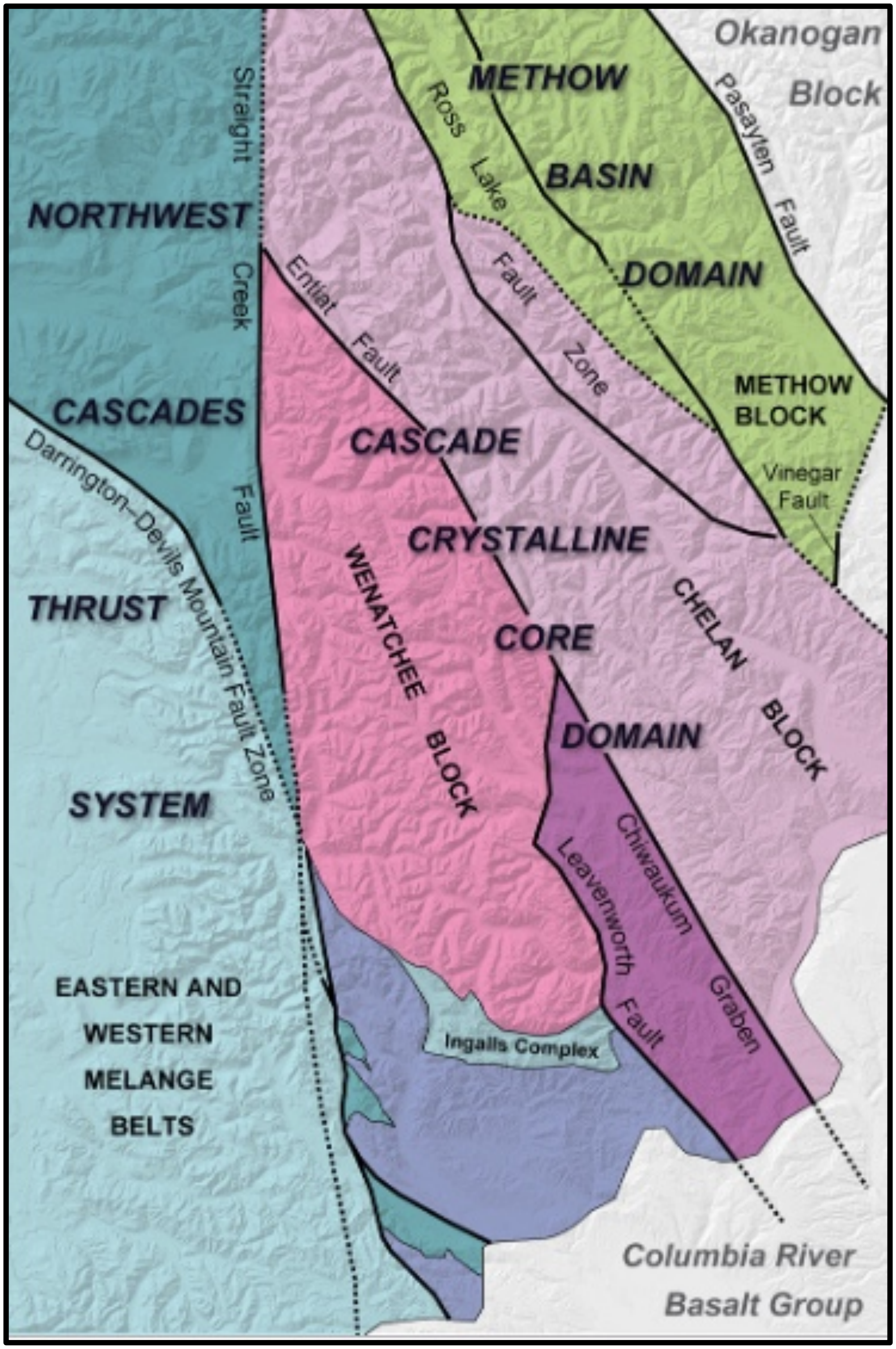


Figure 2. *Map showing the major faults bounding and within the Washington state portion of the terranes of the Cascade Range (Washington State Department of Natural Resources, 2019). Note that the Paysaten and Fraser River-Straight Creek faults (here labeled Straight Creek fault) merge at their northern extremities in British Columbia (beyond the northern limit of the map) and form the eastern boundary of the terranes of the Cascade Range.*

regionally contiguous exposures occurs near Leavenworth, but isolated exposures of greenschist and phyllite occur in the core of a partially eroded anticline near Easton along Interstate 90. About 65 km further south in the central Cascades west of Yakima along U.S. 12, the Rimrock Lake inlier (an area of older rocks surrounded by younger ones typically formed by erosion) exposes Mesozoic metaplutonic arc root rocks of the Indian Creek complex and tectonic mélange of the Russell Ranch complex within the surrounding Cenozoic cover. These may correlate with exotic terranes in the Cascade Range (or possibly other terrane packages of the PNW or western Cordillera) (Miller, 1989).

The complexities of the terranes of the Cascade Range may be simplified by organizing them into geologic domains (Tabor and Haugerud, 1999), crustal blocks (Tabor and Haugerud, 2016) or by their accretionary histories (Mongor and Brown, 2016). The terranes are bisected by several prominent high-angle north- and northwest-trending faults that delineate the geologic domains or blocks (**Fig. 2**).

The easternmost domain or block of the terranes of the Cascade Range is the Methow domain, which lies between the Pasayten fault to the east and the north-northwest-trending Ross Lake fault to the west (Tabor and Haugerud, 1999; Tabor and Haugerud, 2016) (**Fig. 2** and **Table 1**). It consists of two terranes: the Hozomeen and Methow terranes (Haugerud and others, 1996; Tabor and Haugerud, 1999). In Canada, the Bridge River terrane is roughly correlative with the Hozomeen terrane.

The Metamorphic Core domain forms the backbone of the Cascade Range between the Ross Lake fault zone to the east and the north-trending Fraser River-Straight Creek fault to the west (Tabor and Haugerud, 1999) (**Fig. 2**). It is so named because it consists mostly of highly metamorphosed rocks, whereas the adjoining domains consist of either unmetamorphosed or low-grade metamorphic rocks. This domain consists of two blocks: 1) the Chelan block, which lies between the Ross Lake fault to the northeast and the Entiat fault to the southwest; and 2) the Wenatchee block, which lies between the Entiat fault to the northeast and the Fraser River-Straight Creek fault to the west (**Fig 2**). The Metamorphic Core domain consists of the Chelan Mountains terrane, the Chelan Migmatite Complex, the Nason terrane, the Swakane terrane, the Ingalls terrane, and the Skagit Gneiss Complex (Tabor and Haugerud, 1999; Tabor and Haugerud, 2016) (**Table 1**).

The Western domain lies west of the Fraser River-Straight Creek fault in the western foothills of the northern Cascades of Washington and beneath the Puget Lowlands and San Juan Islands (Tabor and Haugerud, 1999; Tabor and Haugerud, 2016) **(Fig. 2** and **Table 1**). Several other names have been attributed to this structural block (the Northwest Cascades Thrust System of Washington Department of Natural Resources (2019), the Northwest Cascades System of Monger and Brown (2016), the San Juan-Northwest Cascades thrust system of Tabor and Haugerud (1999) and Cowan and Bruhn (1992), and the San Juan-Cascade nappes of Brandon (1989). It comprises a complex array of thrust nappes and mélange belts discussed in detail below.

Mongor and Brown (2016) divide the terranes of the Cascade Range into three groups based on their accretionary histories (**Table 2**). These histories are determined by detailed studies of overlap sequences (sequences of sedimentary or volcanic rocks

	Western Domain		Metamorphic Core Domain				Methow Domain		
			Wenatchee block		Chelan block				
Wrangellia	**Shuksan nappe** SHUKSAN THRUST **Welker Peak nappe** WELKER PEAK THRUST **Excelsior nappe** EXCELSIOR RIDGE THRUST **Nooksack nappe** **Helena-Haystack mélange belt** DARRINGTON DEVILS MOUNTAIN FAULT ZONE	FRASER RIVER-STRAIGHT CREEK FAULT	**Chelan Mountains terrane** **Nason terrane** **Swakane terrane** **Ingalls terrane**	ENTIAT FAULT	**Chelan Mountains terrane** **Chelan Migmatite Complex** **Swakane terrane** **Skagit Gneiss Complex**	ROSS LAKE FAULT ZONE	**Methow terrane** **Hozomeen terrane (Bridge River terrane)**	PASAYTEN FAULT	**Quenellia**
Siletzia	**Western mélange belt** **Eastern mélange belt**								

Table 1. *Domains of the terranes of the Cascade Range (adapted from Tabor and Haugerud, 1999; Tabor and Haugerud, 2016). Note that the position of the Western, Eastern, and Helena-Haystack mélange belts denotes relative geographic position north of (above in the table) and south of (below in the table) the Darrington Devils Mountain Fault Zone, not their actual structural position above and below this high-angle fault zone. Not labeled: the boundary between Siletzia and Wrangellia is the Leech River fault on the southern portion of Vancouver Island, which is inferred to merge with the Darrington Devils Mountain Fault Zone in that vicinity.*

<table>
<tr><td colspan="6">Swakane gneiss</td></tr>
<tr><td colspan="6">GROUP 3
Mid-Mesozoic and younger oceanic, arc, continental margin rocks and mélanges</td></tr>
<tr><td colspan="2">Western mélange belt
Easton terrane
Bell Pass mélange</td><td colspan="2">Eastern mélange belt
Fidalgo (Decatur terrane) & Ingalls ophiolite complexes</td><td colspan="2">Helena-Haystack mélange
Constitution formation
Pacific Rim clastics</td></tr>
<tr><td colspan="3">GROUP 2
Paleozoic and Mesozoic arc-related rocks</td><td colspan="3">GROUP 1
Late Paleozoic, early Mesozoic oceanic and arc-related rocks;
Middle and Late Jurassic – Early Cretaceous overlapping clastic rocks</td></tr>
<tr><td rowspan="2">Wrangellia (Insular superterrane)</td><td rowspan="2">Nooksack-Harrison terrane</td><td rowspan="2">Chilliwack terrane</td><td>Bridge River terrane</td><td>Cadwallader terrane</td><td>Methow terrane</td></tr>
<tr><td colspan="2">Chiwaukum & Settler schists</td><td>Cogburn, Cascade River, Napeequa schists</td></tr>
<tr><td colspan="6">Terranes accreted to the pre-Cordilleran continental margin by Middle Jurassic time (Intermontane superterrane)</td></tr>
<tr><td colspan="3">Cache Creek terrane</td><td colspan="3">Quesnellia</td></tr>
</table>

Table 2. *Terrane groups of the Cascade Range according to their accretionary histories (modified from Monger and Brown, 2016).*

that were deposited across terrane boundary faults) and stitching plutons (plutons that intruded into but are not cut by terrane boundary faults) and thus provided constraints on accretion timing and sequencing. Group 1 corresponds roughly with the Methow domain and portions of the Metamorphic Core domain and consists of the Bridge River and Methow terranes, as well as the Cadwallader terrane far to the north in British Columbia (Monger and Brown, 2016) (**Table 2**). However, Monger and Brown (2016) also include probable metamorphic correlatives of these in the Metamorphic Core domain (the Chiwaukum and Settler schists, and the Cogburn, Cascade River, and Napeequa schists). Group 2 broadly corresponds with the structurally lower nappes of the Western domain but also includes part of the Insular superterrane (**Table 2**). It comprises the Wrangellia, Nooksack-Harrison, and Chilliwack terranes (Monger and Brown, 2016). Group 3 broadly corresponds to the structurally higher nappes of the Western domain and the southern portion of the Metamorphic Core domain (**Table 2**). It comprises the Bell Pass mélange; the Fidalgo and Ingalls ophiolite complexes; the Constitution formation and Pacific Rim clastics; and the Western, Eastern, and Helena-Haystack mélange belts (Monger and Brown, 2016). An additional noteworthy point is that Monger and Brown (2016) do not include the Swakane gneiss of the Metamorphic Core domain in any of these three groups.

The Western Domain

The Western domain lies structurally between the Fraser River-Straight Creek fault on the east and the Wrangellia and Siletzia terranes on the west. It underlies the western flank of the Cascade Range in northern Washington and southern British Columbia, the northern portion of the Puget Lowlands, and the San Juan Islands. It is bisected by the left-lateral, strike-slip Darrington-Devils Mountain Fault Zone (DDMFZ) **(Fig. 2**). This complex structure strikes roughly east just south of the San Juan Islands. Its western extent merges with the Leech River fault on the southern end of Vancouver Island, a north-dipping terrane boundary thrust fault that juxtaposes Siletzia beneath Wrangellia (Monger and Brown, 2016, Fig. 10.2). To the east near Darrington and Devils Peak, the DDMFZ bends southward and becomes a north-northwest-striking structure. From there, it continues south-southeastward across the western Cascade foothills until it merges with the Fraser River-Straight Creek fault near Skykomish (Monger and Brown, 2016, Fig. 10.2; Tabor and Haugerud, 2016, Fig. 11.1) (**Fig. 2**).

The DDMFZ separates the Western domain into two segments (**Fig. 2**). Northeast of this structure, the Western domain comprises nappe sheets emplaced into their present position along thrust faults. Lying mostly southwest (but partially along on the northeast side) of the DDMFZ are three thrust-stacked mélange belts: the Helena-Haystack mélange, and the Eastern and Western mélange belts (Tabor and Haugerud, 2016) (**Table 1**). The locations to be visited on this field trip lie within the terranes of the thrust-faulted nappe system, so these are discussed in more detail below.

<u>Nappes of the Western Domain North and East of the Darrington-Devils Mountain Fault Zone</u>

A series of thrust-faulted nappe structures underlie the western flank of the Cascade Range in northern Washington and the San Juan Islands between the Straight Creek fault and the DDMFZ **(Fig. 3**). In the western foothills of the North Cascades, this nappe system is broadly folded into an anticlinorium (regional scale anticline), whose crest is partially eroded, exposing the structurally lower nappes in the core (**Fig. 3**). Further west, in the San Juan Islands, the nappes are northwestward-verging.

The nappes that comprise this portion of the Western domain, from structurally lowest to highest, include the Excelsior, Welker Peak, and Shuksan Nappes. The Nooksack formation lies beneath these nappes and has been considered to be the autochthonous base to them by some workers (Tabor and Haugerud, 2016), although given the mobile nature of these terranes, this is likely not the case. Here, we will treat the Nooksack

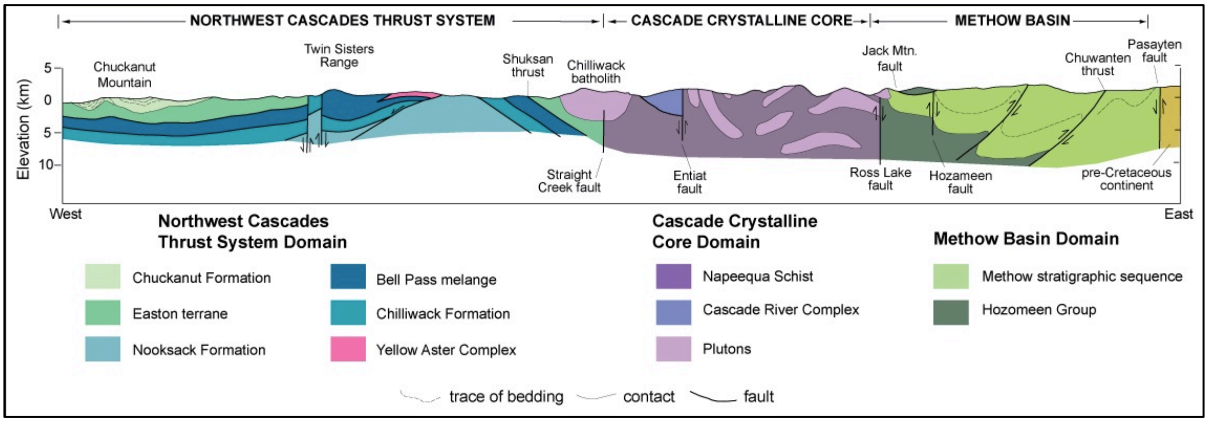


Figure 3. *Cross-section showing the structural relations of the terranes of the Cascade Range (from Washington Department of Natural Resources, 2019). Note the position of the Twin Sisters Range in the Bell*

formation as the structurally lowest nappe (**Table 1**).

The Nooksack nappe is separated from the overlying Excelsior nappe along the Excelsior Ridge thrust fault (Tabor and Haugerud, 2016) (**Fig. 3** and **Table 1**). It is found in a large patch of rocks in the north-central part of the Western domain (Tabor and others, 2009). It comprises the Middle Jurassic Wells Creek volcanics and the conformably overlying Late Jurassic-Early Cretaceous Nooksack group (Brandon, 1989; Haugerud and others, 1994). Together, these units represent an island arc volcanic system (Wells Creek volcanics) and the overlying sediments (Nooksack group), including deep marine turbidites, which indicate the strata are not overturned.

The Excelsior nappe overlies the Nooksack nappe along the Excelsior thrust fault (Tabor and Haugerud, 2016, and Tabor and others, 2009) (**Fig. 3** and **Table 1**). It is found in an irregular swath in the eastern part of the northwest Cascades, and may also be exposed in the San Juan Islands. It consists primarily of the Early Devonian-Early Permian Chilliwack Group, which, like the Nooksack nappe, is primarily composed of island arc volcanic and associated marine sedimentary rocks (Tabor and Haugerud, 2016; Haugerud and others, 1994). However, unlike Nooksack nappe rocks, strata of the Chilliwack River terrane are severely faulted, folded, overturned, and mildly metamorphosed.

The Welker Peak nappe overlies the Excelsior nappe along the Welker Peak thrust fault (Tabor and Haugerud, 2016) (**Fig. 3** and **Table 1**). It is primarily composed of the Bell Pass mélange (Tabor and Haugerud, 2016; Tabor and others, 2009). It is found in scattered exposures throughout the northern part of the western Cascades, which consists of fragments of oceanic rocks, continental crust, and mantle rocks. The Elbow Lake formation is its primary component, which contains Permian, Triassic, and Lower and Middle Jurassic chert, lithic sandstone, argillite, greenstone, and mafic tuff (Haugerud and others, 1994) and is similar to the Deadman Bay terrane of the San Juan Islands (Burchfiel and others, 1992). It also contains exotic “knockers” (colloquial field term for hard, resistant lithologically-distinct blocks, a few feet to a few hundreds of feet across, that stand out in mélange and resist the knocking of a geologist’s hammer) (Tabor and Haugerud, 1999; Klaus and others, 2005) of the Precambrian-early Paleozoic Yellow Aster complex gneiss and gneissic plutons (Haugerud and others, 1994). Km-scale crustal blocks of the Yellow Aster complex are found scattered throughout the western Cascade Range in northern Washington. The Bell Pass mélange also contains blocks of the Vedder complex, composed of Permian high-pressure metabasalt and metachert schists (Haugerud and others, 1994) embedded within argillite and chert. These schists correlate with the Permian Garrison schist in the San Juan Islands, and perhaps with similar schists in the Stuart Fork terrane of the Klamaths, and elsewhere in the Cordillera (Haugerud and others, 1994). Another significant unit of the Bell Pass mélange is the rootless Twin Sisters dunite (a peridotite composed almost of at least 90% olivine) exposed at Twin Sisters Mountain, one of the stops on this field trip.

The Shuksan nappe overlies the Welker Peak nappe along the Shuksan thrust fault (Tabor and Haugerud, 2016) (**Fig. 3** and **Table 1**). It is composed of rocks of the Early Cretaceous Easton Metamorphic suite overlying the Shuksan thrust (Tabor and others, 2009). It is exposed on both limbs of the nappe anticlinorium discussed above: an eastern swath just west of the Fraser River-Straight Creek fault, and a western swath in the Cascade foothills and eastern Puget Lowlands. It is composed of high-pressure, low-temperature blueschist facies metamorphic rocks, and includes the Shuksan greenschist (consisting of both greenschist and blueschist) and the Darrington phyllite, the other focus of this field trip.

A similar series of stacked nappe sheets underlies the San Juan Islands. These are separated by west-verging thrust faults and overlie Wrangellia. For decades, the relationship between the nappes of the Cascade foothills discussed above and those in the San Juan Islands had not been completely worked out (Burchfiel and others, 1992), primarily because the transition between the two in the Puget Lowlands is buried beneath thick sedimentary cover. However, some common elements exist. For example, part of the Chilliwack River Group of the Excelsior Nappe is equivalent to the East Sound Group in the San Juan Island, the Bell Pass mélange of the Welker Peak nappe corresponds to the Constitution Formation, and the Easton Metamorphic Suite may be equivalent to the Lummi Formation and overlying Obstruction Island Formation (Tabor and Haugerud, 2016).

There are many complexities and enigmas regarding the terranes of the Cascade Range that are beyond the scope of this work. Please refer to the sources cited herein for details.

II. ROAD LOG

The primary focus of this field trip is to visit the Twin Sisters dunite at the Swen Larsen Quarry operated by Twin Sisters Olivine. Corky Smith of Twin Sisters Olivine has graciously agreed to provide us with a tour and collecting opportunities there. Because this visit would likely not fill up the day, Tom Bush offered to lead two additional stops to observe outcrops of the Darrington phyllite near Alger, in keeping with the accreted terrane theme of the Twin Sisters stop. Heather Vick graciously volunteered to assist with the writing and editing of this field guide, even though she did not sign up for the trip. There will collecting opportunities at all the stops. See **Figure 4** for stop locations.

Readers using this field guide on their own will not have access to the Swen Larsen

Figure 4. *Map showing the locations of the stops on this field trip. STOP 1 is at the Twin Sisters dunite at the Swen Larsen Quarry, and STOPS 2 and 3 are at the Darrington phyllite.*

Quarry at Stop 1 because this requires permission and accompaniment by quarry personnel. Stops 2 and 3 are accessible to the public.

7:30 AM Meet at the Northgate Transit Center Park and Ride, 10104 3rd Ave NE, Seattle, WA. 98125.

7:58 AM Depart. Proceed north on Interstate 5 for ~63 miles.

Exit 230-SR 20. Turn east (right).

Follow the signs for eastbound SR 20 through Burlington for 5.2 miles to Sedro Wooley.

At Sedro Wooley, navigate through town following the signs for northbound on SR 9.

Proceed north from Sedro Wooley on SR 9 for 15.5 miles to Acme. Time-permitting, brief stop at the Acme General Store for restroom break and to purchase lunch items, if necessary.
Just after crossing the South Fork of the Nooksack River just north of Acme, turn east (right) onto Mosquito Lake Rd. Proceed for about 12 miles to the high steel bridge that crosses the Middle Fork Nooksack River.

10:00 AM Continue another ¼ mile past the bridge to the olivine stockpile and loading area on the right. Meet Corky Smith here for the remaining drive to the Swen Larsen Quarry.

10:30 AM Arrive at STOP 1 (2 hours).

STOP 1: TWIN SISTERS DUNITE AT SWEN LARSEN QUARRY

Because geophysical evidence indicates that Earth's mantle comprises various forms of peridotite, the occurrence of such ultramafic slabs at Earth's surface provides unique opportunities to study the physical and chemical nature of the mantle (**Fig. 5**). These occurrences include ophiolite sequences (sections of oceanic lithosphere that include the ultramafic upper mantle and the overlying crustal rocks and sediments) that are scattered throughout the accreted terranes of the PNW. These include the Josephine ophiolite in the Klamath terranes, and in the Cascade Range, the Ingalls terrane in the Wenatchee block (**Fig. 2**), the Fidalgo ophiolite in the San Juan Islands, and the Twin Sisters dunite in the western

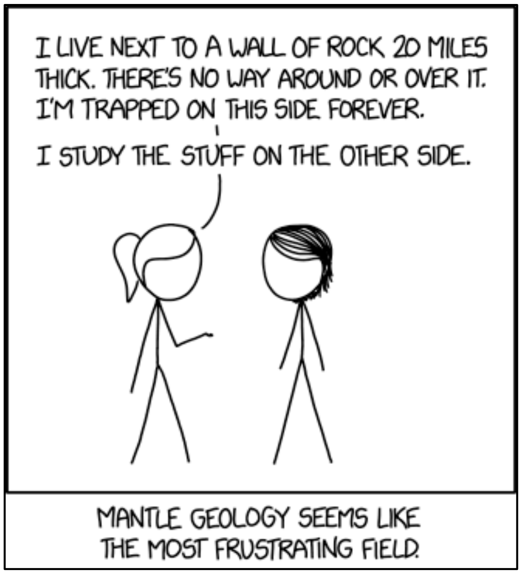


Figure 5. *Comic strip illustrating the challenges of directly studying the mantle (Explain xkcd, 2018).*

foothills of the Cascade Range, a major focus of this field trip.

Accretion of mantle fragments onto continental margins is not common because of the greater density of oceanic lithosphere, including sections of the mantle. This generally occurs through a process known as obduction, which is when oceanic lithosphere thrusts over continental lithosphere at a convergent boundary, bringing sections of the former to the surface as ophiolite sequences or portions thereof. There are several mechanisms by which this may occur but it is typical of orogeny involving subduction where a small plate is caught between larger continental and oceanic plates. Wedges of oceanic lithosphere may be slivered off wall of the oceanic trench and become accreted to the continental margin, in many cases accompanied by high-pressure metamorphism (Dewey, 1976).

The Twin Sisters dunite underlies the Twin Sisters range (**Figs. 6** and **7**), named for

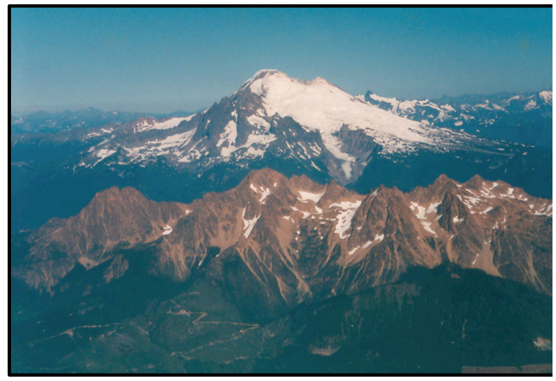


Figure 6. *Aerial view of the Twin Sisters range (light brown in foreground) looking northeast with Mt. Baker in the distance (T. Bush photo). The light brown color of the range is typical of weathered dunite (see text for details). The Swen Larsen Quarry is located in the lower-left portion of the photo (not visible).*

North and South Twin peaks in its northern portion. The range lies within the western flank of the Cascade Range in northwestern Washington, ~ 130 km north-northwest of Seattle, ~39 km east-southeast of Bellingham, and ~15 km southwest of Mt. Baker in Mt. Baker-Snoqualmie National Forest in Whatcom County. South Twin is the highest peak in the range at 2,025 m in elevation. Access to the range is limited to the summer months and is only by Forest Service roads from the southeast and northwest. The northern portion of Twin Sisters occurs within the drainage of the Middle Fork of the Nooksack River. This field trip will visit the Swen Larsen Quarry operated by Twin Sisters Olivine at the north end of range (**Fig. 7**), accessed from the west by primitive forest service roads from Acme or Deming. The quarry site itself lies between ~850 and 975 m in elevation. The mine was named by Corky Smith's father after a local logger whom he admired.

The Twin Sisters dunite body forms the entire Twin Sisters Range and is an elliptical mass (~10 x 4 km) with a total area of about 36 square km (**Fig 7**). Dunite is exposed vertically from elevations of about 450 to

Figure 7. *Aerial view of the Twin Sisters range southwest of Mt. Baker (north is to the top). Note the light brown weathering that is apparent even from high altitude. (Google Earth image, 7/28/16). Mt. Shuksan is in the upper-right corner of the image.*

2,025 m above mean sea level, the highest point in the range. The site is steep and mountainous, with the steepest slope at a 100% slope. As discussed above, it occurs within the Western domain of the terranes of the Cascade Range, within the stacked nappe sequences between the Fraser River-Straight Creek fault and the DDMFZ, and within the Bell Pass mélange of the Welker Peak Nappe. Like peridotite, dunite is of mantle origin, so it requires a tectonic mechanism to bring it to the surface. However, the Twin Sisters is rootless, being bounded beneath by a thrust fault with no structural connection to the mantle. This, along with its size, makes this allochthonous block a true crustal scale mélange knocker.

Dunite is a form of peridotite, an ultramafic phaneritic (coarse-grained) rock of plutonic origin. Essential minerals in dunite include clinopyroxene (monoclinic pyroxenes, including augite), orthopyroxene (orthorhombic pyroxenes, including hypersthene), and olivine. Dunite is a peridotite containing at least 90% olivine by volume, so the pyroxenes are present in subsidiary amounts (Strekeisen, 2018) (**Fig. 8**). It may also contain plagioclase, spinel, ilmenite, pyrope garnet, magnetite, and chromite in trace amounts. Dunite was named by German geologist Ferdinand von Hoshstetter in 1859 for Dun Mountain in New Zealand, with the name of the mountain coming from its "dun" (brownish-gray) color that results from its weathering in a temperate climate (Strekeisen, A., 2018) (**Figs. 6** and **7**).

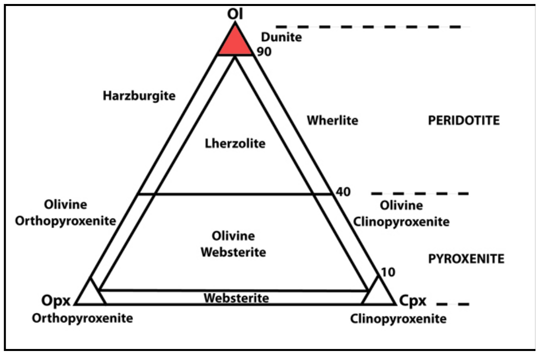


Figure 8. *Ternary diagram showing the classification of ultramafic rocks (Strekeisen, 2018). Cpx = clinopyroxene, Opx = orthopyroxene, Ol = olivine.*

Olivine is a silicate mineral containing ferrous iron and magnesium in solid solution with the formula $(Mg,Fe)_2SiO_4$ (or $2(Fe,Mg)O + SiO_2$). The solid solution ratio of Fe to Mg ranges from entirely Mg (forsterite) to entirely Fe (fayalite) where Fe and Mg may substitute for each other in any ratio. Forsterite is the magnesium higher-temperature end member, crystallizing at about 1900°C under atmospheric pressure, whereas fayalite is the iron end member that crystallizes at 1205°C (Klein and Hurlbut, 1993) (**Fig. 9**). Forsterite is named for Adolarius Jacob Forster (1739-1806), an English mineral collector, and the name fayalite comes from Fayal Island in the Azores, its type locality. Since neither is generally found alone in nature, olivine as always a combination of the two. As such, olivine is the first igneous rock mineral to crystallize from a magma on the discontinuous branch of Bowen's Reaction Series (Klein and Hurlbut, 1993). Because olivine is a high-temperature mineral, it is meta-stable at the lower temperatures of Earth's surface and easily alters to serpentine minerals, magnesite, and iron-oxide minerals, especially in the presence of water (Klein and Hurlbut, 1993). This explains why dunite masses at Earth's

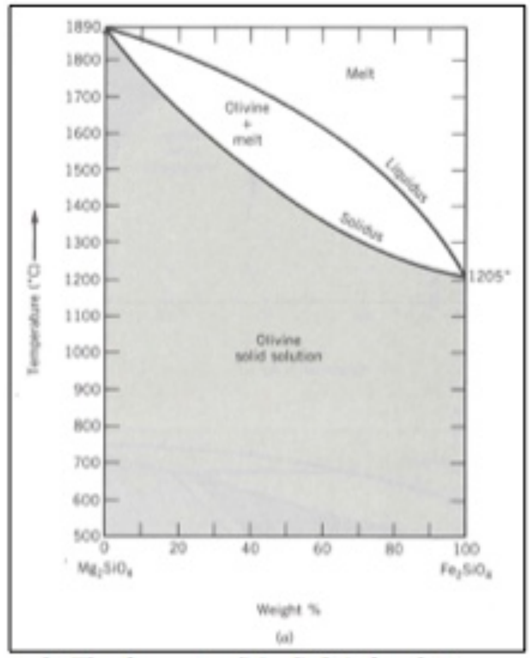


Figure 9. *The forserite (Mg_2SiO_4)-fayalaite (Fe_2SiO_4) solid solution series of olivine (Klein and Hurlbut, 1991).*

Figure 10. *A chromite-rich zone (dark area) within the dunite at the Swen Larson Quarry (T. Bush photo). U.S. 50-cent piece coin for scale.*

surface often appear brownish-gray ("dun") in color due to weathering.

The rock of the main Twin Sisters body and the two smaller masses is typically medium to coarse-grained, virtually unaltered enstatite-bearing dunite with accessory amounts of chromite and chromium diopside (enstatite is a Mg-Fe-bearing clinopyroxene, while diopside is a Ca-Mg-bearing orthopyroxene) (**Fig. 10**). The Twin Sisters dunite weathers to a distinctive reddish-brown (dun) color. With the exception of one locality however, the contacts are poorly exposed.

The olivine composition at Twin Sisters is virtually 100% forsterite. A chemical analysis of a Twin Sisters sample yielded 49.4% MgO, 41.2% SiO2, 7.1% Fe_2O_3, 0.2% CaO, 1.8% other oxides (Al_2O_3, TiO_2, MnO, NiO, CaO, K_2O, Na_2O), and 0.7% LOI (loss on ignition, a measure of hydrated minerals that produce volatiles when heated, an undesirable quality). Note the absence of FeO.

Olivine is a chemically inert mineral, which does not generate inorganic contaminants other than silt. However, olivine comprising more than 85% fayalite is not useful for most industrial purposes because the iron content makes it less refractory due to its lower melting temperature. The use of olivine in industrial applications began in Norway in the 1930s when a material was needed that would have no free silica. The many, primarily industrial, uses of olivine include molding sand in metals casting, a component in refractory lining of combustion chambers, fluid bed material, sand blast media, steel mill aggregate, gemstones, platinum group host, and CO_2 sequestration. Olivine offers an alternative source to materials that contain free silica, a mineral known to create serious health hazards (United States Department of Agriculture, Forest Service, 2017). Specific uses of olivine include:

Steel – the largest tonnage user of olivine is as a flux and a slag conditioner in the steel industry. Olivine also improves the performance of sinter and reduces coke consumption.

Foundries – Major foundry users of olivine are the manganese steel producers. For a variety of properties, olivine is used extensively in brass, aluminum, magnesium, titanium and iron casting.

Other uses include in refractories, abrasives, agriculture as a source of magnesium, roofing tiles, in North Sea oil rigs for ballast, and as fluid bed media (Smith, 1992).

While ultramafic mantle rocks such as peridotite are obviously abundant where they reside below the Earth's crust, they are rarely found in large sizes within continental mountain systems. In particular, the mineral olivine is found in pure form in few places on earth. Our first field trip stop, Twin Sisters Mountain, holds one of the world's largest dunite deposits.

At the base of the Twin Sisters Mountain, olivine is mined at the Swen Larsen Quarry. In operation since 1953, the quarry is one of the few places in the United States known to have access to olivine. Twin Sisters Olivine (formerly known as United Western Supply) has owned this site and Olivine Corporation has consulted on operations since January 2012 to the present time. Current production is 50,000 tons/yr, producing a projected mine life of 50 yrs. Interestingly, it has been estimated that the entire Twin Sisters range contains roughly 200 billion tons of dunite.

The olivine from the Sven Larsen Quarry is mainly used for molding sand in metals casting, a component in refractory lining of combustion chambers, and for artistic use in the community. Current mining operations include excavation of material, crushing and screening on-site, and the hauling of material off-site for further processing and sale to market. The active mining season is one to two months a year.

Every section of the Twin Sisters deposit shows evidence of cataclasis, a process of deformation or metamorphism in which the grains of a rock are fractured and rotated. The rock is granulated and exhibits bending of mineral grains and translation bands in olivine. Recrystallized cataclastic features consist of fine-grained, unstrained olivine mosaic zones surrounding and embaying large strained porphyroclasts. Locally, thin mosaic zones cut single large crystals and the translation bands have recrystallized into band-like forms with irregular, sutured boundaries.

The Twin Sisters dunite and two smaller dunite bodies are ~150 Ma in age (Cretaceous) and are located along a northwest-trending, nearly vertical fault. They intrude into several thrust plates and locally into the unconformably overlying Chuckanut formation. The time of emplacement was post-Paleocene so later that the main Cretaceous orogeny (Ragan, 1963).

The dunite at the Swen Larsen Quarry displays several features that are pertinent to its emplacement and history (Cheney, personal comm., 2019). The dunite is light greenish-gray, medium grained rock displaying faint gneissic layering with subparallel fractures commonly centimeters apart. Veins of secondary minerals are present along fractures that range in size from hairline up to 4 cm thick. Apple green to dark blue serpentine minerals are common along joint surfaces. Chromite occurs as disseminated blebs comprising ~0.5% of the rock and as veins <1 mm thick. Stringers of chromite grains range from a few grains thick to 10 cm wide and up to 1 m long (**Fig. 10**). Brittle features at the quarry, such as porphyroclasts, veins, and subparallel fractures, were likely formed as the dunite was transported and emplaced along faults.

Additional details may be provided about the quarry and its operation while here.

12:30 PM Retrace route back to Acme and then navigate to Interstate 5 west of Alger via Park Rd, S Bay Dr, Cain Lake Rd, and Angler-Cain Lake Rd (restroom break at the convenience station). Brief lunch stop at a place TBD or while driving, depending on time.

Proceed west across Interstate 5 on Lake Samish Rd, which bends north for 0.5 miles.

Turn west (left) onto Barrell Springs Rd. Follow this southward for 0.7 miles.

Turn west (right) onto Blanchard Hill Trail. Follow this for 1.8 miles to the parking area.

Walk north along the gravel road another 0.4 miles to the quarry on the left.

2:00 PM Arrive at STOP 2 (30 minutes).

STOP 2: DARRINGTON PHYLLITE AT CHUCKANUT MOUNTAIN

The rock quarried here (quarry history unknown) is the Darrington phyllite, which, together with the Shuksan greenschist, makes up the Jurassic Easton Metamorphic Suite. As discussed above, the Easton Metamorphic Suite is exposed throughout the Cascade Range foothills as the Shuksan nappe, the upper-most nappe of the region, separated from the Welker Peak nappe below by the Shuksan thrust.

The Easton Metamorphic Suite also occurs on the east side of the Fraser River-Straight Creek fault near its southern extremity in the Metamorphic Core domain along Interstate 90 near Easton, the locality from which it derives its name. It has been offset along this fault by ~ 100 km in a right-lateral manner.

The Shuksan greenschist consists of both greenschist and blueschist and derives its name from Mt. Shuksan ~17 km east-northeast of Mt. Baker (which may be visible from here, weather-permitting) (**Fig. 11**). The Darrington phyllite derives its name from exposures near Darrington on SR 530 ~60 km south-southwest of Mt. Baker. It is comprised of mostly phyllite, but as we will see at the next stop, other lithologies are present in places. The Easton Metamorphic Suite is interpreted to be accreted ocean floor rocks. The Shuksan was formerly ocean floor basalt, and the Darrington was formerly the overlying sediments. Together they underwent high deformational pressure-low temperature blueschist metamorphism during accretion, with the two resulting metamorphic rock types being due to the different parent rocks.

Figure 11. *Mt. Shuksan looking east. (J.T. Figge photo (cover photo, The Geology of Washington and Beyond, Eric S. Cheney, ed., 2016)).*

Northwest of here a short distance at Chuckanut Mountain (aka Blanchard Mountain or Blanchard Hill), the Darrington phyllite is unconformably overlain by the Eocene Chuckanut formation, a thick cover sequence correlative with other Eocene arkosic sandstones throughout the PNW, such as the Carbonado, Swauk, and O'Brien Creek formations (Cheney, 2016B; Cheney, 1994).

We will briefly examine the Darrington phyllite exposed in the quarry at this stop. The most interesting exposures are at the northern end, where the foliation transecting relict bedding planes at high angles is apparent in places. Shallowly-plunging, northwest-trending, outcrop-scale open folds deform the foliation. Numerous milky quartz veins, presumably produced by hydrothermal fluid migration during metamorphism, are common here.

Walk back to the vehicles. Proceed south on Blanchard Hill Trail for 0.2 miles.

Turn west (right), following the westward continuation of Blanchard Hill Trail for 0.3-0.4 miles and park wherever possible (this may be difficult).

3:00 PM Arrive at STOP 3 (30 minutes).

Figure 12. Photo of rosettes of stilpnomelane in milky quartz (scale unavailable) (Mindat, 2019). Specimen is from the outcrop visited on this trip.

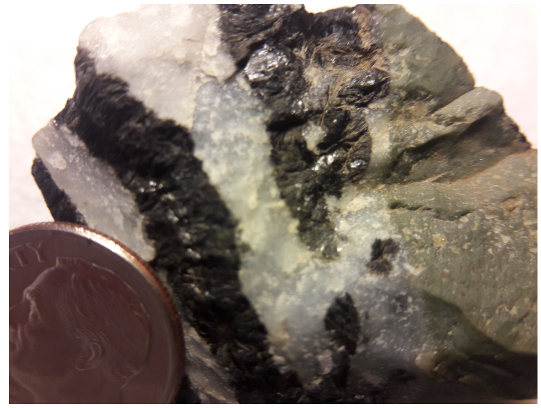


Figure 13. Stilpnomelane (dark) in milky quartz with green chert. F. Lalague specimen, T. Bush photo. This specimen is from the outcrop visited on this field trip.

STOP 3: STILPNOMELANE IN THE DARRINGTON PHYLLITE AT CHUCKANUT MOUNTAIN

This outcrop is another exposure of the Darrington phyllite, but the interest here is in the small, black rosettes and veinlets of the mineral *stilpnomelane* (pron.: stilp-NOM-e-lane) (**Figs. 12** and **13**). The occurrence of stilpnomelene here was discovered in 1998 when construction of a logging road exposed this outcrop (Mustoe, 1998). The rosettes are a few mm to ~ 1 cm in diameter in size (a hand lens will be useful). They occur within a complex zone of milky quartz veins ~150 m wide hosted by steeply dipping beds of green chert within the Darrington phyllite (Mustoe, 1998). Look for crystals and veinlets scattered throughout the outcrop, which are abundant in chert near the quartz vein margins (Mustoe, 1998), as well as the quartz.

Stilpnomelane is a phylosilicate mineral very similar in its structure, chemistry, and physical properties to biotite, and is generally impossible to distinguish from the latter in hand sample (Klein and Hurlbut, 1993); however, its presence here has been verified by x-ray diffraction by Edwin Brown at Western Washington University (Mustoe, 1998). It is a chemically complex hydrous iron-magnesium alumino-silicate ($(K,Ca,Na)(Fe^{2+},Mg,Al)_8(Si,Al)_{12}(O,OH)_{36} \cdot nH_2O$) with basal cleavage and sub-vitreous to pearly to sub-metallic luster (Mindat, 2019). Ernst Friedrich Glocke named the mineral in 1827 from the Greek “stilpnos” (shining) and “melanos” (black) (Mindat, 2019). Stilpnomelane forms under blueschist metamorphic conditions in iron-rich rocks (Mustoe, 1998), thus its presence here is evidence of this metamorphic grade. It may also form where iron was introduced into silica-rich rocks by hydrothermal activity. Stilpnomelane also occurs in metamorphosed Precambrian banded-iron formation deposits (Mustoe, 1998). In addition, stilpnomelane occurs in the blueschist rocks of the Franciscan complex, California, and iron deposits of the Lake Superior region (Mustoe, 1998). Its presence here is due to the hydrothermal introduction of iron into the silica-rich green cherts (Mustoe, 1998). As at the previous stop, the quartz veining provides evidence of the hydrothermal activity.

The occurrence of stilpnomelane at this outcrop is exciting because it is not a common mineral; in addition to observing its significance related to the metamorphic conditions, this is a rare opportunity to collect samples.

Retrace route back to Interstate 5 and proceed southbound back to the Northgate Transit Center Park and Ride.

5:30 PM Arrive at Northgate Transit Center Park and Ride.

REFERENCES CITED

Brandon, M.T., 1989, Geology of the San Juan-Cascade nappes, northwestern Cascade Range and San Juan Islands, in Joseph, N.L., ed., Geologic guidebook for Washington and adjacent areas, Washington Division of Geology and Earth Resources Information Circular 86.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, in Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3.

Cheney, E. S., 2016A, Important Geologic Concepts, *in*, The Geology of Washington and Beyond: From Laurentia to Cascadia, Cheney, E. S., Ed, University of Washington Press, Seattle, 336 p.

Cheney, E.S., 2016B, Overview of the Cenozoic Unconformity-Bounded Sequences of Washington, *in* The Geology of Washington and Beyond: From Laurentia to Cascadia, Cheney, E. S., Ed, University of Washington Press, Seattle, 336 p.

Cheney, E.S., 1994, Cenozoic unconformity-bounded sequences of central and eastern Washington: in Lasmanis, R., and Cheney, E.S., eds., Regional geology of Washington State, Washington Division of Geology and Earth Resources Bulletin 80, p. 115-139.

Cheney, E. S., and Figge, J. T., 2016, Overview of the Terranes of Washington, *in* The Geology of Washington and Beyond: From Laurentia to Cascadia, University of Washington Press, Seattle, 336 p.

Cowan, D.S., 1994, Alternative hypothesis for the Mid-Cretaceous paleogeography of the western Cordillera; GSA Today, vol. 4, no. 7, p. 181-186.

Cowan, D.S., and Bruhn, R.L., 1992, Late Jurassic to early Late Cretaceous geology of the U.S. Cordillera, in Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3.

Dewey, J. F., 1976, Ophiolite obduction, Tectonophysics, v. 31, Issue 1-2, pp. 93-120.

Explain xkcd, 2018, 2058: Rock Wall, https://www.explainxkcd.com/wiki/index.php/2058:_Rock_Wall, accessed 5/13/2019.

Gabrielse, H., Monger, J.W.H., Wheeler, J.O., and Yorath, C.J., 1991, Part A: Morphological belts, tectonic assemblages, and terranes, in Chapter 2 of Geology of the Cordilleran Orogen in Canada, Gabrielse, H., and Yorath, C.J., eds., Geological Survey Canada, Geology of Canada, no. 4, p. 15-28.

Haugerud, R.A., Brown, E.H., Tabor, R.W., Kriens, B.J., and McGroder, M.F., 1994, Late Cretaceous and early Tertiary orogeny in the North Cascades, in, Swanson, D.A., and Haugerud, R.A., eds., Geologic field trips in the Pacific Northwest, vol. 2, p. 2E1-2E51.

Haugerud, R.A., Mahoney, J.B., and Dragovich, J.D., 1996, Geology of the Methow block—A guide to a 4-day excursion in the Methow valley, Okanogan County, Washington, Northwest Geological Society Guidebook, Seattle, no. 37.

Klaus, K.E., Neuendorf, J.P.M., Jr., and Jackson, J.A., eds., 2005, Glossary of Geology, 5th Ed., The American Geological Institute, New York, 800 p.

Klein, C., and Hurlbut, C.S., Jr. 1993, Manual of Mineralogy, John Wiley & Sons, Inc., New York, 681 p.

Miller, R.B., 1989, The Mesozoic Rimrock Lake inlier, southern Washington Cascades: Implications for the basement to the Columbia Embayment, Geological Society of America Bulletin, vol. 101, p. 1289-1305.

Miller, R.B., Haugerud, R.A., Murphy, F., and Nicholson, L.S., 1994, Tectonostratigraphic framework of the northeastern Cascades, Washington Division of Geology and Earth Resources, Bulletin 80, p. 73-92.

Mindat, 2019, Stilpnomelane, https://www.mindat.org/min-3789.html, accessed 5/18/2019.

Mongor, J.W.H, and Brown, E. H, 2016, Tectonic evolution of the Southern Coast-Cascade Orogen, Northwestern Washington and Southwestern British Columbia, *in* The Geology of Washington and Beyond: From Laurentia to Cascadia, Cheney, E. S., Ed, University of Washington Press, Seattle, 336 p.

Mustoe, G. E., 1998, Stilpnomelane at Blanchard Mountain, Western Skagit County, Washington, Washington Geology, vol. 26, No. 4, pp. 3-8.

Oldow, J.S., Bally, A.W., Avè Lallemant, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North America Cordillera; United States and Canada, in Bally, A.W., and Palmer, A.R., eds., The Geology of North America—An overview: Boulder, Colorado, Geological Society of America, The Geology of North America, v. A.

Ragan, D.M, 1963, Emplacement of the Twin Sisters dunite, Washington, American Journal of Science, vol. 261, no. 6, pp. 549-565.

Saleeby, J.B., and Busby-Spera, C., 1992, Early Mesozoic tectonic evolution of the western U.S. Cordillera, in Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3.

Smith, Jr., C., 1992. Olivine, the Industrial Mineral. Society for Mining, Metallurgy and Exploration, Reprint No. 92-102.

Strekeisen, A., 2018, Dunite, http://www.alexstrekeisen.it/english/pluto/dunite.php (accessed 5-10-2019).

Tabor, R.W. and Haugerud, R.A., 1999, Geology of the North Cascades: a mountain mosaic, The Mountaineers, Seattle, 143 p.

Tabor, R.W. and Haugerud, R.A., 2016, Geology of the North Cascades: Summary and Enigmas, *in* The Geology of Washington and Beyond: From Laurentia to Cascadia, University of Washington Press, Seattle, 336 p.

Tabor, R.W., Haugerud, R.A., Hildreth, W., and Brown, E.H., 2009, Geologic map of the Mt. Baker 30'- by 60' quadrangle, Washington: U.S. Geological Survey Investigation Series I-2660, http://geomaps.wr.usgs.gov/pacnw/nc/baker1.html (accessed 1/27/2011).

United States Department of Agriculture, Forest Service, Pacific Northwest Region, 2017. Swen Larson Quarry Expansion Project, Final Environmental Assessment. Mount Baker-Snoqualmie National Forest, Whatcom County Washington. August 21.

Washington State Department of Natural Resources, 2019, North Cascades, https://www.dnr.wa.gov/programs-and-services/geology/explore-popular-geology/geologic-provinces-washington/north-cascades#terrane-accretion.1 (accessed 5/15/2019).