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# Nephrite Jade and Related Rocks from Western Washington State, USA: A Geologic Overview

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**Abstract:** The geologic framework of western Washington, USA, is the result of collisional tectonics, where oceanic plate materials were subducted beneath the continental margin. As part of this process, fragments of mantle peridotites were transported into the upper crust along deep faults. The hydration of these ultramafic materials produced bodies of serpentinite. Subsequent regional metamorphism caused metasomatism of the serpentinite to produce a variety of minerals, which include nephrite jade, grossular, chlorite, diopside, vesuvianite, and pumpellyite. Many of the nephrite-bearing rocks are located along the Darrington–Devils Mountain Fault Zone in Skagit and Snohomish Counties. Intense prospecting has led to the establishment of many mining claims, but recreational collecting remains a popular activity.

**Keywords:** jade; nephrite; jadeite; serpentinite; listwanite; rodingite; garnet; diopside; vesuvianite; pumpellyite; sillimanite

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## 1. Introduction

Jade is traditionally divided by gemologists into two forms, jadeite (pyroxene family) and nephrite (amphibole family). From a geologic perspective, this nomenclature is an oversimplification, because many examples from both groups contain an assemblage of minerals. Nephrite jade primarily consists of amphibole that falls within the tremolite-ferro-actinolite solid solution series, but nephrite specimens commonly contain lesser amounts of other minerals. Relict metal oxides include chromite and magnetite. Chlorite (e.g., clinochlore) and diopside are common silicates in nephrite occurrences. Jadeite likewise commonly shows compositional variation. Pyroxene jadeite gives rise to the gemologic name, but this material is perhaps more accurately described by the rock name jadetite. Jadetite is divided into jadeite jade, kosmochlor jade, and omphacite jade [1–3].

Washington State jade is predominately nephrite, though there have been a few discoveries of jadetite specimens. The aim of this report is to provide a general geologic overview of nephrite and associated minerals from sites in northwest Washington State. These occurrences include in situ lode deposits and transported materials in alluvial and colluvial deposits. An earlier publication described nephrite from coastal locations, where material was transported from Canada in the late Pleistocene as a result of continental glaciations [4].

Searches for nephrite jade and related gem materials in western Washington State have long been conducted by amateur collectors and prospectors who seek mineable deposits. Most published reports have been focused on providing advice to collectors (e.g., [5]) or are gemology-based investigations [6–8].

### 1.1. Geographic and Geologic Setting of Washington Nephrite

The petrogenesis of jade and related rocks is a challenging topic because of the complexities inherent in the formation of metamorphic mineral assemblages. For nephrite, the parent material is serpentinite, a rock composed primarily of members of the serpentine family (lizardite, antigorite, and chrysotile). These magnesium silicate minerals are produced by the alteration of ultramafic mantle material (peridotite or pyroxenite) that has been brought to shallow depths by deep-seated faults. These faults are the result of tectonic forces typically associated with subduction zones. Because of this origin, jadite has been referred to as a "plate tectonic gemstone" [9]; the same description can be applied to most nephrite. An exception is the formation of nephrite, which forms from contact metamorphism where dolomitic sediment reacts with Si-rich hydrothermal fluids released from a felsic pluton [10].

The metamorphic terranes in western Washington State are linked to the Cascadia Subduction Zone, where oceanic plates and associated island arcs collided with the North American continent. The oceanic materials were generally in the form of ophiolite complexes, which represent the various components that were present at mid-ocean rift zones (Figure 1). An ophiolite is a section of oceanic crust and underlying upper mantle that has been uplifted. Ophiolites document the existence of former ocean basins that have been consumed by subduction, commonly being emplaced in association with continental crustal rocks to produce mountain belts.

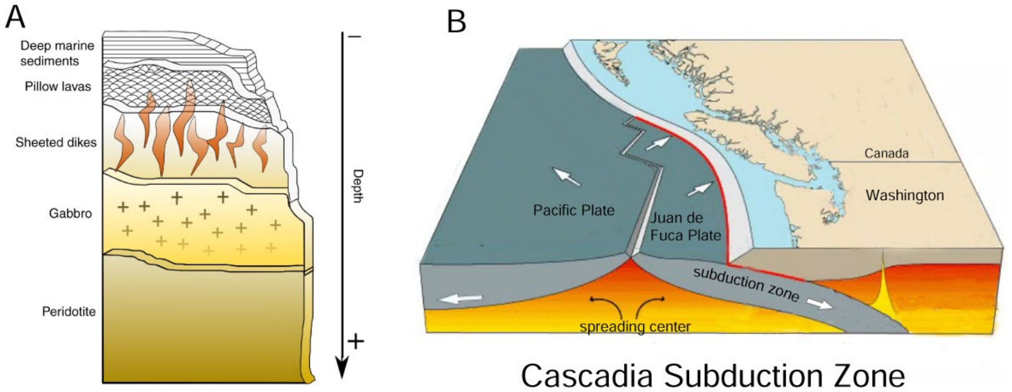

**Figure 1.** Tectonic setting of the western Washington State. (**A**) Ophiolite complex geologic sequence (not to scale). (**B**) Cascadia Subduction Zone. Both images have been adapted from Creative Commons 3.0 licensed mages: (**A**) Wikipedia.org file:Ofioliti.org.svg. (**B**) U.S. Geological Survey graphics.

An ophiolite complex provides the starting environment for the eventual production of jade. The circulation of hydrothermal fluids within the young oceanic crust causes the serpentization of mantle ultramafics and the alteration of igneous seafloor rocks (gabbro and basalt) to form lower-temperature assemblages. Plagioclase, pyroxenes, and olivine in the sheeted dikes may, respectively, alter to albite, chorite, and serpentine.

The emplacement of ophiolite complexes typically involves major deformation, where individual components become intermixed. The coexistence of ultramafic rocks and neighboring formations provides a favorable setting for the paragenesis of nephrite. The nephrite formation process can be traced to the following three fundamental steps:

1. The upward transport of ultramafic mantle material (e.g., peridotite) along deep faults.
2. The conversion of peridotite to serpentinite as a result of hydration. The primary component of mantle material is Mg-olivine (forsterite), so the generalized chemical reaction is as follows:

$$3MgSiO_4 + H_2O + SiO_2 \rightarrow 2Mg_3Si_2O_5(OH)_4$$

Forsterite Serpentine

3. The dissolution of Ca from adjacent rocks and the fluid transport of $Ca^{2+}$ into the serpentinite to produce amphibole, e.g., tremolite.

$$5Mg_3Si_2O_5(OH)_4 + 6Ca^{2+} + 14SiO_2 \rightarrow 3Ca_2Mg_5Si_8O_2(OH)_2 + 12H^+$$

Serpentine Tremolite

Depending on the dissolved elements that are introduced via metasomatism, various minerals may be produced. The availability of dissolved iron may result in an amphibole midway between the tremolite and ferro-actinolite end members. Minerals that commonly occur in association with serpentinite include chlorite and diopside, and relict micro inclusions of chromite and magnetite. Additional minerals may be present in rodingite and listwanite zones that are peripheral to the serpentinite body.

Many of the Washington State nephrite occurrences are related to the Darrington–Devils Mountain Fault Zone (DDMFZ) (Figure 2). In this zone, nephrite-bearing ultramafic rocks occur within the Helena–Haystack Melange Zone (HHMZ) [11]. The HHMZ is exposed along the DDMFZ from the Haystack Mountain in western Skagit County to Helena Ridge in Snohoish County, and intermittently exposed as far south as Manastash Ridge in Kittitas County (Figure 3). Some of its exposures occur at high elevations in the Higgins Mountain and Helena Ridge areas near Darrington, Washington. In addition to serpentinite, the HHMZ contains metavolcanic greenstone, metagabbro, metadiabase, and schistose metavolcanic rocks.

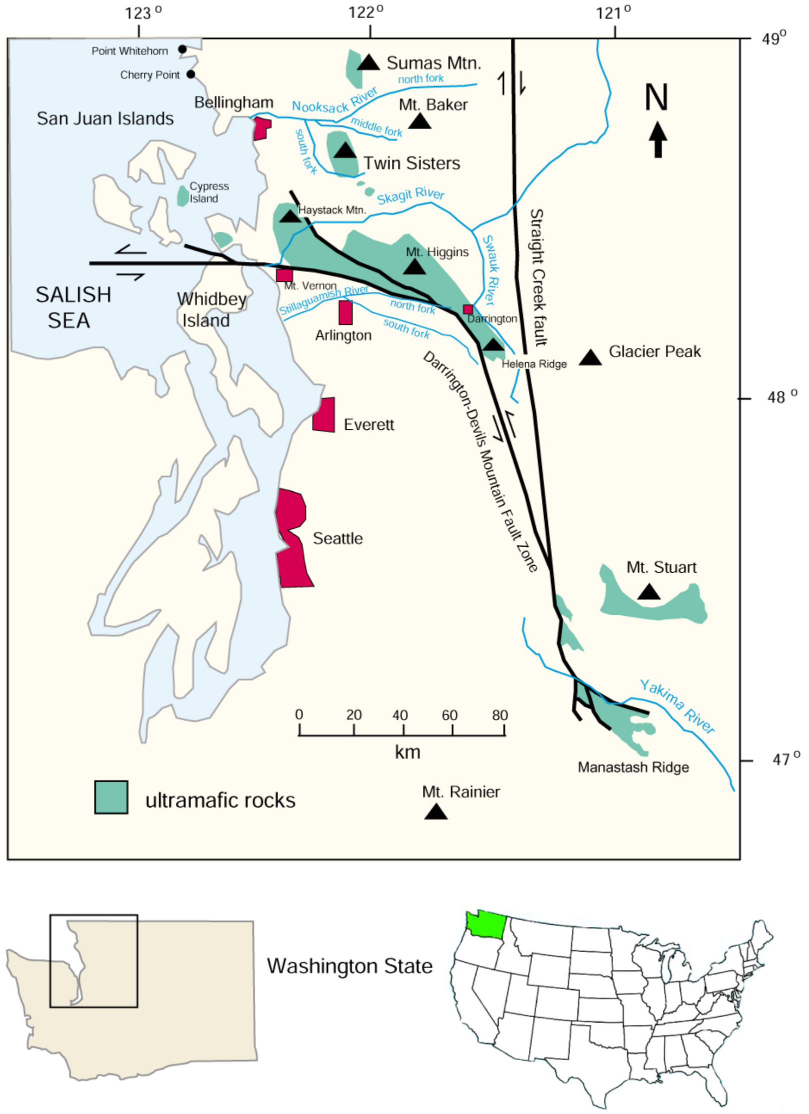

**Figure 2.** Occurrences of ultramafic bedrock in western Washington, USA. Towns and cities are shown in red. Arrows show relative motion of faults.

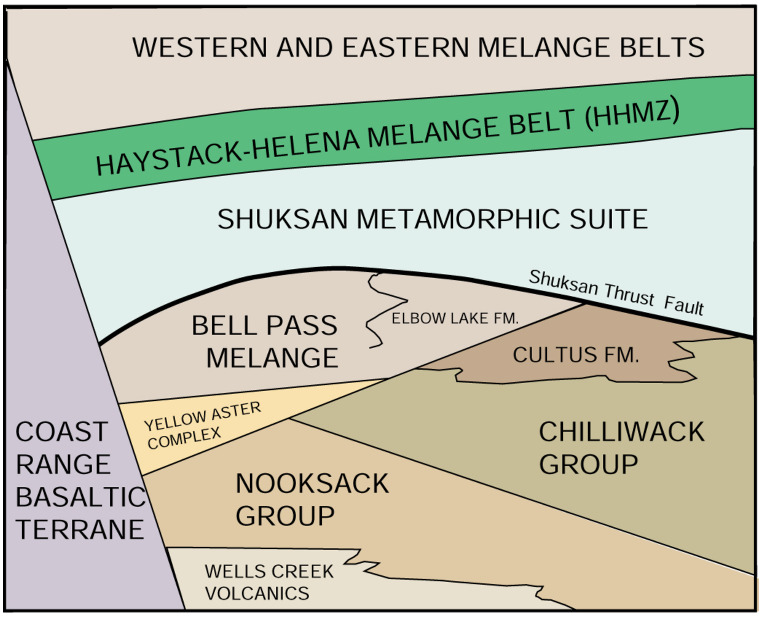

**Figure 3.** The Helena–Haystack Melange is only a small component of the geologic terranes that comprise the structural framework of the northwest Cascade Range of Washington. The DDMFZ occurs within the Haystack–Helena mélange belt. Figure modified from [11].

Although serpentinites of the HHMZ are a principle source of nephrite, this unit comprises a relatively small part of the North Cascade Range, where the thrust fault stacking of exotic terranes accounts for most of the bedrock, the main exception being young granitic plutons, Cenozoic sediments, and extrusive volcanics (Figure 3).

Serpentinite bodies also occur outside of the DDMFZ, typically located along deep faults that have allowed for the upward transport of mantle peridotites. These range in volume from small lenses to the marginal zones of the massive dunite of the Twin Sisters Range (Figure 4) [12], and a large outcrop zone on the west side of Sumas Mountain in northern Whatcom County, Washington.

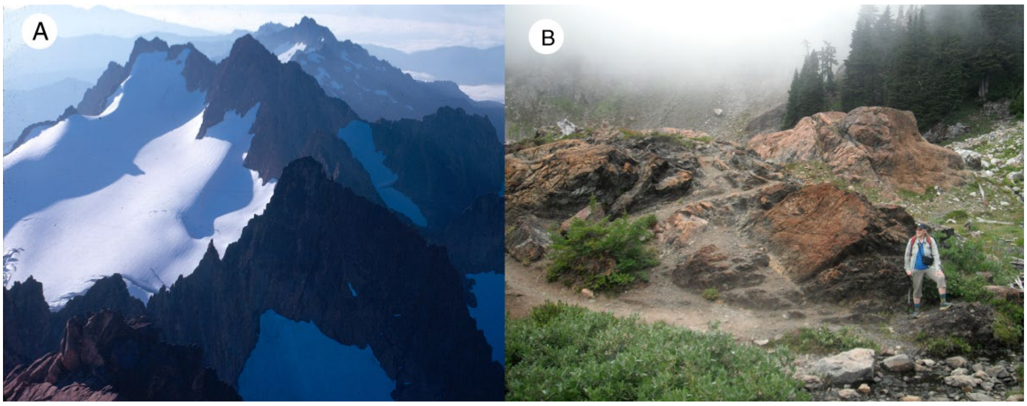

**Figure 4.** Some ultramafic rocks in western Washington are not associated with the DDMFZ. (**A**) Twin Sisters Range in Whatcom County. This alpine massif is composed of olivine-rich dunite that is bordered by a peripheral zone serpentinite zone that formed from hydration of the ultramafic body as it moved upward along a crustal fault. (**B**) Lens-like serpentinite situated along a fault in the Paleozoic Yellow Aster Complex of northwestern Whatcom County.

Metamorphic mineral assemblages are created when physical and chemical conditions favor the stability of particular minerals. The resulting mineralogic zonation provides the foundation for the concept of metamorphic facies (Figure 5).

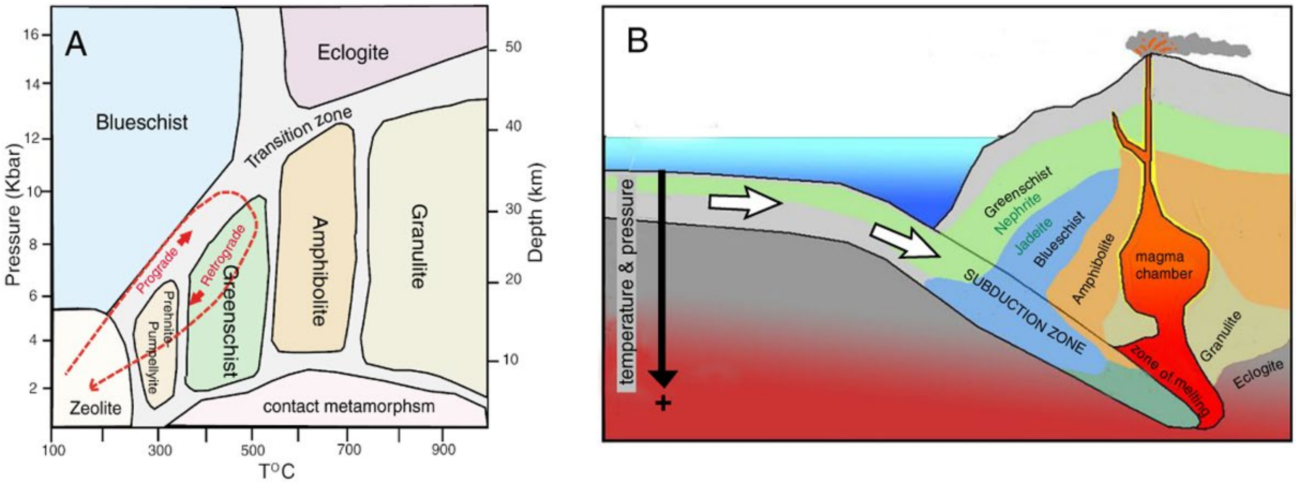

**Figure 5.** Metamorphic facies typical of regional metamorphism. (**A**) Facies in relation to temperature and pressure. Red line shows the cycle of prograde and retrograde metamorphism for the greenschist facies. (**B**) Development of metamorphic facies in relation to subduction zone tectonics.

Prograde mineral transformations are typically endothermic, driven by increases in temperature and pressure that accompany ever-deepening burial. Decreases in temperature and pressure are not likely to reverse retrograde reactions because of the absence of the activation energy needed to initiate chemical change. However, an energy influx can initiate retrograde metamorphism.

The hydration of olivine to produce serpentine is a retrograde process. Subsequent mineral transformations are commonly linked to metasomatism, e.g., the transport of dissolved elements from adjacent strata. Metasomatism does not neatly fit into the prograde/retrograde model. Also, collisional plate tectonics may involve complexities in the stability range of minerals. For example, the retrograde olivine→ serpentine transformation is a characteristic of oceanic plate materials as they are transported away from their origin at a mid-ocean ridge. In the increasing pressures and temperatures of the subduction zone, a prograde reaction may convert serpentine back to olivine [13]. The net effect of these metamorphic processes is that the mineral assemblages found in the nephrite-bearing rocks of western Washington State may be complex, with a variety of minerals coexisting even in a single specimen.

The facies model has limitations. In particular, mineral transformations related to changes in pressure and temperature are not instantaneous. As a result, the facies shown in Figure 5 are separated by transition zones where mineral assemblages may contain members from adjacent facies. Similarly, facies are considered to represent mineral assemblages that have reached a state of equilibrium, but in nature, it is common that metamorphic rock units have not attained equilibrium. As a result, the facies model is a useful theoretical tool, but actual mineral assemblages may be rather different.

Nephrite characteristically forms in the lower part of greenschist facies; jadeite requires the higher pressure of blueschist facies. Because greenschist facies metamorphism rocks are a major component of the rocks of the Northwest Cascade Range, nephrite occurrences can be geographically extensive. However, because nephrites require the unique geochemistry found in serpentine zones, occurrences are limited to fault zones that have brought ultramafic mantle materials into the upper crust. In Washington, nephrite commonly occurs as seams and lenses within serpentinite (Figure 6).

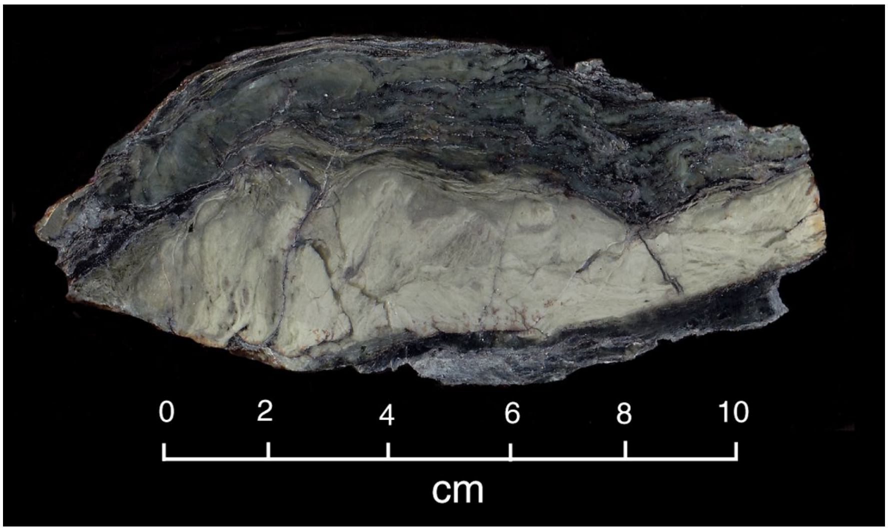

**Figure 6.** Nephrite lens enclosed within serpentine, Helena Ridge specimen LD-1.

### *1.2. History of Washington State Jade Collecting*

Jade-producing locations in Alaska, British Columbia, Wyoming, and California have long histories, but jade in Washington State attracted little attention prior to the 1970s, when commercial operations began. Although amateur collectors have found jade and related rocks in many locations, commercial activity has mostly been focused on sites in the North Cascade foothills. An early article [14] was supplemented by a more recent publication [5]. Commercial mining activity has been focused on areas where nephrite occurs in bedrock exposures. Brief published descriptions have focused on gemological characteristics [6,7]. A more technical report [8] included detailed analytical data for nephrite jade and pleochroic tremolite/actinolite from a mining site near Darrington, WA, USA.

### *1.3. Historic Uses of Nephrite*

Because of its ability to withstand abrasion and impact, nephrite has been used for making stone tools since Neolithic times. These properties, combined with the attractiveness of its color and pattern, also led to the use of nephrite for decorative purposes, including intricate works of art. One of the earliest known locations for the artistic use of jade is in China, where the Xinglongwa Culture (6200–5400 BC = 8150–7350 BP) marked the beginning of jade preeminence in East Asia [15]. Green nephrite was being used for tool-making in Taiwan at ~4500 BP. Within 1000 years, these artifacts were spreading to other southeast Asian islands beyond the Philippines. The mass production of nephrite ornaments began in Taiwan at ~2500 BP, becoming widespread in southeast Asia until ~1000 BC (~2050 BP) [16–19]. Another early location is in the Baikal Lake area, Sakha Republic, Russia, where nephrite adzes and ornamental rings come from a site dated at 2930 BC (=4880 BP) [20].

In North America, native people have been using nephrite for tools and decorations for thousands of years. Early published reports of nephrite use in British Columbia date from 1851 to 1923 [21–23]. In the Pacific Northwest, the earliest use of nephrite for the fabrication of sharp-edged celts began at about 3500 BP, with an abundance of celts recovered from sites dating 2500–1000 BP. This rise in celt production correlates with increased woodworking activities that included carving canoes, the construction of plank houses, and the fabrication of wood storage boxes [22,24,25].

Nephrite tool production was centered at the two following localities along the Fraser River where alluvial nephrite is abundant: the entrance of the Fraser Canyon at Hope, B.C., and the Lytton–Lillooet area in the mid-Fraser River region [24,25]. Nearly all sawn nephrite cores have been found at these two relatively restricted locations. In contrast, the greatest numbers of nephrite celts have been found at sites along the lower Fraser River and Salish Sea coast, two areas that have no known history of nephrite tool production. Celts made from alluvial Fraser River nephrite were also traded to tribes in the Canada Interior Plateau. These celts are relatively large, and they presumably served as indications of personal wealth rather than being useful tools [24,25]. The manufacturing of a single sawn nephrite celt is estimated to have required 40–100 h [26].

By the 1850s, nephrite collected from the Fraser River had become a global resource. The Kunun Mountains of China have long been a major source of nephrite, but by the 1700s, Chinese jade sources were becoming depleted. In the mid-1800s, Chinese placer miners in British Columbia were collecting Fraser River nephrite boulders, sometimes sending them to China in the coffins of those who died and were sent home for burial [27].

The modern mining of British Columbia nephrite dates to 1938, when boulders were discovered in placer deposits in the Cassiar District. In the early 1950s, nephrite boulders weighing up to 10 tons were found along the Fraser and Bridge Rivers near Lillooet, B.C. Later, bedrock deposits in the Cassiar and Omineca areas became major localities for Canadian nephrite mining [28–30]. In Washington State, commercial nephrite activity has been focused on bedrock occurrences of nephrite on the western side of the North Cascade Range, with most prospecting focusing on serpentinite bodies exposed along the Darrington–Devils Mountain Fault zone in the Skagit and Snohomish Counties [5]. Rock and mineral occurrences on Salish Sea beaches have largely been the domain of amateur collectors [4].

### 1.4. Washington State Nephrite Commerce

Beginning in 1968, the first jade mining claims were staked in the vicinity of Mount Higgins, near Darrington, Washington State, USA [5,14]. This small town remains the geographic center for jade mining. About 30 active claims presently exist near Mount Higgins. In recent years, many prospectors have shifted to serpentinite zones located on Helena Ridge, a few kilometers south of Darrington, filing about 20 mining claims. GPS coordinates and ownership records for claim locations are available online as public records [31]. Land ownership in the Darrington region includes privately owned timberlands, state forest land administered by the Department of Natural Resources, and federal timberlands administered by the United States Forest Service. Legal access, therefore, becomes a complex issue.

## 2. Materials and Methods

### 2.1. Materials

This study is based on examination of ~120 specimens from localities in western Washington State, with a particular emphasis on materials from the DDMFZ. Some specimens were collected by the author, but the majority of the samples were donated by amateur collectors and mining claim owners. These people are named in the Acknowledgements. Specimens, which were cataloged with individual identification numbers, are presently archived in the author’s research collection at the Western Washington University Geology Department, Bellingham, WA, 98225 USA.

### 2.2. Analytical Methods

A variety of methods were used for mineral identification. These included optical microcopy, X-ray diffraction, and SEM/EDS analysis. Petrographic thin sections were studied using a Leitz petrographic microscope equipped with a 5-megapixel CMOS microscope camera. SEM images were obtained using a Tescan Vega III SEM (Brno, Czech Republic), with elemental microanalyses performed with an Oxford energy-dispersive X-ray detector using AzTek 4.0 analytical software, analyzing regions on polished blocks mounted horizontally on 1 cm diameter aluminum stubs. Because XRF oxygen peaks are poorly quantifiable, the oxygen values for silicate minerals were calculated based on stoichiometry. A limitation of XRF analysis is that there is no distinction between ferrous and ferric oxidation states. In Table 1, total iron is calculated as FeO.

**Table 1.** Major element composition of Washington State nephrite. Determined by SEM/EDS.

| | Grandy Creek-1 | Grandy Creek-2 | Deer Creek DC-1 | Deer Creek DC-3 | Deer Creek DC-6 | Deer Creek RBN-2 | Deer Creek RBN-4 | Deer Creek DC-TT | Nooksack Middle Fork | Sorenson Creek |
|---|---|---|---|---|---|---|---|---|---|---|
| Oxide Wt. % | | | | | | | | | | |
| $SiO_2$ | 49.01 | 45.62 | 54.00 | 51.79 | 56.57 | 57.41 | 56.26 | 58.20 | 56.14 | 55.77 |
| $Al_2O_3$ | 8.59 | 10.85 | 2.72 | 2.17 | 1.20 | 1.87 | 0.0 | 0.0 | 0.0 | 1.10 |
| FeO [1] | 8.34 | 13.07 | 10.83 | 14.20 | 8.60 | 8.22 | 10.53 | 14.43 | 14.43 | 9.05 |
| MgO | 24.13 | 25.84 | 21.80 | 21.89 | 21.94 | 21.71 | 21.04 | 21.32 | 21.32 | 21.41 |
| CaO | 9.93 | 4.48 | 10.65 | 9.93 | 11.70 | 11.05 | 11.16 | 9.98 | 9.98 | 12.68 |
| Element Wt. % | | | | | | | | | | |
| Si | 22.91 | 21.32 | 25.42 | 24.26 | 26.44 | 26.83 | 26.30 | 27.20 | 26.24 | 26.07 |
| Al | 4.55 | 5.74 | 1.44 | 1.15 | 0.64 | 0.99 | 0.0 | 0.0 | 0.0 | 0.58 |
| Fe | 6.48 | 10.16 | 8.42 | 11.04 | 6.68 | 6.39 | 8.18 | 6.21 | 11.22 | 7.03 |
| Mg | 14.55 | 15.58 | 13.15 | 13.20 | 13.23 | 13.10 | 12.69 | 12.83 | 12.86 | 12.91 |
| Ca | 7.10 | 3.20 | 7.61 | 7.10 | 7.10 | 7.90 | 7.98 | 8.03 | 7.13 | 9.06 |
| O [2] | 44.4 | 43.85 | 44.14 | 43.29 | 43.29 | 45.06 | 44.85 | 44.43 | 44.42 | 44.35 |
| Atomic % | | | | | | | | | | |
| Si | 17.54 | 16.43 | 19.58 | 19.02 | 20.33 | 20.50 | 20.31 | 21.14 | 20.22 | 20.17 |
| Al | 3.69 | 4.69 | 1.18 | 0.96 | 0.52 | 0.80 | 0.0 | 0.0 | 0.0 | 0.48 |
| Fe | 2.50 | 3.94 | 3.28 | 4.36 | 2.59 | 2.45 | 3.18 | 2.43 | 4.35 | 2.74 |
| Mg | 12.87 | 13.88 | 11.78 | 11.99 | 11.76 | 11.56 | 11.32 | 11.52 | 11.45 | 11.54 |
| Ca | 3.81 | 1.73 | 4.14 | 3.91 | 4.51 | 4.23 | 4.32 | 4.38 | 3.85 | 4.91 |
| O | 59.69 | 59.32 | 60.10 | 59.73 | 60.44 | 60.43 | 60.81 | 60.63 | 60.09 | 60.26 |
| Mg/(Mg + Fe) | 0.84 | 0.78 | 0.78 | 0.73 | 0.82 | 0.73 | 0.78 | 0.83 | 0.72 | 0.81 |

[1] Total Fe calculated as FeO. [2] Oxygen calculated by stoichiometry.

X-ray patterns were conducted on packed powders using Ni-filtered Cu K-$\alpha$ radiation on a Rigaku Miniflex 6G diffractometer (Tokyo, Japan) using Smartlab Studio II software.

All analyses were performed by the author using facilities at Western Washington University, Bellingham, WA, USA).

## 3. Results

Washington State nephrite has a felted amphibole fiber morphology that is characteristic of this form of jade (Figure 7).

The purity of the Washington State nephrite specimens is highly variable. The classification of Washington State nephrite depends on the system that is chosen for use. Jutras et al. [8] divided nephrite from a Darrington area claim into the following three categories: Ornamental, Carving, and Gem. An additional material described as “cat’s eye jade” or “chatoyant jade” was placed in a fourth category that was termed “Phenomenal” [8]. As is typical of nephrite deposits, only a small proportion of the mined material is gem-grade. The predominate mine yield is ornamental-grade nephrite that has compositional irregularities that cause it to be suitable only for decorative uses (Figure 8). Nephrite with a greater homogeneity is desirable for artistic carvings (Figure 9). Gem-grade nephrite produces cabochons and beds that span a range of colors and patterns (Figure 10). The rarest commodity is the “cat’s eye nephrite”, which has chatoyant optical properties caused by regions where actinolitic microcrystals have parallel alignments (Figure 11). Hogarth [6,7] considered this material to be “cat’s eye actinolite”, because the parallel orientation of the fibers is contrary to the random interlocking fibers considered to be diagnostic nephrite. The gemologic interpretation is rather arbitrary, given that oriented zones may occur in specimens that have the typical nephrite felted morphology (e.g., Figure 7C). Jutras et al. [8] classified this chatoyant material as a category within nephrite jade.

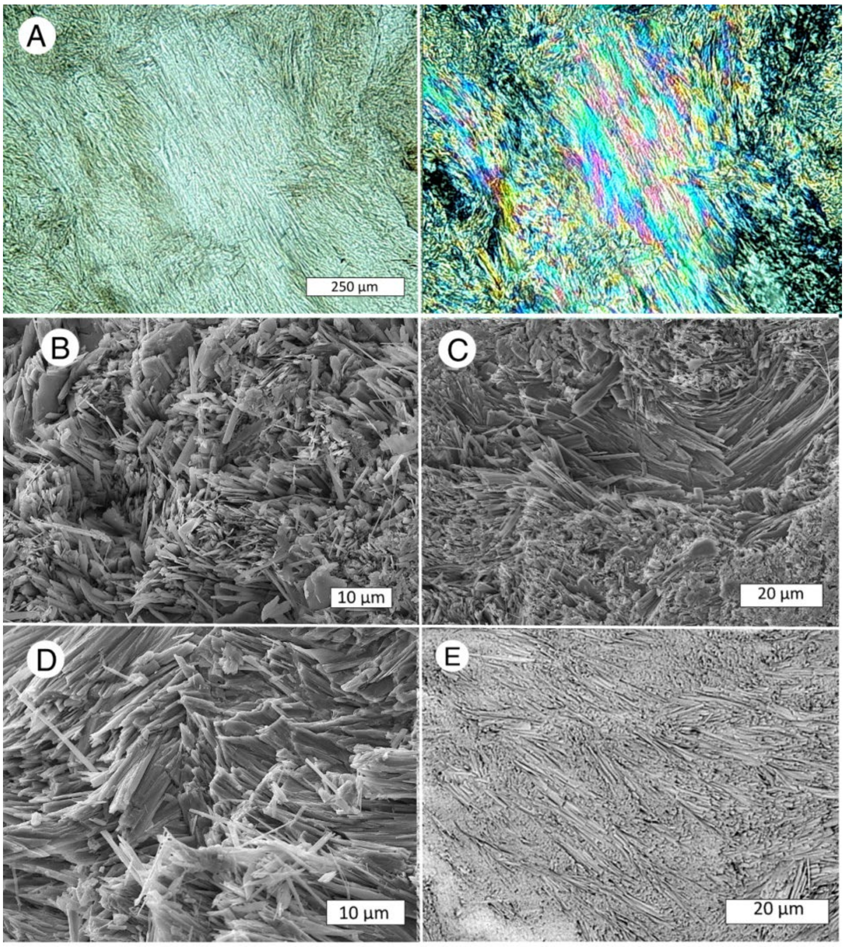

**Figure 7.** Felted microtexture of Washington nephrite. (**A**) Optical microscopy of nephrite from Middle Fork Nooksack River.Transmitted light thin section image on left, polarized light image on right. (**B**) SEM image, nephrite specimen DC-4. (**C**) Specimen DC-4, showing partial alignment of actinolite microcrystals. (**D**) Specimen DC-2. (**E**) Backscattered electron image of polished nephrite, specimen DC-3. Images (**B**–**D**) are secondary electron SEM images.

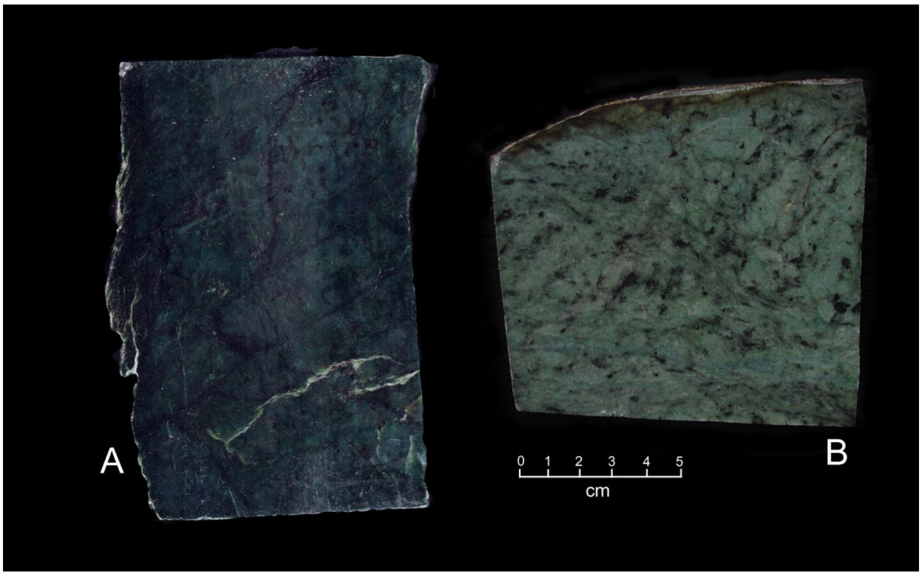

**Figure 8.** Ornamental-grade nephrite. (**A**) Little Cat lode claim, south slope of Mount Higgins, Skagit County, WA. (**B**) Alluvial nephrite, Deer Creek, Snohomish County, WA.

**Figure 9.** Nephrite carvings by Nathaniel Cook. Photos courtesy of WashingtonJade.Com.

**Figure 10.** Gem-grade nephrite from Washington State. Photos courtesy of WashingtonJade.Com.

Gemology-based jade classifications have economic significance, but they may be discordant with geological interpretations. Tarling et al. [32] proposed a non-gemologic approach to the classification of nephrite.This scheme divides nephrite into categories that are based on its mode of formation and textural characteristics. These categories are (1) primary nephrite, (2) crenulated nephrite, (3) foliated semi-nephrite, and (4) nodular or domainal nephrite.

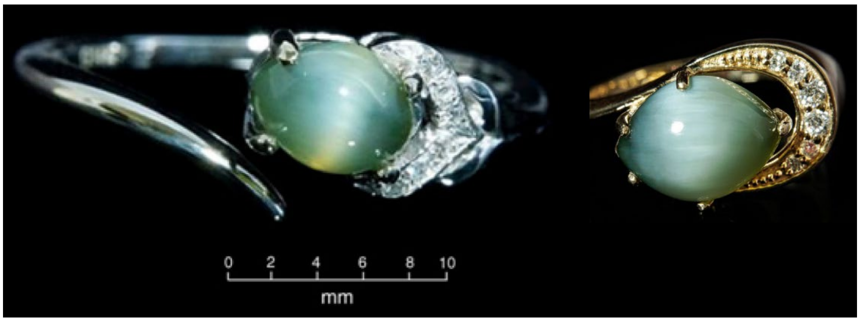

**Figure 11.** "Cat's eye jade" set rings with faceted diamonds. Photos courtesy of WashingtonJade.Com, used with permission.

Tectonism produced deformation that caused many Washington State nephrites to show schistosity and folding. These specimens, which contain mixtures of minerals with nephrite as a major component, are classified as semi-nephrite (Figure 12).

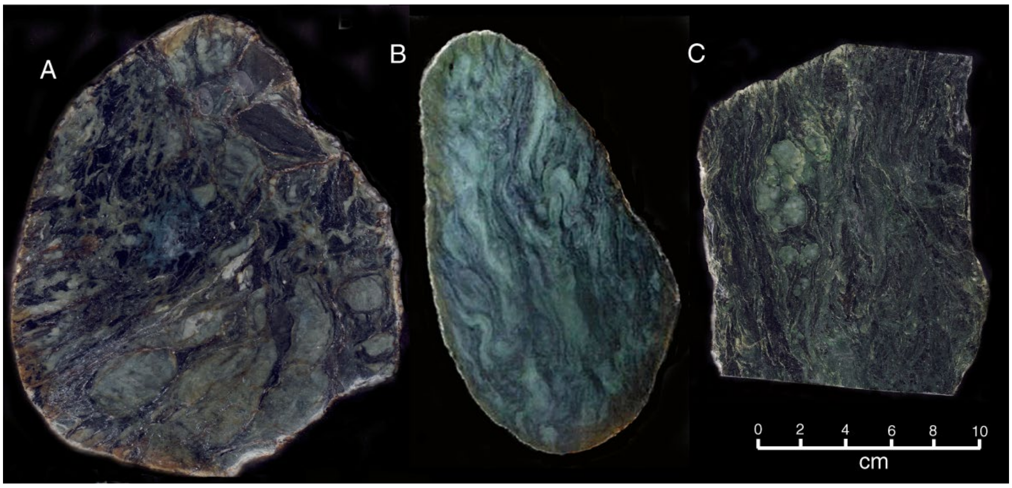

**Figure 12.** Semi-nephrite from northwest Washington State showing deformation textures. (**A**,**B**) Stream-transported specimens from Deer Creek, a tributary of the North Fork Stillaguamish River. (**C**) Nephrite from the Nooksack River Middle Fork in Whatcom County.

Botryoidal nephrite (Figure 13) results from a complex pathway where crystallization is controlled by the development of lattices centered at multiple nucleation points. As fibrous crystals grow outward from these seeds, newly formed spheres overlap with one another to creating a "grape-like" appearance [33]. This botryoidal habit is a notable example of nodular (domainal) nephrite. Some botryoidal specimens from Washington State are primarily composed of diopside rather than nephrite. In these specimens, the lighter color and opacity of diopside can allow this mineral to be distinguished from nephrite, but for intermixtures, mineral identification requires XRD, SEM/EDS, or Raman spectroscopy.

### 3.1. X-Ray Diffraction

XRD patterns are important tools for characterizing the composition of nephrite and associated materials. Members of the actinolite/ferro-actinolite solid solution series have a range of lattice parameters that hinders precise determinations of their mineral composition based on XRD patterns. Figure 14 shows diffractograms for alluvial nephrite specimens collected from the DDMFZ at Deer Creek, and for a Grandy Creek specimen that originated from the Twin Sisters ultramafic body. Peaks measured from a single actinolite crystal from Lake Wenatchee, Washington, are shown as a reference. The nephrite patterns are generally very similar, except for Deer-Creek RBN-1, which shows diopside to be a major constituent. All specimens show prominent peaks for clinochlore.

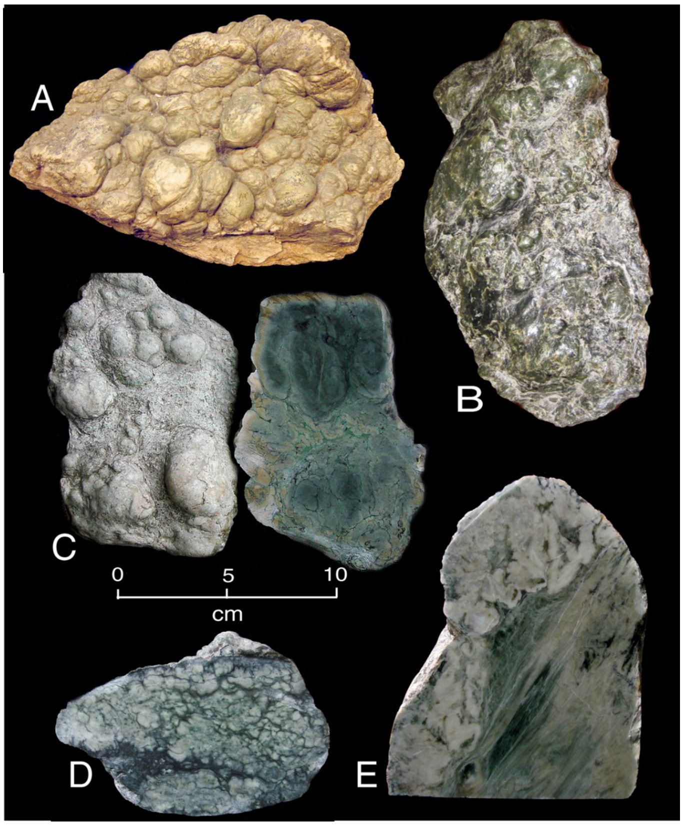

**Figure 13.** Botryoidal textures. (**A**) Specimen from Cultus Mountain, Skagit County, Washington. (**B**–**E**) Specimens from the North Fork Stilliguamish River area. Specimen (**A**) is diopside and (**B**–**E**) are nephrite, as evidenced by XRD.

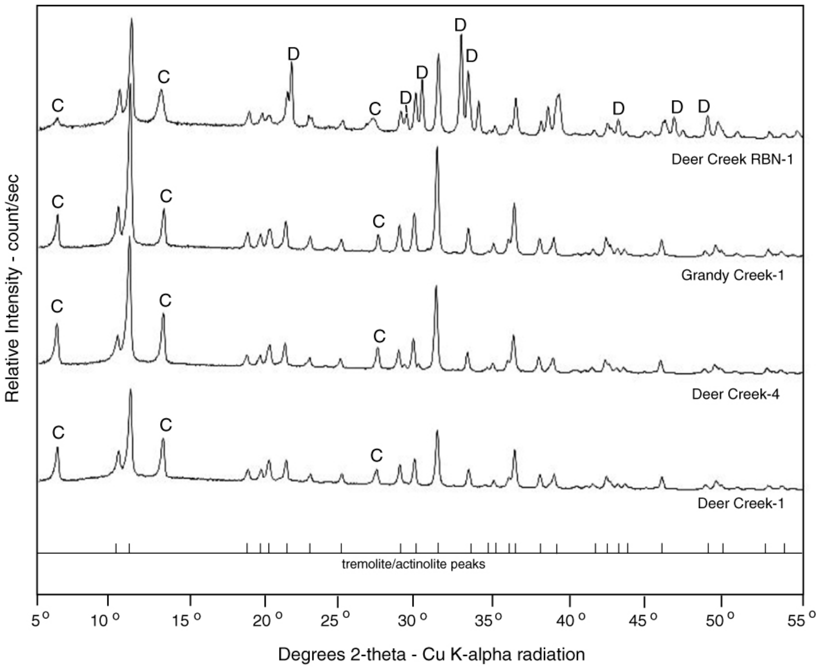

**Figure 14.** XRD patterns for typical nephrite specimens from the DDMFZ. C = clinochlore and D = diopside. Unlabeled peaks are indicative of the tremolite/actinolite series. The lowest pattern shows peak positions measured from a single crystal of actinolite from Lake Wenatchee area, central Washington State, USA. These XRD patterns confirm the lack of purity of the nephrite.

### 3.2. SEM/EDS Elemental Analysis

SEM/EDS elemental data are only semiquantitative, but they are sufficient to provide a basis for the interpretation of mineralogy. The atomic % values for major elements (Table 1) are useful for distinguishing between tremolite [$Ca_2(Mg_{5.0–4.5}Fe^{2+}{}_{0–0.5})Si_8O_{22}(OH)_2$], actinolite [$Ca_2(Mg_{4.5–2.5}Fe^{2+}{}_{0.5–2.5})Si_8O_{22}(OH)$], and ferro-actinolite [$Ca_2(Mg_{2.5–0.0}Fe^{2+}{}_{2.5–5.0})Si_8O_{22}(OH)_2$]. Members of the tremolite/ferroctinolite series can be distinguished by their Mg/(Mg + Fe) ratio [34,35]. Tremolite is characterized by a ratio of >0.9, actinolite has ratios of 0.5–0.9, and ferro-actinolite can be identified by a ratio of <0.5. The values in Table 1 show that the samples lie close to the tremolite/actinolite boundary based on their Mg/(Mg+Fe) ratios, depicted visually in Figure 15.

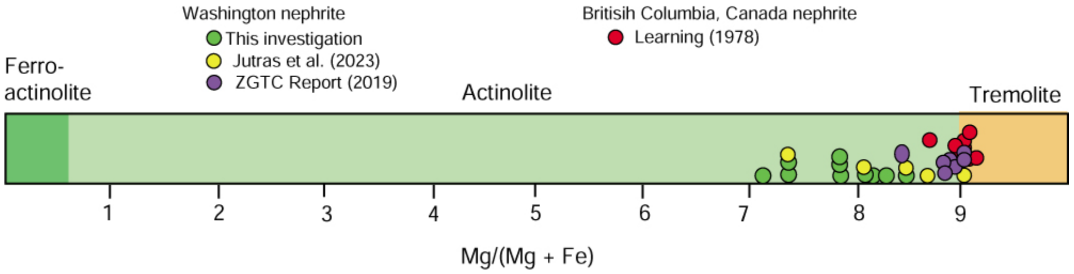

**Figure 15.** Mg/(Mg + Fe) ratios show that Washington State nephrite samples have compositions that range from actinolite to tremolite. Nephrite specimens analyzed from the Cassiar and Omimeca regions of British Columbia, Canada, mostly show tremolite compositions. Data from [8,29,36].

The relative proportions of Ca, Mg, and Fe are illustrated as histograms in Figure 16.

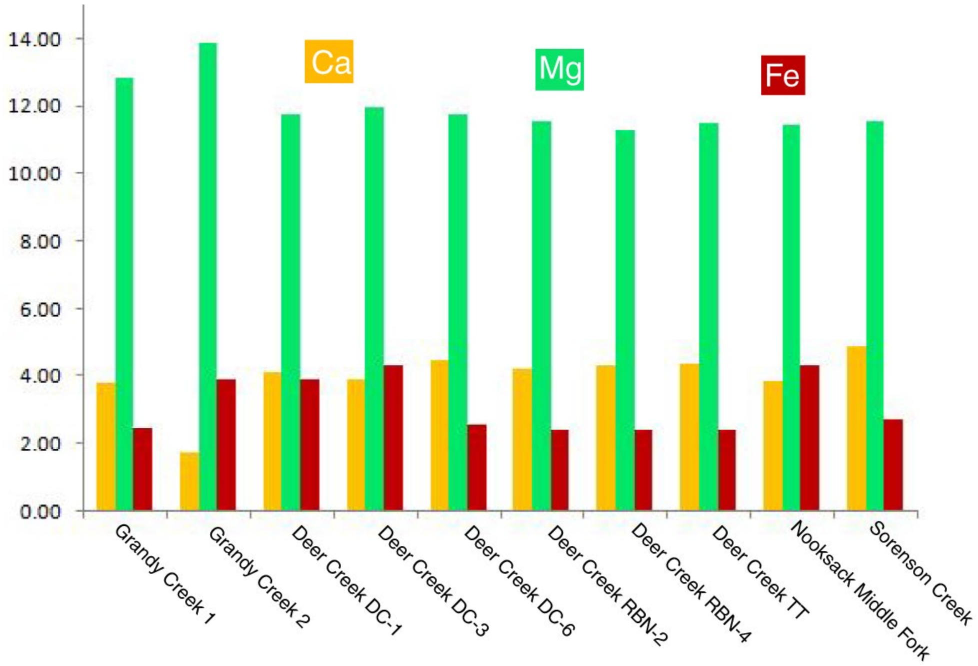

**Figure 16.** Histograms showing Ca, Mg, and Fe atomic ratios for nephrite samples from northwest Washington State.

### 3.3. Nephrite Color

Nephrite specimens from western Washington State commonly have colors that range from light green to dark green, but other colors are present, including grayish, light brown (Figure 17), and bluish green. The origins of nephrite color have received attention from mineralogists and gemologists. Chemical analyses and spectrographic examinations show that this color range is controlled by the abundances and oxidation states of Fe, Mn, Cr, and Ti [37–40].

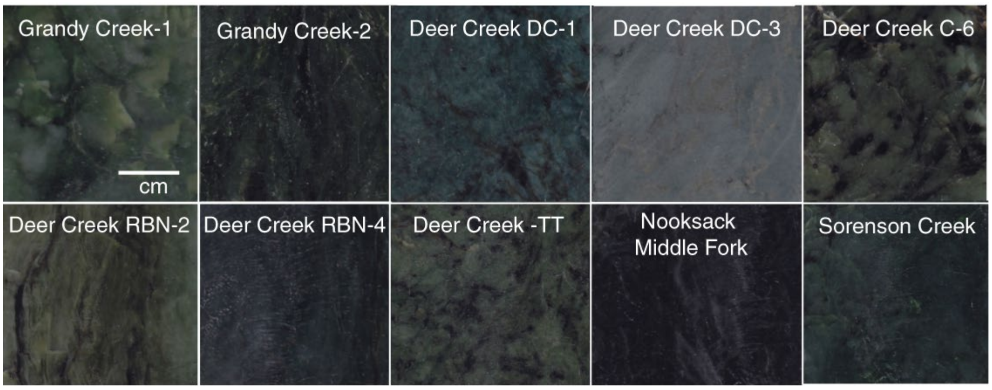

**Figure 17.** Color of nephrite samples listed in Table 1 and Figure 16.

For Washington State nephrite, bluish colors may darken to green when a sawn specimen is exposed to prolonged contact with the atmosphere. This process was described in detail by Ream [5]. Most Washington State nephrite specimens are shades of green (Figure 14), but a small minority of the nephrites are brown (Figure 18).

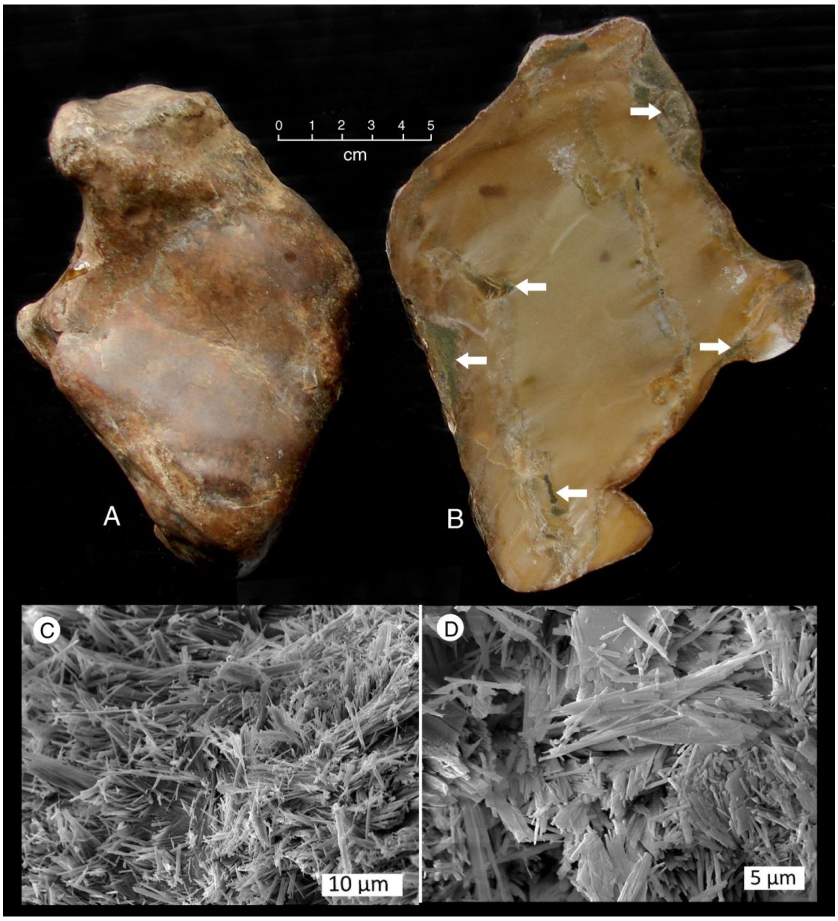

**Figure 18.** Light brown nephrite, Deer Creek specimen MM38, consists of tremolite with minor green chlorite. (**A**) Exterior surface, showing rounding from stream transport. (**B**) Sawn section, with chlorite zones marked with arrows. (**C**,**D**) SEM secondary electron images showing felted texture.

The weathering of nephrite commonly produces a pronounced weathering rind, ranging in color from whitish gray to brownish (Figure 19). Varieties that contain iron may have reddish oxidation patterns, a characteristic that is sometimes described as vulcan jade [5].

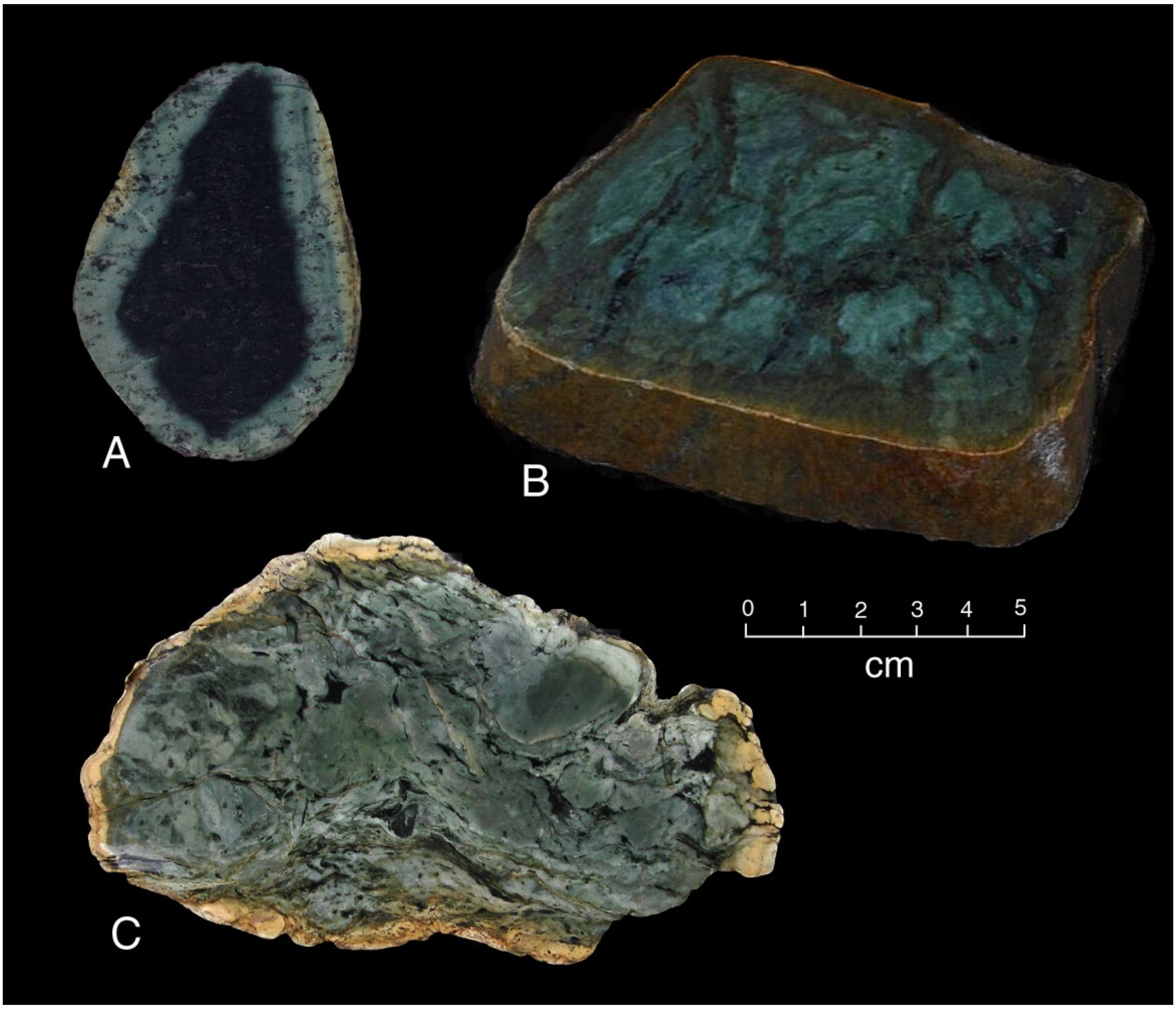

**Figure 19.** Oxidation rinds in nephrite and semi-nephrite from the DDMFZ. (**A**) Finney Creek Specimen FC-1 (**B**) Deer Creek Specimen MM2-28 (**C**). Deer Creek specimen MM36.

## 4. Modes of Nephrite Occurrence

### *4.1. Lode Deposits*

Commercial prospecting has resulted in the filing of many mining claims, the majority of which are still active. Nearly all of these have been filed as lode claims in areas where serpentinite occurs as near-surface outcrops, even though surficial sediments and dense forests combine to limit bedrock exposures (Figure 20).

Geologic maps prepared by state geologists provide a structural framework for the occurrence of serpentinite bodies that may contain nephrite (Figures 21 and 22).

**Figure 20.** Bedrock occurrences of nephrite in the DDMFZ. (**A**) Jade Cave claim. (**B**) Bedrock outcrop, Mt. Higgins south slope. Photos courtesy of WashingtonJade.Com (**C**). Nephrite-bearing outcrop, Lucky's Dream claim, Helena Ridge. (**D**,**E**) Claim operators Timotheus Kester and Jason Henry, HM claim, Helena Ridge. (**F**) Diamond drill core of nephrite from HM claim. Photos (**A**,**B**) courtesy of Rodney and Nathaniel Cook. Photos (**D**–**F**) by the author.

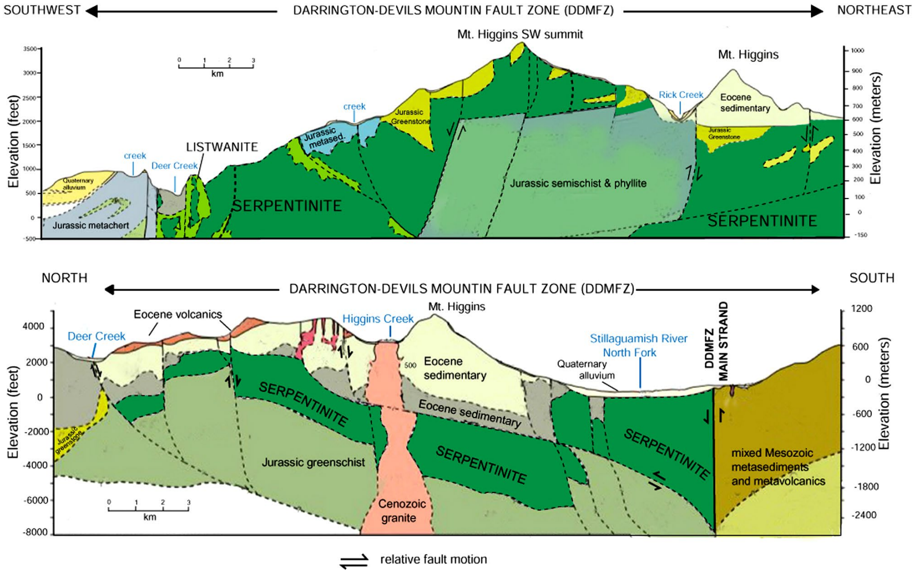

**Figure 21.** Geologic cross-sections of Mount Higgins area showing serpentite occurrences. Adapted from [41,42].

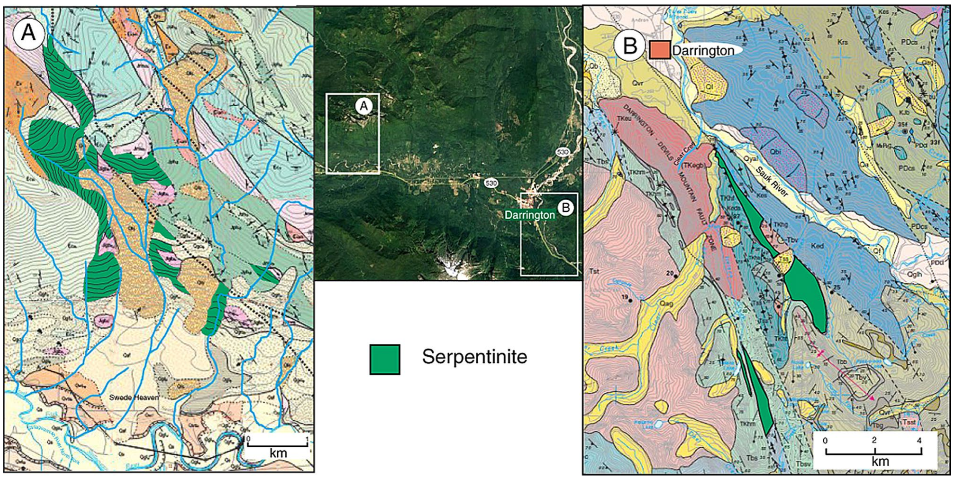

**Figure 22.** Surficial and bedrock geology in the two major jade-bearing zones in the Darrington, WA, area. (**A**) Mount Higgins southeast slope. (**B**) Helena Ridge area. Maps adapted [41–43].

Publicly funded geologic research provides open-source information that can be useful in the search for jade. These open-source maps provide useful data for locating possible jade occurrences. The region adjacent to the Stillaguamish River North Fork provides an example (Figure 22).

### 4.2. Colluvial Deposits

Nephrite has been recovered from surficial colluvial deposits, including very large specimens (Figure 23).

**Figure 23.** Colluvial nephrite. (**A**–**C**) Nephrite boulders in colluvium, HM Claims, Helena Ridge, south of Darrington, WA, USA. (**D**,**E**) Nephrite boulder with a mass of 7300 kg (16,000 lb), discovered near Darrington, WA, USA in 2019 [44]. (**D**) Specimen being transported on logging road by Ed Molsee and Jason Henry. (**E**) Specimen after being sawn, 2024 photo. Note the prominent white exterior rind. Photos (**B**,**D**,**E**) courtesy of Jason Henry, photo (**C**) by David Crafton, used with permission.

### 4.3. Alluvial Deposits

Washington State nephrite commonly occurs as water-worn specimens in alluvial deposits in sizes that range from cobbles to boulders. The common association between nephrite-bearing serpentinites and marginal alteration zones means that streams commonly transport a mixture of these materials. A good example occurs where Deer Creek enters to the Stillaguamish River South Fork near Oso, Washington. Here and upstream, rocky bars contain nephrite, as well as cobbles that contain massive garnet, diopside, pumpellyite, vesuvianite, and other metamorphic materials that have been transported from upstream sources (Figure 24).The physical toughness of the felted texture makes nephrite resistant to abrasion, and the well-rounded morphology of many placer specimens is evidence that they have been transported by high-energy streams from the source outcrop.

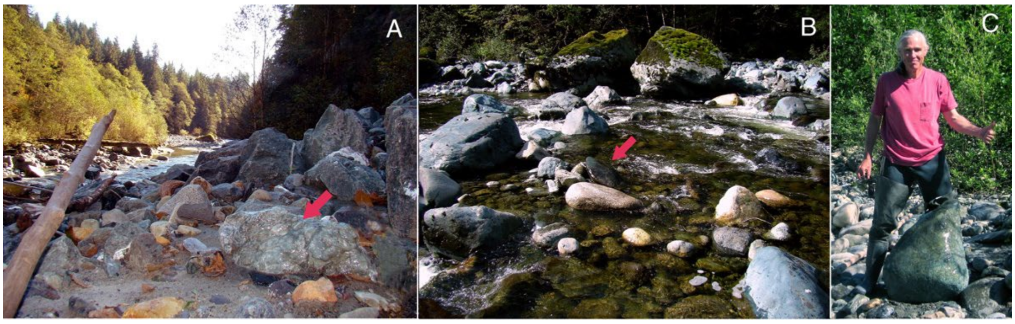

**Figure 24.** Fluvially transported nephrite in the bed of Deer Creek, Snohomish County, Washington. (**A**) Botryoidal nephrite boulder, marked with arrow. (**B**) Water-worn nephrite in mid-stream. (**C**) Large nephrite specimen. Photos courtesy of Vic Showell, used with permission.

Regional geologic mapping provides important clues for understanding where nephrite-bearing rocks may be located. In the case of Deer Creek, the stream valley is extensively covered by a blanket of Quaternary alluvium, but the upper area of the watershed exposes bodies of Paleozoic ultramafic rock (dunite, harzburgite, and serpentinite). These ultramafic rocks are locally in contact with rocks of the Shuksan Metamorphic Suite, an environment that is favorable for the formation of nephrite and various calcsilicates [45,46]. A similar situation occurs at Grandy Creek in Skagit County, WA, where large boulders of nephrite have been collected from the bed of Grandy Creek, which originates near the serpentinized margins of the Twin Sisters dunite. Likewise, nephrite found along the Middle Fork Nooksack River may also have originated in association with the Twin Sisters utramafics.

## 5. Minerals Found in Association with Nephrite and Semi-Nephrite

Nephrite is generally considered to be a member of the amphibole/ferro-actinolite series, as it hasfibrous morphology, but most Washington State nephrites include various accessory minerals. These comprise the following three types: minerals formed during the petrogensis of nephrite, and peripheral rodingite and lisitwanite zones. The first group to be considered here are minerals that commonly occur as constituents within nephrite.

### *5.1. Metallic Oxides and Sulfides*

Dark flecks are a common feature of Washington State nephrite; they are attributable to inclusions of metallic minerals (Figure 25). The most common of these is chromite, a relic from the ultramafic parent rock. Serpentization may cause the degradation of chromite to result in grains that are highly fractured. To the unaided eye, chromite inclusions appear as small black spots. Bright silver- or gold-colored inclusions are typically iron/nickel sulfide that forms during the alteration of peridotite. The mineralogic classification of this material is enigmatic. The name bravoite has been used to describe material with the formula $(Fe,Ni)S_2$, but bravoite is no longer a valid species [47,48]. Fe/Ni sulfides presumably represent an intermediate phase in a solid solution series whose end members are vaesite ($NiS_2$) and pyrite ($FeS_2$). One intermediate mineral has been named violarite $(FeNi_2)S_4$ [49,50]. Listwanite from the serpentine on the west side of Sumas Mountain in Whatcom County, WA, USA, contains inclusions where the Fe/Ni sulfide is intermixed with native copper (Figure 25E,F).

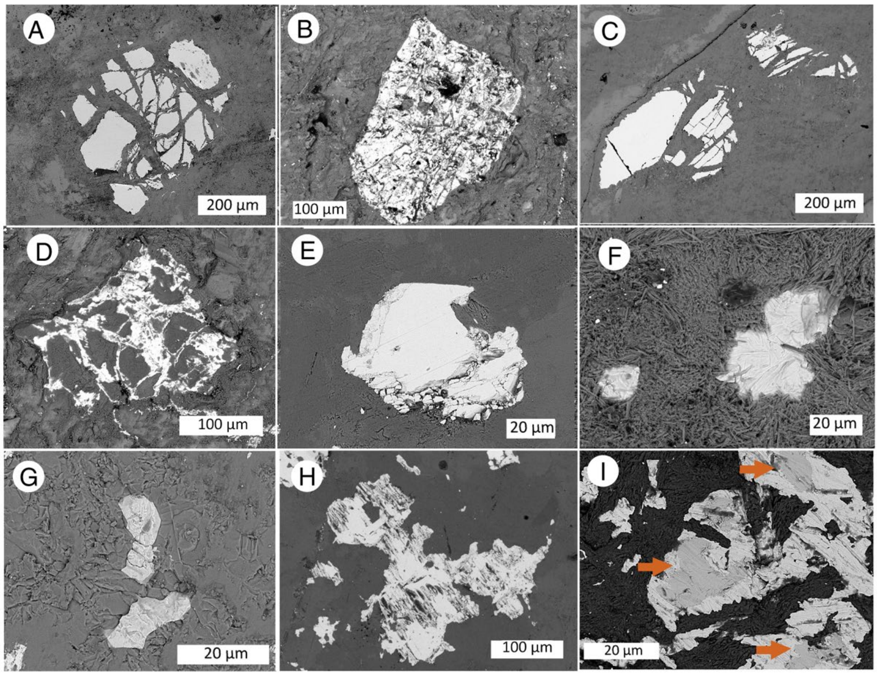

**Figure 25.** Metallic mineral inclusions. (**A**) Chromite, Deer Creek nephrite specimen RBN2. (**B**) Chromite, Deer Creek nephrite DC4. (**C**) Chromite, Deer Creek nephrite specimen DC6. (**D**) Magnetite with fragmental nephrite inclusions, Deer Creek specimen DC4. (**E**,**F**) Iron nickel sulfide, Deer Creek nephrite specimen TT. (**G**) Native copper, Deer Creek nephrite specimen MM19. (**H**) Iron nickel sulfide in Deer Creek nephrite specimen DC 4. (**I**) SEM backscatter electron image of inclusion in listwanite, Ni sulfide encloses native copper (marked with arrows), Sumas Mountain Swift Creek specimen SC-1.

### *5.2. Chlorite Family*

All nephrite samples analyzed in this study included chlorite as a minor constituent (Figure 14. The simplified chlorite formula is $Mg_6Si_8O_{20}(OH)_4 + Mg_6(OH)_{12}$, representing a combination of talc and brucite layers. Si and Mg can be partially replaced by Al in both layers [51]. Members of the chlorite family have layered structures reminiscent of micas. A key difference is that micas contain potassium as an important lattice constituent; the scarcity of this element in the ophiolitic rocks of the Northwest Cascades precludes the likelihood of the occurrence of micas in nephrite-bearing formations, where the abundance of Mg favors chlorite.

The chlorite family comprises 11 members; clinochlore is the most common rock-forming member. Clinochlore is an identifiable component in X-ray diffraction patterns of Washington State nephrite and other serpentinite alteration assemblages, i.e., listwanites and rodingites.

Chlorite may have paragenetic associations with members of the spinel group, which include spinel, $MgAl_2O_4$, chromite, $Fe^{2+}Cr_2O_4$, magnesiochromite, $MgCr_2O_4$, and magnetite, $Fe^{+2}Fe^{+3}{}_2O_4$. The relationship between chlorite and chromite is evident in many nephrite specimens. Optical microscopic views of thin sections and SEM images (Figure 26) commonly show halos of chlorite surrounding chromite inclusions. This chlorite/chromite pairing has been reported in ultramafic rocks at other locations [52]. In these assemblages, chlorite paragenesis is presumed to be related to the breakdown of chromite in the presence of aluminum released from the decomposition of aluminosilicate minerals, e.g., pyroxene [53,54].

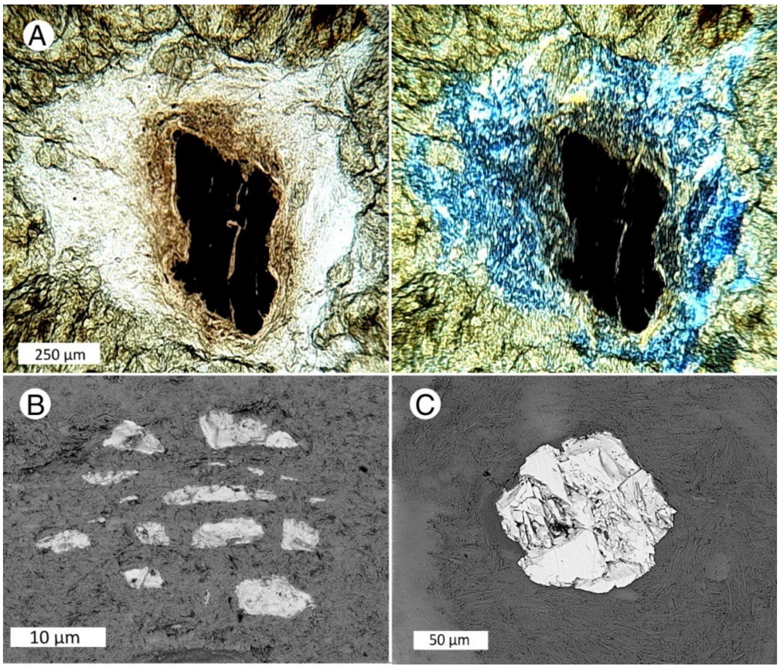

**Figure 26.** Chlorite (clinochlore) in association with relict chromite. (**A**) Optical microscope transmitted light view of a thin section from nephrite specimen Deer Creek 1 Ordinary light view on left, polarized light image on right. (**B**) SEM backscatter electron image of brecciated chlorite enclosed within chlorite, Deer Creek specimen RBN-5. (**C**) Chromite grain surrounded by chlorite, Deer Creek specimen DC3.

Chlorite may be present in relatively pure masses. Because its pigmentation is controlled by trace metals, pure clinochlore may be light-colored and translucent (Figure 27).

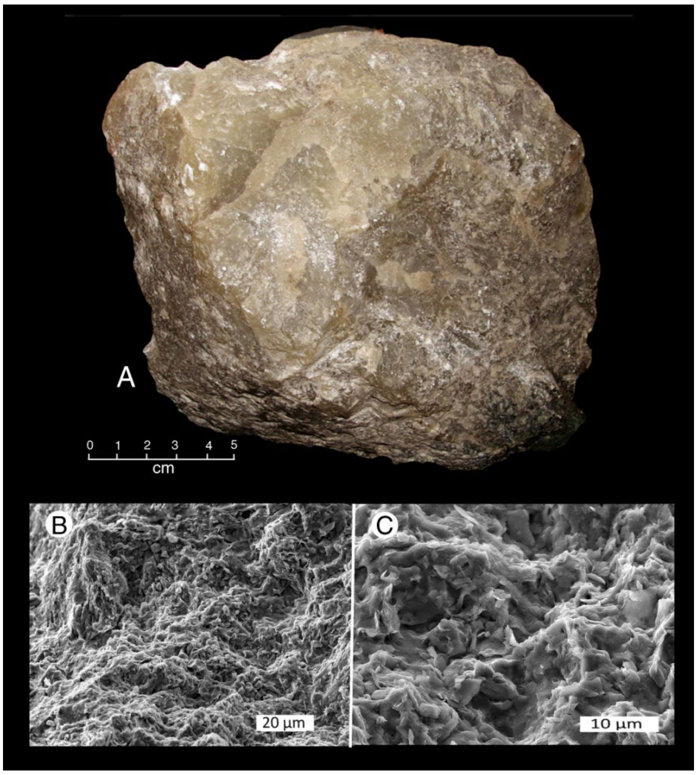

**Figure 27.** Massive clinochlore.(**A**) Translucent, light-colored clinochlore, Deer Creek specimen MM45. (**B**,**C**) SEM secondary electron photos.

### *5.3. Diopside*

Diopside occurs both within nephrite and in surrounding alteration zones. In ultramafic rocks, calcium is commonly present as clinoamphibole (e.g., tremolite) and/or calcic clinopyroxene (diopside). Diopside may form as a primary metamorphic mineral, but it may also result from the breakdown of tremolite, as follows:

$$\underset{\text{tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{calcite}}{3CaCO_3} + \underset{\text{quartz}}{2SiO_2} \rightarrow \underset{\text{diopside}}{5\ CaMgSi_2O_6} + 6H^+$$

A solid solution series exists between diopside, $(Ca,Mg)Si_2O_6$,and hedenbergite, $Ca(Fe,Mn)Si_2O_6$. However, the high Mg abundance in serpentinite favors diopside. In ultramafic rocks, diopside may be present as chrome diopside, $Ca(Mg,Fe,Cr)Si_2O_6$, which has a bright green color. This mineral is present as inclusions within some rodingite grossular specimens. Ordinary diopside may be white, gray, brown, or nearly colorless. These forms commonly occur in DDMFZ occurrences, but diopside is typically intermixed with other minerals, making visual identifications difficult (Figure 28).

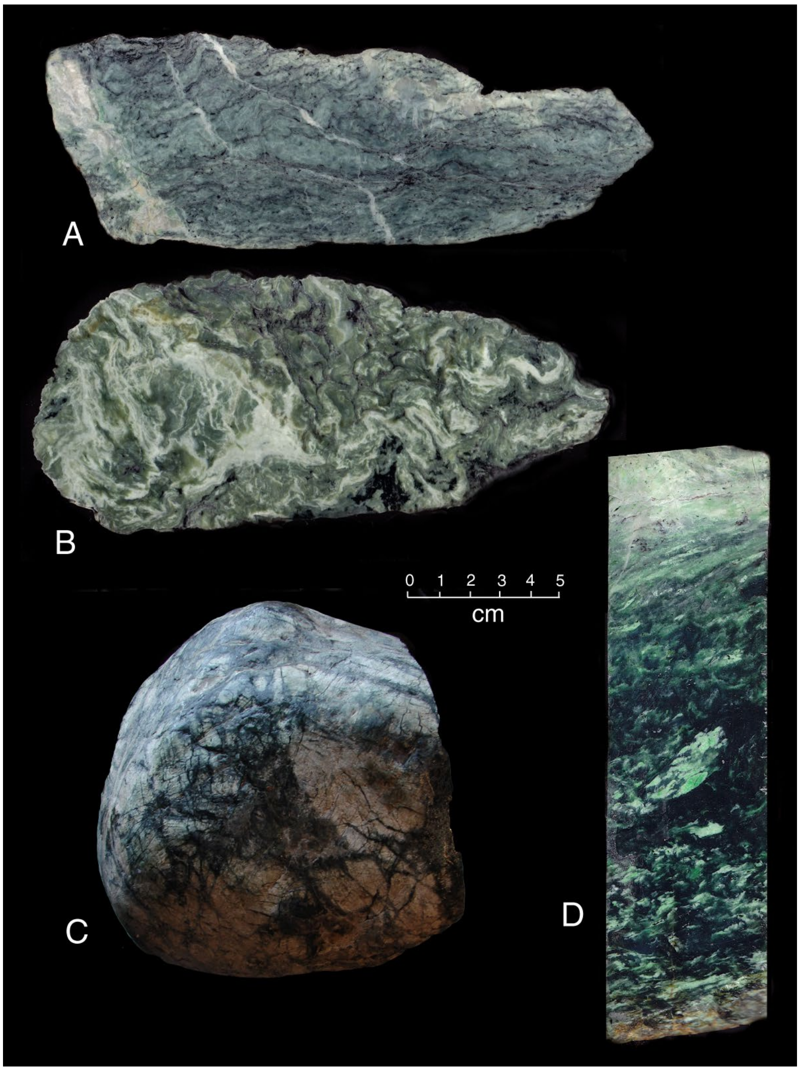

**Figure 28.** Diopside mixtures in DDMFZ specimens. (**A**) Diopside + nephrite + clinochlore, Deer Creek specimen DC2. (**B**) Diopside + nephrite, Pilchuck Creek specimen MM48. (**C**) Diopside + lizardite, Deer Creek specimen MM47. (**D**) Diopside, actinolite, plagioclase. Deer Creek specimen MM2. Mineral identifications were based on XRD.

The coexistence of diopside in Washington State nephrite is evident in the XRD patterns (Figure 29).

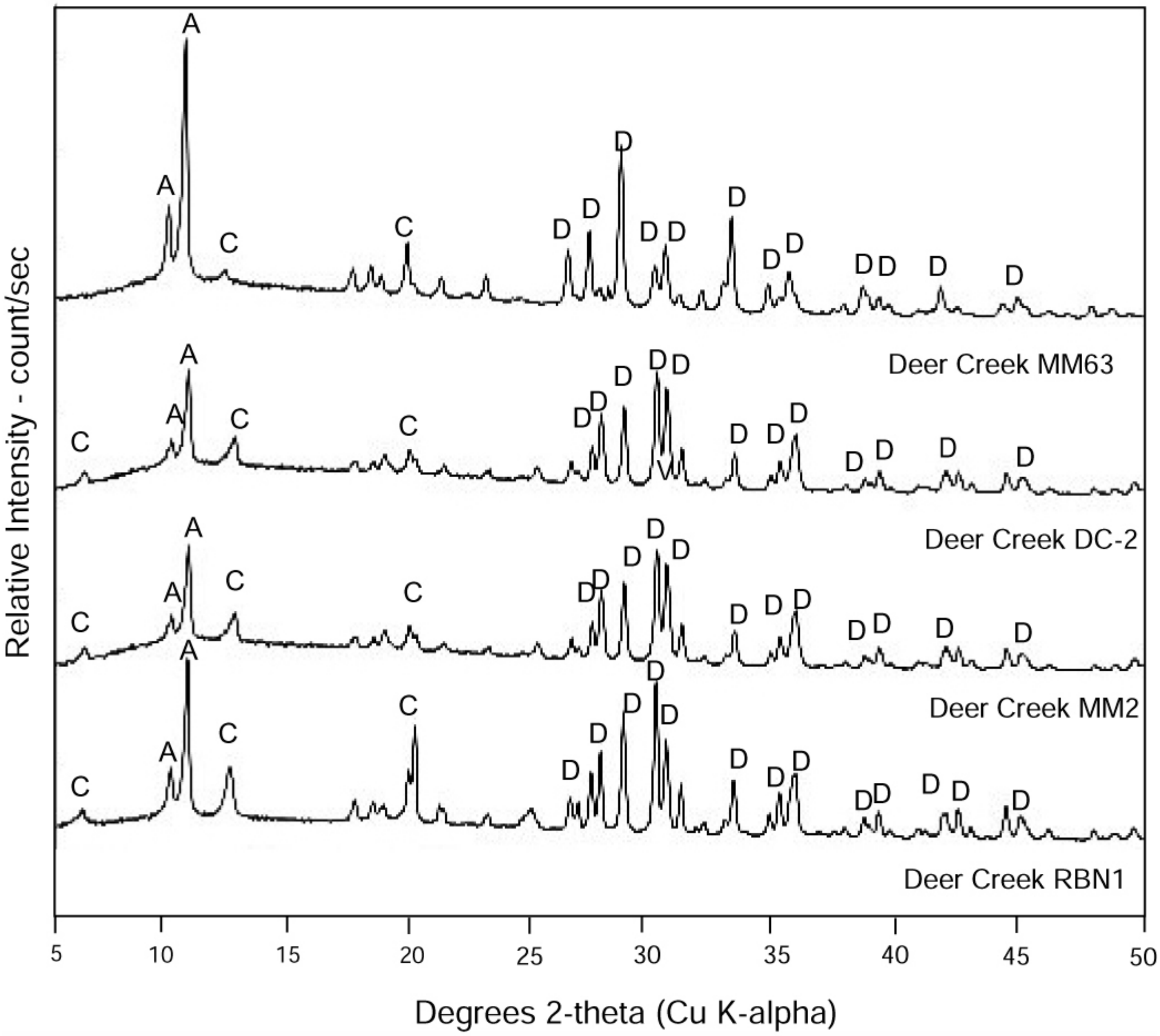

**Figure 29.** XRD patterns showing diopside peaks (D) in association with actinolitic nephrite (A). Clinochlore (C) is a common minor constituent.

### *5.4. Listwanite and Rodingites*

Liswanite and rodingite zones may form as alteration halos around a serpentinite body (Figure 30).

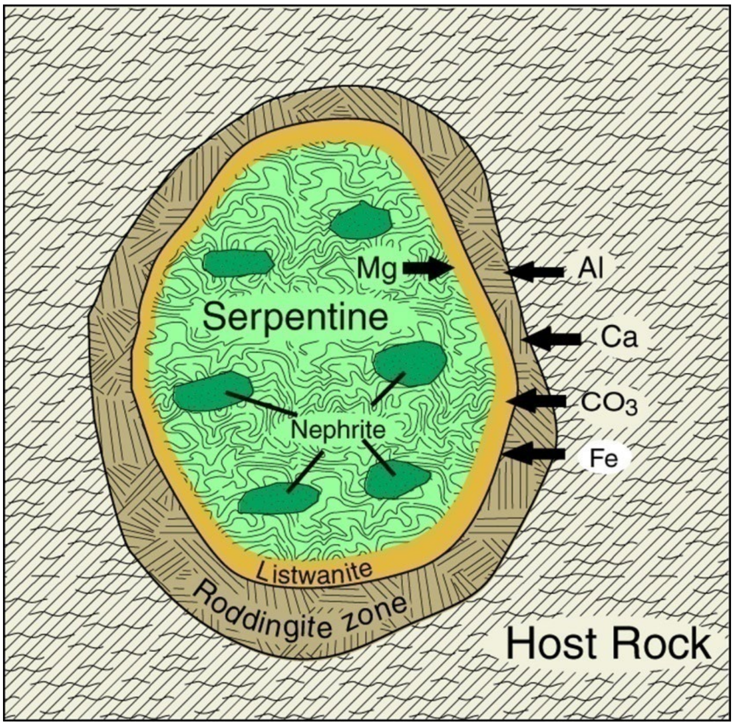

**Figure 30.** Metasomatic alteration may produce bodies of nephrite within the outer regions of the serpentinite body and a peripheral listwanite zone where fractures allow entry of carbonate-bearing solutions. The rodingite zone is an external region characterized by non-carbonate calcsilicate minerals. Because these zones are dependent on fracture-related permeability, the alteration zones are likely to be less symmetric than they are shown in this generalized figure.

### *5.5. Listwanite*

Listwanite alteration may be related to serpentine textures that date from its petrogenesis. The origin of serpentinite was described in detail by [53,54]. Serpentization is used to describe the processes where serpentinite forms from preexisting anhydrous or less-hydrous Mg-rich minerals such as olivine and enstatite. Partly serpentinized rocks consist of lizardite, perhaps in association with antigorite, brucite, and chrysotile. The reactions that produce serpentization involve hydration, as follows:

$$4Mg_2SiO_4 + 6H_2O \rightarrow 2Mg_6Si_4O_{10}(OH)_8 + 2Mg(OH)_2$$

olivine (fayalite) water lizarditebrucite

Serpentization may produce mesh-like textures that originate from hydrothermal alterations of ultramafic rocks at relatively low temperatures. These mesh textures may be preserved during subsequent alteration. Listwanites form as the result of chemical reactions between serpentinite and $CO_2$-rich hydrothermal fluids between the serpentinite and adjacent host rocks. A hallmark characteristic of listwanite is the presence of carbonate minerals that form when carbonate-bearing fluids react with magnesium and iron dissolved from serpentinite. The abundance of Mg in serpentine commonly produces magnesite, $MgCO_3$, or dolomite, $CaMg(CO_3)_2$. The presence of dissolved iron may produce an iron-containing variety of dolomite (ankerite) or siderite, $FeCO_3$. The reaction of serpentine with carbonate leaves behind and excess of silica, so listwanites commonly contain veins of quartz or chalcedony

Oxidation may produce a rusty surface color, but freshly exposed listwanites commonly have a green color caused by the presence of traces of chromium. Brown or reddish tones colors may be evidence of ferruginous minerals (Figure 31).

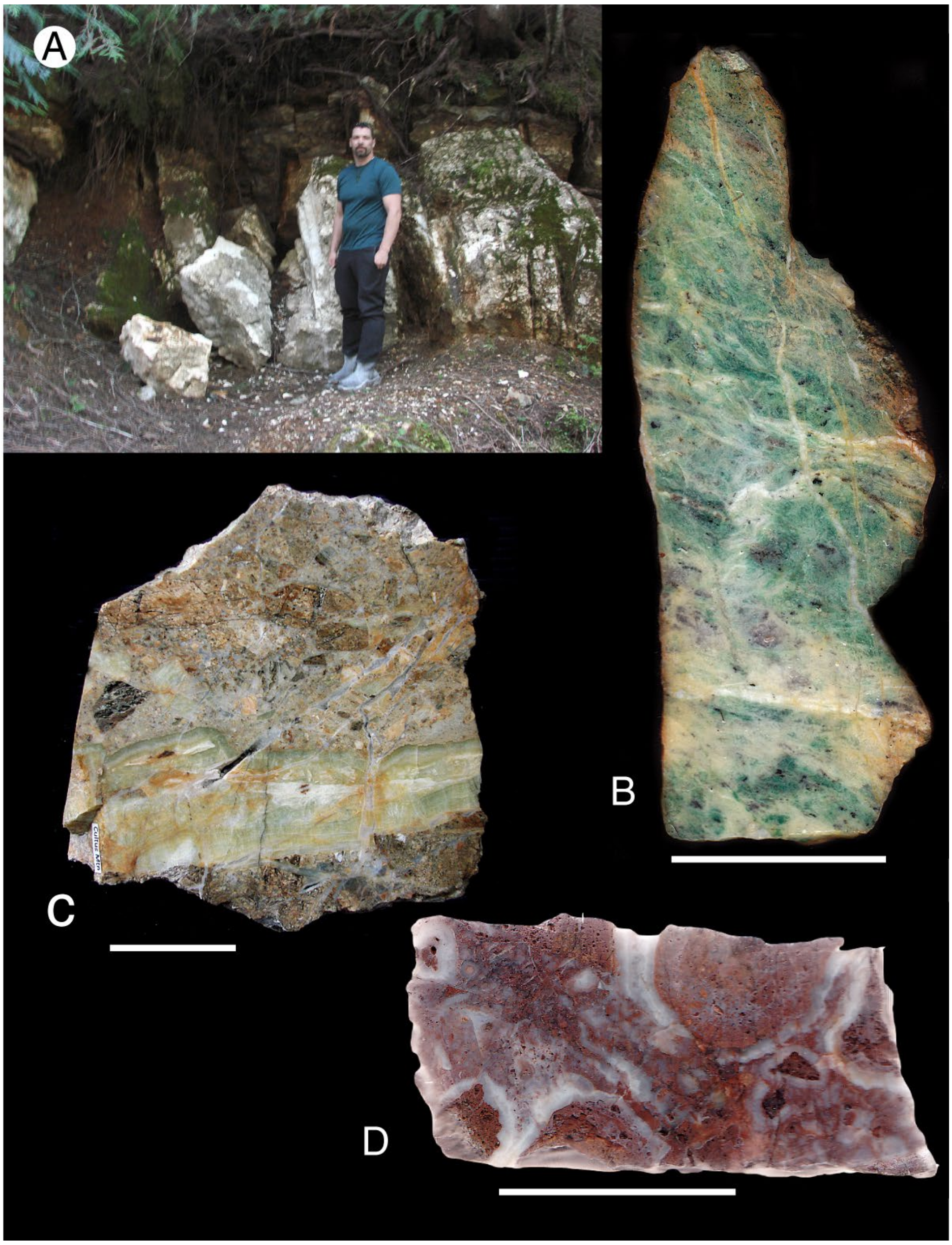

**Figure 31.** Listwanites from the DDMFZ. (**A**) Steeply dipping magnesite and dolomite exposed in a roadcut on Helena Ridge, south of Darrington Snohomish County, WA. (**B**) Magnesite + dolomite + quartz, Deer Creek specimen MM6. (**C**) Magnesite vein in a mylonite zone of altered serpentinite, Cultus Mountain, Skagit County WA. (**D**) Quartz-rich listwanite with red iron oxide from summit of Devils Mountain, Skagit County. Scale bars = 5 cm.

Listwanite zones can be observed at various locations in the Northwest Cascade Range. One notable example is Devils Mountain, in the western part of the DDMFZ (Figure 32). Because of its durability, the magnesite/silica listwanite is resistant to erosion, and it forms a 4 km long ridge connecting the summits of Devils Mountain and Scott Mountain, with widths that range from 20 to 40 m. (70–130 ft) [55]. Listwanite in the DDMFZ was originally studied as a potential source of gold [56], but this element was found to be low in abundance.

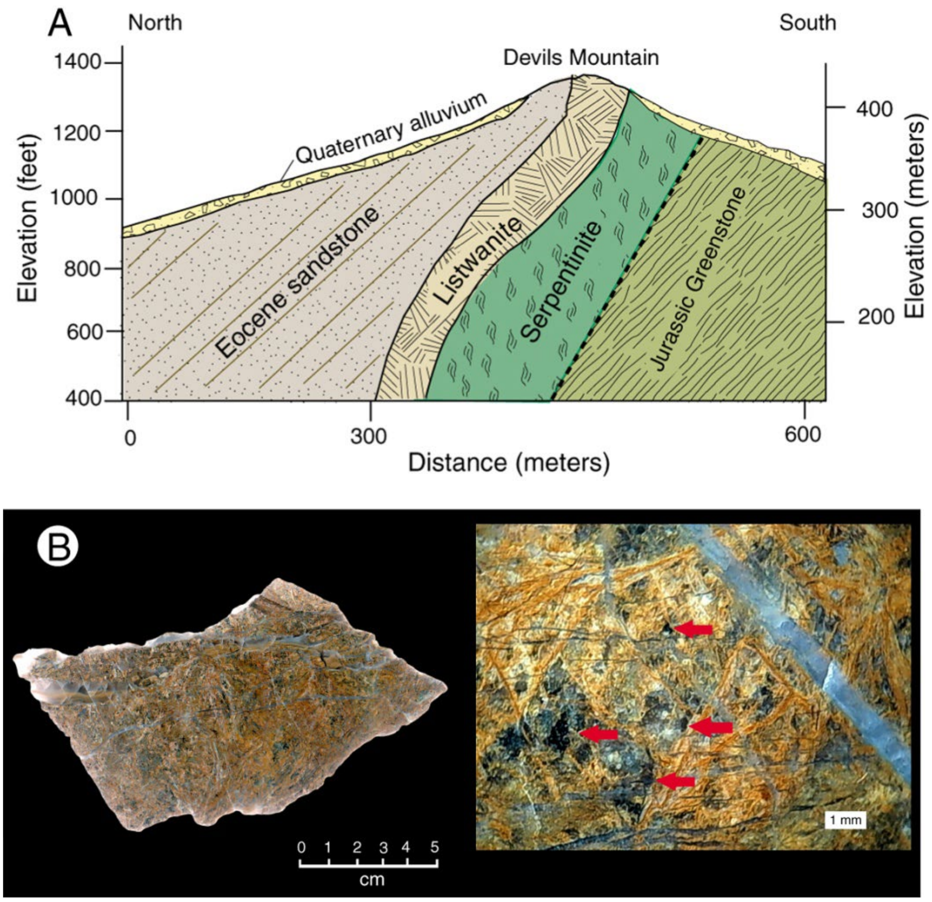

**Figure 32.** Listwanite zone at Devils Mountain, Skagit County, Washington State, USA. (**A**) Listwanite zone occurs as an alteration product of Jurassic serpentinite. (**B**) Listwanite consists primarily of magnesite crosscut by quartz veins. Arrows show small inclusions of relict chromite.

### *5.6. Rodingites*

Like listwanites, rodingites are produced by metasomatic reactions between serpentinite and elements dissolved from host rocks. The compositional difference is that the hydrothermal fluids emanating from the host rocks provide a source of dissolved Ca, Al, and Si, but not carbonate ions. The result is the petrogenesis of calcsilcates rather than the carbonates typical of listwanite. Mg released from serpentine may react with these cations to produce grossular, diopside, vesuvianite pumplellyite, and sometimes other minerals. A fundamental structural difference between listwanites and rodingites is that listwanites form in peripheral regions in serpentinite, while rodingites occur in a halo zone external to the serpentinite body (Figure 29).

Rodingite zones can be observed in situ at some serpentinite surface exposures, including lode deposits that show in situ occurrences of rodingite and nephrite (Figure 33).

Many specimens have been collected from stream beds, where the materials represent a mixture of rock materials transported from higher in the watershed. The identification of these specimens is challenging. For this study, mineral identifications were primarily based on X-ray diffraction patterns, and elemental compositions were determined by electron beam microanalysis (SEM/EDS). The examination of thin sections by optical microscopy was used to examine the textural aspects of some specimens, but SEM images proved to be more useful for this purpose. Rodingite minerals (Table 2) are described individually, but they commonly occur as mineral assemblages.

**Figure 33.** Dark green nephrite seams in direct contact with light-colored rodingite. Specimens from Little Cat Claim, south flank of Mount Higgins, Skagit County, WA, USA, collected by Ed Moslee.

**Table 2.** Minerals commonly found in rodingite zones.

| Mineral | Chemical Formula |
|---|---|
| Grossular garnet | $Ca_3Al_2(SiO_4)_3$ |
| Diopside | $CaMg(Si_2O_6)$ |
| Vesuvianite | $(Ca,Na)_{19}(Al,Mg,Fe)_{13}(SiO_4)_{10}(Si_2O_7)_4(OH,O)_{10}$ |
| PumpellyiteMg | $Ca_2MgAl_2[Si_{12}O_6OH][SiO_4](OH)_2(OH,O)$ |
| Hydrogrossular garnet | $Ca_3Al_2(SiO_4)_{3-x}(OH)_{4x}$ |
| Chlorite (clinochlore) | $Mg_5Al(AlSi_3O_{10})(OH)_8$ |

Rodingite mineral assemblages are evident in the XRD patterns (Figure 34).

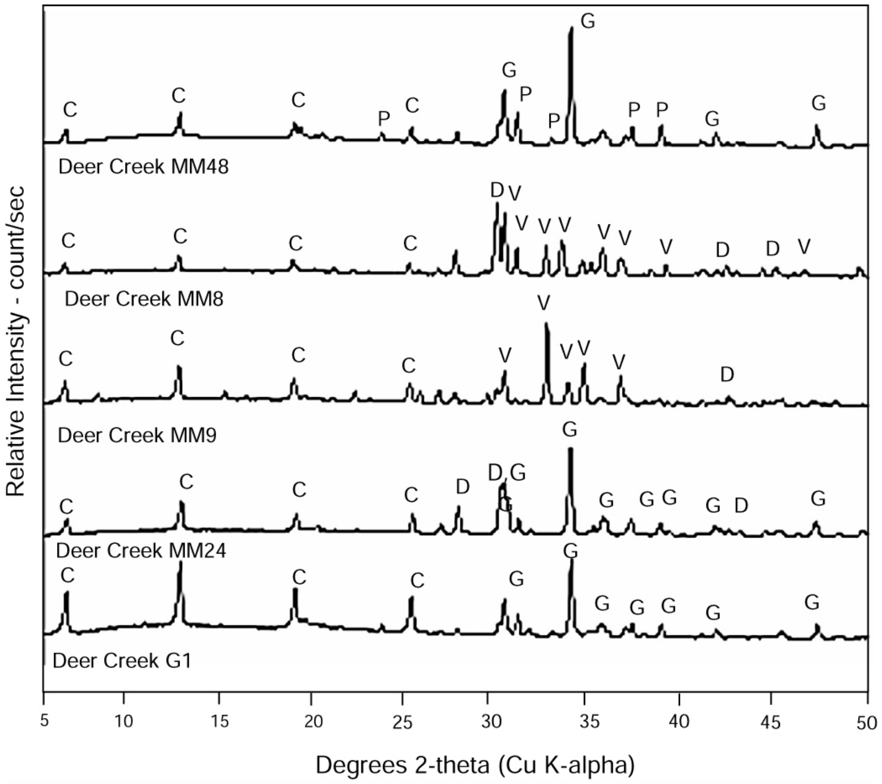

**Figure 34.** XRD patterns for rodingite specimens collected from Deer Creer, Snohomish County, Washington State. C = clinochlore, D = diopside, G = grossular, P = pumpellyiite, and V = vesuvianite.

### *5.7. Grossular*

Masses of microcrystalline grossular are among the most sought-after gem materials in the DDMFZ. The most common form of garnet associated with serpentinite alteration is grossular, which occurs in whitish massive forms, commonly associated with green-colored chlorite inclusions. The coloring agent is typically chromium derived from the original ultramafic parent material (Figure 35).

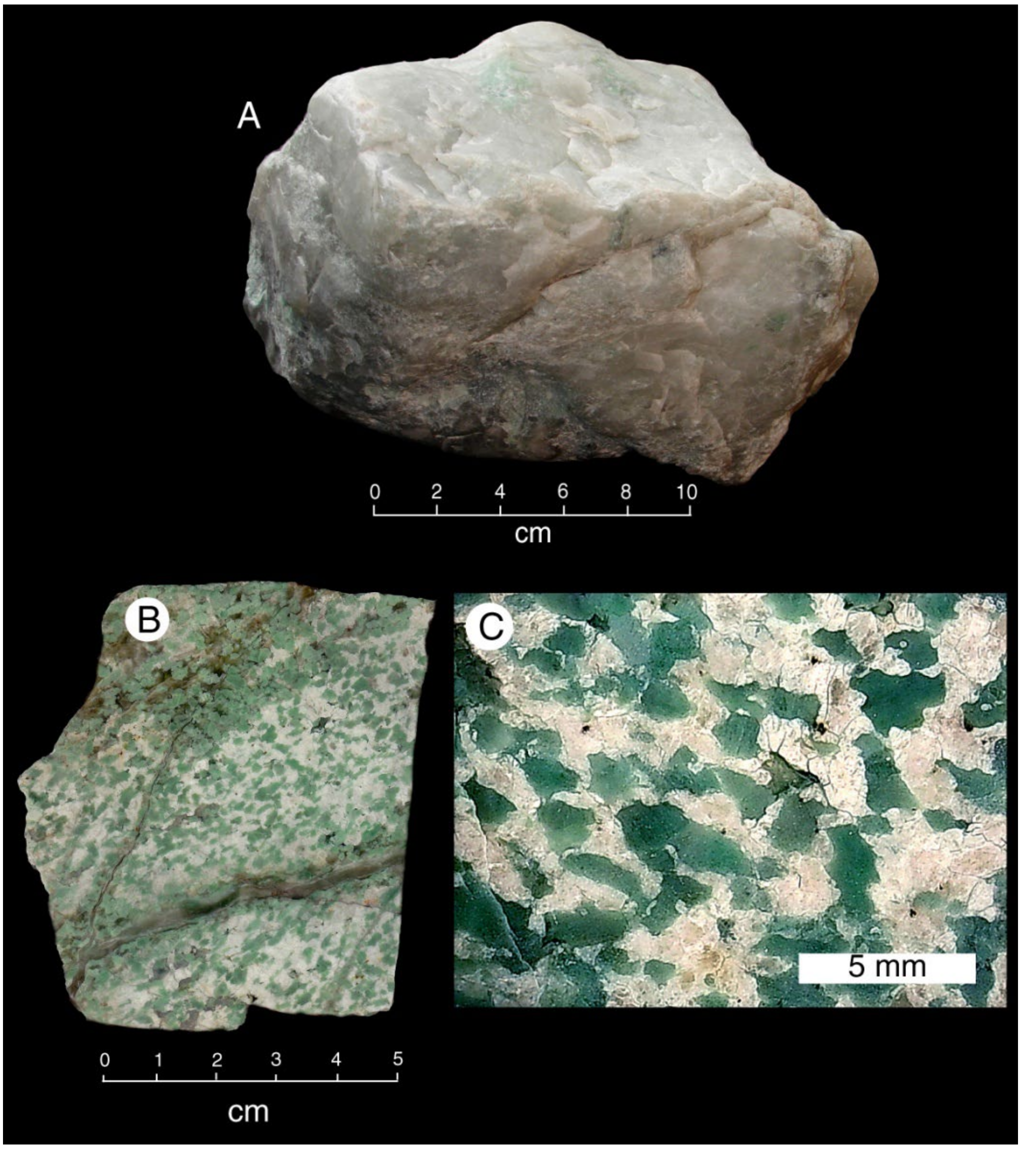

**Figure 35.** Grossular from the DDMFZ. (**A**) Nearly pure grossular Deer Creek specimen V4. (**B**,**C**) Grossular (white) with inclusions of chrome diopside (green), specimen MM-2, Snohomish River, Stilliguamish County, WA.

The microtextures of grossular/chlorite mixtures are visible in the SEM images (Figure 36). Elemental compositions are listed in Table 3.

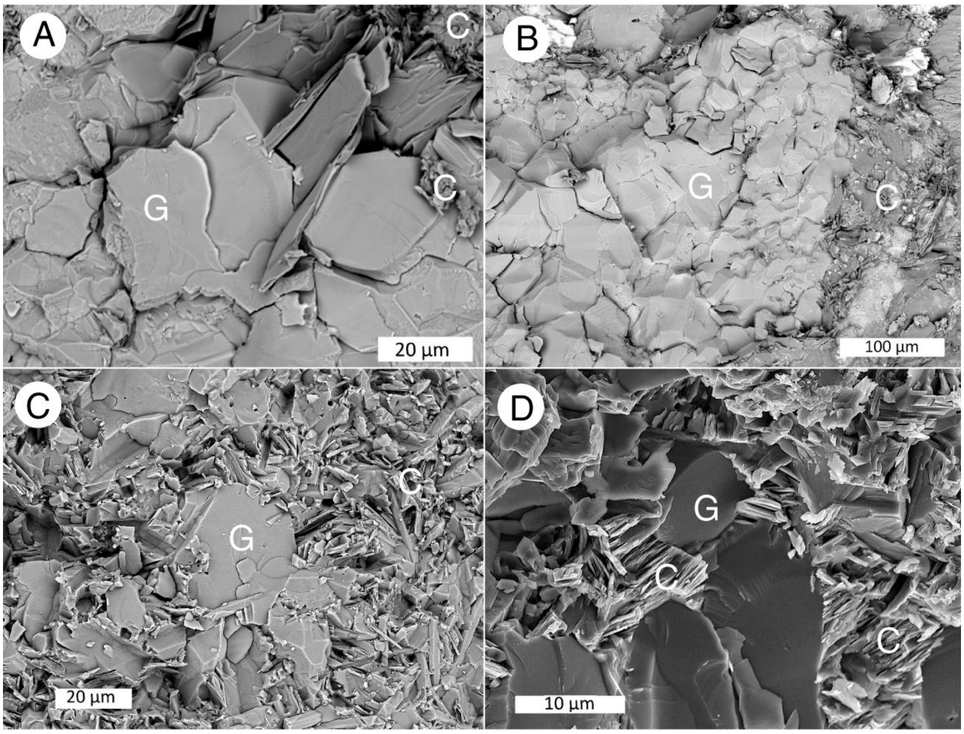

**Figure 36.** SEM images of grossular/chlorite association, Deer Creek specimen G3. G = grossular and C = clinochlore. (**A**–**C**) Backscattered electron image. (**D**) Secondary electron image.

**Table 3.** Semiquantitative SEM/EDS data for grossular in Deer Creek nephrite. Ti, Na, K, and Mn were not present in detectable amounts.

| | **G2 Deer Creek** | **G3 Deer Creek** | **MM19 Deer Creek** | **MM21 Snohomish River** |
|---|---|---|---|---|
| | | Oxide wt. % | | |
| $SiO_2$ | 39.87 | 36.25 | 41.38 | 41.38 |
| $Al_2O_3$ | 24.21 | 19.54 | 19.21 | 20.27 |
| MgO | 0.49 | 2.52 | 3.41 | 3.61 |
| CaO | 35.43 | 34.85 | 33.04 | 35.89 |
| FeO [1] | 0 | 2.95 | 2.55 | 0 |
| | | Element wt. % | | |
| O [2] | 60.09 | 59.83 | 59.83 | 59.73 |
| Si | 14.86 | 13.95 | 15.51 | 15.00 |
| Al | 10.63 | 9.57 | 8.49 | 8.91 |
| Mg | 0.27 | 1.45 | 1.92 | 2.02 |
| Ca | 14.45 | 14.33 | 13.27 | 14.34 |
| Fe | 0 | 0.96 | 0.80 | 0 |
| | | Atom % | | |
| O [2] | 60.06 | 61.63 | 60.13 | 59.56 |
| Si | 14.86 | 13.52 | 15.47 | 15.33 |
| Al | 10.65 | 8.60 | 8.47 | 8.86 |
| Mg | 0.27 | 1.40 | 1.90 | 1.99 |
| Ca | 14.15 | 13.93 | 13.23 | 14.25 |
| Fe | 0.00 | 0.92 | 0.79 | 0.00 |

[1] Total Fe calculated as FeO. [2] Oxygen calculated by stoichiometry.

### 5.8. Vesuvianite (Idocrase)

Vesuvianite is bestknown as a product of the contact metamorphism of limestone (e.g., skarns), but in ultramafic environments, vesuvianite commonly occurs as part of a rodingite assemblage, where it occurs in association with other calcsilicate minerals. Vesuvianite can commonly be recognized by its light color and high translucency (Figure 37). A green variety of vesuvianite occurs in the metamorphic rocks of the California Coast Range, where it is named Californite [57], and designated as the official state gemstone. This is in contrast to Washington State occurrences, where vesuvianite typically occurs intermixed with other silicate minerals (Figure 38).

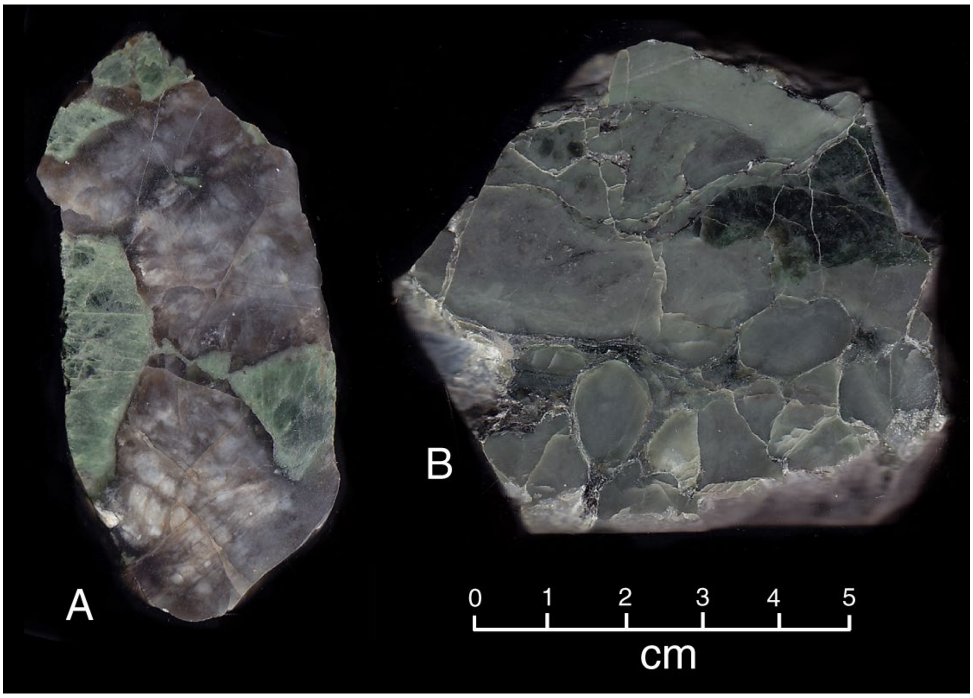

**Figure 37.** Vesuvianite (gray) as a rodingite mineral, associated with diopside (green). (**A**) Deer Creek specimen MM58. (**B**) Deer Creek specimen MM59.

### 5.9. Pumpellyite

One of the surprising discoveries from the DDMZ serpentinite zones is the abundance of pumpellyite. This mineral was discovered during extensive X-ray diffraction studies made by V. Showell circa 2010. The pumpellyite group comprises closely related sorosilicate minerals characterized by varying proportions of Mg, Fe, and Al [58,59]. The most common variety associated with ultramafic rocks is pumellyiteMg, with its composition shown in Table 2. Pumpellyites commonly occur in low-grade regionally metamorphosed rocks, where they may be found in association with prehnite, $Ca_2Al[AlSi_3O_{10})(OH)_2$, a calcium aluminosilicate mineral. This assemblage is a defining characteristic for prehnite–pumpellyite facies (Figure 5). However, prehnite has not been observed in the DDMFZ serpentinites. Some rodingite specimens contain pumpellyite as their major component, with chlorite as an associated mineral.

The apparent absence of prehnite may be related to the scarcity of Al in the serpentinite. Also, pumpellyite may occur in subgreenschist facies at pressures that do not favor the formation of prehnite (Figure 39). When Al is introduced in significant amounts during metasomatism, the product is likely to be grossular garnet, $Ca_3Al_2Si_3O_{12}$. Pumpellyite and grossular commonly occur together in the serpentine areas of the DDMFZ, where they presumably originated as rodingites. Pumpellyite may also be intermixed with diopside and vesuvianite.

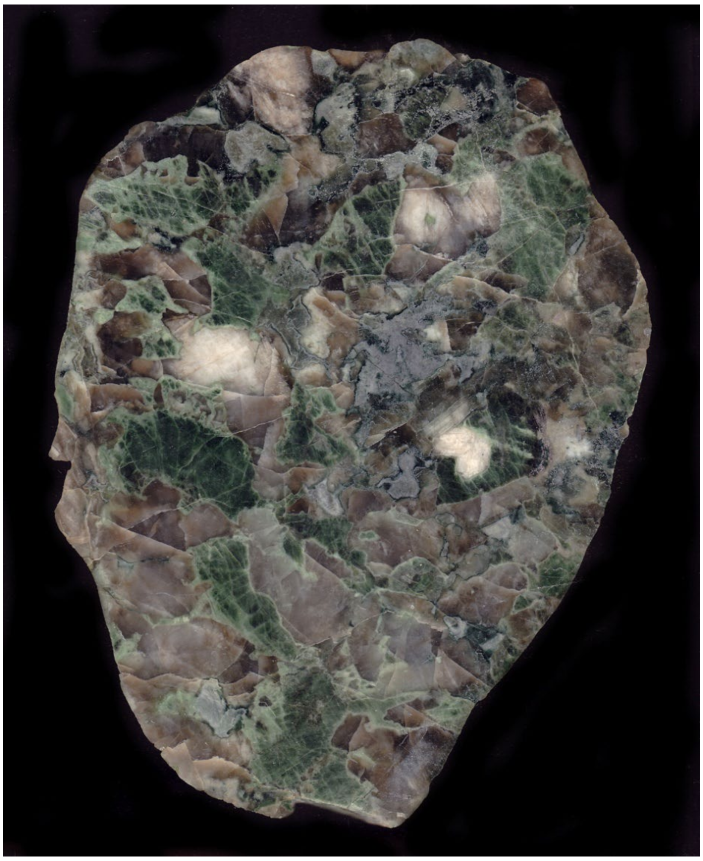

**Figure 38.** Polished rodingite from the DDMFZ in the north Fork Stilliguamish River area. Minerals include grossular (white), diopside (green), and vesuvianite (gray-brown). Specimen provided by Jeff Aylor. Specimen MM-17.

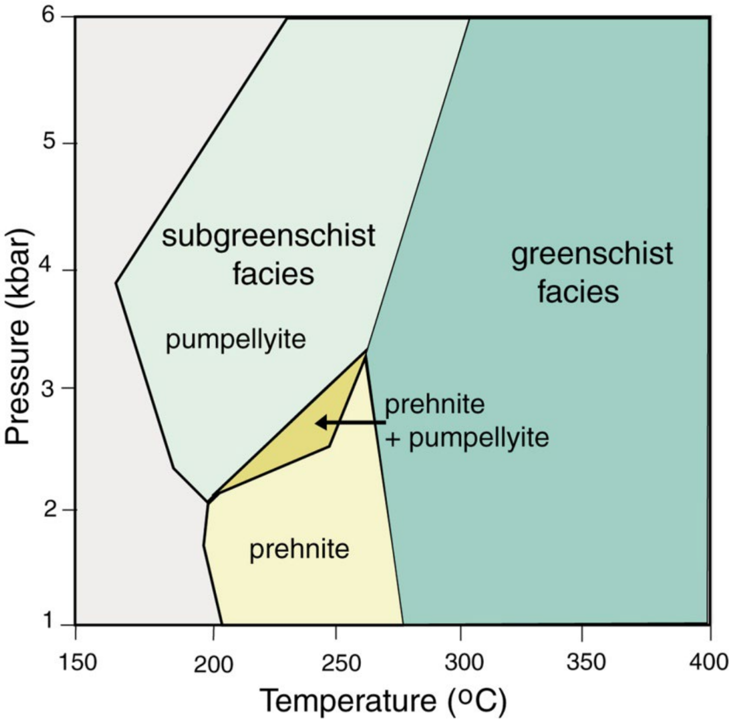

**Figure 39.** Stability fields of prehnite and pumpellyite, based on evidence from metabasic rocks. Modified from [60].

Pumpellyite's color is typically controlled by its trace element content, with colors ranging from white and pale brown to bluish green and bright green (Figure 40). Dark green and black varieties may be visually similar to high-quality nephrite (Figure 40D). In these specimens, pumpellyite is evidenced by densities of around 3.20 g/c$^3$, in contrast to the 2.95–3.00 g/cm$^3$ values typical of nephrite. However, X-ray diffraction provides the most reliable method for identifying pumpellyite. Density determinations are not diagnostic when pumpellyite is intermixed with grossular, diopside, or vesuvianite, minerals that all have densities similar to pumpellyite.

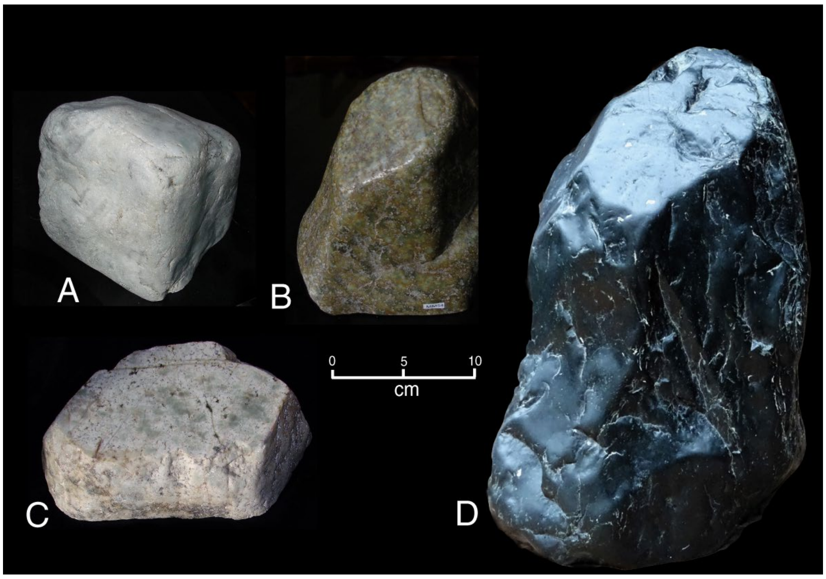

**Figure 40.** Pumpellyite and associated minerals from the DDMFZ. (**A**) Pumpellyite, grossular, diopside, and clinochlore, Pilchuck Creek specimenMM48. (**B**) Pumpellyite, diopside, and clinochlore, Pilchuck Creek specimen MM54. (**C**) Pumpellyite, clinochlore, and plagioclase, Deer Creek specimen MM50. (**D**) Massive pumpellyiteMg mimicking nephrite in appearance. The dark color is probably due to iron, with an Fe content of ~5%, as indicated by SEM/EDS. Specimen V-2-18-24.

## 6. The Jadeite Mystery

Specimens from western Washington State have sometimes been identified as jadeite, but these identifications are almost always incorrect. In the absence of analytical methods such as X-ray diffraction or electron beam microanalysis, distinguishing between jadeite and other jade-like materials is difficult. Because jadeite is a member of the pyroxene family, its crystal structure is very different from that of nephrite, which is a variety of amphibole. Therefore, XRD is a useful tool. Raman spectroscopy is a fast, non-destructive method for use in gemstone identification. Chemical analysis provides a reliable form of discrimination between jadeite and nephrite, because jadeite is a sodium-rich mineral, and this element is not a significant component of tremolite or actinolite, the main components of nephrite. The paragenesis of jadeite was discussed in detail by [61–63].

There are two reasons why jadeite is unlikely to be present in serpentinites. First, these rocks are typically very low in Na. Second, in metamorphic rocks that do contain significant amounts of sodium, this element is likely to be present in plagioclase feldspar. Under high-pressure metamorphism, plagioclase may be converted to jadeite, $NaAlSi_2O_6$ (Figure 41). The occurrence of jadeite + quartz is characteristic of the high-pressure part of blueschist facies. Natural jadeite is commonly a solid solution series with aegirine, diopside, and hedenbergite components [64].

Greenschist facies, rocks that contain abundant nephrite, are not a metamorphic environment that would produce jadeite. However, the bedrock of the Northwest Cascade Range contains areas of blueschist and eclogite facies metamorphism, and these zones could potentially contain jadeite. This mineral has been observed at a microscopic scale [65].

Blueschist and eclogite facies occurrences have been reported in the Gee Point-Iron Mountain area in Skagit County, Washington [66,67] (Figure 42). A single stream-transported jadeite specimen weighing several kilograms was collected by F. Ruggiero from surficial deposits in the upper Little Deer Creek watershed, downslope from blueschist/eclogite occurrences. A small cut specimen appears in Figure 43A. More recently, a water-worn jadeite specimen was collected by V. Showell from the river bar at Deer Creek (Figure 43B). These rare specimens prove that jadeite may occur in the blueschist facies rocks of western Washington, but the greenschist facies localities favored by jade prospectors are not a favorable geologic setting. SEM images show the prismatic crystal textures typical of jadeite from other regions (Figure 44).

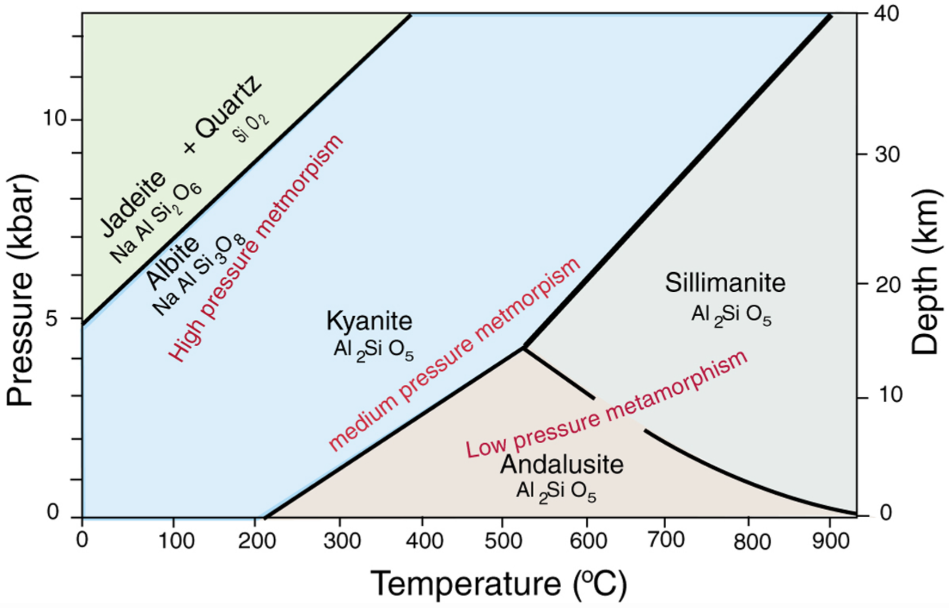

**Figure 41.** Phase diagram showing stability fields for the albite/jadeite transition, and for kyanite/andalusite/sillimanite. Adapted from [60,68].

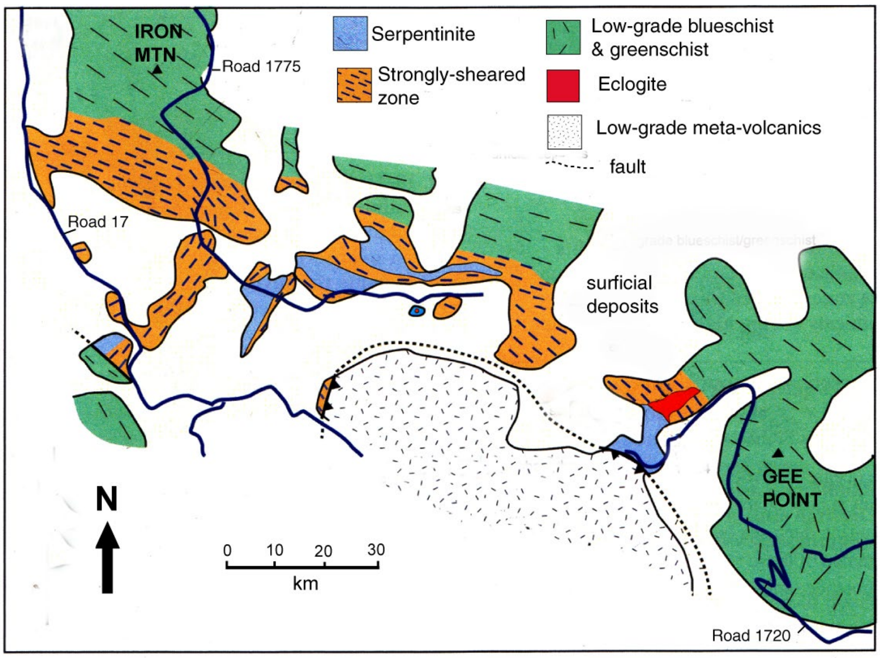

**Figure 42.** Geologic map of the Gee Point–Iron Mountain area, Skagit County, Washington, USA. Adapted from [65,67].

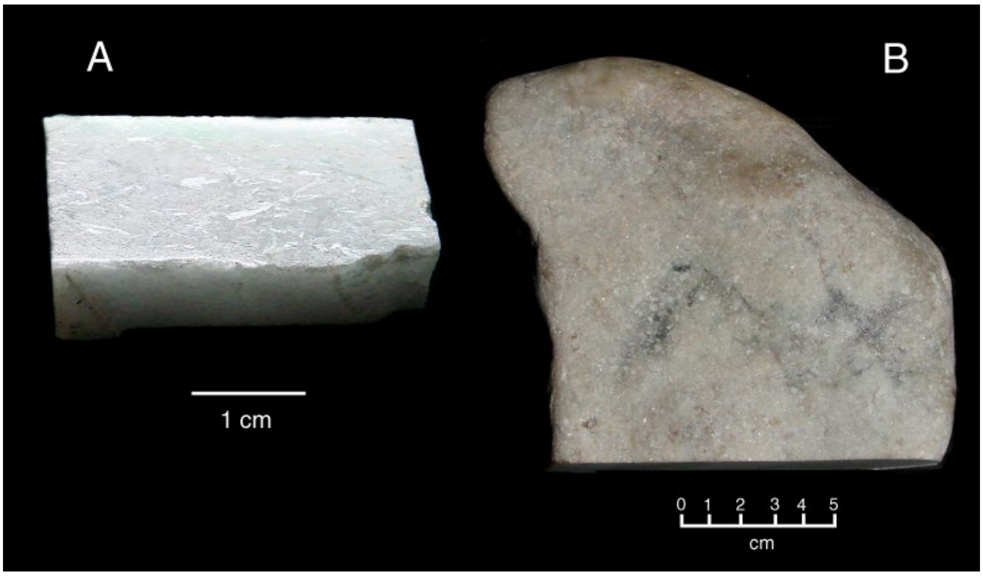

**Figure 43.** Jadetite from North Cascades localities. (**A**) Jadite from blueschist facies rocks of upper Finney Peak, Skagit County, WA, USA. (**B**) Jadetite containing a mixture of jadeite and muscovite, as evidenced by XRD. Alluvial specimen collected from Deer Creek, Snohomish County, WA, USA.

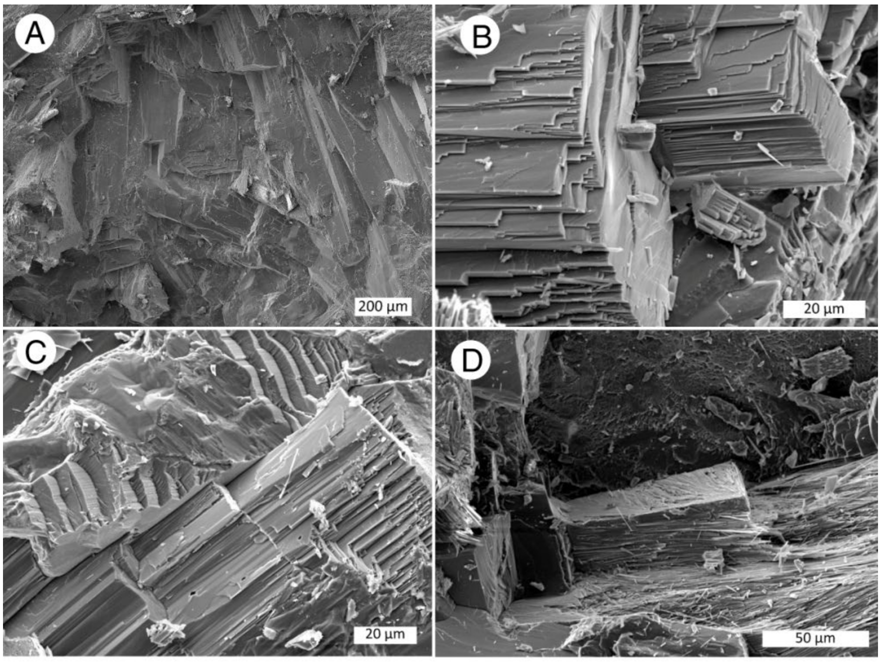

**Figure 44.** SEM photos of jadeite specimen from Iron Mountain-Gee Point area (see text for details). Secondary electron images show the 90-degree interfacial angles characteristic of members of the pyroxene family. (**A**) Low-magnification image reveals the interfingering pattern of prismatic microcrystals, very different from the matted needles typical of nephrite (Figure 2). (**B**,**C**) Jadeite microcrystals commonly show a degree of parallel alignment. (**D**) A single jadeite crystal shows the 90-degree angles of crystal faces. The right side of the image shows a small area of fibrous amphibole.

## 7. Rhodonite

Rhodonite may occur in geographic proximity to nephrite-bearing rocks, but the petrogeneses of the two materials result from different metamorphic pathways. Rhodonite is not a member of the listwanite or rodingite assemblages, and this mineral does not require the presence of serpentinite. Instead, the parent material of rhodonite issea floor sediment that is high in manganese content. Rhodonite occurs in the DDMFZ at both Mount Higgins and Helena Ridge in masses that range in mass from a few kilograms to several tons [69]. The manganese composition is well-documented for large ocean areas where manganese nodules carpet the sea floor [70,71]. In the North Cascades, metamorphism transformed marine sediment to schist, preserving the trace metal content. The petrogenesis of rhodonite involves metosomatism, where a calcareous host rock supplies soluble Ca; although pure rhodonite is $MnSiO_3$, natural material commonly contains up to 20 wt. % CaO, and may also contain Fe and Mg, giving a compositional range of (Mn, Fe, Mn, Ca)$SiO_3$.

The mineralogy of DDMFZ rhodonite has not been studied in detail, but X-ray diffraction patterns from a Mt. Higgins sample showed the composition to be bustamite, a member of the wollastonite family that contains high levels of Ca and Mg, and bannisterite, an aluminous member of the stilpnomelane family. Bustamite is commonly less pink in color than rhodonite, with some specimens having a brownish pink color. Bannistertite tends to have a yellowish color. The alteration of rhodonite family minerals commonly produces maganese oxide (pyrolusite), which forms prominent veinlets and surface coatings. Indeed, prospecting for rhodonite generally involves looking for rocks with a black exterior color, not pink (Figure 45).

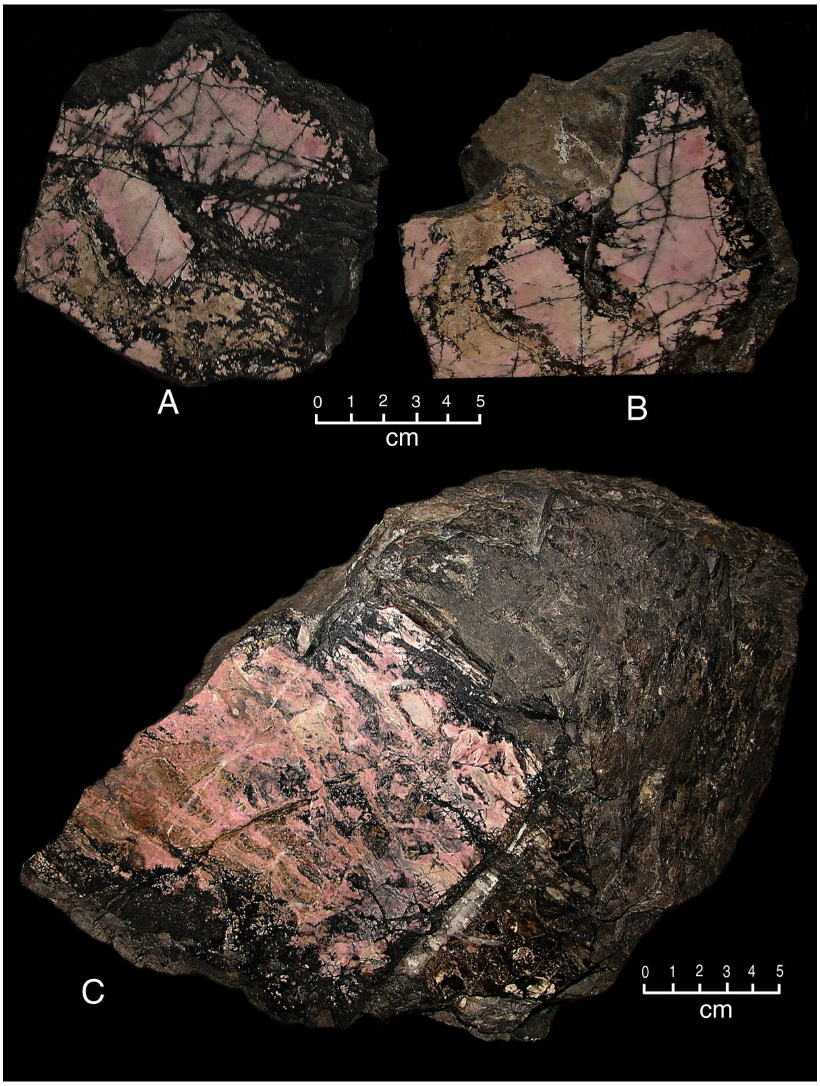

**Figure 45.** Rhodonite from Mount Higgins. (**A**,**B**) Slices cut from (**C**), a colluvial boulder. X-ray diffraction patterns show this material to be an intermixture of rhodonite and bannisterite.

## 8. Summary

The tectonic environment of Washington State provides a favorable setting for the occurrence of serpentinites that host nephrite and associated listwanite and rodingite assemblages. These rocks are commonly located in proximity to the Darrington–Devils Mountain Fault Zone (DDMFZ), a dominant regional structural feature that juxtaposes ultramafic rocks with phyllite, schist, and metavolcanic greenstone that provide sources of Ca and other elements important for metasomatic alteration. In the North Cascade foothills, nephrite and related assemblages occur as bedrock lodes, colluvial deposits on landslide-prone slopes, and transported alluvial deposits. This geologic overview provides insights into the petrogenesis of nephrite and jadetite in exotic terrane rocks in western Washington, offers information useful for understandingthe geologic settings of current nephrite mining claims, and provides guidelines for prospecting for as-yet undiscovered occurrences.

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**Data Availability Statement:** Specimens used in this study are presently part of the author's active research collection at the Western Washington University Geology Department.

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**Conflicts of Interest:** The author declares no conflicts of interest.

**Dedication:** This report is dedicated to the memory of Ed Molsee (Figures 23D and 46), an avid rock and gem enthusiast who was unmatched in his knowledge of Washington jade. He was a pioneering prospector and holder of many mining claims. Ed was always willing to share his expert knowledge with others. His hope of participating in this investigation was precluded by escalating health issues. Ed Molsee will long be remembered by those who are fortunate to have known him.

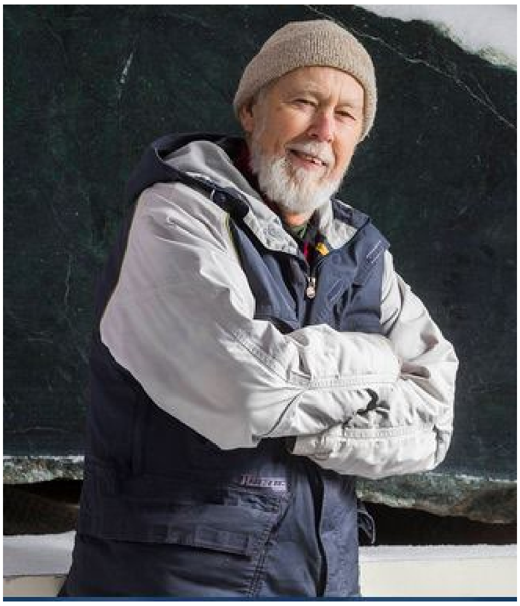

**Figure 46.** Ed Molsee (1947–2024). Photo by Andy Bronson.

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