Prepared in cooperation with Washington State Division of Geology and Earth Resources, U.S. National Park Service, and U.S. Forest Service

Geologic Map of the North Cascade Range, Washington

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Nontechnical pamphlet to accompany

Scientific Investigations Map 2940

Looking south from the North Klawatti Glacier [Mbse]. In the right foreground, the glacier breaks into a heavily crevassed icefall where it descends steeply. Rock in the foreground knob is Eldorado Orthogneiss (unit TKgo), a 90 million-year-old stitching pluton, which here includes numerous dikes of light-colored pegmatite. Mount Buckner on the left skyline and Mount Forbidden hidden in clouds are also eroded from the Eldorado Orthogneiss (photographed in 1987).

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Introduction

The North Cascade Range, commonly referred to as the North Cascades, is the northern part of the Cascade Range that stretches from northern California into British Columbia, where it merges with the Coast Mountains of British Columbia at the Fraser River. The North Cascades are generally characterized by exposure of plutonic and metamorphic rocks in contrast to the volcanic terrain to the south. The rocks of the North Cascades are more resistant to erosion, display greater relief, and show evidence of more pronounced uplift and recent glaciation. Although the total length of the North Cascade Range, extending north from Snoqualmie Pass in Washington, is about 200 mi (320 km), this compilation map at 1:200,000 scale covers only that part (~150 mi) in the United States. The compilation map is derived mostly from eight 1:100,000-scale quadrangle maps that include all of the North Cascade Range in Washington and a bit of the mostly volcanic part of the Cascade Range to the south (fig. 1, sheet 2). Overall, the area represented by this compilation is about 12,740 square miles (33,000 square kilometers).

The superb alpine scenery of the North Cascade Range and its proximity to major population centers has led to designation of much of the area for recreational use or wilderness preservation. A major part of the map area is in North Cascade National Park. Other restricted use areas are the Alpine Lakes, Boulder River, Clearwater, Glacier Peak, Henry M. Jackson, Lake Chelan-Sawtooth, Mount Baker, Noisy-Diobsud, Norse Peak, and Pasayten Wildernesses and the Mount Baker, Lake Chelan, and Ross Lake National Recreation Areas. The valleys traversed by Washington State Highway 20 east of Ross Lake are preserved as North Cascades Scenic Highway.

The map area is traversed by three major highways: U.S. Interstate 90, crossing Snoqualmie Pass; Washington State Highway 2, crossing Stevens Pass; and Washington State Highway 20, crossing Washington Pass. Major secondary roads, as well as a network of U.S. Forest Service roads and a few private roads mainly used for logging, are restricted mostly to the flanks of the range. Although much of the mountainous core is inaccessible to automobiles, numerous trails serve the foot or horse traveler.

Using This Report

We designed this map for two audiences: those who visit the North Cascades (fig. 1) and want to have a feeling for the rocks around them, and those who have geologic training, are familiar with North Cascade geology, and want a geologic overview of the range. In this nontechnical pamphlet accompanying the map, we present text and rock descriptions in plain terms, with as little jargon as possible. The Description of Map Units for the nonspecialist emphasizes how the rocks are formed and their geologic history. Much of the nonspecialist text and some illustrations (figs 3, 6, 10, 11,18, and 21) in this pamphlet are adapted from The Geology of the North Cascades: A Mountain Mosaic by Rowland Tabor and Ralph Haugerud (1999), The Mountaineers, Seattle. The technical pamphlet is a summary of material presented in the eight 1:100,000-scale geologic maps and other technical sources and heavily references them. Both technical user and nonspecialist may want to refer to both versions of the pamphlet for the complete story.

Because the geologic map is large and complex, we appended location codes in brackets after geographic place names and geologic unit and feature names where needed. The eight 1:100,000-scale quadrangles are outlined on the map, and quadrangle names and their abbreviations are labeled along the edges of the map, as well as in figures 1 and 5. The quadrangle maps may be further subdivided into quadrants indicated by compass directions. The location code may consist of the quadrangle(s) abbreviation or a combination of the quadrangle and quadrant abbreviations. Thus, the location code "[MBnw]" following a place name, unit name, or geologic feature name indicates a location in the northwest quadrant of the Mount Baker quadrangle.

Additional photographs may be accessed at the publication website (http://pubs.usgs.gov/sim/2940).

Map Preparation

We compiled the map electronically from digital databases for eight 1:100,000-scale geologic quadrangle maps of the North Cascades (fig. 1). We and our colleagues mapped and compiled the geology of the eight maps from 1975 through 2003: Chelan (Tabor and others, 1987), Mount Baker (Tabor and others, 2003), Robinson Mountain (R.A. Haugerud and R.W. Tabor, unpub. field maps), Sauk River (Tabor and others, 2002), Skykomish River (Tabor and others, 1993), Snoqualmie Pass (Tabor and others, 2000), Twisp (R.A. Haugerud, J.B. Mahoney, and R.W. Tabor, unpub. field maps), and Wenatchee (Tabor and others, 1982). The predominant sources of the geology are revealed on each of the individual 1:100,000-scale maps. Although we have not moved contacts or faults shown on the published 1:100,000-scale maps, we have changed the interpretation of a few structures based on insights gained during this compilation, new published work, and (or) new field data. References are sparse for a map of this size and complexity. In the Description of Map Units, we cite one or more of the 1:100,000-scale geologic maps most appropriate for more information about the unit. We tried to include references to more current work, some that may directly conflict with our interpretations.

Major Sources of New Data

The northeastern third of the Twisp quadrangle represents new compilation based on extensive field work by R.A. Haugerud, J.B. Mahoney, and R.W. Tabor, mostly in 1993–96. Quaternary deposits in this area were largely interpreted by Haugerud from aerial photographs and published 1:24,000-scale topography.

Ongoing work by R.B. Miller, his students, and their collaborators, mostly in the southern part of the map area, continues to improve our understanding of Cascade geology. We include some of their new ages for metamorphic rocks.

We also incorporate some of the continuing work of C.A. Hopson (written commun., 2005; Hopson and Mattinson, 1994) along the southwest margin of the Twisp quadrangle (fig. 2, sheet 2) and in the Lake Chelan area of the Chelan quadrangle.

Locally, considerable large-scale geologic mapping was completed since publication of the 1:100,000-scale quadrangles, in particular at 1:24,000 scale near and west of Darrington by J.D. Dragovich and his colleagues with the Washington Division of Geology and Earth Resources. We did not compile directly from this new mapping, but we mention specific areas where their maps differ from our compilation; little of this new detailed data effects this 1:200,000-scale compilation.

Acknowledgments

For a project this big and inclusive that has taken a long time to complete, we must acknowledge that, although we continually tried to keep up with new work and ideas, our pursuit has been imperfect. We greatly appreciate the help of reviewers, blessed in current information, and their discussions: Joe Dragovich, Robert Miller, and Richard Waitt. Richard Waitt, in particular, vigorously improved our syntax. Clifford Hopson and Brian Mahoney provided unpublished map data and critical information for the Twisp quadrangle. Jon Riedel contributed to our understanding of the Cordilleran Ice Sheet extent and provided unpublished data.

Plate Tectonics and the North Cascades

The theory of plate tectonics holds that the Earth's outer shell is made up of several large, relatively rigid plates floating on a denser layer of plastic rock, the lower part of the Earth's mantle (fig. 3, sheet 2). These plates move about at speeds no greater than a few inches per year. Where plates converge, the crust thickens and mountains rise up; where they pull apart, oceans form.

In general, where tectonic plates converge, ocean-deposited sediments, turned into sedimentary rock, commonly are scraped off, deformed, and transferred to the overriding plate. Some ocean-floor sediments are carried beneath the overriding plate in a subduction zone, where increasing heat and pressure turn them into metamorphic rocks, such as those forming the foundation of the North Cascades. The subducted oceanic plate and overlying sedimentary rocks are rich in water, which is driven off as the rocks move deeper and get hotter. The rising water lowers the melting point of the already hot upper mantle and lower crust, causing them to melt, expand, and become less dense than the unmelted rocks around them. The molten rock rises buoyantly, working its way toward the surface by exploiting zones of weakness, such as faults. Where the molten rock reaches the surface, volcanoes form along a curving line called a volcanic arc. A large amount of igneous rock is generated by the subduction process.

As a consequence of Earth's moving tectonic plates, large slabs of crust are moved great distances around the globe over long periods of time. Many mountain belts contain rocks that formed in a different setting from their neighbors. Rocks from the flanks of a volcanic arc on the continent may be adjacent to rocks of the same age that formed in the middle of a deep ocean far from a volcano.

Many of the rocks now seen in the North Cascades were formed in the collision zone between the Pacific Ocean plate and the North American continental plate. Most of these rocks, as well as older rocks caught up in the convergence, were smashed on a huge scale as the plates slowly collided or slid by each other along faults.

Sometimes a piece of one plate breaks off and becomes attached to another plate. Commonly such an orphaned fragment will travel along with the new plate only to be sheared off and be attached to yet another plate. These separated, transported pieces are called tectonic terranes or, sometimes, exotic terranes. Most of the structural blocks making up the foundation of the North Cascades are themselves a mosaic of several distinct tectonic terranes (figs. 4 and 5, sheet 2).

The Geologic Story of the North Cascades

The North Cascades record at least 400 million years in the geologic history (fig. 6) of this restless Earth—time enough to have collected a jumble of different rocks. The North Cascade Range is a geologic mosaic made of volcanic island arcs, deep ocean sediments, basaltic ocean floor, parts of old continents, continental-margin submarine fans, and even pieces of the deep subcrustal mantle of the Earth. Disparate pieces of the North Cascades mosaic formed far from one another but subsequently drifted together, carried along by the ever-moving tectonic plates. Over time, these plates eventually beached the various pieces of the mosaic at a place we now call western Washington.

As if this mosaic of unrelated pieces were not complex enough, some of the assembled pieces were uplifted, eroded by streams, and then locally buried in their own eroded debris; other pieces were forced deep into the Earth to be heated and squeezed, almost beyond recognition, and then raised again to our view.

About 40 million years ago, in the Tertiary Period (fig. 6), a volcanic arc (Cascade Magmatic Arc) developed on this complex mosaic of old terranes. Volcanoes erupted to cover the older rocks with lava and ash. Large masses of molten rock (called magma) invaded the older rocks. The volcanic arc is still active today, decorating the skyline with the volcanic cones of Glacier Peak and Mount Baker (figs. 7 and 8, sheet 2).

The deep canyons and sharp peaks of the present North Cascades are products of profound erosion. Running water excavated canyons and valleys of the range, landslides softened the abrupt edges, local glaciers scoured the peaks and high valleys, and, during the Ice Age, the Cordilleran Ice Sheet overrode much of the northern part of the range (fig. 9, sheet 2) and rearranged the stream courses. Erosion revealed the complex mosaic of the bedrock.

The assemblage of the numerous terranes in the North Cascades thickened the crust more in the north part of the Cascade Range than in the south; this resulted in more uplift of the thick crust, which tilted the range up to the north. As a consequence, erosion has whittled the northern part of the range deeper into the foundation of terranes to reveal the older rocks, and it has produced greater local relief (fig. 10).

In southern and central Washington, the Cascade Range is made of young volcanic rocks, ranging from 0 to about 40 million years old (Tertiary), that erupted from many volcanoes forming the Cascade Volcanic Arc. In various places near Snoqualmie Pass (Interstate 90), the foundation of older rocks can be seen under this volcanic cover. Farther north, fewer young volcanic rocks are preserved and more of the foundation shows. Also exposed are the granitic rocks that once, as magma, invaded the foundation of older rocks and became the reservoirs of magma that fueled now-eroded volcanoes.

Looking mostly at the foundation of older rocks making up the range, we see that it is sliced by three major faults and a couple of lesser faults separating the rocks into distinct blocks (figs. 4 and 5). Faults are significant breaks in the Earth's crust where the rocks on each side have moved relative to each other. The westernmost major fault is the Straight Creek Fault; east of it is the Ross Lake Fault. Because the Ross Lake Fault consists of many fault strands, it is sometimes called the Ross Lake Fault Zone or Ross Lake Fault System. Farther east is the Pasayten Fault.

In the region west of the Straight Creek Fault, the Darrington-Devils Mountain Fault Zone (DDMFZ) separates the

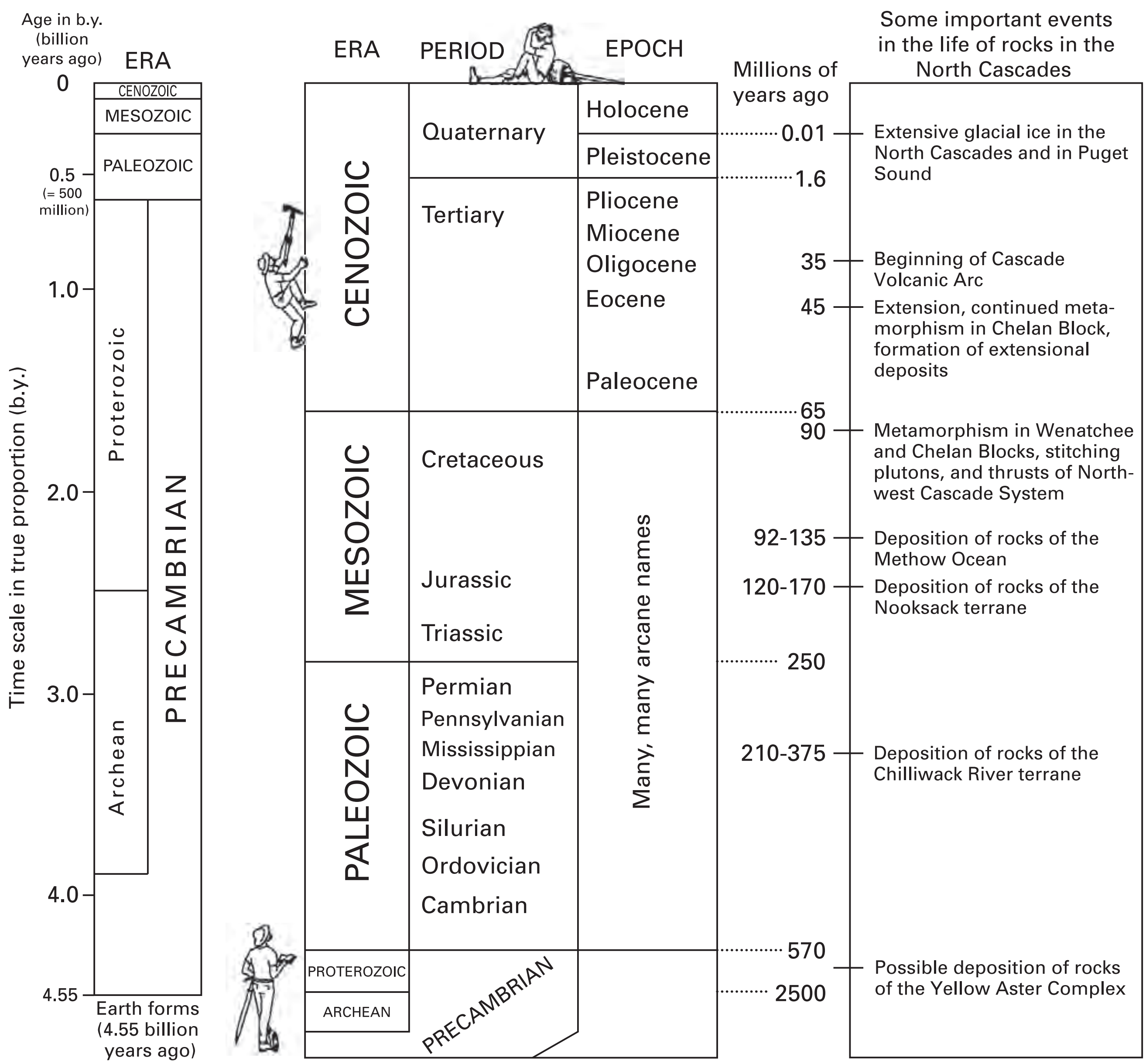

Figure 6. Geologic time scales relative to some geologic events in North Cascades, Washington.

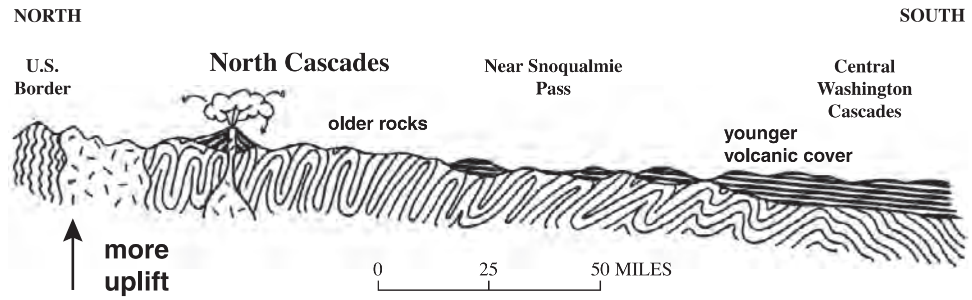

Figure 10. Sketch showing a north-south cross section of the Cascade Range in Washington. Erosion removed more of the volcanic deposits in the north than in the south, because uplift is greater in the north. Contact between volcanic deposits and underlying, folded older rocks is an angular unconformity.

Northwest Cascade System on the north from the mélange belts to the south (figs. 4 and 5). On both sides of the DDMFZ sedimentary and volcanic rocks dominate the region. Although these rocks are complexly faulted and folded, they still retain textures and structures, such as sedimentary bedding, that reveal their origins on the surface of the Earth. Some of these rocks contain fossils that have helped to establish their age. The separate and somewhat disparate terranes of the area have been roughly handled. Some are broken, faulted, and smeared into mélanges (mixed rocks). Most were stacked along thrust faults on a colossal scale (fig. 11)

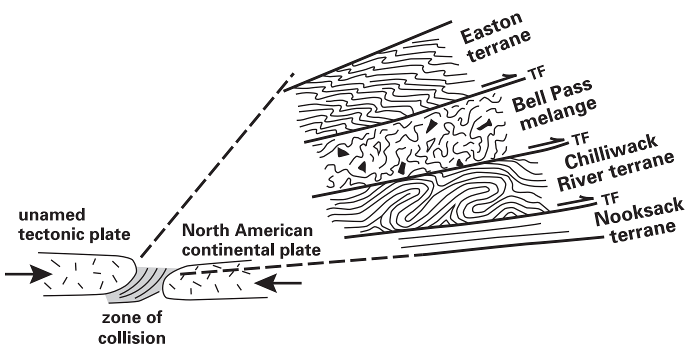

Figure 11. Sketch of cross section showing how terranes (nappes) became stacked in Northwest Cascade System along thrust faults (TF) during collision between tectonic plates. Half arrow (⟶) shows direction of movement along faults.

Between the Straight Creek Fault and the Ross Lake Fault Zone, Wenatchee and Chelan blocks contain severely squeezed and recrystallized metamorphic rocks that were once at great depth in the Earth's crust. Their story is complex. If they ever contained fossils, the fossils were destroyed by metamorphism. How these rocks originally formed can only be inferred from their composition and from vague relics of original structures and textures.

The wide Ross Lake Fault Zone contains some rocks that are clearly part of the Chelan block and some that are part of the Methow block, but the Methow rocks are metamorphosed. At least one terrane in this zone, the metamorphosed Skymo Complex of Wallace (1976), is unlike rocks in the adjoining blocks.

Between the Ross Lake Fault Zone and the Pasayten Fault, the Methow block is primarily unmetamorphosed sedimentary and volcanic rocks. Its deformation through folding and faulting is less complex than in rocks in the other blocks and it contains fossils, in places, abundantly.

East of the Pasayten Fault, rocks of the Okanogan block resemble those in the Chelan block but appear to be older and to have been metamorphosed earlier and at shallower depths, suggesting that they have a different history. Recent work (Tabor and Haugerud, in press) indicates that the geologic history may not be so different but may be much more complicated.

DESCRIPTION OF MAP UNITS

[Age in parenthesis after the unit name is age of assemblage or metamorphism for mélange and metamorphic units. The eight 1:100,000-scale quadrangles are outlined on the map, and quadrangle names and their abbreviations are labeled along the edges of the map, as well as on figures 1 and 5. Location codes in brackets that follow place names, unit names, geologic feature names or unit descriptions may consist of a quadrangle abbreviation or a combination of quadrangle and quadrant abbreviations; for example, [MBnw] indicates a location in the northwest quadrant of the Mount Baker quadrangle]

UNCONSOLIDATED DEPOSITS

NONGLACIAL DEPOSITS

Qa **Alluvium of valley bottoms (Holocene and Pleistocene)**—Sand and gravel of today's rivers and streams. Includes some older gravel in terraces above present rivers and streams. Locally includes small side stream alluvial fans and other unconsolidated deposits

Qu **Alluvium (Holocene and Pleistocene)**—Valley-bottom sand and gravel in small streams, hillslope debris, wind-blown debris, soil, alluvial fans, and landslide debris. Unit is gradational with other Quaternary units

Qt **Talus deposits (Holocene and Pleistocene)**—Mostly angular rock rubble fallen from cliffs or steep rock slopes above. At higher elevations, includes some young, barren glacial moraines. Surfaces generally unvegetated

QTl **Landslide deposits (Holocene, Pleistocene, and Pliocene?)**—Broken rocks and slope debris derived from upslope by rapid sliding or slow creep. Includes both transported material and unstable scarp (steep slope vacated by landslide at its head), if present. Older landslides are generally large and have somewhat subdued hilly topography

Qlh **Lahars (Holocene and Pleistocene)**—Muddy, gravelly volcanic rock debris with local beds of sand and gravel deposited by catastrophic mudflows, commonly associated with volcanic eruptions. In drainages around Glacier Peak volcano [SRse], lahars about 12,000, 5,000 and 1,800 years old contain characteristic clasts of pumice and volcanic rocks from Glacier Peak and flowed far to the west onto the Skagit River delta. Some of these mudflows raced down the river valleys to reach Puget Sound.

In the White River valley [SPsw] on the south edge of the map area and in adjacent lowlands, unit includes deposits of numerous Holocene catastrophic mudflows from Mount Rainier volcano south of the map area. The largest mudflow, the Osceola, spilled out of the mountain valleys to reach Puget Sound about 5,600 years ago. Similar deposits, derived from Mount Baker volcano, underlie valley-bottom alluvium in the Baker River and Middle Fork Nooksack River drainages [MBnw]

GLACIAL DEPOSITS

Qag **Alpine glacial deposits (Holocene and Pleistocene)**—Deposits range from glacial moraine in uplands and the upper ends of valleys to gravel or sand outwash on broad valley floors (fig. 12, sheet 2). Mostly deposited by glaciers originating in the North Cascades. Includes subordinate stream deposits, alluvial fans, small landslide deposits, and other uncemented deposits. Areas of thin, sparse drift not distinguished from bedrock. Includes areas of unvegetated Holocene moraine

Qga **Deposits of alpine glaciers and Cordilleran Ice Sheet (Holocene and Pleistocene)**—Deposits ranging from boulder till in uplands and upper valleys to gravel or sand outwash on broad valley floors. Most of the area where these deposits are mapped was overidden by the Cordilleran Ice Sheet (fig. 9). Its rock debris is mixed with deposits from local alpine glaciers. On valley sides and uplands, includes areas veneered with drift but also includes subordinate areas of bedrock, alluvial fans, soil, or talus deposits. On valley floors, also includes small alluvial fans, bogs, and modern stream alluvium.

Deposits of Vashon stade of Fraser glaciation of Armstrong and others (1965) (Pleistocene)

Qvr **Recessional outwash deposits**—Bedded sand and gravel, moderately sorted to well sorted, and well-bedded silty sand to silty clay. Deposited by streams and rivers draining the Cordilleran Ice Sheet as it melted (receded) at the end of the ice age. Many beds of silt and sand were deposited in lakes formed between the melting ice sheet and hills and ridges beyond the ice. Recessional outwash deposits are mostly found in the lowland areas

Qvt **Till**—Mainly compact unsorted rock debris with subangular to rounded clasts, transported by the Cordilleran Ice Sheet and deposited from the ice

Qva **Advance outwash deposits**—Well-bedded gravelly sand, sand, and bedded silt deposited by streams and rivers that drained the Cordilleran Ice Sheet as it advanced into Washington from the north. Much of this material was deposited as deltas growing into lakes that formed as the ice sheet dammed valleys sloping toward the glacier, such as when the advancing ice sheet in the Puget Lowland flowed up west-flowing rivers and streams from the Cascades

Qud **Upland deposits (Holocene and Pleistocene)**—Mostly upland deposits of Fraser Glaciation age or older. Deposits in the southeast part of the map area are mostly windblown glacial silt derived from glacial outburst flood deposits

Qgf **Deposits of glacial outburst floods (Pleistocene)**—Bedded silt, sand, and gravels in the Chelan, Wenatchee, and Columbia River drainages, related to catastrophic floods along the Columbia River. During the ice age, glacial Lake Missoula in western Montana broke through its glacial dam nearly 100 times. Its waters poured down the Columbia River in huge floods, some almost 1,000 feet deep at Wenatchee (Waitt, 1980, 1985). Gravel bars and terraces, some with giant ripple marks, testify to the power of these floods. Wave-like ripples on fine sediment beds commonly are spaced a few inches apart; they are caused by the gentle wash of wind or water. The giant ripples of the glacial outburst floods are hundreds of feet from crest to crest. As the floods coursed down the Columbia River valley, water also surged up tributary drainages, such as the Wenatchee River [Cse, Wne], depositing fine sand and silt

GLACIAL AND NONGLACIAL DEPOSITS

Qpf **Nonglacial and glacial sedimentary deposits older than Fraser glaciation (Pleistocene)**—Moderately to deeply weathered clay, sand, and gravel, as well as some alpine glacial deposits older than Fraser glaciation

QTog **Older gravel (Pleistocene, Pliocene, and Miocene?)**—Weakly cemented to uncemented boulder to pebble gravel with silt and sand. Some deposits are rich in angular volcanic rocks, suggesting that they are remnants of debris flows from ancient, completely eroded volcanoes. Generally found capping ridges and (or) deeply cut by modern streams. Includes Thorp Gravel, deposited about 4.5 million years ago by the Yakima River [Wsw], when it was blocked by growing folds in the lavas of the Columbia River Basalt Group south of the map area (Waitt, 1979)

ROCKS OF CASCADE MAGMATIC ARC

Qcav **Rocks of young Cascade volcanoes (Holocene and Pleistocene)**—Includes Glacier Peak and Mount Baker volcanoes (figs. 7, 8), an older, highly eroded volcano at Black Buttes immediately west of Mount Baker, and scattered volcanic deposits erupted from other local sources. Predominantly andesite but ranges from dacite to basalt. The rocks of Mount Baker and Glacier Peak volcanoes are all probably less than about 600,000 to 700,000 years old; most of the Black Buttes volcanic edifice formed between about 500,000 and 300,000 years ago

QTcc **Caldera deposits (Pleistocene, Pliocene, and Miocene)**—Mostly rhyolite and dacite; includes Kulshan, Hannegan [MBnw], and Gamma Ridge [SRse] calderas. Calderas form when the rock roof of a magma (molten rock) chamber collapses during a huge, cataclysmic eruption of the underlying magma. Much of the erupting volcanic debris falls back into the caldera. Kulshan Caldera east of Mount Baker formed about one million years ago; volcanic ash from its eruption reached Tacoma. Gamma Ridge caldera formed about 2 million years ago (Tabor and others, 2002), and Hannegan Caldera formed about 3.7 million years ago (Tucker, 2004; Tucker and others, 2007)

QTcp **Intrusive rocks of Cascade Pass family (Pleistocene, Pliocene, and Miocene)**—Tonalite, granodiorite, granite, and rare gabbro that crystallized between 1 and 20 million years ago. This and the other intrusive rock families formed as magma crystallized beneath the volcanoes of the Cascade Magmatic Arc. The overlying rocks have since been eroded to expose these fossil magma chambers (fig. 12). [SRne]

Tcaf **Volcanic rocks of Fifes Peak episode (Miocene)**—Predominantly basaltic andesite and basalt flows and breccias, as well as rhyolitic ash flow tuffs. These deposits erupted from many volcanoes about 20 to 24 million years ago. The volcanoes themselves were buried by the deposits of younger volcanoes or were eroded away

Tcas **Intrusive rocks of Snoqualmie family (Miocene and Oligocene)**—Similar to rocks of the Cascade Pass family but crystallized between 22 and 28 million years ago. See figure 7 for a view of erosion-resistant granodiorite of the Cloudy Pass batholith [TWsw]. [SPne]

Tcao **Volcanic and sedimentary rocks of Ohanapecosh episode (Oligocene)**—Range from basalt to rhyolite, but mostly basalt and andesite. Remnants of another series of volcanoes that erupted from about 34 to 30 million years ago. Near Wenatchee [Wne], includes sandstone of the Wenatchee Formation with rare volcanic tuff beds. Only small, mostly down-faulted remnants of these rocks remain in the northern part of the map area due to the greater uplift and consequent erosion of the Cascade Range to the north (fig. 10)

Tcai **Intrusive rocks of Index family (Oligocene)**—Similar to Cascade Pass family but crystallized between 29 and 35 million years ago. [SKnw]

FLOOD BASALT AND ASSOCIATED DEPOSITS

Te **Ellensburg Formation (Miocene)**—Sandstone and minor conglomerate. Includes volcanic tuff and breccia in southwest corner of map. Interlayered with basalt flows of the Columbia River Basalt Group. Basalt lava erupted southeast of the Cascade Range and flowed against the mountains. Rivers and streams from the mountains were dammed by the lava, deposited their load of sediment on earlier basalt flows, and were later covered by more basalt flows. Northeast of the Yakima River, where the streams deposited sediment eroded from the older rocks of the North Cascades, the Ellensburg Formation is mostly sand and conglomerate made up of quartz and feldspar. Southwest of Yakima River where the streams drained active volcanoes, the Ellensburg Formation is mostly volcanic debris (Swanson and others, 1982). [Wsw]

Yakima Basalt Subgroup of Columbia River Basalt Group (Miocene)—About 17 million years ago, after the Cascade volcanic arc was well established, hot mantle material (fig. 3) began to rise deep beneath northeastern Oregon. As hot mantle material rose, it melted. At the same time, the Earth's crust stretched, magma-filled cracks extended to the surface, and magma erupted as flood basalt. These hot, fluid basalts, which mostly erupted in a geologically short period between16.5 and 15 million years ago, flowed far across the relatively flat landscape and now cover most of central and southeastern Washington, northeastern Oregon, and parts of western Idaho. These lava flows in the map area are divided into Wanapum Basalt and Grand Ronde Basalt

Tyw **Wanapum Basalt**—Fine- to medium-grained basalt flows containing sparse large crystals of olivine and plagioclase surrounded by tiny crystals and volcanic glass

Tyg **Grand Ronde Basalt**—Fine- to medium-grained basalt flows with few or no large crystals. Many flows are continuous for tens to hundreds of miles, indicating that the lava was very fluid and the land surface was flat

ROCKS OF LATE- AND POST-OROGENIC TRANSTENSION

EXTENSIONAL DEPOSITS

Tes **Extensional sedimentary rocks (early Oligocene and Eocene)**—Sandstone and conglomerate with subordinate shale deposited by streams in fault-bounded basins. About 52 to 40 million years ago, the Pacific Northwest slowly stretched and broke along faults. Blocks of the Earth's crust settled and tipped, forming low areas that quickly filled with sediment brought in by rivers and streams. Much of the extensional sandstone and shale contains leaf fossils. In some basins, swamps prevailed where thick layers of plant debris collected to become coal. Coal seams in these rocks fueled development of the North Cascades region in the late 1800s and early 1900s. Locally, mapped as Early extensional sedimentary rocks

Tees **Early extensional sedimentary rocks (middle and early Eocene)**—Mostly stream-deposited sandstone and conglomerate. The most extensive deposit is the Swauk Formation, wrapped around the Wenatchee block (figs. 4, 5, and 13, sheet 2). The Silver Pass Volcanic Member is locally interbedded in the Swauk Formation

Teev **Silver Pass Volcanic Member of Swauk Formation**—Mostly dacite and andesite flows and pyroclastic rocks erupted from early volcanoes of this extensional episode. [SPne]

Tev **Volcanic rocks (early Oligocene and Eocene)**—Mostly basalt and rhyolite flows, breccia, and tuff intermixed with some sandstone and conglomerate like unit Tes. Stretching and cracking of the crust allowed molten rock to reach the surface and erupt to form volcanoes that coalesced into extensive deposits of volcanic rock

OTHER ROCKS

Tei **Intrusive rocks (middle Eocene)**—Mostly granite and granodiorite, light-colored rocks rich in silica that crystallized in magma chambers beneath the volcanoes about 45 to 50 million years ago. Also molten rock was injected as dikes into the metamorphic rocks now known as the Skagit Gneiss Complex, but these dikes are too small to show at map scale. Not all geologists agree that the granite plutons are related to the extensional process in the North Cascades, as implied on this map. Cowan (2003) suggested that the Mount Pilchuck stock [SRsw] and Bald Mountain batholith [SRsw] were produced by subduction of a spreading ridge, that is, an oceanic ridge similar to a mid-ocean ridge (fig. 3), brought close to the subduction zone by plate motion

Trr **Raging River Formation (middle and early? Eocene)**—Shallow-marine and alluvial sandstone and shale. Fossils of ocean-dwelling animals distinguish the upper part of this unit from the stream-deposited sandstone and shale of contemporary extensional deposits. [SPnw]

OROGENIC AND PRE-OROGENIC ROCKS MOSTLY WEST OF STRAIGHT CREEK FAULT

ROCKS SOUTHWEST OF DARRINGTON-DEVILS MOUNTAIN FAULT ZONE

TKwb **Rocks of western mélange belt (middle Eocene to Late Cretaceous)**—Mostly pervasively foliated sandstone and semischist. Minor fine- to medium-cobble conglomerate, locally stretched. Commonly interbedded with argillite or phyllite. Includes chert, marble, greenstone, weakly metamorphosed diabase, gabbro, tonalite, and very rare serpentinized peridotite and dunite. Except for the partly metamorphosed igneous rocks (including peridotite and dunite), most of the components of the western mélange belt could have been part of a once-continuous pile of sandstone, shale, and rare volcanic rocks. Fossils indicate that these rocks were deposited in a Jurassic and Early Cretaceous ocean. Torn apart by subduction processes (fig. 14, sheet 2), the original rock layers or beds are no longer continuous. Marble blocks generally contain fossils much older (Permian; fig. 6) than the disrupted marine shale and sandstone and may be pieces of uplifted older beds that slid into the basin where the younger sediments were deposited

TKwg **Quartz Mountain stock (Middle Jurassic)**—Slightly metamorphosed tonalite and granodiorite. [SPse]

TKeb **Rocks of eastern mélange belt (middle Eocene to Late Cretaceous)**—Mostly mafic volcanic rocks and chert with subordinate sandstone and foliated sandstone, argillite, phyllitic argillite, and marble. Includes large masses of gabbro, metatonalite, and gneissic amphibolite. Locally contains serpentinite and serpentinized peridotite. Like the western mélange belt, the eastern mélange belt may have formed in a subduction zone. Its rock components range from Devonian to Late Cretaceous in age based on fossils and isotope ages. Large bodies of migmatitic gneiss within the mélange are locally mapped

TKebg **Migmatitic gneiss**—Highly mixed metamorphic and granitic rocks, with much amphibolite and gneiss and minor serpentine. These rocks make up the impressive summits of Mount Baring and Merchant and Gunn Peaks [SKne] (fig. 15, sheet 2). Hard amphibolite and gneiss stick out of the relatively softer, more easily eroded metasedimentary rocks that surround them. They are exotic blocks or knockers in the mélange displayed on a grand scale

ROCKS IN DARRINGTON-DEVILS MOUNTAIN FAULT ZONE

Helena-Haystack mélange (middle Eocene and (or) Late Cretaceous)—A mélange is a geologic formation of contrasting rock types all mixed together. This mélange contains blocks of rock that could not have formed in the same place as the matrix, the material that surrounds them. Geologists commonly call such blocks exotic. Mixing may have taken place on the ocean floor as a result of extensive submarine landsliding, in a subduction zone as the two plates ground material between them or in some other large fault zone. The components of this mélange suggest derivation from deep ocean floor; that is, they are fragments of original ophiolite layering (fig. 3). We map this unit as peridotite and serpentinite matrix and as blocks of resistant rock. [SRsw]

TKhm **Serpentinite**—Weak material in the mélange matrix tends to smear between blocks of stronger rock. In this mélange, the matrix is serpentinite derived from iron- and magnesium-rich rock (peridotite) that first crystallized in the Earth's mantle

TKhg **Blocks of resistant rock**—Metabasalt, metadiabase, and metagabbro (all called greenstone); rare chert; sandstone; phyllitic argillite; semischist; foliated metavolcanic rocks; amphibolite; and rare tonalite. Some blocks are pieces of the eastern mélange belt (see unit TKeb), and some are blocks of schist or phyllite from the Easton Metamorphic Suite of the Northwest Cascade

System (units Ked, Kes). These rocks are all exotic to the mantle-derived matrix surrounding them and many are exotic to each other. Whether exotic or not, blocks that are harder than the matrix tend to weather in relief and may be referred to as knockers (fig. 16, sheet 2)

ROCKS NORTHEAST OF DARRINGTON-DEVILS MOUNTAIN FAULT ZONE

Northwest Cascade System

[The Northwest Cascade System is mostly made up of huge fault-bounded slabs, called nappes (fig. 11). Some of these nappes were offset across the Straight Creek Fault and, thus, lie east of the fault in the southern part of the map area]

Rocks of Autochthon

KJn **Nooksack Formation (Early Cretaceous to Middle Jurassic)**—Massive to laminated black argillite and thick-bedded volcanic-lithic sandstone and pebble conglomerate. Described here as sedimentary rocks, although much of the unit is weakly metamorphosed. Originally, partly deposited on a submarine fan or fans not far from a volcanic arc. Locally shown as Wells Creek Volcanic Member. [MBnw]

Jnw **Wells Creek Volcanic Member (Middle Jurrassic)**—Incipiently recrystallized dacite, dacite breccia, dacitic tuff, and andesite with some argillite interbeds. [MBnw]

Welker Peak and Excelsior Nappes

KJb **Bell Pass mélange (Cretaceous to Late Jurassic)**—Disrupted argillite, slate, phyllite, sandstone, semischist, ribbon chert, and basalt with tectonic blocks of meta-igneous rocks, gneiss, schist, ultramafic rocks, and marble. See previously described Helena-Haystack mélange for characteristics of mélange. Locally divided into Yellow Aster Complex of Misch (1966), Twin Sisters Dunite of Ragan (1961, 1963), and Vedder Complex of Armstrong and others (1983). [MBsw]

KJya **Yellow Aster Complex of Misch (1966) (Paleozoic or older original age)**—Medium- to coarse-grained gneiss and associated weakly deformed granitic rock; rare marble. Includes serpentinite. Some gneiss is metamorphosed sedimentary rock containing zircons older than 1,800 million years, eroded from an ancient continent. [MBnw]

KJts **Twin Sisters Dunite of Ragan (1961, 1963)**—Dunite (made up of the mineral olivine) and other ultramafic rocks, locally metamorphosed to serpentinite by addition of water at a temperature below 500ºC. The Twin Sisters Dunite is a huge block of the Earth's mantle caught up in the mélange (fig. 8; Ragan, 1963). [MBsw]

KJv **Vedder Complex of Armstrong and others (1983) (pre-Permian original age)**—Metamorphic rocks derived from sedimentary and volcanic rocks of unknown age, but we know that they were older than the 250-million-year age of their metamorphism

Chilliwack River Terrane

JTrc **Cultus Formation of Brown and others (1987) (Early Jurassic and Late Triassic)**—Siltstone rich in volcanic rock fragments, sandstone, and argillite; mostly thin bedded to finely laminated. Also includes dacite and associated sedimentary rocks rich in volcanic rock fragments. Beds were deposited on the edges of a volcanic arc that flourished about 200 million years ago; this unit is the youngest part of the stack of rocks called the Chilliwack River terrane

PDc **Chilliwack Group of Cairnes (1944) (Permian, Carboniferous, and Devonian)**—Mostly well bedded gray to brown and black argillite and dark-colored sandstone with minor pebble conglomerate, marble, and rare chert. Also includes greenstone and basalt, andesite, dacite, volcanic breccia, and tuff. Deposits were associated with a long-lived volcanic arc or arcs that erupted from about 375 to 250 million years ago

Shuksan Nappe

Easton Terrane

Ket **Tonalite gneiss of Hicks Butte (Early Cretaceous)**—Lineated, medium-grained hornblende tonalite and tonalite gneiss. A deformed and metamorphosed igneous intrusive rock that was faulted against the Shuksan Greenschist while still at great depth in the Earth. [SPse]

Easton Metamorphic Suite—These fine-grained rocks are metamorphosed basalt (unit Kes) and mud and sand (unit Ked) from the deep ocean floor. The occurrence of blueschist indicates that these rocks were transported deep into the Earth and brought back up rapidly (in geologic time) before they had time to heat up much. Geologists interpret such a metamorphic history to subduction followed by rapid uplift and removal of the overlying rocks. The Easton Metamorphic Suite is made up of the Darrington Phyllite and Shuksan Greenschist. [SPse]

Ked **Darrington Phyllite (Early Cretaceous)**—Predominantly black phyllite, typically with abundant quartz veinlets; commonly complexly folded. Locally interlayered with unit Kes. Formed from the metamorphism of deep ocean mud and sand, which presumably was deposited on top of the basaltic ocean floor that became the Shuksan Greenschist. [SRsw]

Kes **Shuksan Greenschist (Early Cretaceous)**—Predominantly fine grained greenschist and (or) blueschist derived mostly from probable Jurassic ocean-floor basalt. Blueschist contains an unusual dark-blue amphibole. The crystals are typically very small and, even with a hand lens, are not easily distinguished. By trying to make artificial rocks containing the same minerals under a variety of conditions, geologists found that this blueschist must have formed at a depth of about 15 miles in the Earth and at a temperature of about 700°F, which is unusually cool for that depth. Usually, rocks buried so deeply become much hotter, and brown to black amphibole, such as hornblende, forms in metamorphosed basalt. [MBnw]

OROGENIC AND PRE-OROGENIC ROCKS EAST OF STRAIGHT CREEK FAULT

ROCKS UNIQUE TO WENATCHEE BLOCK

Ingalls Terrane

Jis **Ingalls terrane (Jurassic)**—Ultramafic rocks, including peridotite and foliated and massive serpentinite. These rocks are dark, heavy, and rich in iron and magnesium. Most ultramafic rocks initially form many miles below the Earth's surface during sea-floor spreading, where they constitute the lower layer of newly formed lithosphere (the upper, rigid, mantle; fig. 3). They commonly undergo metamorphic recrystallization at very high temperatures. Most ultramafic rocks only reach the surface of the Earth by way of complex crustal upheavals, in this case during collision of tectonic plates. By the time they reach the Earth's surface, the original iron-magnesium-silicon-oxide minerals that contain no water are commonly metamorphosed at lower temperatures to water-bearing serpentine minerals. Resistant blocks of igneous, meta-igneous, and sedimentary rocks are locally mapped in the serpentinite. [Wnw]

Jbi **Resistant blocks of igneous and meta-igneous rocks**—Gabbro, diabase, greenstone, and amphibolite derived from the ocean-floor crust that once overlay the ultramafic mantle. Some of these rocks have Jurassic radiometric ages

Jbs **Resistant blocks of sedimentary rocks**—Argillite, phyllite, metasandstone, and minor chert, metachert, and marble all derived from ocean floor sediments. Geologists call the assemblage of ocean floor and mantle rocks an ophiolite or an ophiolite assemblage (fig. 3)

Nason Terrane

Knmg **Nason Ridge Migmatitic Gneiss (Late Cretaceous)**—In southern part of outcrop area, mostly mixed light-colored gneiss interlayered with mica schist and amphibolite similar to the Chiwaukum Schist (unit Kncs). Many of the rocks are so mixed and variable with cross-cutting sills, dikes, and irregular bodies of light-colored granitic rocks that they are called migmatite. Grades northward into more uniform, mostly medium grained biotite gneiss with small red garnets. Rocks like this form deep in the crust during metamorphism. Melted rock invades more solid rock, commonly intruding along old bedding planes or other structures in the recrystallizing rocks. Most of the igneous material in this unit could be considered part of the stitching plutons (See Skagit Gneiss Complex, unit TKsg). [Cnw]

Kncs **Chiwaukum Schist (Late Cretaceous)**—Mostly well layered graphitic mica schist. Locally contains minerals that only form in aluminum-rich rocks, which suggests that the schist was once ocean floor mud rich in aluminum-rich clay minerals. Graphite, the mineral form of carbon, is the metamorphosed remains of organic matter in the original mud and imparts the dark color to many of these rocks. [Csw]

ROCKS IN WENATCHEE AND CHELAN BLOCKS

Terrane Overlap Units and Stitching Plutons

TKsg **Skagit Gneiss Complex (middle Eocene to Late Cretaceous)**—Mix of schist, amphibolite, and rare marble and ultramafic rocks mostly derived from marine sedimentary and volcanic rocks that is intruded by sills of igneous rocks, which are now metamorphosed to orthogneiss. The original schist, amphibolite, and marble may have been continuous with the Napeequa Schist (units TKns, Kns) and (or) the Cascade River Schist (units TKcs, Kcs) described below. Orthogneiss bodies range from a few centimeters thick in the layered gneisses to several kilometers thick in mapped bodies of orthogneiss. Many of these rocks are crosscut by a variety of lighter colored igneous dikes and are so mixed that they are called migmatite. These rocks were about 16 miles deep in the Earth when intruded by magma and metamorphosed about 75 to 90 million years ago. Metamorphism of these rocks continued until, or resumed at, about 45 million years ago when more light-colored magma invaded the rock. Locally shown as orthogneiss and orthogneiss of The Needle. [MBse]

TKso **Orthogneiss**—Gneissic hornblende-biotite tonalite. Relatively uniform granitic rock, but locally migmatitic with many crosscutting light-colored dikes

TKsn **Orthogneiss of The Needle**—Hornblende tonalite to granodiorite orthogneiss that appears to have originally crystallized about 220 million years ago with the Marblemount plutons (units TKmd, Kmd) but was thoroughly recrystallized about 75 to 90 million years ago. [MBse]

TKgo **Granodioritic orthogneiss (middle Eocene to Late Cretaceous)**—Mostly granodioritic orthogneiss but ranging to tonalite. Includes the Hidden Lake [SRne] and Foam Creek [SRse] stocks, the Eldorado Orthogneiss [MBse] (fig. 17, sheet 2), and the orthogneiss of Alma Creek [MBse]

Kt **Tonalitic plutons (Late Cretaceous)**—Mostly tonalite, gneissic tonalite, and tonalitic to granodioritic gneiss, with both hornblende and biotite. Includes the tonalitic gneiss of Bench Lake [SRne]; the Sloan Creek [SRse], Excelsior [SKne], Chaval [SRne], Tenpeak [SRse], Dirty Face [Cnw], and parts of the Bearcat Ridge [TWsw] and Entiat [Cne] plutons; the Clark Mountain [TWsw] and Grassy Point [SRse] stocks; the Mount Stuart batholith [Wnw]; the Beckler Peak stocks [SKse]; the eastern part of the Black Peak batholith; and minor bodies. Most of these rocks and the granodiorite plutons (unit Kg) were intruded and metamorphosed about 75 to 90 million years ago, but they lack evidence of continuing or younger metamorphism at about 45 million years ago as found in the rocks associated with the Skagit Gneiss Complex (unit TKsg)

Kg **Granodioritic plutons (Late Cretaceous)**—Mostly granodiorite and granodioritic orthogneiss ranging to tonalite. Includes the Cyclone Lake [SRne], Jordan Lakes [SRne], Sulphur Mountain [SRse], and High Pass [TWsw] plutons; the Downey Creek sill complex [SRne]; the light-colored gneiss of the Mad River terrane of Tabor and others (1987) (now Napeequa Schist, units TKns, Kns); and smaller bodies

Chelan Mountains Terrane

TKns, Kns **Napeequa Schist (middle Eocene to Late Cretaceous)**—Predominantly fine-grained hornblende-mica schist, fine-grained hornblende-rich schist, and amphibolite and quartz-rich schist, as well as minor gneiss, marble, and ultramafic rock. Most of these rocks were derived from deep ocean sediments and ocean-floor basalt. The quartz-rich schist is metamorphosed chert, a rock composed of the tiny siliceous shells of marine plankton. The age of the original oceanic rocks is uncertain, but comparison to unmetamorphosed fossil-bearing rocks in Canada suggests to many geologists the Napeequa Schist includes Permian and (or) Triassic rocks. Locally mapped as ultramafic rocks (units TKnu, Knu). [Tsw]

TKnu, Knu **Ultramafic rock**—Serpentinite and other rocks derived from the Earth's mantle. Mantle rocks generally lie beneath ocean floor basalt; but they may be mixed with oceanic sediments when mantle material is uplifted above a subduction zone and blocks slide onto the ocean floor

TKcs, Kcs **Cascade River Schist (middle Eocene to Late Cretaceous)**—Mostly fine grained, easily split green, brown, and black micaceous schist, as well as amphibolite, fine-grained gneiss, and metamorphosed conglomerate. Many of these rocks were derived from volcanic material erupted from the Late Triassic volcanic arc whose roots eventually crystallized as the

Marblemount plutons. The metamorphosed conglomerate (fig. 17) indicates that streams eroded the arc and delivered material to the ocean. [MBse]

TKmd, Kmd **Marblemount plutons (middle Eocene to Late Cretaceous)**—Meta-quartz diorite, metatonalite, and tonalitic gneiss; light-colored metatonalite dikes. These rocks (fig. 7) are metamorphosed plutons (crystallized magma chambers) that fed an arc of volcanoes about 220 million years ago (Late Triassic). Metamorphosed volcanic tuff in the Cascade River Schist (units TKcs, Kcs) is the same age, suggesting that the metamorphosed volcanic rocks in the Cascade River Schist are also derived from the Late Triassic volcanic arc. Locally mapped as Magic Mountain Gneiss. [MBse]

TKmm **Magic Mountain Gneiss (middle Eocene to Late Cretaceous)**—Light-colored chlorite-rich gneiss interlayered with greenschist. This well-layered rock looks like it was transformed by deep, hot metamorphism typical of other well-layered gneisses in the North Cascades, but its minerals indicate metamorphism occurred at relatively shallow depths and low temperatures. Geologists have argued the origin of the pronounced layering, but recent studies indicate that the light-colored gneiss layers are derived from igneous sills, originally the Marblemount magma, that intruded along weak bedding in the sedimentary rocks that elsewhere became the Cascade River Schist (units TKcs, Kcs). However it formed originally, the low-grade gneiss is unique in the North Cascades. [SRne]

Swakane Terrane

Kswg **Swakane Biotite Gneiss (Late Cretaceous)**—Well-layered biotite gneiss formed by metamorphism of sandstone. Zircons separated from the gneiss and analyzed for uranium and lead isotopes give ages of 1,600 million years, among the oldest ages found in the North Cascades. Although geologists debated for many years about the significance of the old zircons, the most recent work (Matzel, 2004) shows that the old zircons are accompanied by other, younger zircons merely 73 million years old. The old zircons are now thought to be grains eroded from much older rocks and deposited, along with the younger zircon grains, more recently than 73 million years ago. Not long after these grains were deposited, the sandstone was deeply buried by the rocks of the Chelan Mountains terrane that were thrust over it. The sandstone was metamorphosed and eventually unroofed (exposed) when the overlying rocks slid off during the extensional event. [Cse]

Terrane Uncertain

Kcxm **Chelan Migmatite Complex of Hopson and Mattinson (1994) (Cretaceous)**—Metatonalite, metabasite, and metaplutonic migmatite. A dome-shaped upwelling of deeply formed igneous material that appears to have pushed aside the schist and gneiss of the Chelan Mountains terrane. [Cne]

ROCKS UNIQUE TO ROSS LAKE FAULT ZONE

TKrb **Ruby Creek heterogeneous plutonic belt of Misch (1966) (middle Eocene to Late Cretaceous)**—Numerous small igneous intrusive bodies. Includes granitic igneous rocks similar to the Golden Horn batholith and darker tonalite similar to the Black Peak batholith. This complex mix of igneous material and dark phyllite may have been broken many times by movement in the Ross Lake Fault Zone. [RMsw]

TKsx **Skymo Complex of Wallace (1976) (middle Eocene to Late Cretaceous)**—Partially metamorphosed gabbro and ultramafic rock. These coarse-grained iron- and magnesium-rich rocks are unlike anything else in the North Cascades. Their original age is not known. [MBne]

TKm, Km **Metamorphosed rocks of Methow Ocean (middle Eocene to Late Cretaceous)**—Metamorphosed shale, sandstone, and conglomerate. Schist and metaconglomerate exposed from Easy Pass [RMsw] to the upper Twisp River [TWne] appear to be equivalent to rocks in the Pasayten Group (units Kps, Kpv), exposed farther east in the Methow block, in particular the conglomerates of the Virginian Ridge Formation of Barksdale (1975) [RMse]. On the west side of the upper Twisp River, metamorphosed conglomerate of the Virginian Ridge Formation overlies more highly metamorphosed rocks of the Napeequa Schist, indicating that the Methow block and the Chelan block, in spite of their grossly different histories, were together by mid-Cretaceous (Dragovich and others, 1997)

TKmo **Tonalitic orthogneiss (middle Eocene to Late Cretaceous)**—Gneissic light-colored biotite tonalite. This rock formed in much the same way as the orthogneiss in the Skagit Gneiss Complex (unit TKsg)

ROCKS IN METHOW BLOCK

Kpc **Pipestone Canyon Formation (Late Cretaceous)**—Conglomerate, feldspathic sandstone, and interbedded volcanic tuff and breccia. Along Pipestone Canyon, this small but scenic onlap accumulation of alluvial fans, debris flows, and volcanic deposits is eroded into interesting columns and overhangs. [Tne]

Onlap Assemblage and Stitching Plutons

Ktm **Tonalite plutons in Methow block (Late Cretaceous)**—Tonalite and granodiorite. Makes up large Pasayten dike [RMne] and Fawn Peak [RMse], Lost Peak [RMne], Rock Creek [RMnw], Chancellor [RMnw], and Barron [RMnw] stocks, as well as unnamed plutonic bodies. These rocks crystallized from magmas 70 to 90 million years ago. They are part of the same intrusive suite as the tonalitic orthogneiss plutons in the Wenatchee and Chelan blocks, but most have not been metamorphosed

Pasayten Group of Kiessling and Mahoney (1997) (Late Cretaceous)—Mostly river and volcano deposits formed on the site of the now-filled ancient Methow Ocean. Divided into volcanic and sedimentary rocks. [RMnw]

Kpv **Volcanic rocks**—Predominantly andesitic breccia and tuff; locally fluviatile maroon siltstone, sandstone, and conglomerate. About 90 million years ago, volcanoes erupted on the flood-plains of rivers that flowed over sediments of the former Methow Ocean, burying both the river deposits and the underlying Methow Ocean sediments under volcanic rocks. Fossil soils that developed on stream deposits associated with the volcanic rocks are oxidized, forming rocks with a distinctive maroon color

Kps **Sedimentary rocks**—Mostly sandstone, shale, and pebble conglomerate. As the ancient Methow Ocean filled with marine sediments, streams and rivers deposited sand, gravel, and mud on top of them (fig. 18). In a few areas, ocean deposits are interlayered with the stream deposits. Ultimately the stream deposits predominated

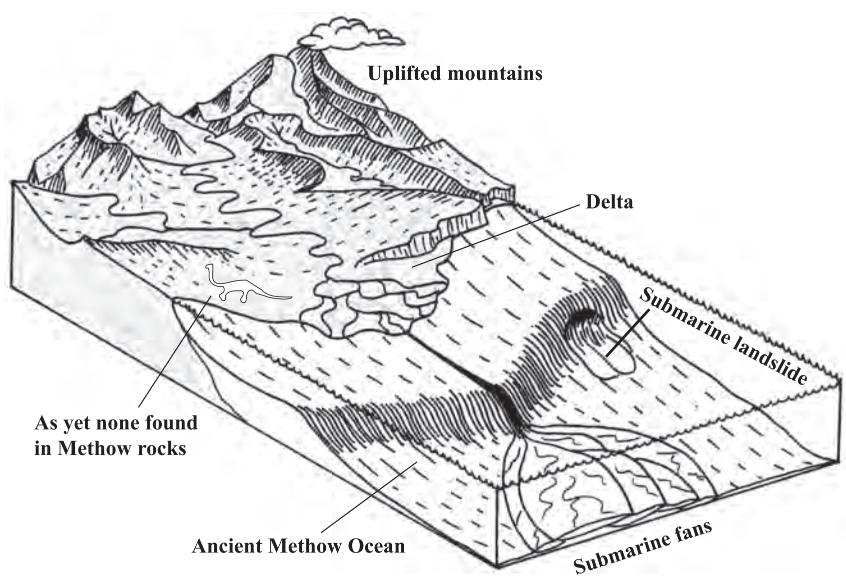

Figure 18. Sketch showing Cretaceous setting for accumulation of sediments that became rocks of Methow Ocean and younger depostis (after a drawing by David G. Howell).

Rocks of Methow Ocean and Onlap Assemblages

Ktf **Three Fools sequence of Haugerud and others (2002) (Cretaceous)**—Predominantly thick bedded sandstone, minor thin-bedded sandstone, argillite, and conglomerate deposited in deep-water submarine fans (fig. 19, sheet 2). Between 105 and 110 million years ago, upthrust Hozomeen Group rocks formed islands in the western part of the Methow Ocean. The weight of these islands caused the ocean to deepen. Occasional flows of sediment-rich water (turbidity currents), perhaps created by submarine landslides or storm waves, cascaded from the east and west into the depths to create these turbidite deposits. [RMnw]

KJos **Older sedimentary rocks (Early Cretaceous and Late Jurassic)**—Predominantly siltstone, minor sandstone, and conglomerate. Earliest deposits of the ancient Methow Ocean, which was relatively shallow at this time. In places, includes river deposits

Rocks of Methow Ocean floor

KJi **Tonalite intrusions (Early Cretaceous and Late Jurassic)**—Biotite-hornblende tonalite. Includes the Button Creek [RMse] and Alder Creek [Tne] stocks. Some of these stocks are fossil magma chambers of the Newby volcanic arc

Jnb **Newby Group of Mahoney and others (2002) (Late Jurassic)**—Volcanic and sedimentary rocks of an arc of volcanic islands. Composition varies widely; includes deep-marine argillite and extensive volcanic breccia and rhyolite. Locally mapped as metamorphosed rocks of McClure Mountain. [Tne]

Jnbm **Metamorphic rocks of McClure Mountain**—Schist metamorphosed from rocks of the Newby Group. [Tne]

Jl **Ladner Group of Mahoney (1993) (Middle Jurassic)**—Thin-bedded sandstone and shale with minor volcanic ash represents deposits of a volcanic island arc in an ocean older than the Methow Ocean

Hozomeen Terrane

MzPzh **Hozomeen Group (Mesozoic and Paleozoic)**—Ocean-floor basalt, deep-ocean sandstone and shale, and chert (fig. 20, sheet 2). Some of the basalt erupted at a mid-ocean ridge; much erupted at 220-million-year-old mid-ocean volcanic islands like Hawaii; and some may have erupted as part of a volcanic island arc. Mud, ooze formed of silica-rich plankton shells (radiolaria now cemented into ribbon chert), and some sand were deposited on top of the basalt. Many of these rocks are disrupted, broken, and mixed, probably by slumping on the submarine slopes of volcanic islands. [MBne]

ROCKS IN OKANOGAN BLOCK

Okanogan Terrane

Ktd **Tonalite and diorite (Late Cretaceous)**—Texas Creek [Tse] and Yockey Creek [Tse] stocks

Kog **Granite and granodiorite (Early Cretaceous)**—Medium- to coarse-grained biotite granite. Includes Cathedral batholith of Daly (1912). This magma invaded older metamorphic and granitic rocks of the Okanogan terrane 100 million years ago and remains undeformed (not squeezed or stretched into gneiss). The magmas of the Texas Creek and Yockey Creek stocks intruded later and also escaped deformation. This history contrasts with that of the Wenatchee and Chelan blocks of the North Cascades to the west

Kor **Remmel batholith (Early Cretaceous)**—Light-colored biotite tonalite and gneissic tonalite; local garnet-biotite tonalite and granodiorite. An unusually large body intruded about 110 million years ago. [RMne]

Kot **Older tonalite (Early Cretaceous)**—Gneissic tonalite with large splotchy biotite crystals; little-deformed hornblende-biotite tonalite

KJh **Hornblendic metamorphic rocks (Early Cretaceous and Jurassic)**—Amphibolite, hornblende-biotite schist, and biotite schist with layers of quartzite, calc-silicate schist, and marble. Metamorphosed at least 115 million years ago. Some of these rocks may have been marine sedimentary rocks (shale and limestone) and some may have been basalt, but their original depositional age is not known

KJog **Mylonitic granodiorite, gneissic trondhjemite, and banded gneiss (Early Cretaceous and Jurassic)**—Metamorphosed granitic rock, most with scattered layers and swirls richer in biotite. Some rock strongly sheared and (or) strongly layered

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GLOSSARY OF GEOLOGIC TERMINOLOGY

[See figure 6 for geologic ages. Glossary modified from Tabor and Haugerud, 1999, with permission from The Mountaineers]

A

age (geologic) Rock ages are established by the identification of key fossils or by radiometric dating of certain minerals. Ongoing extinction of plant and animal species and evolution of new species have led to assemblages of fossils that are diagnostic of distinct periods of time in the Earth's history. The basic fossil associations have been recognized since the early 1800s and are the source of age terms, such as Paleozoic, Mesozoic, Cretaceous, Tertiary, and Oligocene. In rocks where fossils are preserved, the identification of key fossils remains the most useful way to establish the age of the enclosing rocks.

Some elements in minerals, such as potassium, are made up of stable and unstable isotopes. The unstable isotopes break down at a constant rate, emitting particles from the atomic nuclei (radioactivity) and changing into a daughter element. The amounts of the radioactive isotope and its daughter products can be measured to establish the length of time since the rock formed. Radioactive elements-daughters commonly used to determine ages in rocks and minerals include uranium-lead, rubidium-strontium, and potassium-argon.

alaskite Intrusive igneous rock similar to granite or granodiorite but containing less than five percent biotite and (or) hornblende. Strikingly light colored rock.

alluvium, alluvial fan Sand, gravel, and silt deposited by rivers, streams, and debris flows in a valley bottom. A debris flow is a flowing mixture of mud, rock debris, and water. An alluvial fan is a cone-shaped accumulation of sediment formed where a side stream empties onto a relatively flat valley floor.

amphibole A family of silicate minerals forming prismatic or needle-like crystals. Amphibole minerals generally contain iron, magnesium, calcium, and aluminum in varying amounts with water. Hornblende always contains aluminum and is the most common dark-green to black variety of amphibole; it forms in many igneous and metamorphic rocks. Blue amphibole contains sodium and, of course, is bluish in color.

amphibolite A metamorphic rock most commonly derived from basalt; mostly made of hornblende and plagioclase.

andesite Fine-grained, generally dark colored, volcanic igneous rock containing more silica than basalt (fig. 21). Commonly includes visible crystals of plagioclase feldspar. Generally occurs in lava flows but also as dikes. The most common rock in volcanic arcs.

antiformal fold An arch-like, upright fold in layered rocks. Commonly sedimentary rocks in an anticline are still in the order of deposition, oldest at the bottom, youngest at the top. If the fold looks like an anticline but the order of deposition is not known, such as in some layered metamorphic rocks, the fold is antiformal. A synformal fold is arched downward. An overturned antiformal fold is on its side.

arc *See* volcanic arc.

argillite Fine-grained sedimentary rocks, such as shale, mudstone, siltstone, and claystone that do not split easily along bedding planes. Commonly black; typically compact.

ash *See* tuff.

ash-flow tuff *See* rhyolite.

autochthon A terrane or structural block that has not moved from its place of origin. Because of the constant motion of tectonic plates that make up the Earth's crust, this centuries-old term may only be useful for young terranes.

B

banded gneiss *See* gneiss.

basalt Very fine grained, generally black, volcanic igneous rock relatively rich in iron, magnesium, and calcium. Generally occurs as lava flows, but also as dikes (fig. 21).

basin A low area where sediments accumulate, such as an ocean basin or a river basin.

batholith Very large mass of slowly cooled, intrusive igneous rock such as granite. A mass of intrusive rock must be at least 50 square miles in exposed area to be called a batholith. See pluton and stock.

bedding, bedded Layers in a sedimentary rock. Beds are distinguished from each other by visible differences in grain size and composition. Subtle changes, such as beds richer in iron-oxide that appear red, help distinguish bedding. Most beds are deposited essentially horizontally.

bedrock The older, more solid rock that lies beneath loose materials, such as soils and river gravels.

biotite *See* mica.

block, structural block A part of the Earth's crust with some geologic coherence and separated by faults from other blocks. Generally defined for descriptive purposes. Whereas the rocks of a terrane share a common depositional or intrusive history, a structural block may be defined by shared late history of metamorphism, or lack of metamorphism, or by folding and faulting. One terrane may occur in several structural blocks, and a block may include more than one terrane.

blueschist Metamorphic rock rich in blue amphibole. *See* amphibole.

breccia, volcanic breccia Rock made of angular fragments of other rocks. Volcanic breccia is made of volcanic rock fragments generally blown from a volcano during eruption or eroded from it.

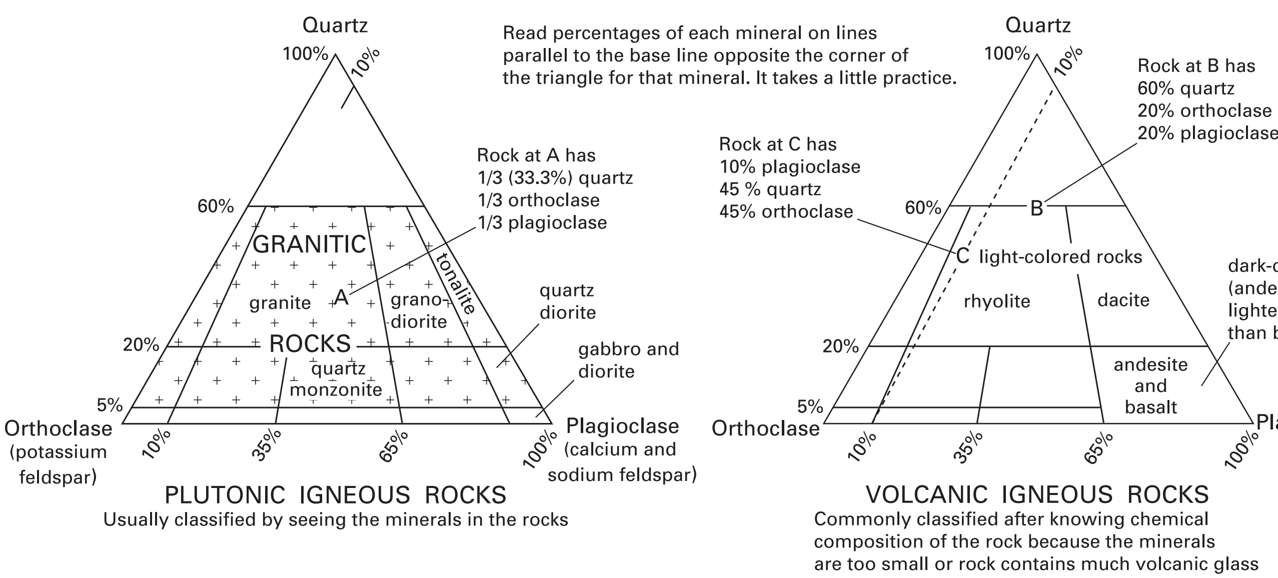

Figure 21. Ternary diagrams showing classification of igneous rocks by percent content of light-colored minerals (shown at corners of triangular diagrams). Dark minerals like biotite and hornblende are not included in percentage calculation. All rocks in patterned area of plutonic triangle can be called granitic because they resemble granite. Only some rock names are shown.

C

caldera Large, generally circular, fault-bounded depression caused by the withdrawal of magma from the crust below a volcano or volcanoes. Commonly, magma is withdrawn by explosive eruptions (like Krakatoa) and falls back to Earth as volcanic ash.

chert, ribbon chert Sedimentary rock made of extremely fine grained quartz. Usually made of millions of globular siliceous skeletons of tiny marine plankton called radiolarians, which collect on the ocean floor. Ribbon chert is chert and shale in thin alternating beds that resemble parallel ribbons stretched across a rock exposure.

chlorite Family of platy silicate minerals containing various amounts of magnesium, iron, aluminum, and water, as well as small amounts of other elements. Some mineralogists include chorite in the mica family because the crystals form small flakes. Generally formed by metamorphism of other minerals at moderate temperature (300–700ºF). Commonly green.

clay Family of silicate minerals containing various amounts of aluminum, potassium, and sodium, as well as water. Generally forms platy crystals too small to be seen even with a microscope. May form at room temperature and is a common product of rock weathering, especially from rock containing abundant feldspar. The term "clay" is also used to refer to very small sedimentary grains, whether or not they really are made of clay minerals.

conglomerate Sedimentary rock made of pebbles, cobbles, and boulders, usually mixed with finer grains and fragments of rock. To qualify as a conglomerate, some of the fragments must be at least 2 mm (about 1/13th inch) across.

Cordilleran Ice Sheet A very large glacier or ice cap that grew in western North America during the Pleistocene Epoch, forming in Canada and covering much of British Columbia, Alaska, northern Washington and Idaho, and western Montana. The Cordilleran Ice Sheet formed and then disappeared several times during the 2,000,000 years of the Pleistocene Epoch.

crust Outermost more-rigid layer of Earth, varying from about 3 km thick under the oceans to as much as 50 km thick under the continents. Richer in silica and alumina than the underlying mantle. *See* figure 3.

crystal Atoms in a regular, repeating arrangement. Crystals have specific physical properties that help identify them. In contrast, glass has no regular arrangement of atoms and is not a crystal. All minerals are crystals.

D

dacite Generally light colored volcanic rock; chemically the same as plutonic rocks, such as granodiorite and tonalite (fig. 21).

diabase A dark-colored plutonic rock like gabbro but finer grained.

dike Tabular body of igneous rock formed where magma fills a crack in pre-existing rock. A sill is a dike that parallels sedimentary bedding or metamorphic foliation.

diorite Intrusive igneous rock made of plagioclase feldspar, amphibole, and (or) pyroxene. Similar to gabbro only not as dark and contains less iron and magnesium (fig. 21).

drift Loose deposits on the surface of the earth. Commonly used when referring to glacial drift, which is deposited by a glacier. Glacial drift may be deposited directly from melting ice or by water issuing from the melting ice.

dunite *See* ultramafic rock.

E

element In this pamphlet, mostly refers to chemical elements, the fundamental atoms or building blocks that make up the physical universe. Iron, copper, silicon, and oxygen are examples of elements.

epidote—Family of silicate minerals mostly containing calcium, aluminum, iron, and magnesium, as well as water. Apple green epidote generally forms small, stubby, prismatic crystals. Most common in metamorphic rocks, but some epidote forms in igneous plutons that crystallize very deep in the Earth's crust.

exotic terrane *See* terrane.

extension The process of stretching the Earth's crust. Usually cracks (faults) form, and some blocks sink to create sedimentary basins. *See* transtension.

F

fault Crack in the Earth's crust where the rocks on one side of the break move relative to the rocks on the other. Abrupt movements on faults cause earthquakes. Where the crack is roughly vertical, a high-angle fault, the blocks may move up or down relative to each other. The blocks move mostly sideways along a strike-slip fault. If the fault is inclined at a low angle to the Earth's surface and rock on the upper side of the fault moves up and over rock on the lower side, it is a thrust fault; if rock on the upper side moves down and away from rock on the lower side, it is a low-angle normal fault.

feldspar Family of silicate minerals containing varying amounts of aluminum, potassium, sodium, and calcium. Potassium feldspars contain considerable potassium. Plagioclase feldspars contain considerable sodium and calcium. Feldspar crystals are stubby prisms, generally white (plagioclase) or pink (potassium feldspar), and look glassy or like porcelain.

flood basalt Very extensive accumulations of mostly flat lying basalt flows, probably erupted from fissures.

fluviatile Related to a stream or river. Fluviatile rocks come from sediments deposited by a river or stream.

foliation Rock structure produced by the parallel arrangement of minerals—especially platy minerals such as micas—like pages in a book or leaves on the ground. Foliated rocks tend to break along the foliation to form slabs. Mostly found in metamorphic rocks.

formation Refers to a particular rock deposit, usually layered volcanic or sedimentary rocks or their metamorphosed equivalents. Capitalized when used as part of a formal geologic name, such as the Nooksack Formation.

fossil In rocks, petrified remains of plants or animals or a structure testifying to the former presence of plants or animals. May be used metaphorically for geologic structure, such as fossil magma chamber.

Fraser Glaciation Last major glaciation of the Pacific Northwest, lasting from about 25,000 to 10,000 years ago. The Cordilleran Ice Sheet extended into the Puget Sound area from about 17,000 to 13,000 years ago and, in the North Cascades, covered all but the highest peaks. In contrast, the alpine glaciers of the North Cascades reached their maximum about 22,000 to 18,000 years ago.

G

gabbro An igneous rock made of calcium-rich plagioclase mixed with amphibole or pyroxene. A dark, coarse-grained rock chemically equivalent to basalt (fig. 21).

garnet Family of silicate minerals containing varying amounts of iron, magnesium, manganese, calcium, and aluminum. Schist and gneiss commonly contain garnets, which look like tiny, glassy red spheres but are really dodecahedrons.

geologic age *See* age.

glacial moraine *See* moraine.

glacier, glaciation Large mass of ice formed by compaction and recrystallization of snow that survives from year to year and deforms under its own weight. Valley glaciers form on mountains and generally flow down stream valleys. Ice sheets are extensive and extremely thick; they spread in all directions regardless of underlying landform. Glaciation refers to formation, movement, and recession of glaciers.

glass, volcanic glass In rocks, quickly chilled lava that did not form mineral crystals. *See* crystal.

gneiss, banded gneiss A light-colored metamorphic rock containing foliation or lineation but including granitic minerals and having the look of a granitic rock. Feldspar is prominent. Banded gneiss is made of alternating layers of dark schist or amphibolite and light granitic gneiss.

granite A coarse-grained igneous rock with considerable potassium feldspar, as well as quartz and subordinate plagioclase feldspar, in visible crystals. Usually contains biotite and may include hornblende (fig. 21).

granitic rock A general term for igneous rock that looks like granite. Includes quartz diorite, tonalite, granodiorite, and granite (fig. 21). All granitic rocks are light colored; feldspar and quartz are visible.

granodiorite A coarse-grained igneous rock with more plagioclase than potassium feldspar; otherwise similar to granite (fig. 21).

greenschist Same as greenstone except that deformation has aligned platy and needle-shaped minerals.

greenstone A metamorphic rock derived from basalt or chemically equivalent rock, such as gabbro. Greenstone contains sodium-rich plagioclase feldspar, chlorite, and epidote, as well as quartz. May include green amphibole. Chlorite, epidote, and green amphibole provide the green color.

H

hornblende *See* amphibole.

I

ice cap, ice sheet *See* Cordilleran Ice Sheet.

igneous rock Rock formed by crystallization of molten rock (magma). Plutonic igneous rocks form at depth within the Earth and crystallize slowly, forming coarse crystals. In contrast, volcanic igneous rocks form at or near the Earth's surface and crystallize rapidly, forming fine crystals.

intrusion Usually an igneous rock that was intruded as a fluid (magma) into pre-existing rocks. Dikes, sills, and batholiths are differently shaped intrusions.

intrusive Refers to an igneous rock that intruded pre-existing rocks. Contrast with volcanic rock on the Earth's surface, which is called extrusive igneous rock.

isotope, isotopic age *See* age.

J

jökulhlaup An Icelandic term for a glacial outburst flood. Some glacier-dammed lakes grow until the lake is deep enough to float a portion of the glacier dam and the dam fails, releasing a flood. This process can happen repeatedly.

L

lahar Sand and gravel deposited by mudflows mostly caused by turbulent eruption of hot volcanic debris onto ice, snow, or water.

laminated *See* shale.

landslide Any piece of the Earth's crust that slid downhill. May be made of rock, soil, and alluvium (or votes).

lava Magma that flows onto the Earth's surface.

limestone A rock made of the mineral calcite (calcium carbonate). Commonly formed from the shells of marine creatures.

lithosphere More rigid upper part of the Earth. Includes the crust and the upper part of the mantle. *See* fig. 3.

low-angle normal fault *See* fault.

M

mafic Refers to a rock rich in magnesium and iron. Basalt and all its metamorphic derivatives are mafic rocks. Biotite and hornblende are mafic minerals. Ultramafic rocks contain more magnesium and iron than mafic rocks.

magma, magma chamber Melted rock formed within the Earth. When magma pours onto the Earth's surface, it is called lava. A magma chamber is an accumulation of melted rock within the Earth that may feed a volcano and eventually solidify, that is crystallize, into a pluton.

magmatic arc *See* volcanic arc.

mantle Interior part of the Earth surrounding the core and below the crust. Made of dense iron- and magnesium-rich (ultramafic) rock, such as dunite and peridotite. *See* figure 3.

marble Metamorphic rock of calcium carbonate recrystallized from limestone.

massive In geology, uniform texture or structure without layering or alignment of minerals, such as bedding or foliation.

matrix Finer grained material surrounding coarser constituents. In a conglomerate, the sand surrounding pebbles; in a basalt, the very fine crystals and (or) volcanic glass surrounding large mineral crystals. *See* also mélange.

mélange Mixture of rocks formed by landsliding or repeated faulting that brings different rock types together. Usually consists of a matrix of weak material, like shale or serpentinite, containing blocks of harder exotic rocks, such as basalt, limestone, or gneiss.

metamorphic rock, "meta" Changed rocks. Rocks that are buried deep in the Earth are recrystallized by the increased pressure and temperature into new rocks containing different minerals or textures from the original rock. Recrystallization is a chemical reaction; the metamorphic rock does not melt. The prefix "meta" applied to igneous and sedimentary rock names indicates that the rocks were changed, or metamorphosed, to some degree but generally retain some of the original rock characteristics (metatonalite, metavolcanic, metasandstone).

mica, micaceous Group of silicate minerals composed of varying amounts of aluminum, potassium, magnesium, and iron mixed with water. All micas form flat, plate-like crystals that break, or cleave, into smooth flakes. Biotite is dark, black, or brown mica. Muscovite is light-colored or clear mica, sometimes called eisenglass when it occurs in large, useful flakes. Micaceous: containing mica.

mid-ocean ridge Major Earth structure where tectonic plates moving away from each other allow magma to well up from the mantle and erupt on the ocean floor. *See* figure 3.

migmatite Mixed igneous-metamorphic rock. Migmatite is usually conspicuously mixed light- and dark-colored rock, generally formed of dark schist and (or) gneiss and light igneous intrusive dikes and sills; it looks like the rock was mixed while it was still hot enough to be plastic.

mineral A naturally occurring element, chemical compound, or limited mixture of chemical compounds. Minerals generally form crystals and have specific physical and chemical properties that can be used to identify them.

moraine A hill- or ridge-like pile of rock rubble located on or deposited by a glacier. (Till with attitude).

mudflow A landslide containing enough water to flow, carrying abundant mud, debris, and rock.

muscovite *See* mica.

N

nappe *See* thrust plate.

nunatak Hill or mountain isolated by a surrounding glacier (fig. 9).

O

oceanic rock Rock formed in the ocean, without evidence of nearby land. Includes fine-grained sedimentary rocks deposited on the ocean floor, as well as basalt of the oceanic crust. Commonly associated with slices of the underlying mantle (ultramafic rocks).

olivine Silicate mineral containing iron and magnesium. Glassy-green and formed at high temperature. Common in basalt, especially ocean-floor basalt, and in ultramafic rocks. Gem-quality olivine is called peridot. Rock rich in olivine is called peridotite. Rock made entirely of olivine is called dunite.

onlap assemblage Generally, stratified rocks deposited on two or more exotic terranes, showing the terranes were adjacent when the younger rocks were deposited.

ophiolite, ophiolite assemblage An assemblage of rocks characteristic of origin at an ocean spreading center (fig. 3). Contains remnants of the three layers forming oceanic lithosphere, from top to bottom: (1) deep ocean sedimentary rocks that are primarily accumulations of organic debris, like chert, but also shale and sandstone; (2) ocean-floor basaltic rocks, including pillow basalt, sheeted dikes, and massive gabbro; and (3) ultramafic rock, commonly serpentinite, derived from the upper mantle. Ophiolite assemblages are commonly torn apart (dismembered) by faulting before we see them on land.

orthogneiss Gneiss formed by squeezing (deformation and commonly some recrystallization, that is, metamorphism) of a granitic igneous plutonic rock.

outwash Meltwater issuing from a glacier; sometimes used colloquially by geologists to refer to sand, silt, and gravel deposited by glacial meltwater streams.

P

peridotite *See* ultramafic rock.

phyllite A very fine grained, foliated metamorphic rock, generally derived from shale or siltstone. Phyllite is usually black or dark gray; the foliation is commonly crinkled or wavy (folded). Differs from less recrystallized slate by its sheen, which is produced by barely visible flakes of mica.

pillow basalt Basalt erupted underwater displaying bulbous, pillow-like structures. The first magma (lava) oozing from a crack in the ocean is quickly chilled to a bulbous welt in a roll or bolster-like form. This hardened roll cracks and new hot lava oozes out. A continuation of this process builds up a pile of elongate rolls. Later erosion of this pile reveals the rolls end on, looking like pillows.

plagioclase *See* feldspar.

plankton Generally tiny animals or plants that live floating in water.

plate *See* tectonic plate.

pluton Body of igneous rock formed by solidified, or crystallized, magma deep in the Earth. Batholiths are made of one or more plutons. Stocks are generally single plutons; dikes and sills are not normally considered plutons unless they are very big.

protolith Original rock before metamorphism. Commonly used in reference to age. The protolith age of a mica schist would refer to the depositional age of the shale which was metamorphosed to schist.

pumice A frothy, light-weight igneous rock, commonly mostly volcanic glass and bubbles. Some pumice is so light that it floats.

pyroclastic rock Rock formed from lava fragments and crystals blown from a volcano. Commonly rich in tiny fragments of volcanic glass.

pyroxene Family of silicate minerals containing iron, magnesium, and calcium in varying amounts. The most common variety, augite, also contains aluminum. Generally forms very dark green to black stubby prisms. Pyroxenes are similar in composition to amphiboles but lack water.

Q

quartz A crystalline form of silicon dioxide (SiO_2, also called silica). One of the most common minerals in the Earth's crust (and in New Age boutiques). Crystals are clear, glassy, six-sided prisms. Looks dark and glassy in igneous rocks. Commonly milky white in veins.

quartz diorite Intrusive igneous rock made of plagioclase feldspar, quartz, and amphibole or biotite. Similar to diorite but contains some quartz and is not as dark (fig. 21).

R

radiometric age *See* age.

recrystallize, recrystallization *See* metamorphic rock.

rhyolite A volcanic rock chemically equivalent to its plutonic counterpart, granite. Usually light colored and very fine grained. May be glassy and dark colored. May have visible crystals of quartz and (or) feldspar dispersed in a white, green, or pink groundmass or matrix. Rhyolite commonly erupts in a violent gas-charged cloud of glass and crystal fragments that settle and flow rapidly down slope as an ashflow tuff.

ribbon chert *See* chert.

rock formation *See* formation.

S

sandstone Rock made of sand grains, mostly quartz and feldspar derived from erosion of older rocks.

schist Conspicuously foliated metamorphic rock, usually derived from fine-grained sedimentary rock such as shale. Mica schist is rich in mica, such as biotite and (or) muscovite.

sedimentary rock Rock formed from pieces of pre-existing rocks that accumulated on the Earth's surface. Most consist of small grains once transported by water. Also refers to rocks made of organic remains of animals or plants, such as chert, limestone, and coal. Visible variations in composition and (or) grain size form sedimentary bedding.

semischist A metasandstone in which the sand grains are flattened and aligned to give the rock a schist-like appearance, although metamorphic mineral growth may be minimal or absent.

serpentine, serpentinite A family of silicate minerals rich in magnesium and water, derived from low-temperature metamorphism of pyroxene and olivine. Serpentinite is a rock made of serpentine minerals and is formed by metamorphism of ultramafic rock. Serpentine minerals are commonly light to dark green, greasy looking, and slick to the touch.

shale Sedimentary rock derived from mud. Commonly finely bedded (laminated). Most particles in shale are clay minerals, mixed with tiny grains of quartz eroded from pre-existing rocks.

silica The chemical compound SiO_2. *See* quartz.

silicate Refers to the chemical unit silicon tetroxide, SiO_4, that is the fundamental building block of silicate minerals. Silicate minerals form most rocks we see at the Earth's surface.

siliceous Generally refers to a rock rich in silica (SiO_2).

sill *See* dike.

silt Fine particles of rock in a size range between sand and clay. Rock dust.

slate Metamorphic rock characterized by closely spaced parallel cracks formed by deformation (generally squeezing) that forces pre-existing minerals into parallel positions, aligned with the cracks. With further metamorphism, slate becomes phyllite.

stade A period of time within a glaciation that is characterized by more extensive ice and thus inferred to have a colder and (or) wetter climate. Stades are separated by interstades, during which ice is less extensive.

stitching plutons Plutons that intrude adjoining tectonic terranes after the terranes were faulted together. The plutons do not really stitch the terranes together, but they help record when terranes were juxtaposed.

stock Relatively small globular- or column-shaped body of plutonic igneous rock. Smaller than a batholith.

subduction, subduction zone Process of one crustal plate sliding down and below another crustal plate as the two converge (fig. 3). The subduction zone is the boundary between the two plates, a giant thrust fault.

submarine fan Fan- or cone-shaped accumulation of sedimentary debris—sand, gravel, mud—under the ocean along the edge of the land, either a continent or a volcanic arc. Submarine fans may be a few miles to a hundred or more miles across.

T

talus Pile of rock rubble below a cliff or chute.

tectonic plate Very large, rigid piece of the Earth's lithosphere that is separated from adjoining tectonic plates by spreading centers, transform faults, and (or) subduction zones. Seven plates (African, North American, South American, Eurasian, Indo-Australian, Pacific, and Antarctic) underlie most of the Earth's surface. The Earth's tectonic plates are constantly moving at relative velocities of a few inches per year or less.

terrace A level or near-level area of land above a body of water and separated from it by a steep slope. A terrace may be underlain by river deposits such as gravel or sand, or it could be cut on bedrock by the river. The terrace records a time when the river flowed at a higher level. A glacial terrace or outwash terrace was formed by a stream or river issuing from an upstream glacier.

terrane, tectonic terrane, exotic terrane A rock formation or assemblage of rock formations that share a common geologic history. A geologic terrane (or tectonic terrane) is distinguished from neighboring terranes by its different history. A terrane must be separated from its neighbors by faults. An exotic terrane was transported to its present location from some great distance.

till Unsorted, unstratified rock rubble or debris carried on and (or) deposited by a glacier.

thrust fault *See* fault.

thrust plate—Slab of rock, generally the size of a mountain or larger, bounded by two thrust faults.

tonalite Intrusive igneous rock made of plagioclase feldspar, quartz, and amphibole or biotite. May be similar to diorite but is not as dark and contains considerable quartz; chemically, has less calcium, iron, and magnesium (fig. 21).

transtension Deformation of Earth's crust that indicates crust was stretched (extended) at the same it was displaced along major strike-slip faults. *See* fault.

trondhjemite A light-colored tonalite with very few crystals of biotite and (or) hornblende. Analogous to alaskite.

tuff Rock made of volcanic ash (volcanic rock fragments and mineral crystal fragments that are mostly smaller than 0.25 inches across). Volcanic ash is commonly composed of fragments of volcanic glass and crystals, formed by the explosive frothing of magma during a violent volcanic eruption.

turbidite, turbidity current Sedimentary rock deposited under water from a dense slurry of sand and mud that flowed downslope (turbidity current), most commonly on a submarine fan. Characterized by beds that have a diminishing grain size from bottom to top (graded beds); the heaviest particles settle first.

U

ultramafic rock A dense rock very rich in iron and magnesium that contains much less silicon and aluminum than most crustal rocks. Igneous varieties are peridotite, made of olivine and pyroxene, and dunite, composed only of olivine. A common metamorphic variety is serpentinite. Most ultramafic rocks come from the Earth's mantle.

unconformity, angular unconformity The contact between older rocks and younger sedimentary rocks, where erosion removed some of the older rocks before deposition of the younger rocks. An unconformity represents a time gap in the geologic record. An angular unconformity, where there is an angle between the truncated older beds and the overlying younger beds, shows that the older rocks were deformed and eroded before the younger sedimentary rocks were deposited (fig. 10).

V

vein Tabular rock filling a generally small crack, such as a quartz vein. A product of chemical precipitation from a watery solution, in contrast to a dike crystallized from magma, although gradations exist.

volcanic arc, volcanic island arc Arcuate chain of volcanoes formed above a subducting plate. The volcanic arc forms where the descending plate becomes hot enough to release water and gases that rise into the overlying mantle and cause it to melt. Arc rocks are mostly volcanic rocks from the volcanoes and sedimentary rocks made of eroded debris from the volcanoes. Melted rock that crystallizes at depth becomes plutons, such as batholiths. Essentially synonymous with magmatic arc, which specifically includes the plutons under the volcanoes.

volcanic ash *See* tuff.

volcanic glass *See* glass.

volcanic rock Rocks formed at or very near the Earth's surface by the solidification of magma. Volcanoes produce volcanic rock.

W

weathering Process of rock alteration and degradation on the Earth's surface. Caused by chemical changes induced by water and organic acids from plants, as well as by mechanical processes such as water in cracks freezing and expanding or temperature changes that expand and shrink individual minerals enough to break them apart

Z

zircon Mineral composed of zirconium, silicon, and oxygen (zirconium silicate). Generally glassy looking, microscopic, four-sided prisms. Most commonly formed in igneous rocks. Uranium is a common impurity. Often the age of a rock is determined by analysis of radioactive uranium and its daughter product, lead, contained in zircon crystals (see age).