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Effects of Cenozoic subduction along the outboard margin of the Northern Cordillera: Derived from e-book on the Northern Cordillera (Alaska and Western Canada) and adjacent marine areas

Warren J. Nokleberg¹, David W. Scholl¹, Thomas K. Bundtzen², and David B. Stone³

¹U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA

²Pacific Rim Geological Consulting, P.O. Box 81906, Fairbanks, Alaska 99708, USA

³Department of Geology and Geophysics, University of Alaska, P.O. Box 755940, Fairbanks, Alaska 99775, USA

ABSTRACT

This article describes the regional effects of Cenozoic subduction along the outboard margin of the Northern Cordillera (Alaska, USA, and Western Canada), and thereby acquaints the reader with several chapters of the e-book *Dynamic Geology of the Northern Cordillera (Alaska, Western Canada, and Adjacent Marine Areas)*. This article and the e-book are written for earth-science students and teachers. The level of writing for the article and the source e-book is that of popular science magazines, and readers are encouraged to share this article with students and laypersons.

The main thrust of the article is to present and describe a suite of ten regional topographic, bathymetric, and geologic maps, and two figures portraying deep-crustal sections that illustrate the regional effects of Cenozoic subduction along the outboard margin of the North American Cordillera. The regional maps and cross sections are described in a way that a teacher might describe a map to students.

Cenozoic subduction along the margin of the Northern Cordillera resulted in the formation of the following: (1) underthrusting of terranes and oceanic lithosphere beneath Southern Alaska; (2) landscapes, including narrow continental shelves along Southern and Southeastern Alaska and Western Canada (the Canadian Cordillera) and continental-margin mountain ranges, including the Alaska Peninsula, Chugach Range, Saint Elias Mountains, and Cascade Mountains; (3) sedimentary basins; (4) an array of active continental

strike-slip and thrust faults (inboard of subduction zones); (5) earthquake belts related to subduction of terranes and oceanic plates; (6) active volcanoes, including continental-margin arcs (the Aleutian, Wrangell, and Cascade Arcs) linked to subduction zones, and interior volcanic belts related to strike-slip faulting or to hot spots; (7) lode and placer mineral deposits related to continental margin arcs or subduction of oceanic ridges; (8) hot springs related to continental-margin arcs; (9) plate movements as recorded from GPS measurements; and (10) underthrusting of terranes and oceanic lithosphere beneath the Northern Cordillera.

INTRODUCTION

This article, written for the earth science-inclined layperson, describes the effects of Cenozoic subduction along the margin of the Northern Cordillera (Alaska, USA, and Western Canada). The article is synthesized from: (1) several chapters of the e-book, *Dynamic Geology of the Northern Cordillera (Alaska and Western Canada) and Adjacent Marine Areas: Tectonics, Hazards, and Resources* (Nokleberg et al., 2017a), (2) the published and unpublished studies of the authors, and (3) research articles listed in the e-book. The authors each have several decades of experience in federal and state geological surveys, universities, and private companies.

The contribution is built around 12 page-size figures, including 10 topographic, bathymetric, geologic, and geophysical maps, and 2 figures portraying deep-crustal cross sections. Together,

the maps and cross sections, and their descriptions, illustrate the effects of Cenozoic subduction of oceanic lithosphere and mid-ocean ridges in the region.

Because the article and the source e-book describe major geologic features for an important region of the globe, they should be valuable to students and teachers at the high-school and undergraduate college levels. A major aid to understanding the dynamic geology of the region is learning earth science terms, including the general parts of the geologic time scale (Walker et al., 2018). This paper is largely concerned with geologic events of the Cenozoic Era (66 million years ago [Ma] to the Present), but it is also occasionally necessary to discuss the Late Cretaceous Period (100–66 Ma). In addition, this paper deals with other geologic time periods in the Cenozoic Era for which the reader will need to understand the geologic time scale. We refer unfamiliar readers to primary references in a general source like *Wikipedia*, to learn more about the geologic time scale and for definitions of unfamiliar terms.

WHAT ARE THE NORTHERN CORDILLERA AND ADJACENT MARINE AREAS?

The first topic that a geoscientist wants to know about an area is its geography. Figure 1 (Nokleberg, 2017b) illustrates the Northern Cordillera as the region of Alaska, Western Canada, and the Pacific Northwest, USA. Figure 1 also displays marine areas adjacent to the western and southern margins

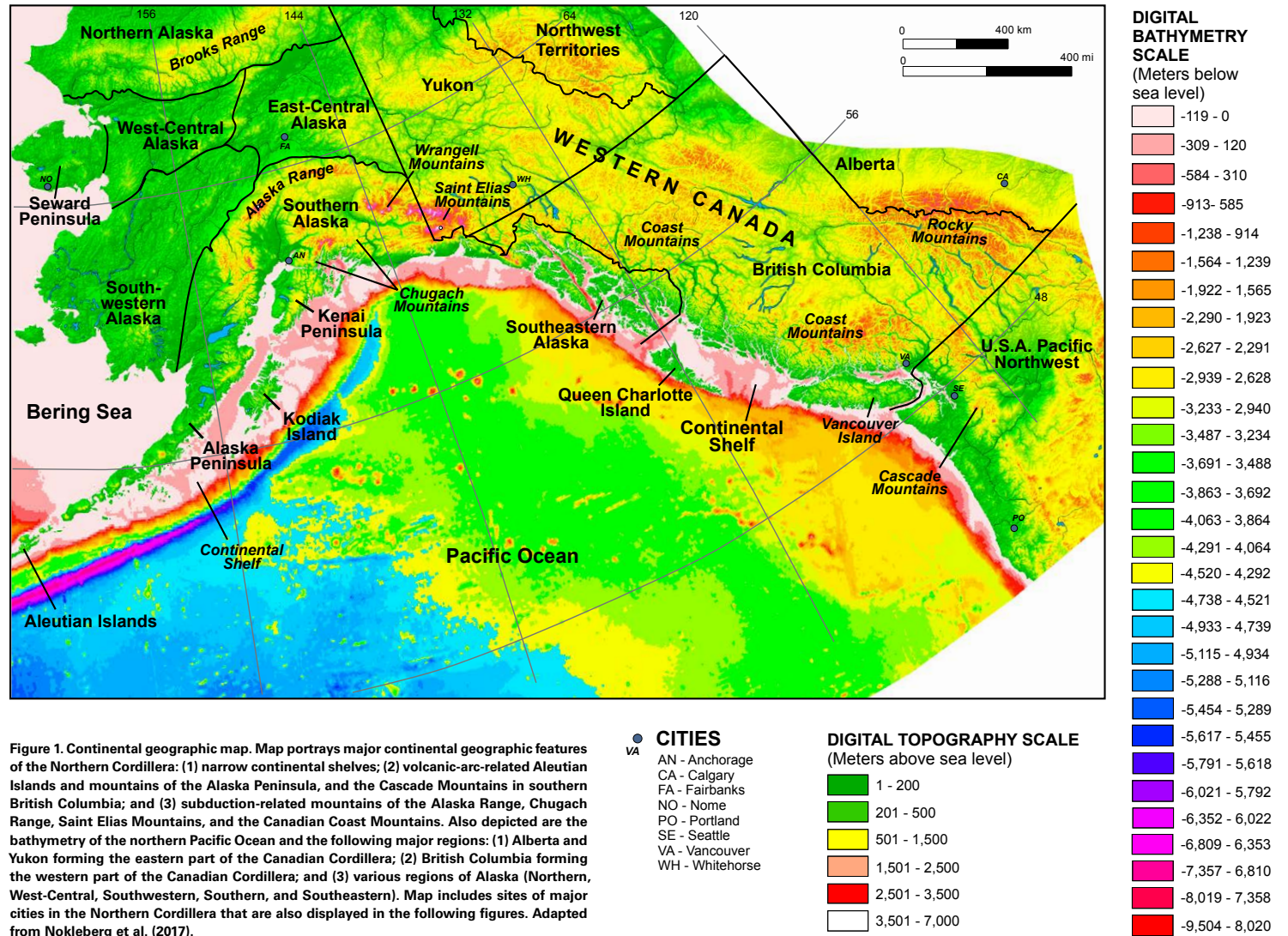


Figure 1. Continental geographic map. Map portrays major continental geographic features of the Northern Cordillera: (1) narrow continental shelves; (2) volcanic-arc-related Aleutian Islands and mountains of the Alaska Peninsula, and the Cascade Mountains in southern British Columbia; and (3) subduction-related mountains of the Alaska Range, Chugach Range, Saint Elias Mountains, and the Canadian Coast Mountains. Also depicted are the bathymetry of the northern Pacific Ocean and the following major regions: (1) Alberta and Yukon forming the eastern part of the Canadian Cordillera; (2) British Columbia forming the western part of the Canadian Cordillera; and (3) various regions of Alaska (Northern, West-Central, Southwestern, Southern, and Southeastern). Map includes sites of major cities in the Northern Cordillera that are also displayed in the following figures. Adapted from Nokleberg et al. (2017).

of the Northern Cordillera. In order to understand the earth science of the Northern Cordillera, it is essential to learn about the geology, bathymetry, and tectonics of the adjacent marine areas, vast parts of which have interacted with the Northern Cordillera throughout geologic time.

■ LANDSCAPES RELATED TO CENOZOIC TECTONISM

Overview

Geoscientists also want to know about landscapes and their tectonic origins. Figure 2 (Nokleberg et al., 2017b) displays topography, continental-margin arcs, and major Cenozoic faults. Also depicted is the bathymetry of the vast area of the North Pacific Ocean. Color scales for both topography and bathymetry illustrate the major surface features of the continent and ocean floor.

Major Landscapes

Figure 2 displays major Cenozoic landscapes that are the result of continental-margin arcs, dextral-slip faulting, and subduction of the Yakutat Terrane. Note that a few of the resultant landscapes are too small to depict on Figure 2. The major landscapes related to Cenozoic continental-margin arcs are: (1) to the Southwest, the Aleutian Arc underlying the Aleutian Islands and the Alaska Peninsula; (2) in eastern Southern Alaska, the Wrangell Arc that underlies the Wrangell Mountains; and (3) to the southeast, the Cascade Arc that underlies the Cascade Mountains.

The major landscapes related to middle through late Cenozoic dextral-slip faulting are: (1) in Northern and West-Central Alaska, disrupted (offset) topography and geologic units along the parts of the Kobuk, Kaltag, and Nixon Fork faults; (2) in interior Southern Alaska, fault-related troughs (basins) and uplifted mountains (including Denali, the highest mountain in North America) adjacent to the dextral-slip Denali and Totschunda faults; (3) in the southern part of Southern Alaska (labeled on

Fig. 1), disrupted (offset) topography and geologic units (too small to depict on Fig. 2) along parts of the Lake Clark, Castle Mountains, and Bruin Bay faults; and (4) in East-Central Alaska and the northern Western Canada, the dextral-slip Tintina Fault.

The major landscapes related to rapid Cenozoic subduction of the Yakutat Terrane and underlying Pacific Plate are: the Chugach Mountains in eastern Southern Alaska and the Saint Elias Mountains in southwestern Yukon (Fig. 1), including Mount Saint Elias and Mount Logan, the two highest mountains in Western Canada.

Tectonic Origins of Major Landscapes

Landscapes along the outboard margin of the Northern Cordillera have formed and are forming from three major tectonic processes (Nokleberg et al., 2017b): (1) subduction of oceanic lithosphere of the Pacific and Juan de Fuca plates, and the Yakutat Terrane; and (2) formation of continental-margin volcanic arcs; and (3) dextral-slip faulting along major faults resulting in major mountain ranges and fault-related troughs (basins).

■ MARINE SEASCAPES

Overview

Geoscientists also want to know about seascapes in the marine areas adjacent to the Northern Cordillera. Figure 3 (Scholl and Nokleberg, 2017) shows bathymetry, ocean plates, major Cenozoic faults, and Cenozoic continental-margin arcs.

Features of Major Marine Seascapes

On Figure 3, first observe the color gradation on the Pacific Plate, away from the Juan de Fuca Ridge. Also note the color zonation from east to west along the Alaska megathrust and the collinear Aleutian Trench. This major trench deepens westward to almost 7,300 m in depth, a depth that is greater than the height of Denali, the tallest mountain in

North America! As described below, this extremely long trench is the locus where the Pacific Plate is being subducted under Southern Alaska to form the Aleutian Arc.

Observe the shallow continental shelves, denoted by gray colors, which occur along the outboard margin of the Northern Cordillera from the Southern Canadian Cordillera and Southern Alaska to the southwestern edge of the Alaska Peninsula and the Aleutian Islands. These shallow marine areas represent zones of submerged continental crust and are inboard of subduction zones.

Nature and Tectonic Origins of Marine Geology Seascapes

The major marine geology seascapes are the Juan de Fuca Ridge, Juan de Fuca Plate, and the northern part of the Pacific Plate. The marine areas adjacent to the Northern Cordillera are tectonically important because major ocean plates, composed of oceanic lithosphere, have been and are being subducted underneath continental margins, thereby forming major continental-margin arcs. In addition, the subduction of oceanic ridges under continental plates has resulted in rifting of the continental plates. And in a few cases, entire oceanic plates have been subducted and have disappeared under the Northern Cordillera.

Juan de Fuca Ridge

The Juan de Fuca Ridge is a divergent plate boundary (a tectonic spreading center) offshore from the Pacific Northwest, USA, and southern British Columbia. Along the ridge, new oceanic crust is being formed from upwelling of hot magma along a chain of marine basalt volcanic fields that are being actively rifted. To the west is the Pacific Plate.

Juan de Fuca Plate

The Juan de Fuca Plate (Fig. 3) is a remnant of the once-vast Farallon Plate, which is now largely

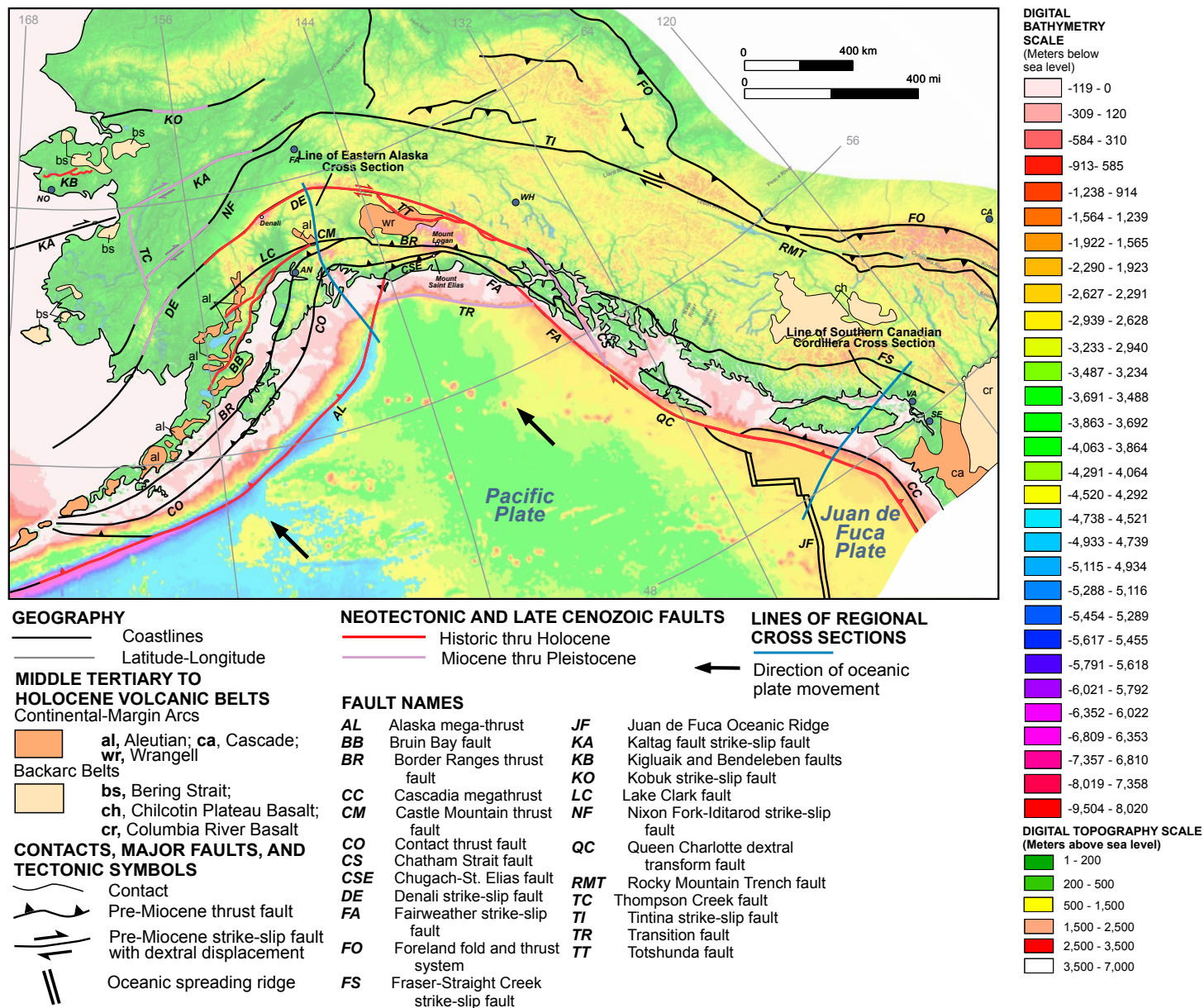


Figure 2. Landscapes related to Cenozoic tectonism. Map portrays origins of major landscapes of the coastal and nearby inland regions of the Northern Cordillera: (1) narrow continental shelves underlain by accreted terranes; (2) several subduction-related continental margin arcs in the Northern Cordillera, including the Aleutian Arc forming the Aleutian Islands and the Alaska Peninsula, the Wrangell Arc forming the Wrangellia Mountains, and the Cascade Arc forming the Cascade Mountains; and (3) the subduction-related mountains of the Chugach Ranges, Saint Elias Mountains, and the Canadian Coast Mountains. Also depicted are two major oceanic plates, the Pacific and Juan de Fuca plates, and the Juan de Fuca Ridge. Adapted from Nokleberg et al. (2017). City abbreviations as in Fig. 1 legend.

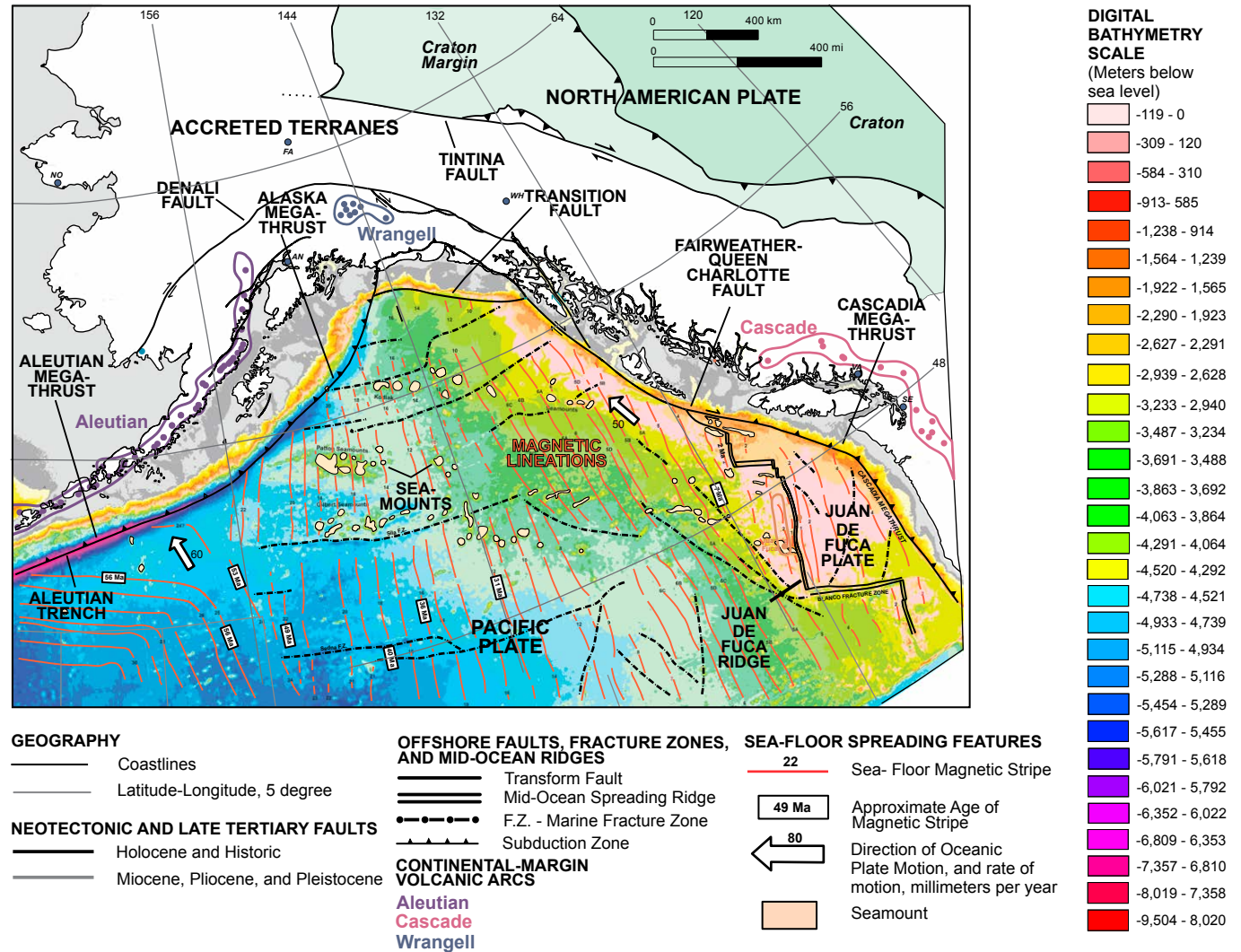


Figure 3. Marine geology and seascapes. Map portrays: (1) major marine features including the Pacific Plate, Aleutian Trench, Cascadia Trench, Juan de Fuca Ridge, Juan de Fuca Plate, magnetic lineations and progressively older ages of magnetic stripes, seamounts, fracture zones, and movement vectors for the Pacific Plate with rates of movement; (2) major faults, including the Alaska megathrust, Cascadia megathrust, and Fairweather-Queen Charlotte (dextral-slip) Fault; and (3) the area of accreted terranes that comprise most of Alaska and the Canadian Cordillera, and the North American Plate composed of craton margin and craton. Adapted from Scholl and Nokleberg (2017).

subducted under the North American Plate along the Cascadia megathrust. Subduction of the Juan de Fuca Plate formed the Cascade Mountains, the Cascade Arc, and the Coast Mountains along the west coast of North America. These features extend from British Columbia to Northern California.

Pacific Plate

The large Pacific Plate (Fig. 3), with an area of 103 million km², is the world's largest tectonic plate. The eastern edge of the Pacific Plate is the Juan de Fuca Ridge. View the color zonation (indicated by the bathymetry scale) of the surface of the northern Pacific Plate. Adjacent to the Juan de Fuca Ridge and the Fairweather-Queen Charlotte Fault to the east, the surface of the plate is relatively shallow, as denoted by the shades of pink and orange. Progressively to the west, the Pacific Plate sinks to great depths, as denoted by the darker shades of blue.

Subduction Zones—Destruction of Oceanic Plates and Creation of Volcanic Arcs

Cascadia Megathrust and Tectonically Associated Cascade Arc

The Cascadia megathrust lies in the eastern part of Figure 3 and stretches from northern Vancouver Island to northern California. The North American Plate moves generally west, overriding the east-migrating Juan de Fuca Plate, thereby forming a subduction zone. The subduction zone setting is defined by three components: (1) the subducting plate; (2) the volcanic arc developing on the overriding plate; and (3) sediment filling the trench on the ocean side of the arc. Tectonic processes active in the Cascadia megathrust include accretion, subduction, active magmatism (volcanism and plutonism), and deep earthquakes.

Although the last major earthquake was in 1700, because of subduction, this major fault and the adjacent continental margin have

potential for major events. In July 2015, The New Yorker Magazine published “The Really Big One,” an article by Kathryn Schulz, describing how the next major earthquake on the Cascadia megathrust might strongly affect humanity and civilization in the coastal Pacific Northwest (Schulz, 2015).

Aleutian-Alaska Megathrust and Tectonically Associated Aleutian Arc

The Aleutian megathrust, to the west, offshore of the Aleutian Islands, and the collinear Alaska megathrust, to the east, offshore of the southern margin of Southern Alaska (Fig. 3) extend for almost 3,400 km to the margin of the Russian Northeast. Along the Aleutian-Alaska megathrust, the Pacific Plate is being subducted beneath the North American Plate, which gives rise to the Aleutian Trench, and inboard, the Aleutian Arc. The megathrust is one of the world's most seismically active faults. It has been a source for a number of giant earthquakes and related tsunamis. The 1964 Great Alaska Earthquake, produced by this fault, was the largest recorded in the United States with a 9.2 moment magnitude and the second largest ever recorded anywhere. Due to the shallow dip of the subducting plate, large sections stick to the overriding plate, thereby causing the world's largest earthquakes, with moment magnitudes that can exceed 9.0. No other type of known tectonic activity can produce earthquakes of this scale. This subduction zone and the adjacent continental margin will continue to produce similar major earthquakes.

MARINE SEDIMENTARY BASINS

Overview

Geoscientists also want to know about marine sedimentary basins and their tectonic origins. Figure 4 (Scholl and Nokleberg, 2017) displays major marine sedimentary basins, ocean plates and ridges, and major Cenozoic faults.

Features and Tectonic Origins of Marine Sedimentary Basins

Cook Inlet, Kodiak Shelf, Sanak, Stevenson, and Tudigak Marine Basins—Formed along the Aleutian Forearc

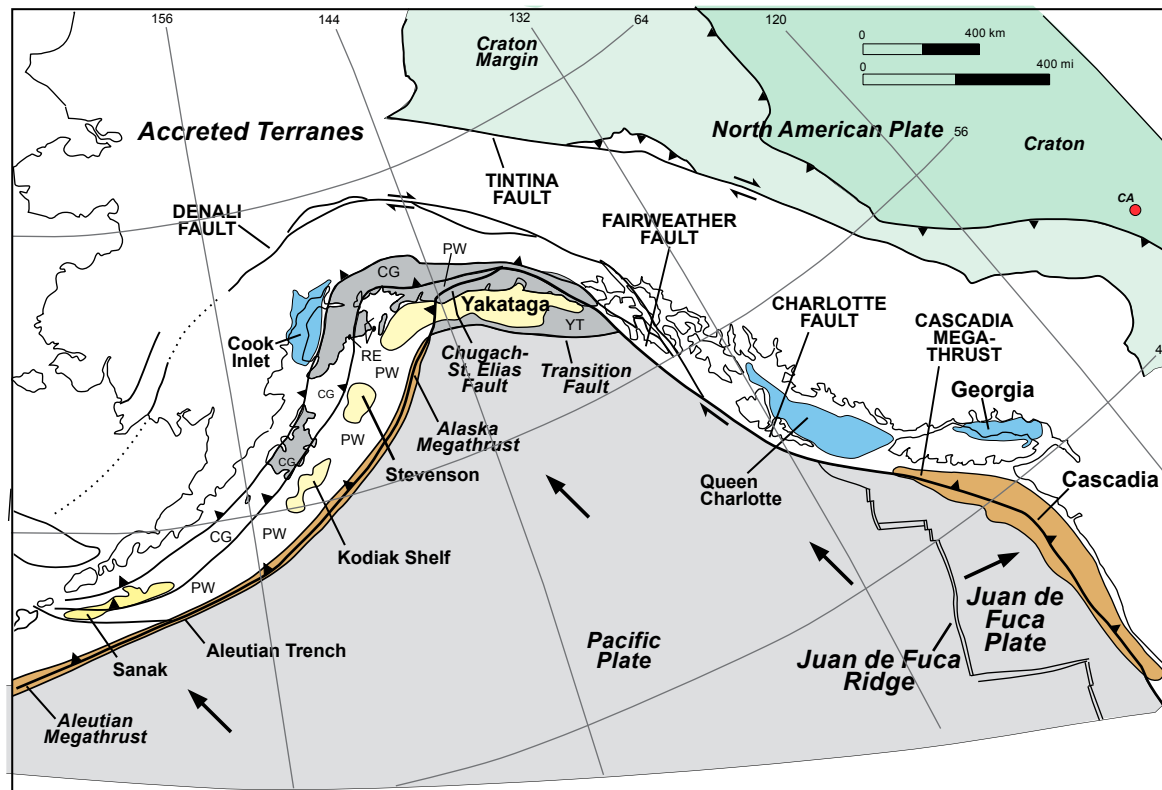
The Cook Inlet, Kodiak Shelf, Sanak, and Stevenson marine basins are seaward and offshore of the Aleutian (continental-margin) Arc along the Alaska Peninsula (Fig. 1). They contain chiefly early Cenozoic and younger turbidite sandstone, siltstone, and shale. Sedimentary thicknesses range up to 7 km. The four marine basins constitute a series of elongated forearc marine basins along the Aleutian Arc.

Aleutian Trench and Cascadia Marine Basin—Forming along Active Subduction Zones

The Cenozoic Aleutian Trench and the Cascadia Basin directly reflect the sinking oceanic crust in the subduction zones that border the Northern Cordillera. The Aleutian Trench is one of the longer and narrower basins on the globe. In contrast, the Cascadia Basin is shorter and wider.

Aleutian Trench. The Cenozoic Aleutian Trench occurs along the Aleutian-Alaska megathrust bordering the margin of Southern Alaska. The trench extends for 3,400 km. The trench is formed where the northern margin of the Pacific Plate is subducting beneath Southern Alaska and the Aleutian Islands. The deepest part of the Aleutian Trench is ~7,300 m. The basin is the locus of marine sedimentation, with movement of turbidite flows along the trench, along with partial subduction of young sediments. The trench fill consists of distal turbidites (dirty sandstones) that are interbedded with diatom-rich deposits.

Cascadia Basin. The Cenozoic Cascadia Basin occurs offshore of the Pacific Northwest, USA, and the Southern Canadian Cordillera. The basin contains chiefly early through late Cenozoic marine turbidite sandstone, siltstone, mudstone, and shale. Local common features include scattered clay-rich bands, silt laminae, zones of bioturbation, concentrations of calcareous fossils, and pyrite nodules.



MARINE SEDIMENTARY BASINS

Cenozoic Marine Sedimentary Basins on Submerged Continental Crust. Outline of basin at 1.5 km thickness.



Cenozoic Marine Sedimentary Basins along Subduction Zones



Mesozoic and/or Early Cenozoic Marine Sedimentary Basins on Continent and Submerged Continent



SUBDUCTION ZONE TERRANES

CG, Chugach; PW, Prince William; RE, Resurrection; YT, Yakutat

OCEANIC PLATES



TECTONIC SYMBOLS

— Oceanic spreading ridge

← Direction of oceanic plate movement

Figure 4. Marine sedimentary basins. Map portrays the Cenozoic Aleutian Trench Basin and the wider Cascadia Basin formed along major megathrusts, and continental shelf basins formed along the margin of the Northern Cordillera (Sanak, Kodiak Shelf, Stevenson, Cookj Inlet, Yakataga, Queen Charlotte, and Georgia basins). Adapted from Scholl and Nokleberg (2017).

The Cascadia Basin overlies and occurs along the Cascadia megathrust, along which the Juan de Fuca Plate is subducted beneath the Pacific Northwest, USA. The basin is completely filled, with a nearly flat upper surface. Subduction-related faulting has produced complex patterns of faults and folds, which led to considerable structural relief in sedimentary layers as young as late Cenozoic.

Differences between the Aleutian Trench and Cascadia Basins. Although both basins are formed along active subduction zones, the Aleutian Trench and Cascadia basins exhibit some notable differences. First, the Aleutian Trench is one of the deepest parts on the globe that is still being filled by abundant continent-derived sediment, whereas the Cascadia Basin is being overtopped by voluminous sediment. Second, the Aleutian Trench Basin is one of the longest and narrowest basins on the globe, whereas the Cascadia Basin is shorter and wider, probably because of slower subduction.

The cause of these differences is quite simple. Active and rapid subduction is occurring along the Aleutian-Alaska megathrust, and sediment, which is being dumped into the Aleutian Trench, is being washed to the west along the trench. For this trench, the rate of sedimentation is not keeping up with subsidence. In contrast, because of slow subduction along the Cascadia megathrust, the Cascadia Basin is overwhelmed by sediment, with the result that the basin is completely filled with sediment slopping overboard along the edges.

Early Cenozoic Georgia, Queen Charlotte, and Yakataga Marine Basins—Formed on Accreted Terranes in the Canadian Cordillera

Three major Cenozoic marine basins formed on accreted terranes in the central and southern Canadian Cordillera. Each basin displays a unique geologic and tectonic history.

Queen Charlotte Basin. The Queen Charlotte Basin, which is situated on submerged continental crust composed of accreted terranes, is offshore and adjacent to the central Canadian Cordillera. The basin, which is ~360 km long by 60 km wide,

extends parallel to the coast and the outboard Queen Charlotte Fault. The basin contains mainly middle and late Cenozoic marine sedimentary rocks, mostly sandstone, siltstone, mudstone, and shale. The maximum thickness is ~5 km. The basin overlaps the Wrangellia terrane in the western Canadian Cordillera.

Georgia Basin. The Georgia Basin straddles submerged continental crust composed of the accreted terranes of eastern and southeastern Vancouver Island and adjacent offshore areas. The basin contains 2–5 km of dominantly marine siliciclastic (continent-derived) sediments. The basin, which is a Late Cretaceous forearc basin, outboard of the Cascade Arc, overlaps the Wrangellia terrane on Vancouver Island and the Coast plutonic belt on the mainland. Major episodes of sedimentation in the basin are linked to periods of rapid convergence between the Farallon (oceanic) Plate and the North American Plate.

Yakataga Marine Basin. The Yakataga (mostly marine) Basin is associated with the active dextral-slip Fairweather-Queen Charlotte Fault in eastern Southern and Southeastern Alaska. The chief features of this complex basin are: (1) deposition of marine sediments on the northern part of the Yakutat Terrane; and (2) early Cenozoic coal and sandstone, early and middle Cenozoic marine sandstone and tuff, and middle and late Cenozoic marine glacial rocks. The basin is ~10 km thick, and is deformed into a south-verging thrust and fold belt that is associated with subduction and underthrusting of the structurally underlying Yakutat Terrane. This basin originally formed to the south in the southern Canadian Cordillera, and was transported northward during dextral-slip movement on the Fairweather-Queen Charlotte Fault (described below).

■ CENOZOIC FAULTS RELATED TO SUBDUCTION

Overview

Faults are another important feature of the Earth's crust and thereby, geoscientists want to

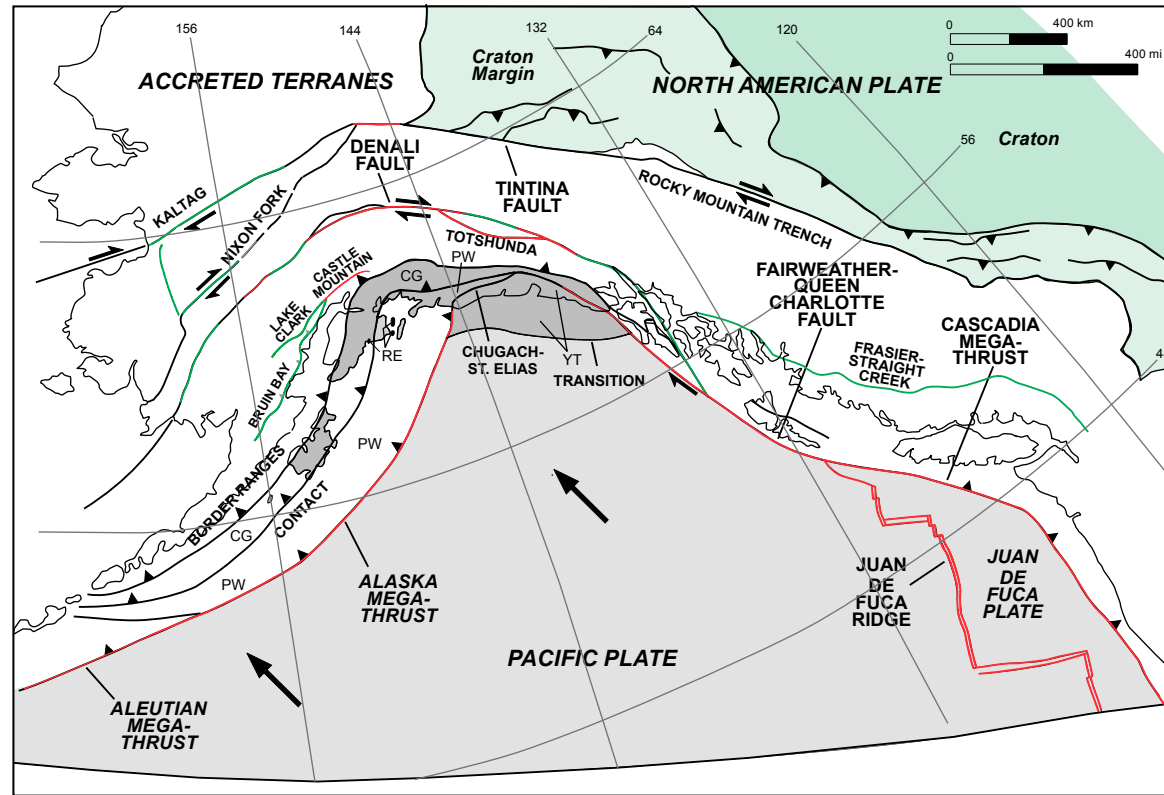
know about their tectonic origins. Figure 5 (Nokleberg and Stone, 2017a) displays major historic and Cenozoic faults, ocean plates and ridges, and terranes accreted in the Cenozoic. Note that the figure depicts older (pre-Cenozoic) major faults in black, middle to late Cenozoic faults in green, and active faults (latest Cenozoic) in red.

The major faults that underwent latest Cenozoic movement are: (1) in Northwestern, West-Central Alaska, and Southern Alaska (Figs. 1 and 5), the Kaltag and Nixon Fork, Denali, Lake Clark, Castle Mountain, and Bruin Bay (mainly dextral-slip) faults that are the result of oblique subduction of the Pacific Plate beneath the margin of Southern Alaska; (2) the Aleutian and Alaska megathrusts, and the co-linear Chugach-St. Elias Fault where the Pacific Plate is obliquely to orthogonally subducting beneath the margin of Southern Alaska; (3) the dextral-slip Fairweather-Queen Charlotte Fault where the Pacific Plate moves northwestward along the margin of the North American Plate; (4) the Frasier-Straight Creek and Tintina faults (inboard of the Fairweather-Queen Charlotte Fault) that also are the result of the Pacific Plate moving northwestward along the margin of the North American Plate; (5) the Cascadia megathrust where the Juan de Fuca Plate is subducting beneath the margin of the Pacific Northwest; and (6) the Juan de Fuca Ridge, along which active sea-floor spreading is occurring, thereby driving the Juan de Fuca Plate toward the Cascadia subduction zone.

Tectonic Settings of Cenozoic Faults

Aleutian and Alaska Megathrusts—Formed during Subduction of Pacific Plate

The Aleutian megathrust to the west and the collinear Alaska megathrust to the east (Fig. 5) occur offshore of the Aleutian Islands to the west and Southern Alaska to the east, and extend for almost 3,400 km. The Aleutian megathrust defines most of the northern boundary of the Pacific Plate. The Alaska megathrust also defines part of the northern boundary of the Pacific Plate and the



CONTACTS, MAJOR FAULTS, AND TECTONIC SYMBOLS

- Contact
- Thrust fault
- Strike-slip fault with dextral displacement
- Oceanic spreading ridge
- Direction of oceanic plate movement

NEOTECTONIC AND MIDDLE AND LATE CENOZOIC FAULTS
(Active Major Faults in Red)

- Historic and Latest Cenozoic
- Middle and Late Cenozoic

SUBDUCTED TERRANES

- CG, Chugach; PW, Prince William; RE, Resurrection; YT, Yakutat

OCEANIC PLATES

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Figure 5. Cenozoic faults. Map portrays: (1) the Kaltag and Nixon Fork, Denali, Castle Mountain, and Bruin Bay (strike-slip) faults that are the result of oblique subduction of the Pacific Plate beneath the margin of Southern Alaska; (2) the Aleutian-Alaska megathrust, and the Chugach-St. Elias Fault where the Pacific Plate is being obliquely to orthogonally subducted beneath the margin of Southern Alaska; (3) the dextral-slip Fairweather-Queen Charlotte Fault where the Pacific Plate is moving northwestward along the margin of the North American Plate; (4) the Frasier-Straight Creek Fault (inboard of the Fairweather-Queen Charlotte Fault) that also is the result of the Pacific Plate moving northwestward along the margin of the North American Plate; (5) the Cascadia megathrust where the Juan de Fuca Plate is being subducted beneath the margin of the Pacific Northwest; and (6) as the cause of subduction along the margin of the Northern Cordillera, the Juan de Fuca Ridge along which active sea-floor spreading is occurring. Adapted from Nokleberg and Stone (2017a).

southern margin of the Prince William terrane (unit PW, Fig. 5), now accreted to the North American Plate. Along the megathrusts, the northern Pacific Plate is being subducted beneath accreted terranes to the north.

The evidence for the two megathrusts remaining active is straight forward: (1) the occurrence of the Great Alaskan Earthquake of 1964, with tremendous earth movement, including uplift of a large inboard zone and down drop of adjacent outboard zones; and (2) widespread historic seismicity.

Cascadia Megathrust—Formed during Subduction of Juan de Fuca Plate

The Cascadia megathrust (Fig. 5) is a classic subduction zone offshore of the Cascade Arc in the southern part of the Canadian Cordillera. The megathrust separates the Juan de Fuca Oceanic Plate to the west from the accreted terranes and overlying Cascade Arc to the east.

Bruin Bay Fault—An Intra-arc Strike-Slip Fault

The Bruin Bay Fault (Fig. 5) is a major left-lateral strike-slip fault (with a minor thrust component) that trends northeast for ~530 km along the axis of the Aleutian Arc. Along the Bruin Bay Fault, Jurassic arc and related rocks, and middle Cenozoic volcanic and sedimentary rocks are thrust from south to north over middle Cenozoic rocks. In most areas, the fault is buried under late Cenozoic deposits and no scarps are known. A magnitude 7.3 earthquake occurred near the fault in 1943.

Castle Mountain and Lake Clark Faults—Intra-arc Strike-Slip and Thrust Faults

The Castle Mountain Fault (Fig. 5) is a combined dextral-slip and reverse fault that trends northeast for ~200 km, and has a long history of Cenozoic displacement. The fault dips steeply to the north, displays both right-lateral and north-side-up dip-slip offset, and exhibits latest Cenozoic

displacement. Some postglacial outwash channels (formed before 11,300–15,380 years ago) are dextrally offset by ~36 m across the western segment of the fault. The Castle Mountain Fault poses a significant seismic hazard to Anchorage and adjacent cities that comprise the most populated region of Southern Alaska.

The Lake Clark Fault (Fig. 5) is the southwest extension of the Castle Mountain Fault. The displacement of aeromagnetic anomalies along the fault suggests ~26 km of dextral offset in the past 34–39 million years (m.y.). The Castle Mountain Fault to the east–northeast probably has a greater offset. Glacial moraines along the Lake Clark Fault are offset 25 m vertically (south-side down), but no evidence of latest Cenozoic movement is known.

The Castle Mountain and Lake Clark faults are major intra-arc structures that formed with the Aleutian Arc (and in the subjacent accreted Wrangellia terrane) as a result of subduction of the Pacific Plate under the margin of Southern Alaska. Dextral-transpressional deformation is being caused by a combination of oblique subduction of the Pacific Plate and the Yakutat Terrane, which overlies the Pacific Plate, under the margin of Southern Alaska, and by oroclinal warping of Southern Alaska.

Denali Fault—Forming from Oblique Subduction of Pacific Plate

The Denali Fault (Fig. 5) extends from northern Southeastern Alaska through the Alaska Range to the coast of Southwestern Alaska and probably into the Bering Sea, a distance of more than 2,000 km. Dextral-slip movement on the Denali Fault ranges from 1 to 6.5 km in the late Cenozoic. Rates of latest Cenozoic movement average ~1.5 cm/yr. The major November 2002 earthquake on the Denali Fault had a moment magnitude of 7.9. Both the Denali and companion Totschunda faults ruptured with up to 8.8 m of dextral displacement.

A contrast exists between dextral displacement on the central part of the Denali Fault in eastern Southern Alaska, and little to no slip on the western part of the Denali Fault, west of Denali (Mount

McKinley). However, GPS data along two highway transects across the fault, 100 and 200 km east of Denali, show that the western part of this right-lateral fault system is moving faster (10 ± 2 mm/yr) than the eastern part (6 ± 2 mm/yr). This result is opposite to what is expected from the mechanism described above and provides material for future studies.

For regional neotectonics, the Denali Fault is the result of dextral-transpressional deformation being caused by the oblique subduction of the Pacific Plate and the Yakutat Terrane, riding piggyback on top of the Pacific Plate, under the margin of Southern Alaska.

Queen Charlotte Fault—Locality of Northwest Migration of Pacific Plate

The Queen Charlotte Fault (southern part of Fairweather-Queen Charlotte Fault) (Figs. 4 and 5) is an active dextral transform fault located between the North American Plate to the northeast and the Pacific Plate to the southwest. The fault is Canada's equivalent of the San Andreas Fault in California. The southern terminus of the Queen Charlotte Fault is a triple junction with the Cascadia megathrust and the Juan de Fuca Ridge. Along the fault, the Pacific Plate and the piggyback Yakutat Terrane are migrating northwest. Regional geologic correlations suggest the Yakutat Terrane (and underlying Pacific Plate) have migrated ~1,500 km northward along the Fairweather-Queen Charlotte Fault.

Several large earthquakes have occurred along the Queen Charlotte Fault during the 20th and 21st centuries: (1) a large earthquake on 26 November 1880; (2) a moment magnitude 7.1 earthquake on 24 October 1927; (3) a moment magnitude 8.1 earthquake on 22 August 1949 (Canada's largest recorded earthquake since the 1700 Cascadia earthquake); (4) a moment magnitude 7.8 earthquake on 10 July 1958; (5) an earthquake with moment magnitude 7.6 on 30 July 1972; (6) a moment magnitude 6.8 earthquake on 28 June 2004; (7) a moment magnitude 7.7 earthquake on 28 October 2012; and (8) a moment magnitude 7.5 earthquake on 5 January 2013.

Fairweather Fault—Locality of Northwest Migration of Pacific Plate

The Fairweather Fault (northern part of Fairweather-Queen Charlotte Fault (Figs. 4 and 5) extends northward from the Queen Charlotte Fault. Like the latter, the Fairweather Fault separates the Pacific Plate (and the piggyback Yakutat Terrane) to the southwest from the collage of accreted terranes to the northeast that comprise the northwestern Canadian Cordillera. Onshore, in eastern Southern Alaska, the Fairweather Fault changes from a northwest to a west-northwest trend, and merges with the Chugach-St. Elias Fault that occurs along the northern margin of the Yakutat Terrane.

Geomorphology studies suggest dextral-slip movement at a rate of a few cm/yr for at least the last million years. The associated dip-slip component of motion is several times smaller than the strike-slip component. GPS measurements indicate the Yakutat Terrane is moving extremely fast, at ~45 mm/yr along the Fairweather Fault. The most recent significant earthquake near the Fairweather Fault was a moment magnitude 5.7 event on 9 June 2007.

In 1958, movement along the Fairweather Fault near Lituya Bay created a moment magnitude 7.9 earthquake, and in 1972, a moment magnitude 7.4 event occurred near Sitka. The 1958 Lituya Bay earthquake caused a large rockslide into the bay, which triggered the Lituya Bay megatsunami that had a record height of 524 m. The earthquake was felt as far away as Seattle, Washington, USA.

Tintina Fault—Result of Northwest Migration of Pacific Plate

The dextral-slip Tintina Fault (Figs. 1 and 5) is a large strike-slip fault in western North America that stretches more than 2,000 km from southern British Columbia to northwestern British Columbia to East-Central Alaska (Fig. 1). Total estimated displacement on the fault is ~425 km. Displacement of latest Cenozoic surficial units occurs along a lineament at the northwestern end of the Tintina Fault. The Tintina Fault is also the result of

dextral-transpressional migration of the Pacific Plate along the margin of Southeastern Alaska.

Totschunda Fault—Forming from Oblique Subduction of the Pacific Plate

The dextral-slip Totschunda Fault (Fig. 5) is a major splay of the Denali Fault that extends southward from the Denali Fault in the Eastern Alaska Range, across the northeast edge of the Wrangell Arc, across the northeast edge of the Wrangellia terrane, and merges back into the Denali Fault across the International Boundary. The Totschunda Fault displaces latest Cenozoic volcanic and sedimentary units. GPS measurements indicate latest Cenozoic slip of ~1–2 cm/yr. In the 2002 earthquake on the Denali and Totschunda faults, ~3.5 m of horizontal displacement occurred on the Totschunda Fault. The fault is a regional strike-slip fault that formed along the northern margin of the Wrangell Arc as a result of oblique subduction of the Pacific Plate and the overlying (piggyback) Yakutat Terrane under the margin of Southern Alaska.

EARTHQUAKE BELTS RELATED TO SUBDUCTION (1946 TO 2012)

Overview

Earthquakes and their tectonic origins are also important to geoscientists. For the Northern Cordillera and adjacent marine areas, Figure 6 (Nokleberg and Stone, 2017a) displays earthquake epicenters, grouped into earthquake belts. These features are superposed on the Cenozoic faults map (Fig. 5). Each of the earthquake belts, numbered 1–6, possesses a distinct tectonic origin.

The three earthquake belts related to subduction are: Earthquake Belt 1 related to the Aleutian and Alaska megathrust and the subducting Pacific Plate, Earthquake Belt 3 related to the subducting Yakutat Terrane, and Earthquake Belt 5 related to subduction along the Cascadia megathrust. The two earthquake belts related to dextral strike-slip faults are Earthquake Belt 2 related to the Denali and

Totshunda faults, and Earthquake Belt 4 related to the Fairweather-Queen Charlotte Fault. Earthquake Belt 6 is related to the spreading Juan de Fuca Ridge.

Tectonic Settings of Earthquake Belts Related to Subduction

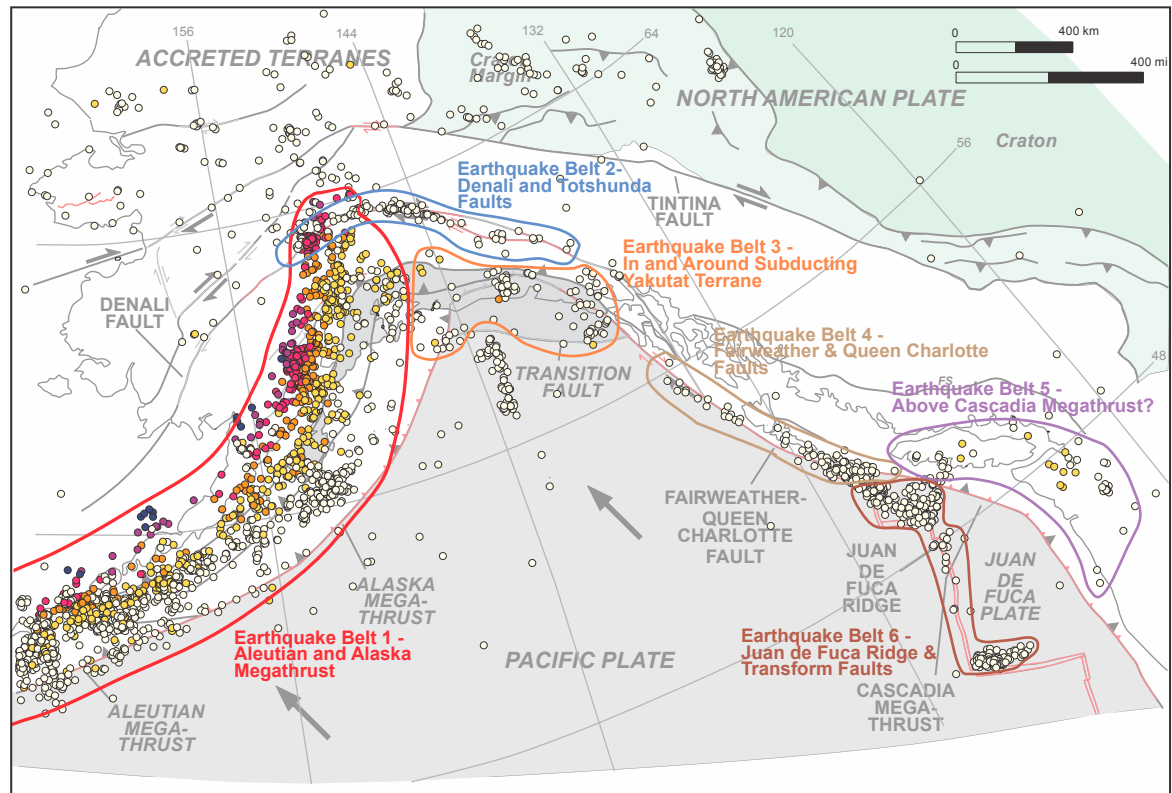
Earthquake Belt 1—Aleutian-Alaska Megathrust

Earthquake Belt 1, outlined by an elongate red polygon on Figure 6, occurs along the eastern Aleutian megathrust and the Alaska megathrust to the northeast. The color codes for hypocenter depths reveal a tremendous depth zonation. More shallow hypocenters (near surface to 34 km depth) occur near the surface trace of the megathrusts, whereas hypocenters occur at successively greater depths progressing inboard, across the volcanic arc. The hypocenters range from near surface to depths of 275 km.

Over most of the length of this belt, the distribution of earthquakes (and volcanoes) relative to the megathrust does not change, but at the northeastern end there is a marked divergence of the deeper earthquakes with respect to the megathrust (Figs. 3 and 6). The shallow earthquakes reveal that the subducting slab dips at a very shallow angle, and then dives steeply down much farther inland than in the western parts of the arc. Progressing westward along the Aleutian-Alaska megathrust, the relative direction of underthrusting changes from highly oblique (inclined) to perpendicular to the arc. The 1964 Great Alaska Earthquake was by far the most energetic event recorded along the Aleutian-Alaska megathrust.

Earthquake Belt 2—Denali and Totschunda Faults

Earthquake Belt 2, outlined by an elongate blue polygon on Figure 6, occurs along the Denali and Totschunda faults. The belt contains only shallow earthquakes with depths of up to 34 km. This is similar to other active strike-slip fault systems around the world that also exhibit predominantly



CONTACTS, MAJOR FAULTS, AND TECTONIC SYMBOLS
(Active Major Faults in Red)

- Contact
- Thrust fault
- Strike-slip fault with dextral displacement
- Oceanic spreading ridge
- Direction of oceanic plate movement

NEOTECTONIC AND LATE CENOZOIC FAULTS

- Historic thru Holocene
- Miocene thru Pleistocene

EARTHQUAKE EPICENTERS
(Magnitude 4.5 and Above)
(Depths in km for 5,907 events)

- 0 to 34.9
- 35 to 70
- 70 to 100
- 100 to 140
- 140 to 190
- 190 to 274

Figure 6. Earthquake belts. Map portrays earthquake belts related to: (1) the Aleutian-Alaska megathrust and the subducting Pacific Plate; (2) the Denali and Totschunda faults; (3) the subducting Yakutat Terrane; (4) the Fairweather-Queen Charlotte Fault; (5) the Cascadia megathrust; and (6) the spreading Juan de Fuca Ridge. Adapted from Nokleberg and Stone (2017a).

shallow-depth hypocenters. Deeper-level earthquakes probably do not occur because high subsurface temperatures prevent the storing of strain. Of interest is that the western end of Belt 2 crosses the northeastern tip of Belt 1. Could two different neotectonic forces be causing two different suites of earthquakes?

Earthquake Belt 3—Subducting Yakutat Terrane

Earthquake Belt 3, outlined by an orange polygon on Figure 6, contains almost entirely shallow earthquakes with depths of 0–34 km. This belt is the result of subduction of the Yakutat Terrane under the eastern margin of Southern Alaska. Some seismic studies suggest the northern margin of the subducting Yakutat Terrane may extend to near the Denali Fault. Still other seismic studies suggest the active Wrangell Arc (described above) represents melting of the northern, deep edge of the Yakutat Terrane.

A tremendous seismic gap exists between the northeastern edge of Earthquake Belt 2 to the west and the western edge of Earthquake Belt 3 to the east. This gap also coincides with a gap in active volcanoes, between the northeastern Aleutian Arc to the west and the Wrangell Arc to the east.

Earthquake Belt 4—Fairweather-Queen Charlotte Fault

Earthquake Belt 4, outlined by an elongate brown polygon on Figure 6, is along the Fairweather-Queen Charlotte Fault. As with the Denali and Totschunda faults, this belt contains only shallow earthquakes, with depths from near surface to 34 km. Again, this observation is similar to other active strike-slip fault systems around the world that also exhibit predominantly shallow-depth hypocenters.

Earthquake Belt 5—Cascadia Megathrust

Earthquake Belt 5, outlined by an elongate purple polygon on Figure 6, occurs in a broad zone

above the Cascadia megathrust where the Juan de Fuca Plate subducts beneath the continental margin of the Pacific Northwest, USA. The belt contains only shallow-level hypocenters (up to 69 km depth). In addition, no depth zonation of hypocenters exists. These data suggest that the Cascadia megathrust is currently locked. The last known major event, estimated at a moment magnitude of 9.0, occurred in January 1700, and is named the 1700 Cascadia Earthquake. Marine geology and geophysical studies reveal that the present-day Cascadia Trench, associated with the megathrust, is filled to the brim with young sediment, indicating that shedding of sediment to the offshore basin has far exceeded sediment removed by subduction.

Latest Cenozoic earthquakes in this area are uncommon, but extremely dangerous because the Pacific Northwest is highly populated. Recent work looking at very subtle *silent* earthquakes (also known as slow-slip events), which occur in discrete packages, may document that the plates have been moving slowly since January 1700. This suggests that catastrophic amounts of strain amounting to the total convergence may not be building.

In both the Pacific Northwest, USA, and California, episodes of very slow slip are being studied using long records from continuous recording GPS stations. Recent studies show that they were accompanied by high-frequency bursts of seismic energy called tremors, so they are now named Episodic Tremor and Slip (ETS). The ETS signals usually continue for a few weeks, in direct contrast to earthquakes where most of the energy is released in seconds to minutes. A Geological Survey of Canada study of the Cascadia megathrust recorded a total surface displacement of ~40 mm over eight years, or 5 mm/yr. This is small compared with the Juan de Fuca Plate approaching the Cascadia megathrust at ~20 mm/yr. As always, a surface measurement of velocity does not necessarily yield the velocity at the depth of the megathrust faulting. The depth between the source of the ETS and the surface is large, and the structure is quite complicated.

Earthquake Belt 6—Spreading Juan de Fuca Ridge

Earthquake Belt 6, outlined by an elongate red-brown polygon on Figure 6, occurs along the Juan de Fuca Ridge and associated transform faults. The belt contains only shallow-level, low-magnitude hypocenters. These shallow depths are typical of spreading centers and associated transform faults around the world.

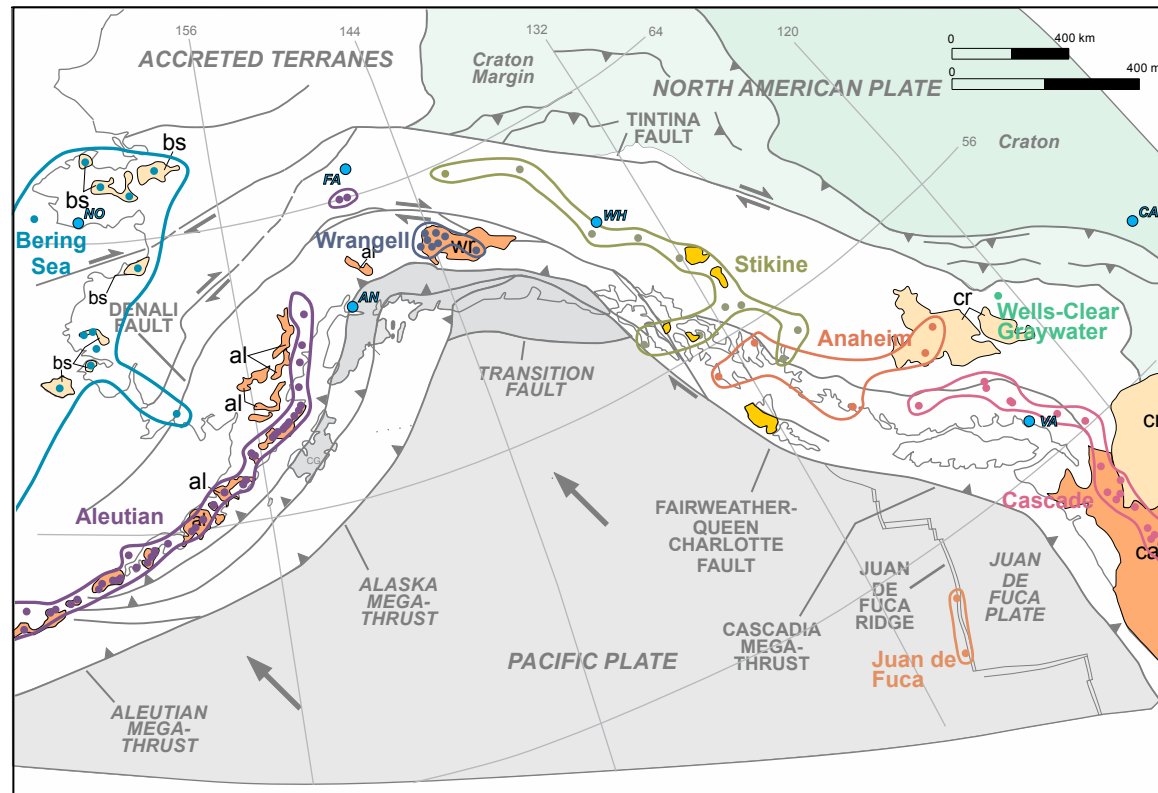
Note that the majority of the earthquakes are located near the transform faults that offset the spreading center. The motion on the transform faults is strike-slip, one side sliding past the other. The spreading center, on the other hand, is hot and has little strength, so it lacks the physical conditions for the sudden movement needed to generate earthquakes.

■ VOLCANIC BELTS RELATED TO SUBDUCTION

Overview

Geoscientists agree that knowledge about volcanic belts is important, both for the origin of major features of the Earth and for society. Figure 7 (Nokleberg and Stone, 2017a) displays active volcanoes (latest Cenozoic) that are superposed on the Cenozoic faults map (Figure 5). Volcanic belts on both the continent and in adjacent marine areas are depicted, each with a distinct tectonic origin. Figure 7 also shows underlying middle to late Cenozoic volcanic belts.

The three major volcanic belts related to subduction are the Aleutian, Wrangell, and Cascadia belts. These belts comprise continental-margin volcanic arcs that are each linked to an outboard subduction zone. In addition, four major volcanic belts, which occur in the continental interior, are related to dextral strike-slip faulting: the Anaheim and Stikine volcanic belts, the Wells Gray-Clearwater volcanic belt in the southern Canadian Cordillera, and the Bering Sea volcanic belt in Western Alaska. A single volcanic belt, the Columbia River Basalt, in the southern Canadian Cordillera, is related to a hotspot (Fig. 7).



CONTACTS, MAJOR FAULTS, AND TECTONIC SYMBOLS
(Active Major Faults in Red)

- Contact
- Thrust fault
- Strike-slip fault with dextral displacement
- Oceanic spreading ridge
- Direction of oceanic plate movement

OUTLINES OF LATEST CENOZOIC AND HISTORIC VOLCANIC BELTS AND MAJOR VOLCANOES

- Aleutian
- VOLCANIC BELTS RELATED TO CONTINENTAL-MARGIN ARCS**
- al, Aleutian; ca, Cascade; wr, Wrangell
- ca, Cascade
- wr, Wrangell
- HOT SPOT BELTS**
- cr, Columbia River Basalt

- BELTS RELATED TO STRIKE-SLIP FAULTING**
- Anaheim
 - Bering Sea
 - Stikine
 - Wells-Clear Graywater

Figure 7. Volcanic belts. Map portrays the following major volcanic belts related to subduction: (1) continental-margin arcs—the Aleutian, Wrangell, and Cascadia Arcs, each linked to an outboard subduction zone; and (2) continental interior volcanic belts—Anaheim, Bering Sea, Stikine, and Wells-Clearwater volcanic belts, each related to strike-slip faulting associated with subduction. Adapted from Nokleberg and Stone (2017a) and Nokleberg (2017b).

Tectonic Settings of Volcanic Arcs Related to Subduction

Continental-Margin Volcanic Belts

The Northern Cordillera hosts three volcanic belts that are formed in continental-margin arcs: from west to east, the Aleutian Arc on the Alaska Peninsula in Southern Alaska, the Wrangell Arc in eastern Southern Alaska, and the Cascade Arc in the southern Canadian Cordillera (Figs. 1 and 7). (Note that the Aleutian Arc also extends to the southwest into the Aleutian Islands where it is a marine arc.) Together, these three great chains of active volcanoes are a substantial part of the Pacific Ring of Fire. The most notable features of these arcs are impressive high volcanoes and extensive volcanic flows, tuffs, and interlayered sedimentary rocks.

Aleutian Arc

Most of Alaska's 130 volcanoes and volcanic fields, which have been active in the last 2 million years, are located along the 2,500 km-long Aleutian Arc (Fig. 7). For geography, the arc extends from west to east in the Aleutian Islands, Alaska Peninsula, and Aleutian Range. In addition to its great length, the arc contains high peaks. The highest volcano in the Aleutian Islands is Shishaldin Volcano, which is 2,857 m high. The highest volcano in the continental part of the arc is Mount Spurr, which is 3,374 m high.

The Aleutian Arc has formed and is still forming from subduction of the Pacific Plate beneath Southern Alaska along the Alaska megathrust to the east, grading to oblique subduction along the Aleutian megathrust to the west.

As an interesting note, many volcanoes have Russian names that stem from the Russian exploration and claiming of Alaska from 1733 to 1867, when Russian America was sold to the USA. Written historical records began ~1760, when Russian sailors and fur traders first explored the Aleutian Islands and the Southern and Southeastern Alaska coast.

Wrangell Arc

The Wrangell Arc occurs in eastern Southern Alaska near the International Boundary with Canada. The Wrangell Arc consists chiefly of shield volcanoes and satellite cones. Ages range from the middle Cenozoic near the Alaska-Yukon border, to Recent at the west end of the arc. The Wrangell Arc is notable for containing high peaks, some almost 5,000 m high, such as Mount Blackburn.

Figure 7 also displays the ~160 km gap between the northeast end of the Aleutian Arc and the western edge of the relatively small, middle to late Cenozoic Wrangell Arc. This volcanic gap, which is also denoted by a gap in earthquake epicenters (described in the "Earthquake Belts Related to Subduction (1946 To 2012)" section) may reveal a major change in tectonic patterns, and/or in the nature of units being subducted under the two arcs. This gap reveals in part that the Wrangell Arc has been forming during subduction of the Yakutat Terrane along the gently north-dipping Chugach-St. Elias and Kayak Faults.

Cascade Arc

The northern part of the Cascade Arc (Fig. 7) occurs in the Southern Canadian Cordillera in the Coast Mountains (Fig. 1) and in the Pacific Northwest, USA. The Cascade Arc includes nearly 20 major volcanoes, among a total of over 4,000 separate volcanic vents, including numerous stratovolcanoes, shield volcanoes, lava domes, and cinder cones. Together, these rock units comprise the Cascade volcanic belt that is over 1,100 km long. The Cascade Arc is the result of subduction of the Juan de Fuca Plate along the Cascadia megathrust.

Volcanic Belts Related to Strike-Slip Faulting Associated with Subduction

Figure 7 displays a major tectonic gap in arc volcanoes, between the eastern end of the Wrangell Arc in eastern Southern Alaska and the northern end of the Cascade Arc in the southern Canadian

Cordillera. The gap coincides with the major Fairweather-Queen Charlotte Fault that extends from the northern limit of the Juan de Fuca Ridge to the south, to the Chugach-St. Elias Fault to the north. The fault defines the northeastern boundary of the Pacific Plate. Three volcanic belts, containing active or historic volcanoes, each with a unique tectonic origin, occur in this gap: (1) the Anaheim volcanic belt; (2) the Stikine volcanic belt; and (3) the Wells Gray-Clearwater volcanic belt. In addition, in Western Alaska and in the Bering Sea, is the Bering Sea volcanic belt that is also associated with dextral-slip faulting in the region.

Anaheim Volcanic Belt. The Anaheim volcanic belt (Fig. 7) contains 37 Quaternary basalt centers and three large shield volcanoes. The belt contains the Nazko basalt cinder cone that last erupted in 1550, and is one of the youngest volcanoes in Canada. The belt formed during transtension consisting of strike-slip faulting, extensional faulting, and continental rifting in the region.

Stikine Volcanic Belt. The Stikine volcanic belt (Fig. 7) contains a series of middle and late Cenozoic volcanoes that extends roughly north-northwest from northwestern British Columbia and the Alaska Panhandle through Yukon to the area south of Fairbanks in East-Central Alaska. The belt forms a corridor that is hundreds of km wide. The belt is the most recently defined volcanic province in the Northern Cordillera, and includes over 100 independent young volcanoes that have been active in the past 1.8 m.y. At least three of them erupted in the past 360 years, making it the most active volcanic area in Canada. Nevertheless, because of the dispersed population in this remote volcanic belt, and infrequent eruptions, few eruptions have been observed. The Stikine Belt is also called the Northern Cordillera Volcanic Province.

The Stikine volcanic belt formed during transtension consisting of strike-slip faulting, extensional faulting, and continental rifting that occurred during the northward sliding of the Pacific Plate along the Fairweather-Queen Charlotte Fault. These tectonic forces stretched the North American Plate, with the formation of near-surface fractures along steeply dipping faults. Hot magma rose between these fractures to create passive or effusive eruptions.

Wells Gray-Clearwater Volcanic Belt. The Wells Gray-Clearwater volcanic belt (Wells-Gray-Clearwater spot on Fig. 7) is a potentially active area of small, scattered volcanic vents that each formed in a short eruptive event. The field, which occurs in east-central British Columbia, contains small basalt volcanoes, basalt flows, and cinder cones that were erupted from 2.58 to 3.6 Ma (late Cenozoic) with the last eruption in 1550(?). The field formed during regional extension associated with dextral slip faulting.

Bering Sea Volcanic Belt. The Bering Sea volcanic belt (Fig. 7) occurs in West-Central Alaska, Seward Peninsula, and offshore on scattered islands in the Bering Sea. The belt consists of widespread basalt flows and cones. The ages of the eruptions range from latest Cenozoic to ~6 Ma. The belt is generally interpreted as forming along young, east-west-trending extensional faults that may be related to both oblique subduction of the Pacific Plate under Southern Alaska, and to the motion of Southern Alaska moving around the Alaska Orocline along the Tintina and Denali faults, with this motion resulting in the opening of stress cracks. A careful look at the distribution of these volcanic rocks shows that they are roughly aligned with the projection of major faults into the Bering Sea.

■ CENOZOIC LODGE MINERAL DEPOSITS FORMED ALONG OUTBOARD MARGIN OF NORTHERN CORDILLERA

Overview

Because the Northern Cordillera is a global mineral province, geoscientists want to know about the abundant Cenozoic lode mineral deposits and their tectonic origins. Figure 8 (Bundtzen and Nokleberg, 2017b) portrays the locations for large and one world-class Cenozoic lode deposits in the Northern Cordillera. (A lode denotes a deposit hosted in rock, as contrasted with a placer that refers to a deposit hosted in gravel.) These locations are superposed on the Cenozoic faults map (Fig. 5). The major features in Figure 8 are geologic sites, sizes, and types

for: (1) ophiolite-hosted deposits associated with the Kula Oceanic Plate (ophiolite is a slab of oceanic lithosphere); (2) orogenic gold quartz vein deposits associated with early Cenozoic subduction of the Kula-Farallon Oceanic Ridge; and (3) lode deposits formed in middle and late Cenozoic rocks of the Aleutian and Cascade arcs.

Lode Deposits Associated with Early Cenozoic Kula Oceanic Plate

Two major deposit types are associated with the early Cenozoic Kula Oceanic Plate: (1) deposits hosted in marine volcanic rocks formed in the upper part of an ophiolite (Copper Bullion, Ellamar, Latouche, and Beatson deposits containing copper, lead, gold, zinc, nickel, and platinum group elements [PGE]); (2) a deposit hosted in mafic and ultramafic plutonic rocks formed in the lower part of an ophiolite (Brady Glacier deposit containing nickel, copper, cobalt, and PGE).

The ophiolite is preserved in discontinuous fragments of the Resurrection terrane (unit RE, Fig. 8) that occurs in fault-bounded slivers in the Prince William terrane. These deposits and the enclosing host rocks, part of the Kula Oceanic Plate, formed immediately before the early Cenozoic subduction and disappearance of the Kula Plate under the margin of Southern and Southeastern Alaska.

Lode Deposits Associated with Early Cenozoic Subduction of the Kula-Farallon Oceanic Ridge

A suite of orogenic gold quartz vein deposits (Alaska-Juneau, Chichigoff, Hirst-Chichagof, Cliff, Kensington, and Treadwell deposits containing gold and silver) occur in accreted terranes along the outboard margin of Southern and northern Southeastern Alaska. These deposits formed in the early to middle Cenozoic, mainly in the Valdez Group that comprises the southern Chugach terrane (unit CG), when the Kula-Farallon Oceanic Ridge was subducted inboard, under the accreting margin of eastern Southern Alaska and Southeastern

Alaska. This genesis of the veins, associated with subduction of the Kula-Farallon ridge, is proposed in journal papers by several groups of mineral resource geologists.

Lode Deposits Formed in Middle and Late Cenozoic Aleutian and Cascade Continental-Margin Arcs

Figure 8 also displays a suite of Cenozoic continental-margin-arc deposits that occur in the Aleutian Arc on the Alaska Peninsula in central Southeastern Alaska, and in the Cascade Arc in the southern Canadian Cordillera.

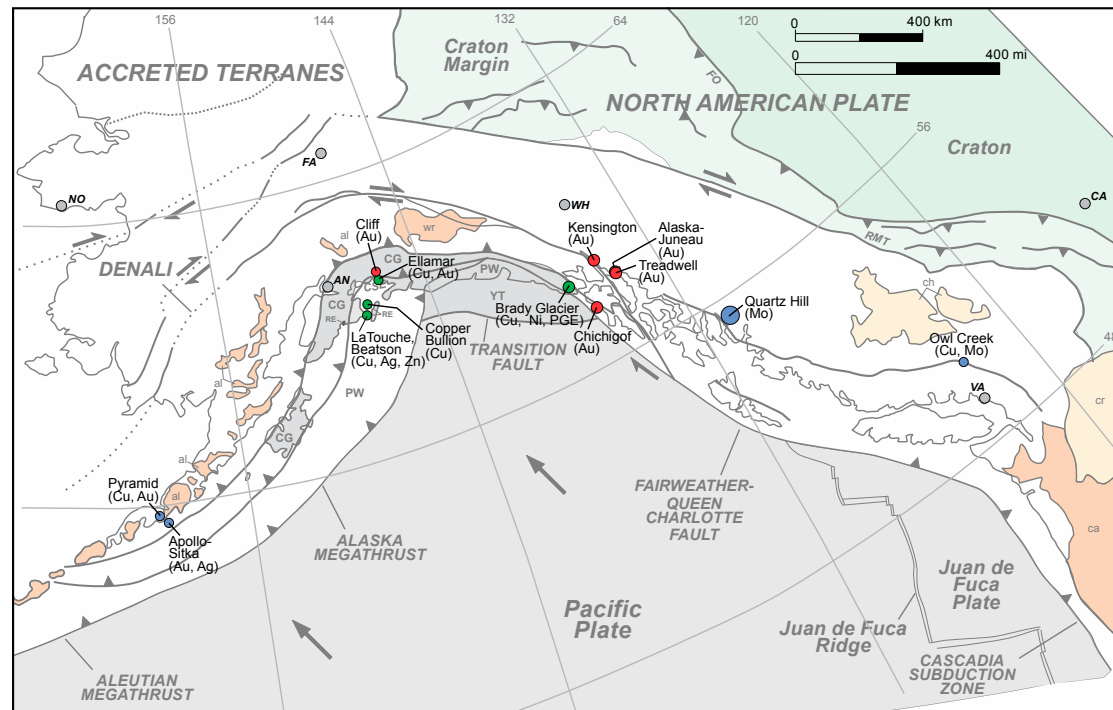
Two types of continental-margin-arc deposits occur in the region: (1) deposits formed in continental-margin arc volcanic rocks (Apollo-Sitka, Owl Creek) that contain gold, silver, copper, and molybdenum; and (2) deposits formed in continental-margin arc granitic rocks (Pyramid, Quartz Hill) that contain molybdenum, copper, and gold. The deposits range from medium to large to world class.

The lode deposits associated with the middle and late Cenozoic Aleutian Arc and the Cascade Arc formed subduction of two different oceanic plates. Since the early to middle Cenozoic, the Aleutian Arc has been forming from subduction of the northern margin of the Pacific Plate along the Aleutian-Alaska megathrust. The Cascade Arc has been forming since the middle Cenozoic from the subduction of the Juan de Fuca Plate along the Cascadia megathrust.

■ GEOTHERMAL ENERGY SITES RELATED TO CONTINENTAL-MARGIN ARCS

Overview

Because geothermal energy sites (mainly Cenozoic age for the Northern Cordillera) are important to society, geoscientists need to know about distribution and tectonic origins. Figure 9 (Bundtzen and Nokleberg, 2017a) displays continental geothermal resources sites (both volcanic and non-volcanic thermal springs) that are superposed on Figure 7. This



GEOLOGIC UNITS

Middle Tertiary to Holocene Volcanic Belts

Continental-Margin Arcs

al, Aleutian; ca, Cascade; wr, Wrangell

Hot Spot Units

ch, Chilotin Plateau Basalt; cr, Columbia River Basalt

Cratons and Craton Margins

Craton

Craton margin

Ocean Units

Oceanic plate

Subducted Terranes

CG, Chugach; PW, Prince William; RE, Resurrection; YT, Yakutat

Ophiolite Terrane

RE, Resurrection

LODE DEPOSIT SIZES

○ World Class
○ Large

LODE DEPOSIT TYPES

● Ophiolite
● Orogenic Quartz Vein
● Continental-Margin Arc

CONTACTS, MAJOR FAULTS, AND TECTONIC SYMBOLS

(Active Major Faults in Red)

— Contact
 Thrust fault
 Strike-slip fault with dextral displacement
 Oceanic spreading ridge
 Direction of oceanic plate movement

Figure 8. Cenozoic lode deposits. Map portrays lode deposit sites, size, and types for: (1) ophiolite-hosted lode deposits (containing copper, lead, gold, zinc, nickel, and platinum group elements) that occur in remnants of the Kula Oceanic Plate; (2) orogenic gold quartz vein deposits (containing gold and silver) that formed during early Cenozoic subduction of the Kula-Farallon Oceanic Ridge; and (3) igneous-rock-related lode deposits (containing gold, silver, copper, and molybdenum) that formed in the middle and late Cenozoic rocks of the Aleutian and Cascade continental-margin arcs. Major metals for each deposit are shown in parentheses next to deposit name. Adapted from Bundtzen and Nokleberg (2017b). The classification of lode deposits into world class or large size, based on resource size, is according to classifications by USGS mineral deposit specialists.

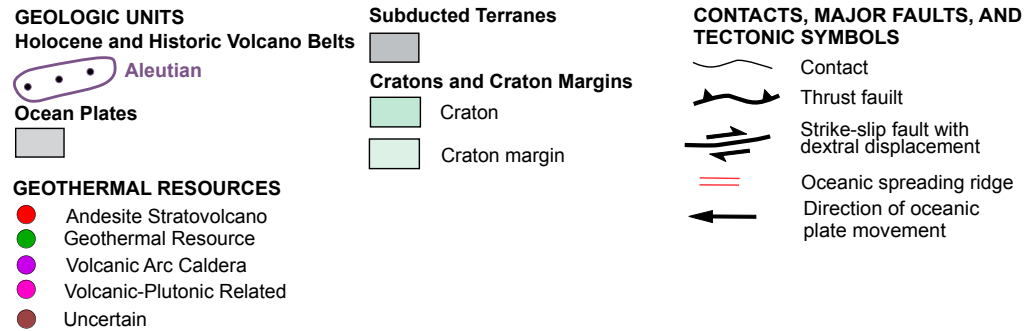
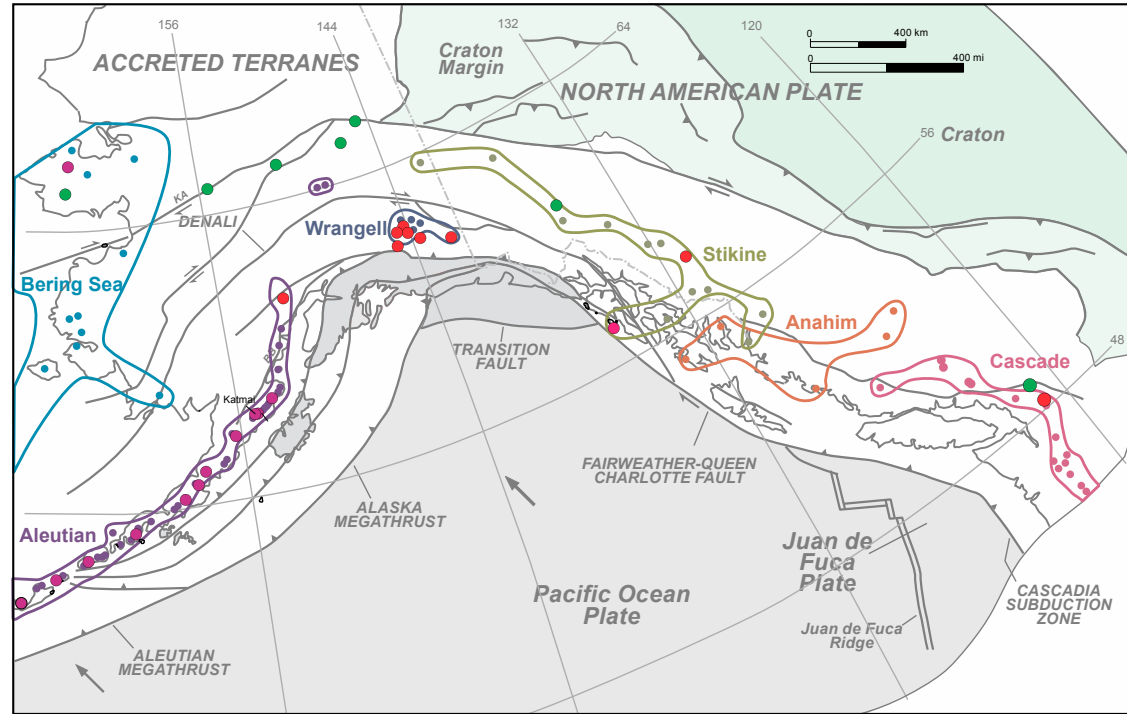


Figure 9. Geothermal energy sites. Map portrays geothermal energy sites for the: (1) Aleutian Arc; (2) Wrangell Arc; (3) Bering Sea and Stikine volcanic belts; and (4) Cascade Arc. Adapted from Bundtzen and Nokleberg (2017a).

figure illustrates the geologic origins of geothermal resources for the region. In more detail, Figure 9 depicts geothermal energy sites that are associated with the: (1) Aleutian Arc; (2) Wrangell Arc; (3) Bering Sea, Anaheim, and Stikine volcanic belts; and (4) Cascade Arc. In addition to substantial geothermal resources, the Northern Cordillera also contains vast coal and petroleum (oil and gas) resources. For information on these resources, we refer readers to Bundtzen and Nokleberg (2017a) in the e-book.

Geologic Setting of Geothermal Resources

Geothermal resources (i.e., sites where geothermal energy may be extracted) are considered renewable because heat is constantly produced within the earth's interior and is manifested as geothermal energy at the surface. Hence, geothermal resources are generally sustainable for centuries, if developed with appropriate technologies.

Shallow geothermal energy resources, such as steam vents, are often associated with recent volcanism and thermal springs, and in associated shallow plutons. Both phenomena occur in the Northern Cordillera, and some have a large geothermal resource potential, as illustrated in Figure 9. Recent to modern volcanic arcs are associated with most of the geothermal resources.

Geothermal Resources Hosted in the Aleutian Arc, Southern Alaska

The area with the greatest potential for geothermal power development is the Aleutian Arc, where over 60 major volcanic centers occur (Fig. 9). More than half erupted during the past 200 years. Of particular interest in geothermal power potential are the more than 20 volcanic calderas in the Aleutian Arc. The calderas contain near-surface magma chambers and associated heat reservoirs that can contain super-heated steam and thermal hot springs. The Aleutian Arc calderas range in size from Great Sitkin (1.6 km²) to Mount Aniakchak, Mount Emmons, and Mount Okmok (all greater than 10 km²). Many, such as Ugashak-Peulik, Makushin,

Novarupta, and Veniaminof, range from 3 to 5 km² in size. Active volcanoes, including Augustine Volcano, Mount Spurr, Mount Dana, and Mount Adagdak, all contain high level magma chambers and therefore probably near-surface heat sources.

Geothermal Resources Hosted in the Wrangell Arc, Eastern Southern Alaska

The Wrangell Arc consists of a thick middle and late Cenozoic volcanic pile that underlies 10,000 km² of the Wrangell Mountains. A few thermal springs are associated with the Wrangell Arc, and Mount Wrangell (4,268 m) has an active thermal area near its summit (Fig. 9). The presence of several latest Cenozoic stratovolcanoes in Alaska, including Mount Drum (3,622 m), Mount Sanford (4,950 m), Mount Blackburn (5,037 m), and Regal Mountain (4,210 m), and in Canada, Mount Churchill (4,500 m), all attest to the nature of recent magmatism (volcanism and plutonism) and associated geothermal potential. One eruptive center, now largely underneath Klutlan Glacier, erupted ~1,250 years ago, and deposited the White River Ash over >300,000 km² of East-Central Alaska and the northwestern Canadian Cordillera.

Geothermal Resources Hosted in Bering Sea Volcanic Belt, Western Alaska

In Western Alaska, potential geothermal resources sites occur in, or near late Cenozoic alkaline basalt centers that are part of the Bering Sea volcanic belt, which covers >20,000 km² on the Seward Peninsula in Western Alaska and in Southwestern Alaska (Fig. 9).

Geothermal Resources Hosted in Stikine Volcanic Belt, Anaheim Magmatic Belt, and Cascade Arc, Southeastern Alaska and Southern Canadian Cordillera

In central Southeastern Alaska and the central and northern Canadian Cordillera, 12 Cenozoic

volcanic complexes contain geothermal power generation potential, which, according to some, ranges from 3,000–5,000 Mw of power. Individual volcanic centers include the Tuya Volcanic Field, and the Hoodoo, Iskut, Edziza, Lava Fork, and Tseax volcanoes. These thermal springs, which are associated with the latest Cenozoic volcanoes of the Stikine Belt, are related to dextral-slip faults formed in association with the active Fairweather-Queen Charlotte Fault that occurs mainly offshore of Southeastern Alaska and the Southern Canadian Cordillera (Fig. 9).

Farther south, in the southern Canadian Cordillera, in the northern Cascade Arc (Fig. 9), is Mount Garibaldi, with potential for geothermal resources. Some of the highest heat flows measured in Canada are at Mount Garibaldi.

Volcanic and Non-Volcanic Thermal Springs, Northern Cordillera

Nearly 260 thermal springs are known in the Northern Cordillera. About 120 of these occur in Alaska, and 140 occur in British Columbia and Yukon. About 50 of the thermal springs in Alaska occur in the Aleutian Arc. The remaining thermal springs in Alaska and Canada, which occur in interior Alaska, Southeastern Alaska, and the Rocky Mountains, have no apparent spatial or temporal association with latest Cenozoic magmatism (volcanism and plutonism). These non-thermal hot springs occur in a number of bedrock terranes. Studies by the U.S. Geological Survey and by the Alaska Division of Geological and Geophysical Surveys indicate a close association with the margins of granitic plutons. Studies by researchers from both agencies propose that deeply circulating meteoric waters gained access to the surface along the fractured contacts of granite plutons and contact-metamorphosed wall rocks.

For >100 years, many of these thermal springs have been popular sites for use in spas or small-scale agricultural developments. For example, greenhouses heated with geothermal heat are used to grow a variety of crops that could not be grown in a sub-Arctic climate. The 140 thermal springs known

in the northern Canadian Cordillera are about equally divided between volcanic belts with high heat flows and Cretaceous and Cenozoic granite plutons.

Well-known, previously or currently developed hot springs systems in Alaska include Serpentine Hot Springs and Pilgrim Hot Springs north of Nome; Melozi Hot Springs near Galena, and Manley, Chena, and Circle Hot Springs near Fairbanks. Hot springs systems in Western Canada include Takhini Hot Springs near Whitehorse, Laird Hot Springs Park near Watson Lake, Banff Hot Springs in Alberta, and Lussier and Halcyon Hot Springs in British Columbia.

Thermal springs in Southeastern Alaska are similar to those in interior Alaska, but are spatially separated from the latter. Although thought to be associated with conduits in competent wall rocks in granitic plutons, similar to the settings in interior Alaska, 14 of the 18 known springs in Southeastern Alaska are localized along prominent northwest-trending fault zones. In the Canadian Cordillera, the thermal springs have a spatial relationship with the Mount Edgecumbe Volcano, part of the Stikine volcanic belt. Geothermometry studies suggest that 55–151 °C water emanates from depths ranging from 2 to 5 km. These thermal springs are associated with the latest Cenozoic volcanoes of the Stikine volcanic belt.

■ PLATE MOVEMENTS RECORDED FROM GPS MEASUREMENTS

Overview

Neotectonic plate motions are a fascinating topic for geoscientists. Figure 10 (Nokleberg and Stone, 2017a) displays GPS vectors, relative to the North American Craton, that are superposed on the continental geographic map (Fig. 1). Areas of co-linear GPS vectors are enclosed by dashed polygons, each with a distinct tectonic origin.

The polygons are numbered, starting from the Alaska Peninsula in the northwest, then stepping generally southeastward to Washington State. Also shown are black movement vectors for the Pacific Plate, Juan de Fuca Plate, and Juan de Fuca Ridge, and a scale bar for GPS vectors. The estimates used

for these vectors are calculated from models of global plate motion averaged over millions of years.

Tectonic Settings of GPS Vectors Related to Subduction

GPS Vector Area 1

This set of GPS vectors (Fig. 10) trends slightly obliquely with respect to the Aleutian Arc and the Aleutian-Alaska megathrust (as depicted on the Cenozoic faults map, Fig. 5), and the direction of Pacific Plate motion. The GPS velocities range around 10–20 mm/yr. Many active volcanoes of the Aleutian Arc occur in this area. The GPS vectors represent northwest migration in response to subduction of the northern part of the Pacific Plate beneath Southwest and Southern Alaska.

GPS Vector Area 2

This set of GPS vectors generally trends south-southeast. The GPS velocities are short to moderate in length, from ~5–18 mm/yr. Seismic studies suggest that southward-directed GPS vectors are the result of uplift after the 1964 Great Alaska Earthquake.

GPS Vector Areas 3a and 3b

These two areas are discussed together because they appear to be connected along their coastal regions; however, no well-defined fault boundary occurs between them. Having the same GPS velocities indicates that they are presently locked together.

GPS Vector Area 3a. This set of GPS vectors trends nearly perpendicular to the Aleutian megathrust. The GPS velocities are high, up to 60 mm/yr—a Neotectonic hot rod! Two active volcanoes occur in this southwestern edge. The highest GPS velocities occur where the Yakutat Terrane is being thrust under Southern Alaska. The vectors reveal that displacement on this part of the Aleutian

megathrust is mainly thrusting. The vectors also indicate that the northern part of the Pacific Plate is being subducted under the margin of Southern Alaska, with mainly thrust movement.

GPS Vector Area 3b. This set of GPS vectors trends nearly parallel to the Fairweather-Queen Charlotte Fault. The GPS velocities are high, up to 40 mm/yr.

GPS Vector Area 4

This set of GPS vectors generally trends from west-northwest in the east to west-southwest in the west, parallel to the broad oroclinal arc of the Denali Fault. The GPS velocities are small, ~5 mm/yr.

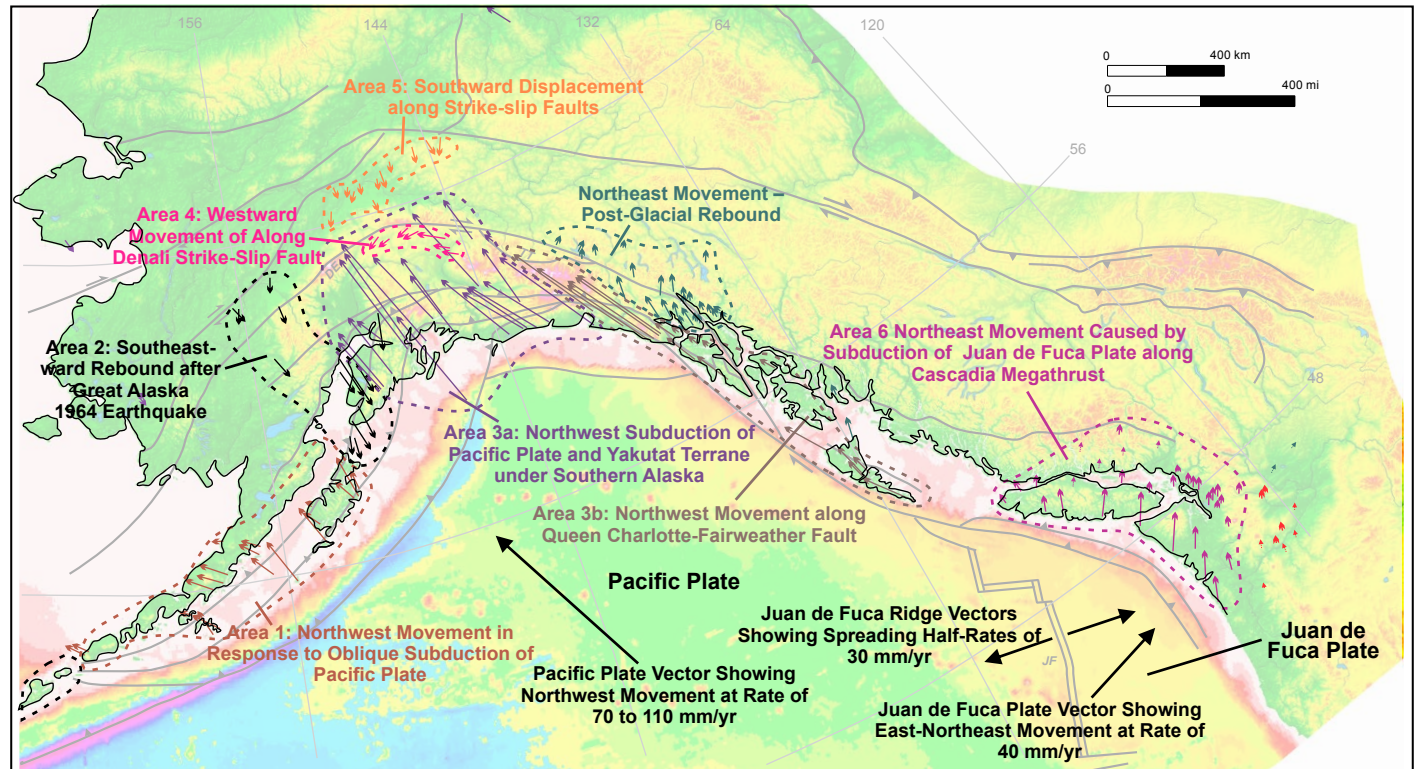
These observations suggest westward movement in response to continuing dextral strike-slip movement along the Denali Fault. Part of this movement occurred on 3 November 2002 when the largest inland earthquake in North America in ~150 years struck Alaska with a moment magnitude of 7.9. The Trans-Alaska Pipeline, which crosses the Denali Fault in the Eastern Alaska Range, experienced 4.3 m of dextral (right-lateral) and 0.76 m of vertical displacement. But because of good engineering, no rupture and no oil spill occurred. For more information on the 2002 earthquake, see Fuis et al. (2003).

GPS Vector Area 5

This set of GPS vectors generally trends south-southeast to south-southwest. The GPS velocities are small, ~5 mm/yr. These observations suggest southward movement along a series of northeast-trending strike-slip faults that occur between the Denali Fault to the south and the Tintina Fault to the north.

GPS Vector Area 6

This set of GPS vectors trends nearly perpendicular to the Cascadia megathrust. The GPS velocities are moderate, up to ~15 mm/yr. The GPS vectors



CONTACTS, MAJOR FAULTS, AND TECTONIC SYMBOLS

- Contact
- Pre-Miocene Thrust fault
- Strike-slip fault with dextral displacement
- Oceanic spreading ridge
- Direction of oceanic plate movement
- Vector showing GPS direction and rate of movement for selected sites on islands and continents

DIGITAL TOPOGRAPHY SCALE (Meters above sea level)

- 1 - 200
 - 200 - 500
 - 500 - 1,500
 - 1,500 - 2,500
 - 2,500 - 3,500
 - 3,500 - 7,000
- Scale for vector rates, mm/yr

DIGITAL BATHYMETRY SCALE (Meters below sea level)

- | | | | |
|----------------|----------------|----------------|----------------|
| -9,504 - 8,020 | -5,454 - 5,289 | -3,863 - 3,692 | -1,564 - 1,239 |
| -8,019 - 7,358 | -5,288 - 5,116 | -3,691 - 3,488 | -1,238 - 914 |
| -7,357 - 6,810 | -5,115 - 4,934 | -3,487 - 3,234 | -913 - 585 |
| -6,809 - 6,353 | -4,933 - 4,739 | -3,233 - 2,940 | -584 - 310 |
| -6,352 - 6,022 | -4,738 - 4,521 | -2,939 - 2,628 | -309 - 120 |
| -6,021 - 5,792 | -4,520 - 4,292 | -2,627 - 2,291 | -119 - 0 |
| -5,791 - 5,618 | -4,291 - 4,064 | -2,290 - 1,923 | |
| -5,617 - 5,455 | -4,063 - 3,864 | -1,922 - 1,565 | |

Figure 10. GPS Neotectonic speedometer map. Map portrays: (1) groups of GPS vectors in various colors for six numbered areas (surrounded by dashed polygons that have distinct Neotectonic settings); and (2) black movement vectors for the Pacific Plate, Juan de Fuca Plate, and Juan de Fuca Ridge. Adapted from Nokleberg and Stone (2017a).

vary from sub-perpendicular to moderately oblique to the Cascade megathrust, suggesting continental compression caused by subduction.

EASTERN ALASKA UPPER LITHOSPHERE CROSS SECTION—UNDERTHRUSTING OF TERRANES, OCEANIC CRUST, AND PACIFIC PLATE OCEANIC LITHOSPHERE BENEATH MARGIN OF SOUTHERN ALASKA

Overview

For geoscientists, cross sections, or slices into the earth, reveal important interpretations of the units and structures below the surface. Figure 11 (Nokleberg and Stone, 2017b) is a cross section through Eastern Alaska in the northern part of the Northern Cordillera. This figure, unlike the previous 10 figures that are areal maps, is a map of a vertical cut through the lithosphere (crust and upper

mantle). And also unlike the previous 10 maps, this cross section is a synthesis and interpretation of work by field geologists mapping surface geology, by geophysicists studying gravity and aeromagnetic maps, and by seismologists compiling maps of earthquakes and interpreting seismic surveys. The line of the cross section is shown on Figure 2.

The Eastern Alaska upper lithosphere cross section portrays the subduction (underthrusting) of terranes and oceanic lithosphere plates, including the Pacific Plate lithosphere beneath the margin of Southern Alaska. From left to right, or south to north, the crustal cross section extends from the Aleutian-Alaska megathrust in the south into interior Alaska to the north. The crustal structure and major geologic units are described below for sites along the cross section, numbered from left to right (south to north). The cross section is best viewed at a magnification (zoom) of ~200%.

The major features on the cross section (Fig. 11) are: (1) Pacific Plate crust atop the Pacific Plate lithosphere mantle extending under the margin of

Southern Alaska; (2) the Aleutian-Alaska megathrust; (3) a suite of terranes and one oceanic plate that have been, or are being, subducted along the margin of Southern Alaska, from the early Cenozoic to the Recent (Yakutat, Prince William, and Chugach terranes, and the Kula Plate); and (4) the Wrangell (continental-margin) Arc occurring above the Alaska megathrust.

Tectonic Settings of Sites along the Cross Section

Alaska Site 1. Aleutian-Alaska Trench and Alaskan Megathrust: Modern-Day Subduction of the Pacific Plate

At this site, Figure 11 illustrates the Aleutian-Alaska Trench and the surface expression of the Alaska-Aleutian megathrust (subduction zone) that are depicted near the left (south) part of the cross section. As depicted on Figure 3 (marine geology

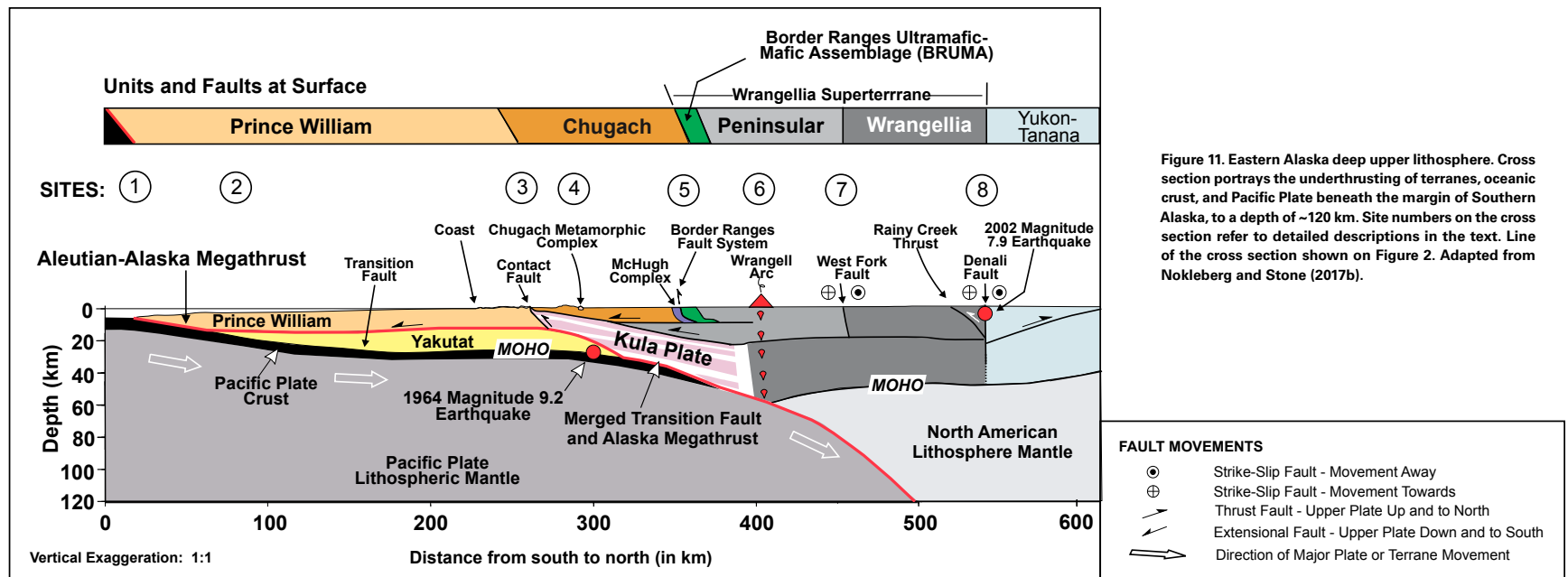


Figure 11. Eastern Alaska deep upper lithosphere. Cross section portrays the underthrusting of terranes, oceanic crust, and Pacific Plate beneath the margin of Southern Alaska, to a depth of ~120 km. Site numbers on the cross section refer to detailed descriptions in the text. Line of the cross section shown on Figure 2. Adapted from Nokleberg and Stone (2017b).

and seascapes map), the trench is a long and continuous trough. Along the northern margin of the trench is the associated megathrust (subduction zone) where the Pacific Plate is being thrust downward and northward at a low angle. The megathrust forms a linear zone along which the Pacific Plate is being pulled by gravity obliquely under the margin of Southern Alaska. Also observe on the cross section that the Alaska-Aleutian megathrust extends shallowly northward for several hundred km before diving into the mantle. Of great interest is the how the Pacific Plate underlies, at shallow depth, the southern third of Alaska!

The megathrust, which extends from the Gulf of Alaska westward down the Aleutian Island chain, consists of two parts operating in very different environments. The western (Aleutian) half of the megathrust has ocean crust of the Pacific Plate on the south side that is being thrust or pulled under older oceanic crust on the north side. In contrast, the eastern (Alaskan) half of the megathrust has oceanic crust of the Pacific Plate being thrust under the North American Plate (consisting in this area of the collage of accreted terranes that constitute Southern Alaska) that is structurally above the Pacific Plate. The boundary between these two parts lies where continental rocks underlying the Bering Sea intersect the Aleutian Arc near Umnak Island. Because of this marked contrast in style, it is appropriate to give the two parts of the megathrust related but separate names, the Aleutian megathrust (subduction zone) to the west, and the Alaska megathrust (subduction zone) to the east.

Alaska Site 2. Underthrust Prince William and Yakutat Terranes—Slabs Being Pulled Down the Subduction Zone of the Aleutian Megathrust

At this site, Figure 11 illustrates, from south to north, and from deeper to more shallow zones, three major tectonic slabs—the Pacific Plate (both crust and mantle), the Yakutat Terrane (described below), and the Prince William terrane (described below). The cross section shows how the younger Yakutat Terrane (sometimes called the Yakutat

block) is thrust *under* the older Prince William terrane, and how the Alaska-Aleutian megathrust forms the major tectonic boundary between the Pacific Plate to the south and the North American Plate (in this area, the collage of terranes forming Alaska) to the north. This tectonic process of underthrusting has reversed the typical stacking of younger rocks over older rocks!

Prince William Terrane. The Prince William terrane consists chiefly of a deep-sea fan sequence of early Cenozoic flysch (deep-marine, fine-grained sediments), and is bounded by the Contact Fault and the Chugach-St. Elias Fault (the northeastern part of the Aleutian-Alaska megathrust) to the north. Along the cross section, observe that the Prince William terrane extends for ~240 km from the Alaska-Aleutian megathrust to the south.

Yakutat Terrane. The Yakutat Terrane is a composite terrane that consists of: (1) Mesozoic mélange, chiefly faulted lenses of interlayered basalt, chert, argillite, tuff, and sandstone; (2) Late Cretaceous flysch that consists mainly of sandstone and siltstone, and younger early Cenozoic oceanic crust composed of basalt, shale, and shallow marine sandstone and siltstone; and (3) still younger early Cenozoic oceanic crust composed of basalt, shale, and shallow marine sandstone and siltstone.

On the Eastern Alaska upper lithosphere cross section, the Yakutat Terrane, resting on Pacific Plate crust, is bordered to the north by the Alaska-Aleutian megathrust (and collinear Chugach-St. Elias Fault). On the cross section, the Yakutat Terrane extends for ~230 km underneath the Prince William terrane and terranes to the north.

Pieces of the Yakutat Terrane are breaking off and are underthrusting themselves. As these pieces separate from the Pacific Plate to become part of Southern Alaska, the crust is thickening and being raised to form the Chugach and Saint Elias mountains (including Mount Saint Elias with an elevation of 5,489 m).

According to GPS measurements, the Yakutat Terrane is moving at ~45 mm/yr, almost parallel to the Fairweather Fault. This convergence rate is among the highest in the world within continental crust. The Yakutat Terrane has migrated perhaps

as much as 1,000 km northward from a site in the Pacific Northwest, USA, since the early Cenozoic when an oceanic plateau, just offshore of the Pacific Northwest, USA, split into two pieces, the Yakutat Terrane and the Siletz terrane, which remains in the Pacific Northwest, USA.

Alaska Site 3. Contact Fault—A Suture between Subduction Zone Terranes

At this site, Figure 11 illustrates the Contact Fault that forms a major, north-dipping suture between the Prince William (subduction zone) terrane to the south and the Chugach (subduction zone) terrane to the north. The Contact Fault extends for ~4,500 km along the eastern part of southern Alaska and offshore to the west and southwest.

The Contact Fault extends down dip for ~20 km where it abuts the Chugach-St. Elias Fault and the co-linear Aleutian-Alaska megathrust. The Contact Fault was active mainly in the middle Cenozoic when the Prince William terrane, being carried northward on the conveyor belt of the Pacific Plate, was broken off, accreted, and thrust under the Chugach terrane. Also near this site is the epicenter of the moment magnitude 9.2 1964 Great Alaska Earthquake, a major historic earthquake that is among the largest ever recorded. At the surface, the major geologic features for this site are: (1) the Prince William terrane, (2) the Contact Fault that dips northward, and (3) the southern Chugach terrane.

Alaska Site 4. Chugach Terrane—A Mesozoic Subduction Zone Complex, A Metamorphic Complex, and the Underthrust Kula Oceanic Plate

Chugach Subduction Zone Terrane. At this site, the main surface feature on Figure 11 is the Chugach Metamorphic Complex (described below). To the south and north of this site is the Valdez Group that forms the main part of the Chugach terrane. The Valdez Group contains mostly Late Cretaceous flysch, with a thick metabasalt sequence that locally occurs along the southern margin of the terrane.

The Valdez Group is metamorphosed mostly to lower greenschist facies. Along the northern margin of the Chugach terrane is the McHugh Complex, a Late Triassic to mid-Cretaceous sequence of oceanic slate and metabasalt tuff. This unit is variably metamorphosed from prehnite facies in the west to greenschist and local blueschist in the east, formed deep in a subduction zone. The Chugach terrane is intensely folded and sheared with folds dismembered into sheared limbs (isoclines). These structures dip moderately northward and formed during successive outboard underplatings (accretions) of sedimentary rocks during subduction.

Chugach Metamorphic Complex. The Chugach Metamorphic Complex contains an early Cenozoic, high-grade, east-west-trending metamorphic belt that is intruded by a belt of granitic plutons, with ages of 65–50 Ma. The metamorphic belt and plutons formed from a heat source called a slab window that was subducted under Southern Alaska in the early Cenozoic. The heat source caused both the metamorphism and partial melting of the sedimentary rocks of the southern Chugach terrane to form migmatite and granitic plutons. (Envision a gas burner being subducted under the continental margin.) The slab window is interpreted as the Kula-Farallon Oceanic Ridge, and the underthrusting caused formation of the Sanak-Baranof belt of granitic plutons (too small and narrow to depict on Fig. 11) that occur discontinuously in both the Chugach and Prince William terranes along the margin of Southern and Southeastern Alaska.

Major Faults Bounding Chugach Terrane. As shown on Figure 11, the northern margin of the Chugach terrane is bounded by the Border Ranges Fault System (BRFS) and the southern margin is bounded by the Contact Fault. At depth, the terrane is underthrust by the structurally underlying and accreted Kula Oceanic Plate (described below). At its northern extent, at about a 5 km depth, the Chugach terrane is truncated by a subhorizontal fault. Beneath is an interpreted faulted slab of the Wrangellia superterrane.

Kula Oceanic Plate. Along the southern margin, the Chugach terrane contains a 1- to 2-km-thick body of oceanic basalt that is above a 10-km-thick package of alternating sedimentary rocks and mafic

to ultramafic rocks that were tectonically underplated and accreted fragments of Kula Plate along the Southern Alaska coast. The existence of the accreted Kula Plate is inferred from: (1) seismic studies along the Eastern Alaska upper lithosphere cross section; (2) fault-bounded, sparsely dispersed remnants of the Resurrection (ophiolite) terrane that occurs along the southern edge of the Chugach terrane, but are too small to depict on the cross section; and (3) magnetic patterns on the Pacific Plate, some of which indicate that a fragment of the plate is preserved offshore in the western Aleutians. The Kula-Farallon Oceanic Ridge was subducted immediately after subduction and accretion of the Kula Plate.

At depth along the Eastern Alaska upper lithosphere cross section, the accreted Kula Plate fragments extend ~140 km from near the surface in the south to depths of ~60 km at the leading (northern) edge. The Kula Plate fragments are structurally above the Alaska-Aleutian megathrust and the subducting Pacific Plate. Incidentally, the term Kula is derived from an Athabaskan Indian word meaning *all gone*. Depending on whether it was a hard K or a soft K, it could mean *all gone* or “*oh no*”

Alaska Site 5. Border Ranges Fault System— Site of a Missing Forearc and a Closed Ocean Basin

At this site, Figure 11 illustrates the BRFS, which is a suture between the Chugach (subduction zone) terrane to the south and the Wrangellia (island-arc) superterrane to the north. The fault system is ~2,500 km long, and forms an arcuate trace in Southern Alaska, both onshore and offshore. The fault was a major subduction zone offshore of Southwestern and Southern Alaska from the Early Jurassic to Late Cretaceous. In the Cenozoic, the fault motion was, and continues to be, dextral-slip.

South of the BRFS on the cross section is blueschist in the Late Triassic to mid-Cretaceous McHugh Complex in the northern Chugach Terrane that formed at moderate depth and low temperature during rapid subduction of cold oceanic sediment and basalt tuff. Blueschist also occurs in

correlative units on northern Kodiak Island and the northwest margin of the Kenai Peninsula.

North of the fault is the high-temperature Border Ranges Ultramafic and Mafic Assemblage (BRUMA) that forms the base of the Late Triassic to Late Jurassic Talkeetna (island) Arc, one of several island arcs that comprise the Wrangellia superterrane. BRUMA extends for several thousand km as an arcuate unit on the north (continent-ward) side of the BRFS. A major tectonic question, before the conception of plate tectonics in the late 1960s was: How could an island arc formed in the ocean end up being in the center of a continent?

Along the BRFS, a process called tectonic erosion caused: (1) removal of the outboard forearc prism (oceanward side of the Talkeetna Arc), (2) the juxtaposition of the cold McHugh Complex along the northern margin of the Chugach terrane with the hot lower crust of the island arc to the north, and (3) closure of the ocean basin to the south of the Wrangellia superterrane. To understand tectonic erosion, imagine how subduction along a megathrust can act like a giant cheese grater.

At depth on the Eastern Alaska upper lithosphere cross section, the BRFS is truncated by a subhorizontal fault. Beneath the fault is an interpreted slab of the Wrangellia superterrane. At greater depths are the subducted fragments of the Kula Plate, the north-dipping Alaska-Aleutian megathrust, and the Pacific Plate.

Alaska Site 6. The Active Wrangell Volcanic Arc and the Wrangellia Superterrane

At this site, Figure 11 illustrates the generation of magma, at ~65 km depth, from the subduction and partial melting of the sedimentary and volcanic rocks of the Yakutat Terrane. The magma ascends to the surface to form the Wrangell (continental-margin) Arc to the east, and the Aleutian (continental-margin) Arc to the west. This relationship illustrates the tectonic linkage of subduction of the Pacific Plate to the formation of these active volcanic arcs.

At this site on the Eastern Alaska upper lithosphere cross section, the Alaska-Aleutian

megathrust occurs at a depth of ~58 km and a distance of 375 km north of the Aleutian-Alaska Trench. Also at this site, the crust of the Peninsular terrane, part of the Wrangellia superterrane, is anomalously thick (~55 km) for an oceanic volcanic arc.

Alaska Site 7. The Copper River Basin and the West Fork Fault—A Buried Suture between Two Parts of the Wrangellia Superterrane

At this site, Fig. 11 illustrates the buried West Fork Fault that occurs between the Peninsular terrane to the south from the Wrangellia terrane to the north, both part of the Wrangellia superterrane. Unusual for the Northern Cordillera, the West Fork Fault is covered by surficial deposits and is shown as an inferred fault (dotted line). The evidence for the West Fork Fault is the close juxtaposition of unmetamorphosed volcanic rock of the Late Triassic through Early Jurassic Talkeetna Arc in the Peninsular terrane to the south, against locally highly metamorphosed volcanic and plutonic rocks in the Wrangellia terrane to the north. At a greater depth on the cross section, the West Fork Fault is interpreted as being truncated and underlain by a fault-bounded wedge of the Wrangellia terrane.

At the surface, three major geologic units occur at this site. One unit is the Copper River Basin (too thin to depict on the cross section) that contains a thick succession of Late Cretaceous marine sedimentary rocks and Cenozoic continental sedimentary rocks. The youngest units at the surface of the basin are the extensive sand and silt glaciofluvial deposits from Glacial Lake Ahtna and glacial moraines from the bordering mountains. The basin covers an area about the size of Massachusetts (27,336 km²), and over 20,000 years ago at the peak of the last ice age, Glacial Lake Ahtna covered over 5,200 km². The lake deposits are nicely exposed along the banks of the Copper River.

The two other major units are the Peninsular terrane to the south and the Wrangellia terrane to the north, both part of the Wrangellia superterrane. The Peninsular terrane, which forms the southern part of the superterrane, consists mainly

of the Late Triassic and Early Jurassic Talkeetna Arc, which was built on the late Paleozoic Skolai (island) Arc. The Wrangellia terrane, which forms the northern part of the superterrane, consists of: (1) volcanic rocks and intrusion of coeval plutonic rocks of the late Paleozoic Skolai Arc; (2) basalt of the Late Triassic Nikolai Greenstone and intrusion of coeval mafic plutonic rocks that came from a plume; and (3) a major Late Jurassic and Early Cretaceous flysch basin and the coeval Gravina Island Arc. Considerable faulting has juxtaposed the Peninsular and Wrangellia terranes.

Alaska Site 8. Denali Fault—Locus of Cenozoic Strike-Slip and Thrust Faults Located in a Mesozoic Accretion Zone

At this site, Figure 11 illustrates, in the core of the eastern Alaska Range, the famous Denali (strike-slip) Fault and related thrust faults. The Denali Fault, which trends east-west at this location, is one of the major tectonic boundaries in North America, and extends over 2,500 km in Southern Alaska and Southeastern Alaska. Two major terranes are juxtaposed for several hundred km along the fault, the Wrangellia (island arc) superterrane to the south and the Yukon-Tanana (metamorphosed craton-margin) terrane to the north. Also at this site are several juxtaposed smaller terranes (Maclaren, Windy, and Aurora Peak), and narrow, fault-bounded slivers of Cenozoic sedimentary rock, all of which are too narrow to depict on the cross section. At the surface on Figure 11, the Denali Fault extends to a depth of at least 20 km.

The Denali Fault has been a major right-lateral strike-slip fault during the Cenozoic. In 2002, ~6 m of right-lateral displacement occurred along this part of the fault during a powerful moment magnitude 7.9 earthquake. (For information on this earthquake, see Fuis et al., 2003.) About 400 km of right-lateral movement has occurred along the fault since the Late Cretaceous. Previously, in the mid- and Late Cretaceous, in Southern and Southeastern Alaska, the ancestral Denali Fault was the zone of accretion of the Wrangellia superterrane onto the North America Craton margin.

Also depicted on Figure 11 is a pair of major thrust faults that occur north and south of the Denali Fault. On the south side of the Alaska Range, the Rainy Creek thrust and McCallum Creek-Slate Creek thrust dip northward or northeastward and displace late Paleozoic and Mesozoic units of the Wrangellia terrane over Cenozoic sedimentary rock. On the north side of the Alaska Range, the Donnelly Dome-Granite Mountain and Hines Creek faults dip south and displace Devonian units of the Yukon-Tanana terrane over Cenozoic sedimentary rock and late Cenozoic glacial moraines. These range-core-dipping thrust faults formed during the oblique compression and associated right-lateral strike-slip displacement that formed the Denali Fault and caused the uplift of the Alaska Range.

■ SOUTHERN CANADIAN CORDILLERA UPPER LITHOSPHERE CROSS SECTION: UNDERTHRUSTING OF TERRANES, OCEANIC CRUST, AND PACIFIC PLATE OCEANIC LITHOSPHERE BENEATH THE MARGIN OF THE SOUTHERN CANADIAN CORDILLERA

Overview

As discussed previously, for geoscientists, cross sections, or slices into the earth, reveal important interpretations of the units and structures below the surface. Figure 12 (Nokleberg and Stone, 2017b) is a cross section through the southern part of the Canadian Cordillera. This figure, like the Eastern Alaska cross section (Fig. 11), is a synthesis and interpretation of work by field geologists mapping surface geology, by geophysicists studying gravity and aeromagnetic maps, and by seismologists compiling maps of naturally occurring earthquakes and by conducting and interpreting seismic surveys. The line of the cross section is shown on Figure 2.

The Southern Canadian Cordillera upper lithosphere cross section portrays the underthrusting of terranes, oceanic crust, and Juan de Fuca Plate oceanic lithosphere beneath the margin of the Southern Canadian Cordillera. From left to right,

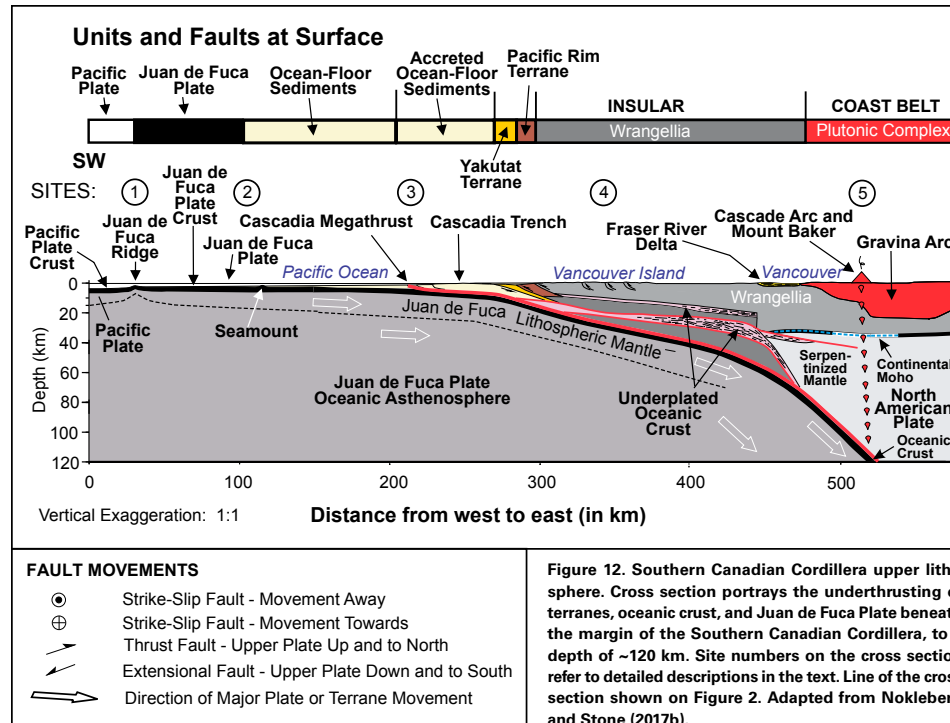


Figure 12. Southern Canadian Cordillera upper lithosphere. Cross section portrays the underthrusting of terranes, oceanic crust, and Juan de Fuca Plate beneath the margin of the Southern Canadian Cordillera, to a depth of ~120 km. Site numbers on the cross section refer to detailed descriptions in the text. Line of the cross section shown on Figure 2. Adapted from Nokleberg and Stone (2017b).

or west to east, the cross section extends from the Pacific Plate, the Juan de Fuca Ridge, and the Juan de Fuca Plate in the west, into the western margin of the North American Plate. The crustal structure and major geologic units are described below for numbered sites along the cross section, numbered from left to right. When reading the text, scroll from left to right (progressively inland) on the cross section. The cross section is best viewed at a magnification (zoom) of ~200%.

The major features on Figure 12 are: (1) Pacific Plate crust at the top of the Pacific Plate lithosphere; (2) Juan de Fuca Ridge; (3) Juan de Fuca Plate; (4) Cascadia megathrust; (5) underplated oceanic crust; (6) Wrangellia terrane; (7) Cascade Arc occurring above the Cascadia megathrust; (8) Mesozoic Gravina Arc overlying Wrangellia terrane; and (9) North American Plate.

Tectonic Settings of Sites along the Cross Section

Canadian Cordillera Site 1. Juan de Fuca Ridge—Modern-Day Sea-Floor Spreading along an Active Oceanic Ridge

Overview of the Juan de Fuca Ridge. At this site, Figure 12 displays several major tectonic relationships. One feature is the Juan de Fuca Ridge along which active seafloor spreading is occurring. To the west is the youngest margin of the Pacific Plate, and to the east is the youngest part of the Juan de Fuca Plate. Across the Pacific Ocean, the oldest part of the Pacific Plate, which formed along this ridge ~145 m.y., is being subducted under the eastern margin of Asia along the Kuril-Kamchatka Trench and the Japan Trench.

The Juan de Fuca Ridge is a tectonic spreading center located off the coasts of the state of Washington in the United States and British Columbia in Canada. The Juan de Fuca Ridge is a remnant of the former Pacific-Farallon Ridge. Along the ridge, new oceanic crust is being formed from upwelling of hot mafic magma to form a chain of marine basalt volcanic fields that are being actively rifted.

Here are some interesting observations about the Juan de Fuca Ridge. The spreading rate is medium-speed, ~5–10 cm/yr. Interspersed with the volcanoes along the ridge are hydrothermal vents (often called black smokers) that are submarine hot springs, which they have built spectacular chimneys up to 14 stories tall. Black smokers support ecosystems of unique life forms by ejecting sulfides that feed bacteria at the bottom of an unusual food chain that exists only in the inky blackness of the deep ocean. The Juan de Fuca Plate is the remnant of the once-vast Farallon Plate, which has been largely subducted under the North American Plate!

Canadian Cordillera Site 2. Juan de Fuca Plate and Ocean-Floor Sediment

Juan de Fuca Plate. At Site 2 on Figure 12 (Southern Canadian Cordillera upper lithosphere cross section), the major crustal units are the Juan de Fuca Plate and a thin veneer of ocean-floor sediments. The Juan de Fuca Plate is a tectonic plate generated at the Juan de Fuca Ridge and is subducting under the southwest margin of the North American Plate at the Cascadia megathrust to the northeast.

This subducting plate system has formed the Cascade Volcanic Arc and the Pacific Ranges along the west coast of North America from southern British Columbia to northern California. These, in turn, are part of the Pacific Ring of Fire, a much larger-scale volcanic feature that extends around much of the rim of the Pacific Ocean.

Ocean-Floor Sediment on Juan de Fuca Plate. A unit of ocean-floor sediments, ranging up to 3 km thick, covers the Juan de Fuca Plate. The ocean

floor sediments are thinnest near the ridge, where new oceanic crust is being created, and increase in thickness to the east where the oceanic crust is progressively older, with the resultant accumulation of more sedimentary debris. Ocean floor sediments are mainly pelagic sediment or terrigenous sediment. The former is a fine-grained sediment that accumulates as the result of the settling of plankton to the floor of the open ocean, far from land. The latter is derived from the erosion of rocks on land (in other words, from *terrestrial*, as opposed to marine, environments).

Canadian Cordillera Site 3. Cascadia Megathrust and Cascadia Trench

Crustal Structure. At this site on Figure 12 is the northeast dipping Cascadia megathrust (shown as a thick red line). To the northeast is the sediment-filled Cascadia Trench, and to the southwest is the Juan de Fuca Plate (and overlying ocean-floor sediments), which is being thrust under the margin of the North American Plate. At this site, the cross section illustrates: (1) the gently north-east-dipping Cascadia megathrust; (2) subducting and tectonically imbricated slices of ocean-floor sediment above the megathrust; (3) a thick, black line of young oceanic crust that was created at the Juan de Fuca Ridge below the megathrust; (4) a thicker unit of Juan de Fuca lithospheric mantle; and (5) oceanic asthenosphere that upwelled along the Juan de Fuca Ridge.

Cascadia Megathrust. The Cascadia megathrust (Fig. 12) is a classic subduction zone that extends from a triple junction in the north with the Queen Charlotte Fault and the Juan de Fuca Ridge, to Cape Mendocino in Northern California where it intersects the San Andreas Fault at the Mendocino Triple Junction.

The megathrust separates the Juan de Fuca Plate to the west from the accreted terranes of the Canadian Cordillera and overlying Cascade Volcanic Arc to the east. It forms a linear tectonic trench along which the Juan de Fuca Plate is being subducted to the northeast beneath the North American Continental Margin. Along the megathrust, at depths of

~150 km, magma is generated and rises to form the Cascade Arc. Associated with the subduction are deep earthquakes, great eruptions and intrusion of granite plutons that form the roots of the arc. Although the Cascadia megathrust has the potential for major earthquakes, only relatively sparse, low-magnitude, and shallow earthquakes have occurred in historic times. The last known major event was the 1700 Cascadia Earthquake.

Cascadia Trench. Oceanic trenches typically extend 3–4 km below the level of the surrounding oceanic floor. However, in this area marine geology and geophysical studies reveal that the Cascadia Trench is filled to the brim with young sediment, indicating that shedding of sediment to the offshore basin has far exceeded sediment removed by subduction. The occurrence of only sparse, shallow, and low-magnitude earthquakes along the megathrust also suggests that the current rate of subduction is relatively slow.

Canadian Cordillera Site 4. Wrangellia Terrane and Tectonically Underlying Slabs of the Pacific Rim and Yakutat Terranes

Crustal Structure. At this site, centered on southern Vancouver Island, Figure 12 reveals several major tectonic slabs. From the surface downward, these are: (1) a thick unit of the Wrangellia terrane with east-dipping thrust faults; (2) two duplexed (tectonically imbricated) sequences of ocean-floor sediments (pale pink slabs) and mantle (dark-gray slabs); (3) below the Cascadia megathrust, a thick, black line representing young oceanic crust that was created at the Juan de Fuca Ridge; (4) the Juan de Fuca lithospheric mantle; and (5) Juan de Fuca Plate asthenosphere that upwelled along the Juan de Fuca Ridge. The lithosphere below the megathrust is subducting eastward.

On the western margin of southern Vancouver Island are two accreted terranes: (1) a thrust-fault-bounded slab of the Pacific Rim terrane that dips moderately eastward under the Wrangellia terrane; and (2) farther west (outboard), a thrust-fault-bounded slab of the Yakutat Terrane that also dips moderately eastward under terranes to the

east. These two terranes are remnants of larger, previously subducted units. Thrust eastward beneath these two terranes is a wedge of ocean-floor sediment.

Wrangellia Terrane. The Wrangellia terrane on Vancouver Island contains three major rock suites. First, the oldest suite is the Late Devonian Sicker Group, which contains mainly volcanic rocks (tuffs, flows, breccias, and dikes ranging from basalt to rhyolite), graywacke, shale, limestone, and Late Devonian granite plutons. The volcanic strata of the Sicker Group represent an island arc assemblage. The next younger suite consists of well-bedded late Paleozoic limestone and fine-grained clastic and volcanoclastic rocks that are correlated with the Skolai Group in Southern Alaska. The Skolai Group rocks are the remnant of a late Paleozoic volcanic island arc. The youngest suite consists of the Karmutsen Formation, which is a Middle(?) to Late Triassic volcanic sequence of pillow basalt and breccia on Vancouver Island. The sequence ranges up to 6,000 m thick. The Karmutsen Formation, and the correlative Nikolai Greenstone in the Wrangellia terrane in Southern Alaska, formed over a plume that caused massive outpouring of basalt on the Wrangellia terrane.

Mesozoic Assemblages Overlapping the Wrangellia Terrane. Overlapping the Wrangellia terrane on southern Vancouver Island are two major overlap assemblages. The older assemblage, the Bonzana Arc, contains Early Jurassic granitic gneiss, amphibolite (metamorphosed volcanic rocks), diorite, and migmatite in the lower parts of the arc and siliceous granite plutons in the island intrusions in the middle part of the arc. The overlying Bonzana Volcanics form the middle and upper parts of the arc. The Bonzana Arc is the southern part of the Talkeetna-Bonzana Arc that occurs discontinuously in Southern Alaska and the Canadian Cordillera. The arc formed a major overlap assemblage on the Wrangellia terrane, forming the northern part of the Wrangellia superterrane, during migration of the superterrane toward North America.

The younger overlap assemblage is the Late Cretaceous Nanaimo Group that contains coarse, greenish to buff weathering, shallow marine sandstone with white shell fragments. At its base, the

Nanaimo Group contains greenish conglomerate with well-rounded pebbles of volcanic rock. The pebbles become coarser downward, and just above the basal contact, consist of angular boulders of the underlying dark green to reddish altered massive metabasalt of the Karmutsen Formation.

Pacific Rim Terrane. The Pacific Rim (subduction zone) terrane contains mainly turbidites and occurs on the southwestern margin of Vancouver Island and in the USA Pacific Northwest. On southwestern Vancouver Island, the terrane consists, from older to younger, of a structural *mélange* of: (1) Late Triassic to Early Jurassic arc-related volcanic rocks; and (2) unconformably overlying, disrupted, Late Jurassic to Early Cretaceous graywacke (a dirty sandstone), argillite, conglomerate, chert, and tuff. The rocks were eroded from a mixed plutonic, volcanic, and metamorphic source. In a few places, the terrane also contains blocks of chert or recrystallized limestone. The terrane is metamorphosed to prehnite-lawsonite facies, but locally contains blueschist facies minerals, including lawsonite. The suite of rocks in the Pacific Rim terrane and deformation reveal that the rocks were scraped off of the top of oceanic lithosphere that was being relatively quickly subducted to great depths. The rare but widespread presence of blueschist facies metamorphic minerals, such as lawsonite, which forms at relatively great depths and low temperatures, reveals the rapid subduction of these rocks and quick return to the surface. The Pacific Rim terrane is lithologically, temporally, and tectonically similar to the Chugach (subduction zone) terrane in Southern Alaska.

Yakutat Terrane. The Yakutat Terrane in the Southern Canadian Cordillera consists of three major early Cenozoic units: (1) a lower unit of gabbro and a sheeted dike complex that formed along an oceanic ridge; (2) a middle unit of pillow basalt, basaltic volcanic breccia, minor silicic tuff, and limestone; and (3) an upper unit of middle Cenozoic marine sandstone, conglomerate, and mudstone. This fragment of the Yakutat Terrane, in the offshore part of the Southern Canadian Cordillera, is the eastern part of a larger block that was faulted away and transported north to eastern Southern Alaska where it is subducting beneath Southern Alaska.

Canadian Cordillera Site 5. Cascade Arc and Mount Baker, Gravina Arc, and Fraser River Delta

Crustal Structure. At this site, which is centered on the Cascade Arc, Figure 12 reveals several major geologic units from the surface to depth: (1) the middle Cenozoic Cascade Arc, including Mount Baker, a major active volcano along this part of the arc; (2) the Late Jurassic and Late Cretaceous Gravina Arc; (3) the Wrangellia terrane; (4) the continental moho at the top of the western North American Plate; (5) a wedge of serpentized mantle formed by ascent of fluids from underlying and subducting ocean-rich sediments; (6) North American Plate asthenosphere; (7) Cascadia megathrust; (8) a thick, black line representing oceanic crust that was created at the Juan de Fuca Ridge; (9) Juan de Fuca lithospheric mantle; and (10) Juan de Fuca Plate Oceanic Asthenosphere. The lithosphere below the megathrust is being subducted eastward. At depths of ~120 km, partial melting occurs in water-rich oceanic sediments to form magma in plutons that are ascending to the surface to form the Cascade Arc.

Cascade Arc. The Cascade Arc extends from southwestern British Columbia into northern California, inboard and above the subducting Juan de Fuca Plate (Fig. 7). The older part of the arc in Canada, beneath the currently active volcanoes, consists of volcanic rocks ranging from ca. 34 to ca. 14 Ma, and granitic rocks ranging from ca. 26 to 17 Ma. The volcanic rocks are preserved in the western part of the Coast Mountains, and the granitic rocks are preserved in the more uplifted and deeply eroded central part. The younger part of the arc is more restricted in extent and consists of dormant volcanoes, lava flows, and a few small granitic intrusions <8 m.y. old. These young volcanic centers are aligned in a roughly north to south direction, ~300 km east of the surface expression of the Cascadia megathrust.

Gravina Arc. Most of the eastern Coast Mountains are underlain by Late Jurassic to mid-Cretaceous granitic rocks that are part of the Gravina (island) Arc. This arc is part of the extensive Gravina-Nutzotin-Gambier volcanic-plutonic-sedimentary belt that extends discontinuously from the Eastern Alaska Range in Southern Alaska into the

western Canadian Cordillera. The belt overlies the inboard parts of the Wrangellia and Alexander terranes (parts of the Wrangellia superterrane), and contains chiefly Late Jurassic to mid-Cretaceous argillite, graywacke, and conglomerate, with lesser andesitic and basaltic volcanic, volcanoclastic rocks, and an extensive suite of plutons. Fine exposures of the arc occur in the southwestern Canadian Coast Mountains, Southeastern Alaska, and Southern Alaska. In the Southern Canadian Cordillera, these volcanogenic strata were deposited in the intra- and forearc Gravina and Gambier basins. Petrologic studies indicate that detritus in the Gravina Basin was derived almost entirely from the arc. Some detritus, including detrital zircons, within the Nutzotin part of the belt in eastern Southern Alaska, may be derived from units to the east.

In the Southern Canadian Cordillera, the Late Jurassic and Early Cretaceous Gravina Arc overlies the eastern part of the Wrangellia terrane, whereas the rocks of the older, Early and Middle Jurassic Bonzana Arc occur to the west on Vancouver Island. In the Middle Jurassic, ca. 170 Ma, the arc magmatism migrated eastward from what is now Vancouver Island into the southwestern Coast Mountains.

■ SUMMARY

The major effects of Cenozoic subduction along the margin of the Northern Cordillera (Alaska and Western Canada) are formation of the following features:

- (1) continental landscapes, including: (a) narrow continental shelves along Southern and Southeastern Alaska and Western Canada; (b) Aleutian Arc Mountains along the Alaska Peninsula; (c) subduction-related mountains of the Chugach Range, Saint Elias Mountains, and Canadian Coast Mountains; and (d) Cascade Arc Mountains in southern British Columbia and the USA Pacific Northwest;
- (2) marine sedimentary basins, including: (a) Aleutian Trench and Cascadia Basin along active subduction zones; and (b) several continental shelf basins along the southern and

- western margins of the Northern Cordillera: Sanak, Kodiak Shelf, Stevenson, Cook Inlet, Yakataga, Queen Charlotte, and Georgia basins;
- (3) active faults and corresponding earthquake belts, which include: (a) Aleutian and Alaska megathrust where the Pacific Plate is being subducted beneath the margin of Southern Alaska; (b) portions of the dextral-slip Denali Fault where areas south of the fault are migrating westward, due to oblique subduction of the Pacific Plate; (c) the dextral-slip Fairweather-Queen Charlotte Fault where the Pacific Plate is moving northwestward along the margin of the North American Plate; (d) the Cascadia megathrust where the Juan de Fuca Plate is being subducted beneath the margin of the Pacific Northwest, USA; (e) earthquakes related to the subducting Yakutat Terrane; and (f) earthquakes related to the spreading Juan de Fuca Ridge;
 - (4) active volcanoes, including: (a) continental-margin volcanic belts or arcs—the Aleutian, Wrangell, and Cascadia arcs, linked to subduction zones; (b) interior volcanic belts related to strike-slip faulting in the Northern Cordillera or to Hotspots—the Anaheim, Bering Sea, Stikine, and Wells Gray-Clearwater volcanic belts;
 - (5) lode mineral deposits related to continental margin arcs and to subduction of the Kula-Farallon Oceanic Ridge;
 - (6) hot springs related to continental-margin arcs;
 - (7) plate movements recorded from GPS measurements, including: (a) north to west-northwest migration of the Pacific Plate; (b) northward movement of the Yakutat

Terrane; and (c) eastward movement of the Juan de Fuca Plate;

- (8) underthrusting of Chugach terrane, Prince William terrane, Yakutat Terrane, and Pacific Plate beneath the margin of Southern Alaska; and
- (9) underthrusting of Wrangellia and Pacific Rim terranes and the Juan de Fuca Plate beneath the margin of the Southern Canadian Cordillera.

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