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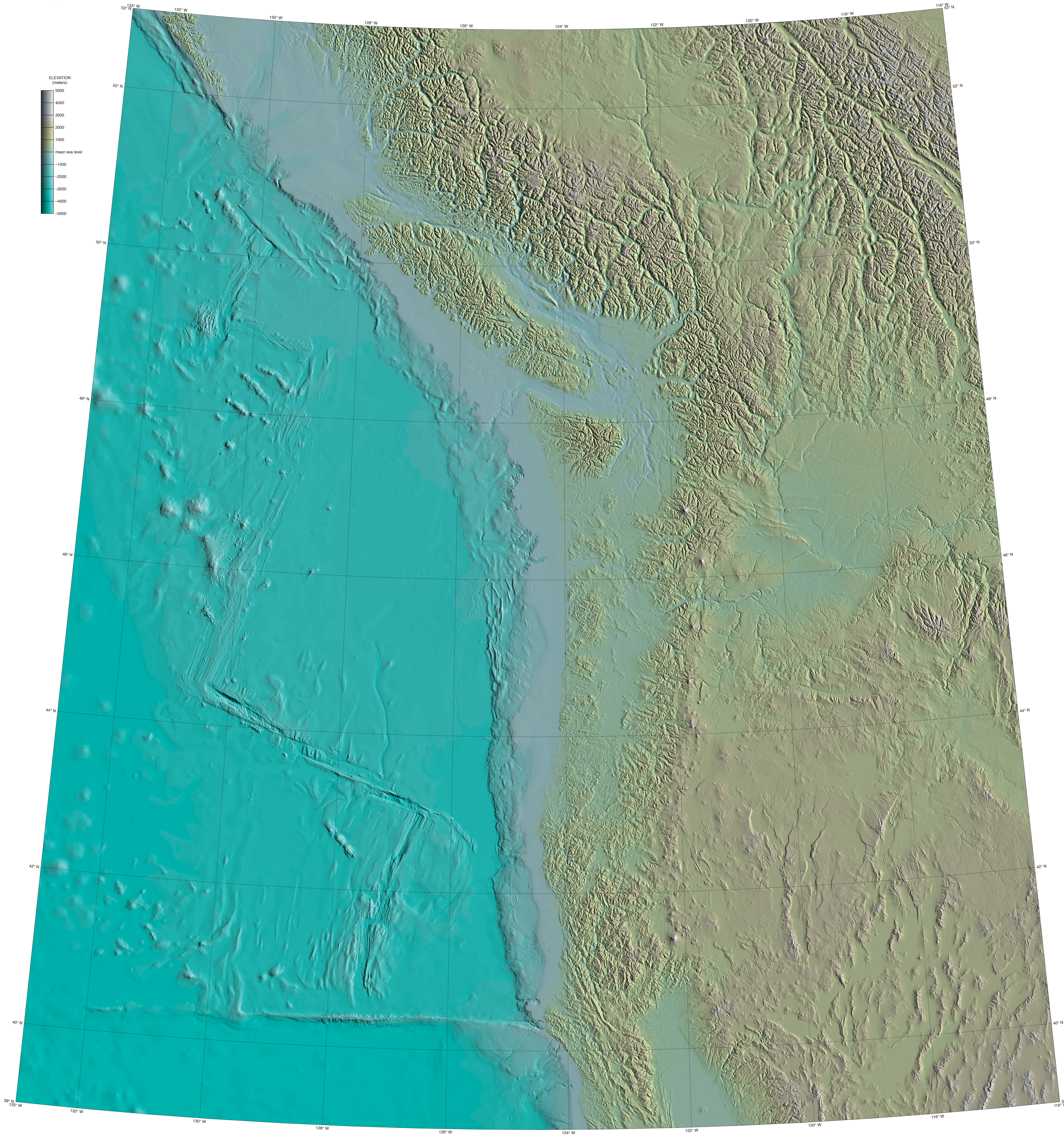

SCALE 1:2 000 000

1 cm = 20 kilometers

Lambert conformal conic projection
Standard parallels 41°30′ N and 50°30′ N

CASCADIA–PHYSIOGRAPHY

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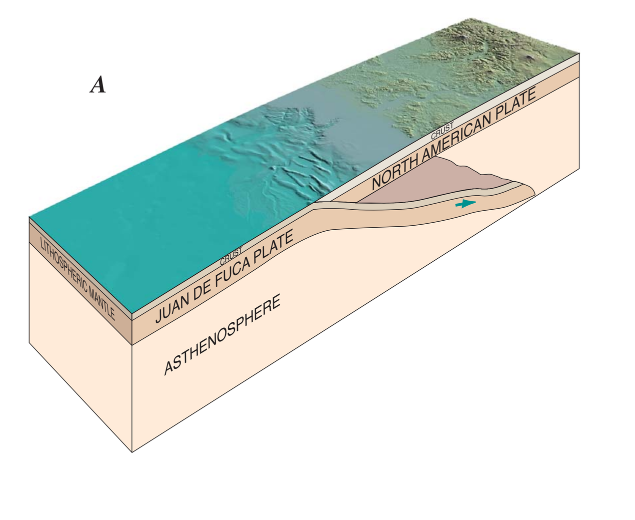


PLATE TECTONICS

The surface of the Earth is underlain by the lithosphere, a rigid shell of rock, which floats on the denser, more deformable asthenosphere. The lithosphere is divided into a number of tectonic plates that move slowly with respect to each other. The lithosphere is also vertically stratified. On top is a 5- to 50-km-thick crust (diagram *A*), rich in silica and alumina and thus significantly less dense than the asthenosphere. Beneath the crust is lithospheric mantle, up to 350 km thick, which is similar in composition to the asthenosphere and, because it is colder, is slightly more dense than the asthenosphere.

Oceans and continents are underlain by different kinds of crust: oceanic crust is thin and basaltic in composition, whereas continental crust is thicker, richer in silica, and less dense. Where plates spread apart at mid-ocean ridges, new oceanic crust is created. Where plates converge at subduction zones, oceanic crust is consumed and continental crust is formed and reformed.

Cascadia provides a splendid laboratory in which to examine the processes that shape the crust of the Earth. It contains examples of most plate-tectonic regimes, including the only active subduction zone in Canada and the coterminous United States.

Subduction in Cascadia has been underway for about 35 million years. It has produced a crustal architecture known from subduction zones around the world (map *B*): an accretionary prism, extending from the deformation front into the continental shelf, where rocks stripped off the downgoing oceanic plate and sediment washed off the continent are kneaded together by plate convergence and submarine landsliding; a fore-arc region, where there is extensive deposition of sediments derived from the volcanic arc; a volcanic arc, which is a linear chain of volcanoes parallel to the subduction zone; and a back-arc region of distributed volcanism and sediment deposition. These features are developed within a pre-existing continental framework, are modified by motion along the continental margin, and are overprinted by other plate-boundary regimes as the extent of the subduction zone changes through time.

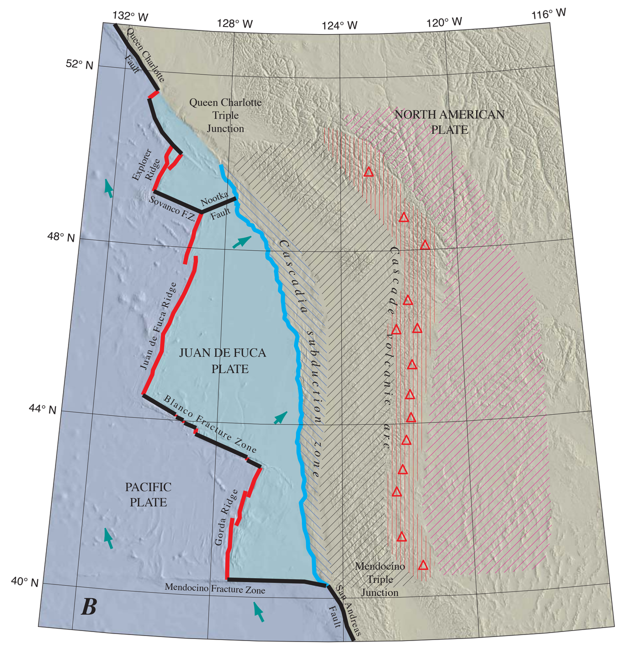


PLATE BOUNDARIES

Spreading ridge

Deformation front—Oceanward extent of subduction zone

Strike-slip fault

Plate velocity relative to stable interior of North America—Length of arrow is distance plate travels in one million years. Pacific Plate velocity is average for last 3 million years (DeMets and others, 1994). Juan de Fuca Plate velocity is average for last 0.78 million years (Wilson, 1993)

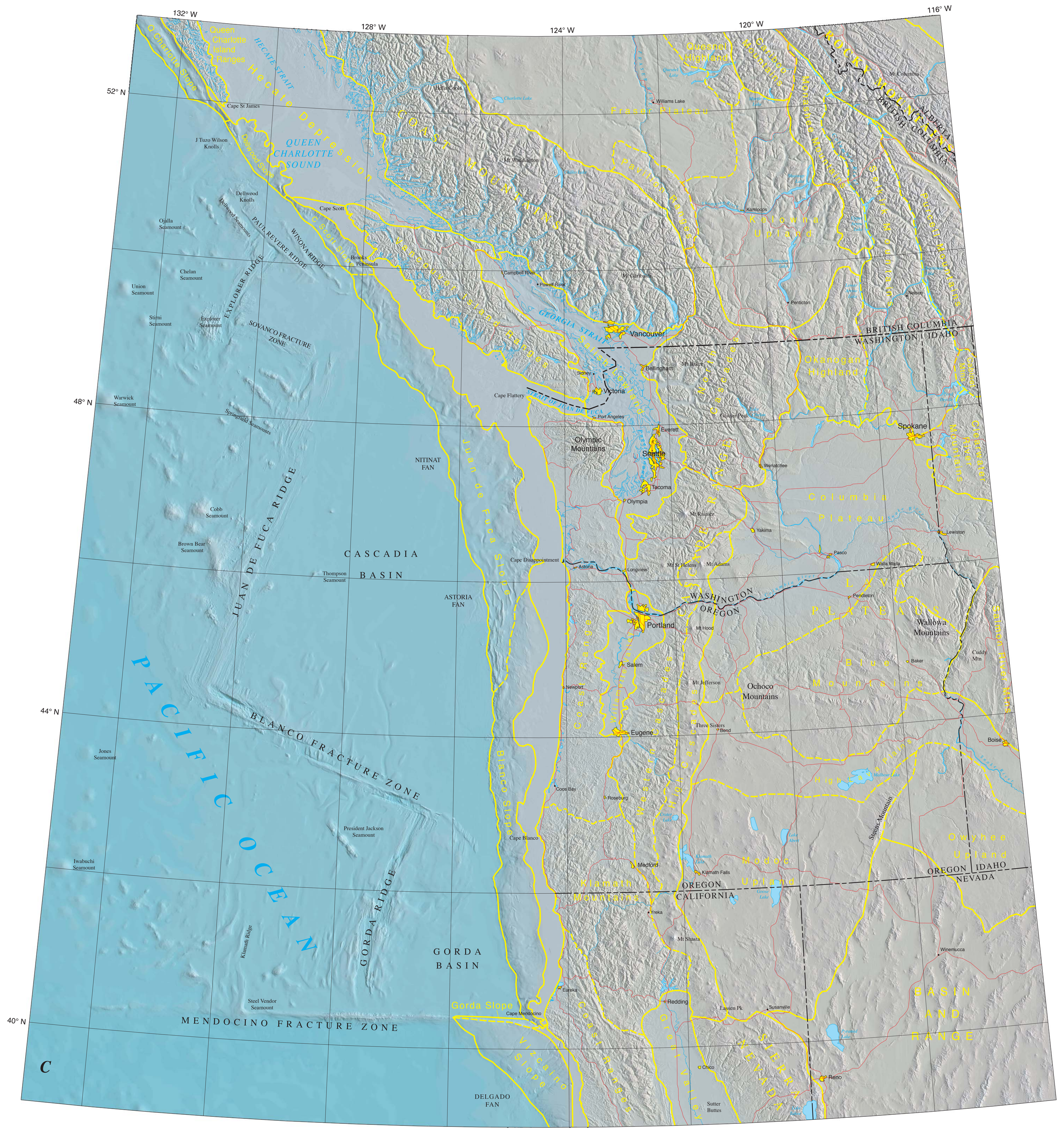
ELEMENTS OF THE CONVERGENT MARGIN

Accretionary prism

Fore-arc region

Arc—Red triangles denote major volcanoes

Back-arc region



CASCADIA

Cascadia encompasses the volcanoes of the Cascade Range and the subduction zone that feeds them. The region is home to nearly 10 million people. Where and how these people live, work, and play are influenced by the shape, or physiography, of Cascadia. This physiography represents millions of years of volcanism, erosion, deposition, and deformation—a history that also determines the distribution of groundwater, gold mines, gas wells, and gravel pits, as well as hazards from earthquakes, volcanoes, landslides, and floods.

This map is a tool for visualizing and interpreting the physiography of Cascadia. It was prepared, using computer techniques, from numerical representations of topography and bathymetry obtained from traditional surveying methods. It is not derived from satellite data, nor is any of it a direct composite of aerial photographs.

ARCHITECTURE OF CASCADIA

Oceanic realm

Relations between physiography and plate-tectonic process are astonishingly simple within the northeastern Pacific Ocean (map *C*). Most deformation occurs at plate boundaries. Erosion is significant only where dense, sediment-laden currents flow down steep submarine slopes and sweep across the deep-sea floor and on the continental shelf where the sea is shallow enough that storm waves occasionally disturb the sea floor.

At the Juan de Fuca, Gorda, and Explorer Ridges, the Pacific and Juan de Fuca Plates are pulling apart at about 4 cm/yr. Scabs of new oceanic crust, formed by eruption and intrusion of basaltic magma, fill the gap and are themselves ruptured by faulting parallel to the ridge axis, resulting in distinctive lineated physiography. As the newly formed crust ages, it chills the underlying asthenosphere to form ever-thicker lithospheric mantle. Over time the oceanic plate becomes denser overall and sinks to greater depths. Given enough time and proximity to land, the lineated surface formed at the spreading ridge is blanketed by sediment.

Isolated volcanism away from the ridge axis produces conical underwater volcanoes, or seamounts. Prolonged eruption can produce chains of seamounts, such as Dellwood Knolls (51° N, 131° W) and President Jackson Seamount (43° N, 128° W), that track the direction they are moving relative to their underlying magma source.

The Blanco and Sovanco Fracture Zones are transform faults for most of their extents. Transform faults join spreading-ridge segments and separate plates moving parallel to the fracture zone yet in opposite directions. Where such transform faults extend beyond the spreading ridge segments they become inactive (crust on each side is moving at the same rate in the same direction), yet separate oceanic crust with different ages and, therefore, temperatures and depths. The Mendocino Fracture Zone east of the Gorda Ridge is a transform fault that separates 2- to 5-million-year-old crust of the Juan de Fuca Plate to the north from 25- to 28-million-year-old crust of the Pacific Plate to the south. West of the Gorda Ridge, the Mendocino Fracture Zone separates different-age segments of the Pacific Plate.

The Juan de Fuca Plate is moving northeast relative to the North American Plate. Where the two plates collide, the denser oceanic plate slides beneath the continental plate at the Cascadia Subduction Zone. Subduction at shallow depths is not continuous: high-precision surveys show that currently, as at most times, the Juan de Fuca and North American Plates are stuck together. Much of the slip at the subduction zone fault happens during great earthquakes that occur at intervals averaging about 500 years. The velocity of long-term collision at the Cascadia Subduction Zone is not well known. It is the sum of the motion of the Juan de Fuca Plate relative to the stable interior of North America (about 4 cm/year, known to within several percent), and less precisely known deformation within western North America.

The North America, Juan de Fuca, and Pacific Plates all meet at the Mendocino Triple Junction in northern California. South of the triple junction, the Pacific and North American Plates are in contact along the San Andreas Fault. This is a strike-slip fault, oriented approximately parallel to relative plate motion. With time the Mendocino Triple Junction must migrate north along the west edge of the North American Plate. The three plates also meet at the Queen Charlotte Triple Junction, west of Vancouver Island. North of this triple junction, Pacific and North American plates are moving parallel to their mutual boundary along the Queen Charlotte Fault. Plate geometry alone does not require that the Queen Charlotte Triple Junction move in any consistent fashion.

The region northwest of the Nootka Fault—between Sovanco Fracture Zone, Explorer Ridge, and the northernmost reach of the Cascadia deformation front—is shown as part of the Juan de Fuca Plate on the plate tectonics map (*B*), though simple geometry requires that this region move independently of the Juan de Fuca Plate. Much evidence suggests that this region, sometimes known as the Explorer Plate, is deforming internally. Similar complexities occur east of the Gorda Ridge and south of the Blanco Fracture Zone, where many earth scientists distinguish a small Gorda Plate.

Where oceanic crust is subducted, it is commonly bent down by the weight of the sinking lithosphere, forming a trench (for example, in the subduction zones of the western Pacific Ocean, or south of the Aleutian Islands.) In Cascadia there is no trench, because sediment washed off the continent has filled what would otherwise be a depression.

Land-derived sediment is carried out onto the continental shelf where it builds up and may eventually collapse in a submarine landslide. The resulting turbulence forms a turbidity current: a cloud of sediment-rich water that is denser than normal seawater and flows down the continental slope and across the flat ocean floor. Recurring turbidity currents from areas of abundant sediment supply eventually build up large, low-slope, conical fans such as the Astoria Fan off the mouth of the Columbia River and the Nitinat Fan off the Strait of Juan de Fuca. On steeper ground, or where they are most turbulent, turbidity currents scour their beds and form channels, one of which is evident on the Astoria Fan.

Continental realm

Deformation in the continental realm is not limited to the plate boundary. All of the continental portion of Cascadia (map *C*), with the exception of a small area in the far northeastern corner of the map, is within the wide, slowly-deforming western margin of the North American Plate. Erosion plays a greater role here than in the oceanic realm, commonly masking other processes. As a result, the relations between physiography and tectonic process are harder to discern.

Flat smooth areas such as the continental shelf and parts of the Basin and Range indicate active deposition. Elevation differences between large areas (such as the contrast between the Great Valley and the Sierra Nevada) can be the result of deformation, but most local topographic relief reflects erosional dissection of formerly smooth areas.

The continental slope along the Cascadia Subduction Zone has two distinct morphologies: steep, narrow, and irregular and gentle, wide, and folded. The Blanco Slope is narrow, steep, and in many places quite irregular. Small to large submarine landslides are widely evident and the deformation front is a sharp crease at the toe of the slope. At these latitudes most of the sediment that mantles the Juan de Fuca Plate is being subducted. To the north, the Juan de Fuca Slope is wider. Thick, well-layered sediments of the Astoria and Nitinat Fans extend across the subduction zone and are not entirely subducted, but are rumpled up into pronounced longitudinal fold-ridges where subduction has forced them into the continental margin. In many places there is no sharp deformation front. This morphology is well-displayed in high-quality multibeam sonar bathymetry south of 46° N. Farther south, the Gorda Slope is the topographic expression of strike-slip faulting along the Mendocino Fracture Zone. The Vizcaino Slope is not now deforming. It is entirely shaped by turbidity currents avalanching off the continental shelf and accumulating on the abyssal plain. Northwest of the Brooks Peninsula, the Cape Scott and Queen Charlotte Slopes are narrow and steep, with linear slope-parallel scarps indicative of current or recent strike-slip faulting along the plate boundary. The wider, gully-and-lobe shape of the Dellwood Slope suggests either erosion or building out of the continental shelf.

The continental shelf is the site of active deposition but also has been leveled by wind-generated currents and by storm waves, surf, and stream activity at times of low sea level during the ice ages, approximately 10,000 to 2 million years ago. The only significant features on these broad flat areas are troughs off the Strait of Juan de Fuca and at the mouth of Queen Charlotte Sound that were eroded by ice-age glaciers and their meltwaters. The Coastal Lowlands (Hecate Depression, Salish Lowland, Willamette Valley, Great Valley) are kin to the continental shelf and, like it, appear to be underlain by denser and (or) thinner crust than the adjacent Coastal and Insular Ranges. Extensive flats of the Coastal Lowlands reflect active deposition. Local topographic highs (for example, the hills east and west of Seattle) are uplifts probably associated with active faulting. Sutter Buttes in the Great Valley are remnants of an inactive volcano.

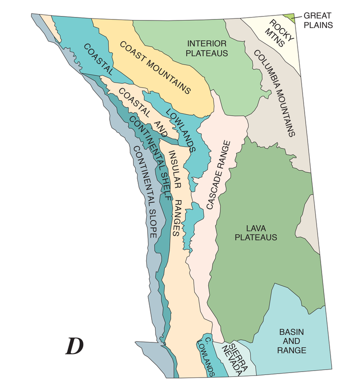
Coastal and Insular Ranges topographic highs seem to have no single origin. Old (100 million years or more), thick, low-density continental crust extends nearly to the plate boundary in the Klamath Mountains and Vancouver Island Ranges. Greater elevation of these areas relative to their surroundings reflects the buoyancy of this crust, further uplifted as subduction pushes low-density sediment under the continental margin. Similar uplift by underplating of low-density sediment affects the Oregon-Washington Coast Range, but here the upper crust is mostly dense basalt and the net effect is minor uplift and consequent erosional dissection. Only in the Olympic Mountains does more-extensive sediment underplating buoy the Coast Range crust to elevations comparable to those of the Klamath Mountains and Vancouver Island Ranges. The California Coast Ranges mostly comprise old continental slope and shelf sedimentary rocks, thickened by northeast-southwest contraction associated with San Andreas strike-slip faulting.

The High Cascades are a linear chain of young—less than a few million years old—volcanoes. Such chains of volcanoes are clearly linked to subduction, yet the exact details of the linkage are largely unknown. Proposed mechanisms include heating and partial melting of the subducted plate as it descends into the Earth, fluxing of the overlying plate by water given off by the subducted crust, and upward flow of hot asthenosphere as it is stirred by the descending plate. The Western Cascades are the eroded remnant of an older (as much as 35 million years old) phase of Cascade volcanism, locally surmounted by young volcanoes. Now as in the past, Cascade volcanism extends north into the North Cascades and southern Coast Mountains. Volcanism once extended south into the northern Sierra Nevada, but the volcanic arc has retreated north as the Mendocino Triple Junction has moved north along the continental margin.

Eruptions, mostly between 5 and 17 million years ago, of great sheets of lava behind the Cascade Volcanic Arc built broad volcanic plains in parts of the Interior Plateaus, Lava Plateaus, and northern Basin and Range Provinces. The lava sheets extend west into the High Cascades and once extended over parts of the North Cascades, Western Cascades, and Coast Mountains. The once-flat sheets of lava have been deformed to produce the west-northwest-trending ridges of the Yakima Folds. Folding and faulting of these lavas are also evident in the Blue Mountains, where consequent erosion has locally unearthed underlying older rocks, and in the Modoc Upland. Even where deformed and uplifted, the volcanic flats are widely preserved because the lavas are commonly strongly fractured and thus highly permeable. This, along with low precipitation in the lee of the Cascade Range, inhibits the formation of streams that would dissect the landscape.

High-standing continental crust in the southeast part of Cascadia is gravitationally unstable and is spreading northwest towards the subduction zone. The near-surface manifestation of spreading is faulting on moderately inclined to steep surfaces. Spreading is most advanced in the Basin and Range Province, but is also evident in the Modoc Upland, at the south end of the High Lava Plains, and at places in the High Cascades and Blue Mountains.

The Coast Mountains, North Cascades, Sierra Nevada, and Columbia and Rocky Mountains are remnants of thick—and therefore high-standing—continental crust formed during an older episode of plate convergence, between 160 and 60 million years ago. Mountains formed during that episode would have eroded away within a few tens of millions of years, but they were rejuvenated by Basin and Range-like spreading between about 55 and 45 million years ago, minor spreading in the Cascade back-arc region, local thickening in the Cascade Volcanic Arc, and (probably) loss of lithospheric mantle during one or more of these events. Loss of some or all of the lithospheric mantle significantly decreases the average density of the lithosphere and thus produces uplift.



PHYSIOGRAPHIC PROVINCES

The continent and adjoining continental shelf and slope are usefully divided into physiographic provinces characterized by broadly similar landforms (maps *C*, *D*). The provinces (map *D*) and subprovinces (map *C*) shown here are defined on the basis of (1) landforms, not underlying geology (though admittedly landforms are seen through a geologist's eyes), (2) previously defined physiographic units (Fenneman, 1946; Freeman and Martin, 1954; Holland, 1964; and Mathews, 1986), and (3) local usage. Some boundaries follow sharply defined natural features. Other boundaries are necessarily imprecise or arbitrary.

A better depiction of the physiography of Cascadia and the need for uniform nomenclature across the 49th parallel lead to significant departures from prior usage, which include:

1. The continental slope is divided into seven subprovinces, each with characteristic physiography: Queen Charlotte Slope, Dellwood Slope, Cape Scott Slope, Juan de Fuca Slope, Blanco Slope, Gorda Slope, and Vizcaino Slope.

2. The lowland that embraces Seattle and Vancouver is here named the Salish Lowland. The Salish Lowland comprises the Georgia Depression, Fraser Lowland, and Puget Lowland of Mathews (1986) and others, and locally higher ground southwest of Bellingham, which could be designated the San Juan Upland. This area is approximately coextensive with the area once inhabited by speakers of Coastal Salish languages, hence the name.

3. Hecate Depression is geologically similar to the Salish Lowland, Willamette Valley, and Great Valley, and is included with them in the Coastal Lowlands Province.

4. The High Cascades and Western Cascades subprovinces of the Cascade Range, previously recognized only in Oregon, are continued north into Washington and south into California. The Cascade Range is thus divided into three subprovinces: the High, Western, and North Cascades.

5. A region in south-central British Columbia is recognized as the Kelowna Upland. It is characterized by a low-relief, high-elevation surface that is traversed by large erosional troughs but otherwise mostly lacks the extensive stream dissection of adjoining highlands.

6. The Okanogan Highland is restricted to the southeastern, more mountainous portion of the area that Holland (1964) and Mathews (1986) designated the Okanagan Highland.

7. Physiography similar to that of the adjoining Selkirk Mountains suggests that the Okanogan Highland is more usefully considered part of the Columbia Mountains Province than the Interior Plateaus Province. To do so emphasizes that, at the 49th parallel, mountains extend from salt water to the Great Plains.

8. A region that extends from Klamath Lake east to Steens Mountain and south to Susanville is characterized by elongate fault-block mountains like those of the Basin and Range Province but lacks the dissected ranges and extensive alluviated basins characteristic of the Basin and Range Province. It is here named the Modoc Upland for the Modoc people who inhabited the southwestern part of this region; Modoc is the Klamath language word for "south of here" (Klamath Lake). The Modoc Upland has affinities with both Lava Plateaus and Basin and Range Provinces; here it is considered a subprovince of the Lava Plateaus Province.

DATA: SOURCES AND MANIPULATIONS

The map is derived from a 250-m digital elevation model (DEM). The DEM is available online, at http://wrgis.wr.usgs.gov, as USGS Open-File Report 99–369. To make the DEM, data from various sources (map *E*) were resampled at a 250-m interval in this map projection and composited. The software used for projecting the data (ARC-INFO GRID, version 7.0.3) did not allow for explicit registration of the output grid, and as a result there are lateral shifts of potentially as much as one grid cell (250 meters) between blocks of data. These shifts are not noticeable in the map. Data sets 8, 9, and 10 were combined, interpolated, and gridded together to produce a surface that is smooth at the data-set boundaries. Other details about data sources and manipulations are given in OFR 99–369.

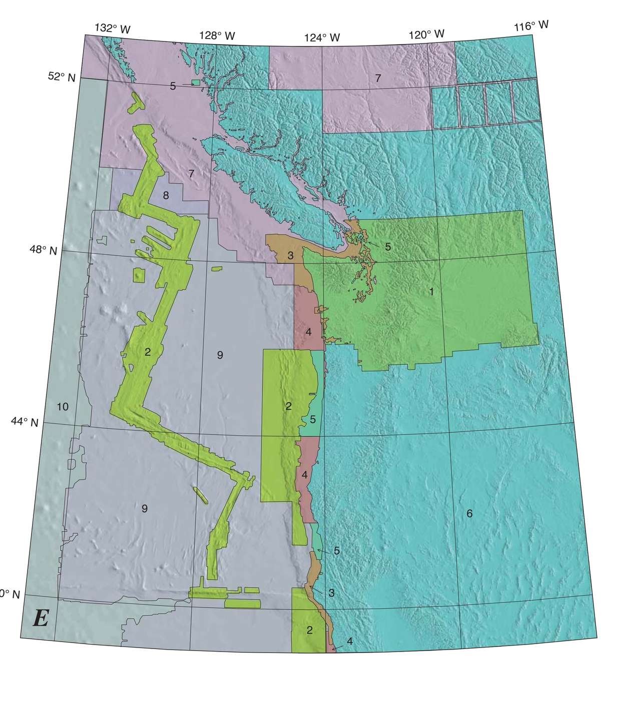
Accuracies of DEMs are largely unknown, as reference data are generally not available. Quality as indicated here reflects nominal horizontal precision of source materials, correspondence between independently derived sets of overlapping or adjoining data, and visual impression.

To make this image, hue and saturation were assigned on the basis of elevation. Luminosity was calculated by assuming a light source 40° above the horizon at an azimuth of N 75° E. The visual effect of elevation mismatches at data set boundaries was minimized by substituting luminosities averaged from values at both sides at all data-set boundaries. The image was then lightened, and contrast increased, by linearly remapping luminosities in the range 32%–85% to the range 15%–100%. Hue, saturation, and luminosity were combined to produce the final image.

Artifacts

Lack of data accounts for much of the apparent smoothness of the floor of the northeastern Pacific Ocean. Some of the smoothness is real, reflecting a blanket of sediment that smothers the oceanic-ridge topography beneath it. But most of the smoothness simply reflects insufficient data—compare the areas from sources 8, 9, and 10 with adjacent areas of high-resolution multibeam sonar surveys (source 2). Similarly, apparent differences in the physiography of the Washington continental slope, relative to adjoining parts of the slope, at least partly reflect differences in data quality.

Additional artifacts result from mismatches between sets of source data. Perhaps the most obvious is at longitude 132° W, extending south from 52° N, where an abrupt change in apparent depth occurs at a source-data boundary. The abrupt northward termination at 46° N of longitudinal ridges in the Juan de Fuca Slope also reflects juxtaposition of differing data sources.



1 **30-meter grids**—Mostly derived by automatic gridding of contours from 1:24,000-scale maps. Defects insignificant when subsampled to 250 m. Excellent quality

2 **Multibeam sonar surveys**—Subsampled from 100-m grids. Original lateral resolution varies with water depth, but is generally better than 50 m. Excellent quality

3 **Hydrographic surveys**—Point soundings from traditional hydrographic survey; point spacing varies. Combined with 1:100,000-scale shoreline and gridded. Apparently very good quality

4 **1:100,000-scale contours**—Bathymetry, topography, and shorelines from 1:100,000-scale maps, gridded. Comparison with adjacent multibeam sonar surveys suggests that sub-sea topography is inflated. Quality good

5 **Nautical charts**—Point depths and bathymetric contours digitized from charts at various scales, mostly larger than 1:250,000, and gridded. Quality variable, but appears to be generally good

6 **3-arc-second (about 90 m) grids**—From automatic gridding of contours on 1:250,000-scale maps. Quality limited by resolution of source maps and poor gridding algorithm. Defects modest when subsampled to 250 m

7 **1-km grid**—Derived by manual gridding of large-scale (1:50,000) maps. Data quality generally good except for offshore areas. Interpolation to 250-m grid introduces significant smoothing

8 **1,500-meter grid**—Bathymetric grid for part of the northeast Pacific, interpolated from various sources. Quality unknown, but appears equal to or better than source 9

9 **1:1,000,000-scale contours**—100-m contour-interval bathymetry. Supplemented in low-relief areas with 1500-m grid (source 8). Moderate quality

10 **5-arc-minute (about 10 km) grid**—Largely derived by automatic gridding of 1:10,000,000-scale charts. Poor quality

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