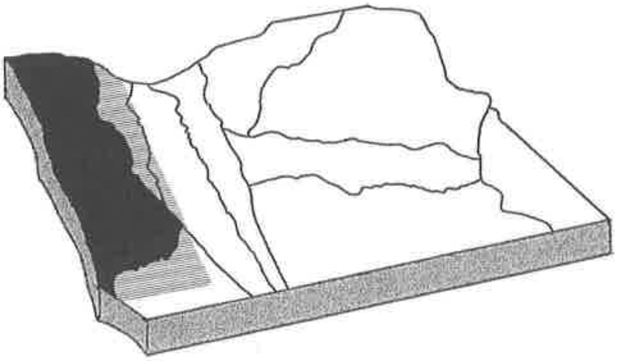
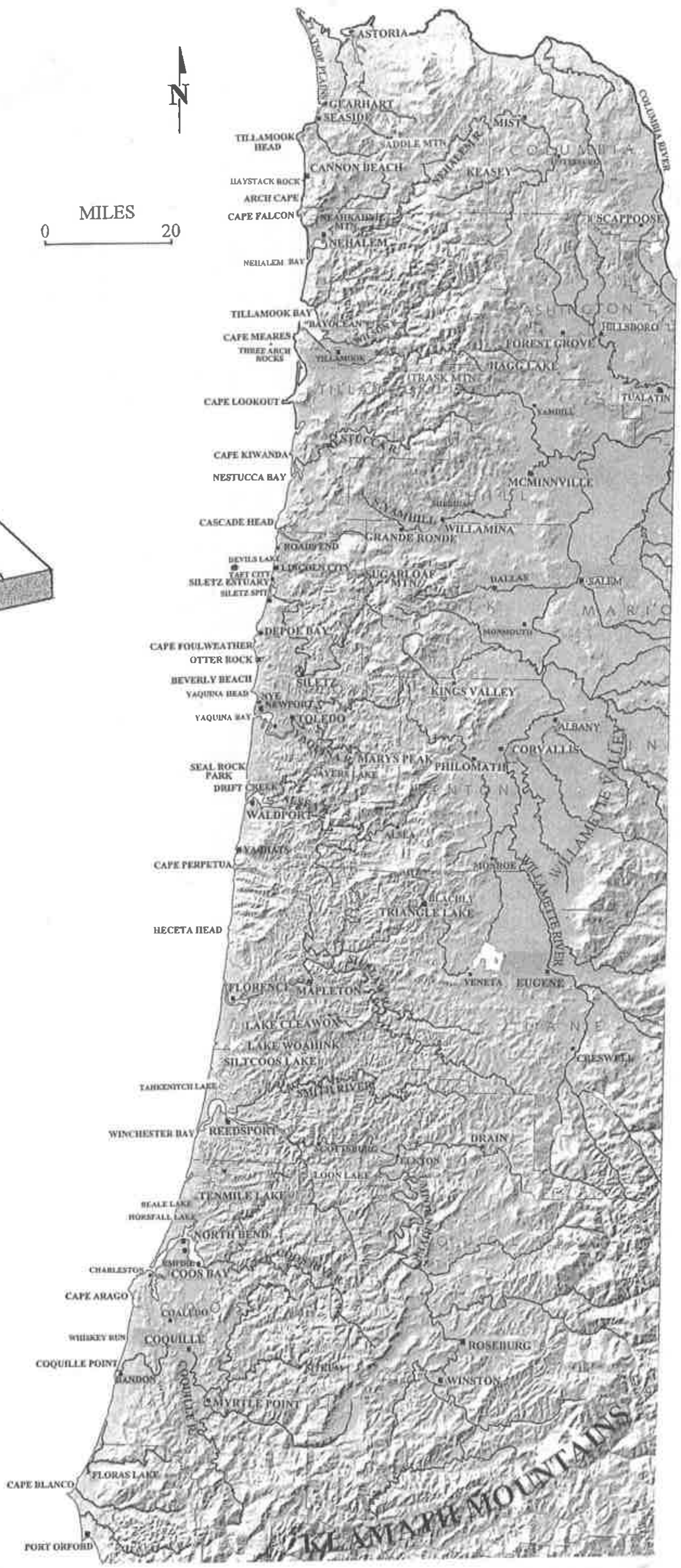




Physiographic map (After Loy, et al., eds., 2001)

Coast Range and Continental Margin

Landscape of the Coast Range and Continental Margin

Moderately high mountains, terraces, rocky headlands, sandy beaches, and an offshore shelf and slope all contribute to the complex topography of the Coast Range and continental margin. From the Olympic Peninsula of Washington, the province continues southward to the Middle Fork of the Coquille River and from the edge of the Willamette Valley west to the base of the continental slope.

The marine influence on western Oregon is responsible for the warmest average winter temperatures, the coolest summers, and the greatest precipitation of any region in the state. Rainfall in excess of 100 inches a year has molded the landscape with intricate stream patterns and dense forests. Because of extensive erosion on the western slope, the crest of the range is offset to the east. The highest elevations are Marys Peak at 4,097 feet, Trask Mountain at 3,423 feet, Sugarloaf Mountain at 3,415 feet, and Saddle Mountain at 3,283 feet.

Most rivers of the Coast Range are moderate in size, and only the Columbia and Umpqua cut entirely across the province. The notable west-flowing Nehalem, Wilson, Siletz, Yaquina, Alsea, Siuslaw, Coos, and Coquille rivers end in broad tidal estuaries. Of those streams flowing into the Willamette Valley, the Long Tom, Marys, Luckiamute, Yamhill, and Tualatin have the greatest discharge and the longest watersheds.

Along the Pacific strand, abrupt headlands are punctuated by bays, estuaries, pocket beaches, sand dunes, and spits. The distinctive terraced promontory at Cape Blanco extends into the Pacific Ocean as Oregon's most westerly point. Offshore, the province continues across the continental shelf and slope.

Past and Present

As with other provinces, the geologic examination of the Coast Range began with the exploration for minerals, the collection of fossils, and mapping. The details of unknown regions had to be filled in before a picture emerged. Joseph Diller's map folios in the late 1800s and early 1900s provided a regional overview as did the stratigraphic study by Ralph Arnold and Harold Hannibal in 1913. Close to the same time oil, gas, and mineral potentials were being assessed by Chester Washburne and Joseph Pardee.

A considerable step forward was initiated with a cooperative mapping and stratigraphic project begun in the 1940s between the U.S. Geological Survey and the Oregon Department of Geology and Mineral Industries (DOGAMI). As part of an investigation for petroleum resources, three Survey geologists W. C. Warren, Hans Norbisrath, and Rex Grivetti worked in the northwest counties. Their efforts were followed by the 1949 publications on the central Coast Range by Harold Vokes and Parke Snavely, also with the Survey. Ewart Baldwin's first revision of Cenozoic stratigraphy appeared about the same time.

First advanced in the 1920s, the theory of plate tectonics, which now dominates West Coast geology, only gained acceptance some 40 years later after research by many geologists and oceanographers confirmed the notion of large moving crustal plates. The concept crossed the continent, where its significance for western North America was ushered in with Robert Dott's "Implications for sea floor spreading" along with Tanya Atwater's papers on tectonics and Cenozoic evolution. William Dickinson's tectonic models of the Paleozoic were published in the late 1960s and early 1970s.

Overview

What is now coastal Oregon had its beginnings in the late Paleocene to early Eocene, with the construction of a volcanic seamount chain along a spreading center between tectonic plates. Transported as a large igneous province, the seamounts of Siletzia collided with and were accreted to the North American plate, forming the basement of the offshore shelf, Coast Range, Willamette Valley, and Western Cascades. Once incorporated around 50 million years ago, Siletzia rotated in a clockwise direction and shifted northward.

As a broad plain and marine shelf west of the emerging Cascade volcanic arc, the subsiding Coast Range slab (Siletzia) accumulated thick sequences of fluvial muds, sands, and volcanic detritus derived from both the Klamath Mountains and western Idaho. Deep-sea fans of layered turbidite sands and muds spread northward in the basin during the early and middle Eocene, but by the late Eocene to early Oligocene the waters had shoaled to deltaic and shoreline environments, when increasing volcanism from the Western Cascades contributed immense volumes of debris.

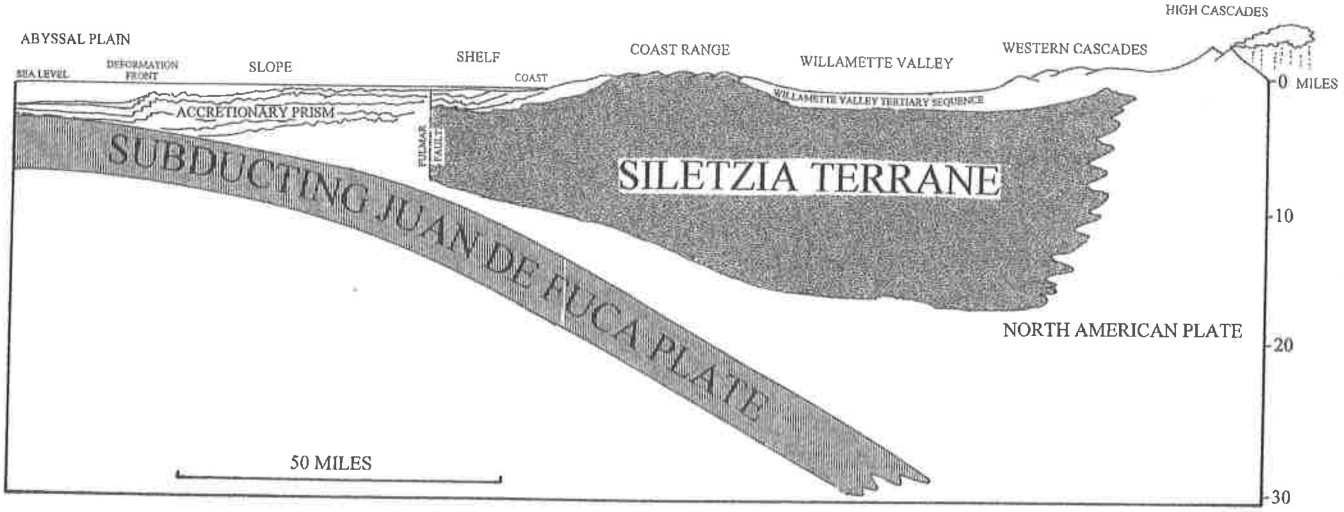
The edge of the North American plate was folded, elevated, and tilted by the subducting crustal slab, limiting marine waters to Miocene basins at Coos Bay, Newport, and Astoria. At this time, lavas from fissures in eastern Oregon and adjacent Washington and Idaho reached across the entire state, invading the softer coastal sediments.

From the 1940s through the early 2000s, Parke Snavely's geologic examination of the Cenozoic onshore and offshore rocks established the basis for unraveling the tectonic processes of the Pacific continental margin. Born in Yakima, Washington, Snavely completed his graduate work at the University of California, Los Angeles. In a 50-year career, he held positions in both the Pacific Marine Geology and the Western Regional Geology branches of the U.S.G.S. until retirement. Snavely died in November, 2003. (Photo courtesy Condon Collection)

Wendy and Alan Niem were both born in New York and entered the University of Wisconsin, Madison, where Alan completed his PhD and Wendy a Bachelors. Accepting positions in geology at Oregon State University, the Niem Team published numerous regional maps and papers. Alan concentrated on sedimentology and stratigraphy of western Oregon and Washington, exploring the offshore region in a two-man yellow submarine and participating in the Deep Sea Drilling Program aboard the *Glomar Challenger*. Wendy worked on stream systems in the central Coast Range while completing graduate work at Corvallis. The Niems retired in 2002, moving to coastal Lincoln County and continuing to work on U.S.G.S. mapping projects. In the photograph the Niems are holding a 1976 map of the Cape Foulweather and Euchre Mountain quadrangles. (Photo taken in 2010; courtesy A. and W. Niem)

Also from suburban New York, Harvey Kelsey spent much of his early life in the outdoors of New England. Moving to the West Coast in 1972, he finished a PhD at the University of California, Santa Cruz. For his research and teaching at Humboldt State University, Kelsey examines Quaternary surface processes, deposits, and faulting to provide insights to tectonic deformation. In addition to publications on coastal marine terraces, uplift, and faulting, he employs evidence of earthquakes and tsunamis in estuaries to decipher the paleoseismic history of the Cascadia and Sumatran subduction zones. Considering himself a westerner in spirit, Kelsey takes time to indulge his passion for road biking. In the photograph, Kelsey is coring the Yaquina Bay estuary. (Photo courtesy H. Kelsey; 2010)

With roots in the eastern United States and France, Anne Tréhu first came to the Pacific Northwest in high school to build trails in North Cascades National Park. Completing her PhD from MIT, she and her husband John Nabelek accepted positions at Oregon State University in 1987, where her research emphasizes geophysical processes and relationships along plate boundaries in order to understand geologic hazards and the tectonic history along fault systems from California to Alaska. Because of her wide outdoor interests, Tréhu is currently involved with the Oregon Adaptive Skiing program. In the photograph she is preparing an ocean bottom seismometer. (Photo courtesy A. Tréhu)



Paleocene to early Eocene volcanic rocks of the oceanic Siletzia terrane lie beneath the continental shelf, Coast Range, Willamette Valley, and Western Cascades. While its origins are still uncertain, Siletzia may have begun as a collection of offshore seamounts that moved eastward as a large igneous province to accrete to the West Coast of North America. (After Duncan, 1982; Fleming and Tréhu, 1999; Schmandt and Humphreys, 2011; Snavely and Wells, 1996; Tréhu, et al., 1994; Wells, Weaver, and Blakely, 1998)

Uplift, in conjunction with subduction and changing sea levels of Pleistocene glacial and interglacial periods, constructed raised terraces along the coast. Deeply eroded and broken into discontinuous sections, the older terraces are highest, while the younger surfaces are at lower elevations.

The offshore portion of the province is distinguished by a shelf, deeper slope, and abyssal plain. The slope is deformed by thrust faults and folds that parallel the coastline. At the base of the slope, the Cascadia subduction zone marks the boundary between the North American and Juan de Fuca plates. Slippage along this interface generates massive earthquakes and tsunamis. At the present time, the earthquake history of the Pacific Northwest is being chronicled with data from coastal marshes and offshore turbidite deposits.

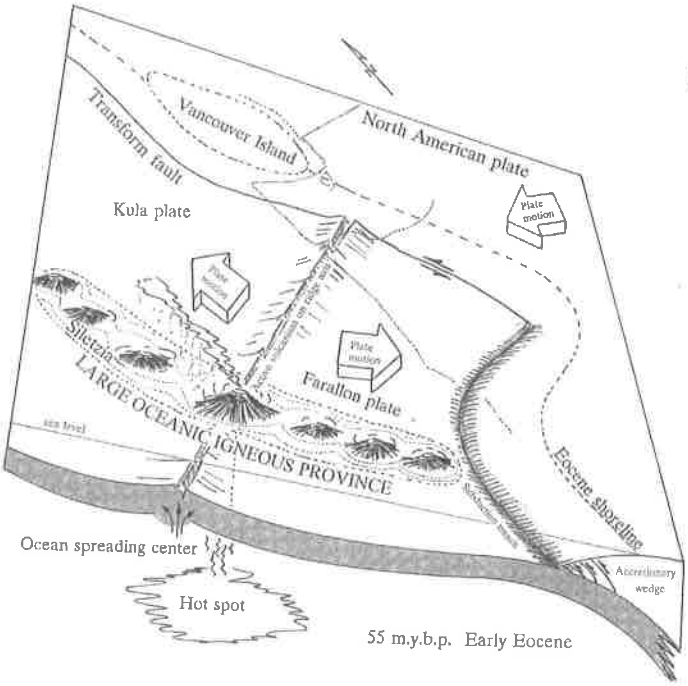
The geomorphology of the coast is continuously altered by uplift, landslides, waves, and erosion, yielding a landscape in a constant state of flux. Sands are seasonally transported on and offshore, while even seemingly durable basalt headlands are slowly being worn down by waves. The province has undergone ill-considered development in the past, and much questionable expansion has been permitted. The present-day recognition of coastal geohazards is guiding many communities to bring building codes in line with an understanding of the risks involved.

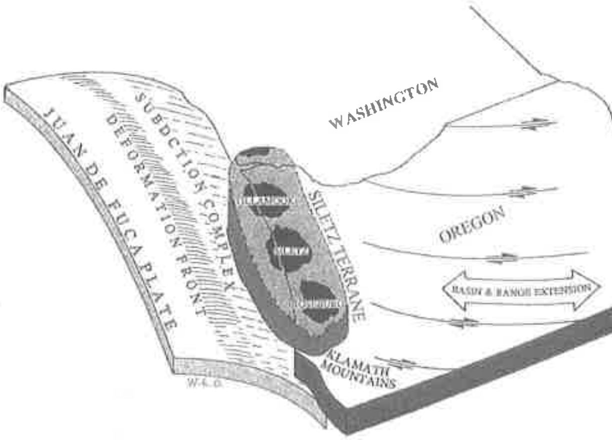
Geologic History

Cenozoic

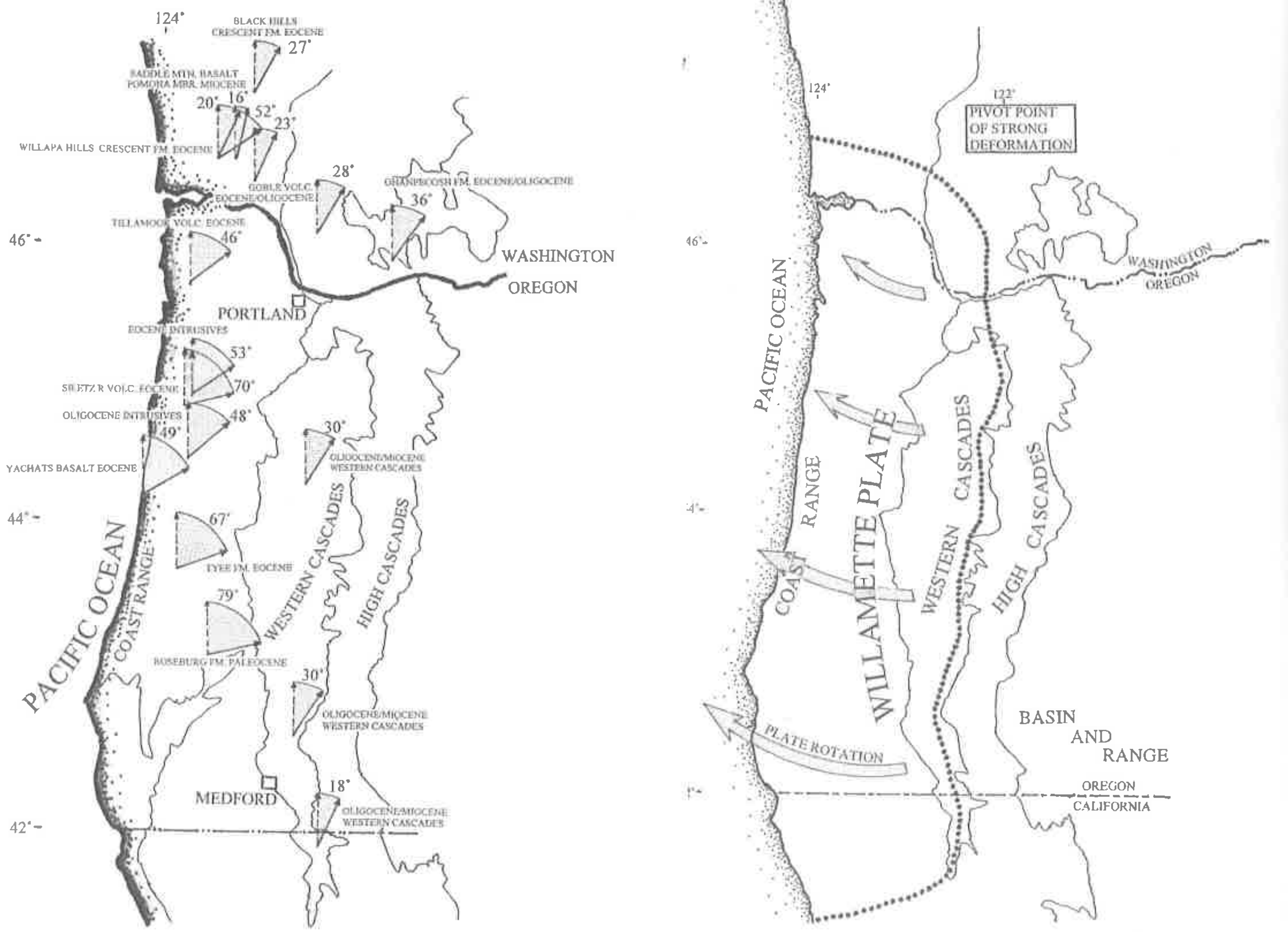
During the Cenozoic Era, the Pacific Northwest experienced major episodes of volcanism, subsidence, and uplift before sedimentation and erosion shaped the final product. The debate as to whether the basalt basement of western Oregon and Washington began as volcanic island archipelagos and ocean crust some distance offshore or from eruptions close to the continental margin is yet to be settled. One model holds that during the Paleocene to early Eocene, between 50 to 60 million years ago, a spreading center along the boundary between the Kula and Farallon plates generated the submarine volcanic plateau of Siletzia. Multiple eruptions built seamount chains that were carried by the Farallon plate to collide with and accrete to North America as the Coast Range block of Siletzia. Following accretion, the old subduction trench was abandoned and the present one established 90 to 110 miles west of the coastline.

An opposing explanation for the origin of the Coast Range block is that the volcanic episodes occurred in-place with rifting and extension along a Mesozoic continental margin. In support of this, geologists cite evidence that the erupted submarine basalts interfinger locally with sediments derived from the North American landmass.





The thickness of the Siletzia terrane varies considerably. Beneath Oregon, it is 15 to 20 miles in depth, while off Vancouver Island the base is less than four miles down. The western boundary of Siletzia is marked by the north-south Fulmar fault, a vertical dextral shear in the crust where the east side moved southward and the west side northward, much like the San Andreas in California. Named by Parke Snavely, the strike-slip fault is estimated to have experienced as much as 120 miles of displacement before motion ceased in the late Eocene, around 37 million years ago. (After Fleming and Tréhu, 1999; Snavely and Wells, 1996; Tréhu, et al., 1994)



Cenozoic clockwise rotation of the Coast Range block (Willamette plate) was most pronounced in the older rocks and toward the south. (After Guffanti and Weaver, 1988; Magill, and Cox, 1981; Magill, et al., 1982; McCrory, 2002; Sherrod and Smith, 1989; Smith, 1989; Wells, 1990; Wells and Heller, 1988; Wells, Weaver, and Blakely, 1998)

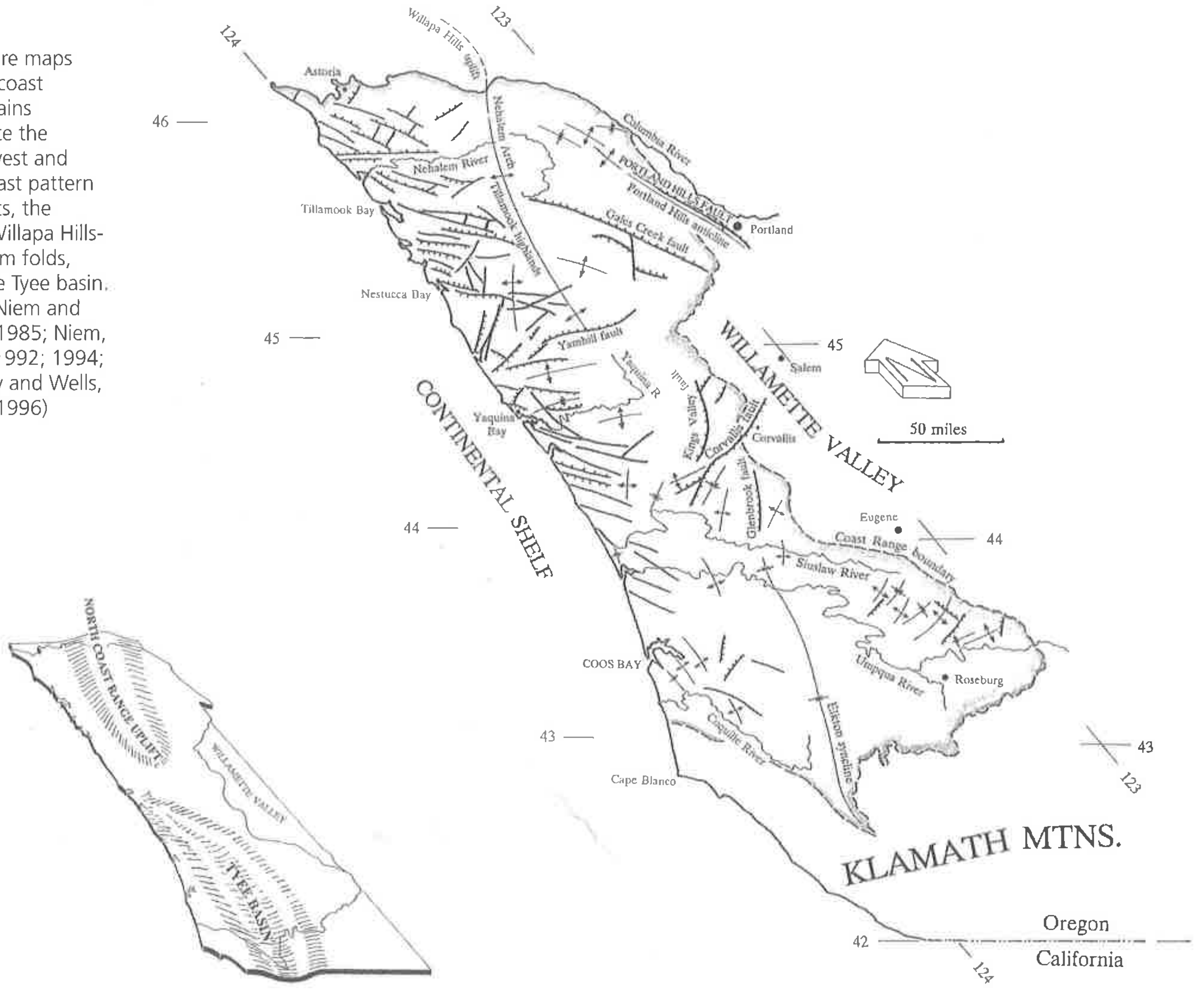
Rotation, faulting, and uplift

The collision of North America with the oceanic Juan de Fuca plate is oblique rather than head-on. Oblique subduction, at a pronounced angle, yielded moderate rotation, faulting, and uplift of the Coast Range between the Eocene and Pleistocene.

With accretion, the rigid Coast Range block rotated in a clockwise direction from a pivotal point in Washington. Ray Wells of the U.S.G.S. has found that rotation was more extensive toward the coast, corresponding with stretching or widening in the Basin and Range and compression of rocks in southwest Washington. It has been calculated that the Coast Range has rotated 51° since late Eocene, up to 44° since the middle Oligocene, and 16° since the middle Miocene, with an average of 1.5° of rotation every 1 million years throughout the 50 million year period.

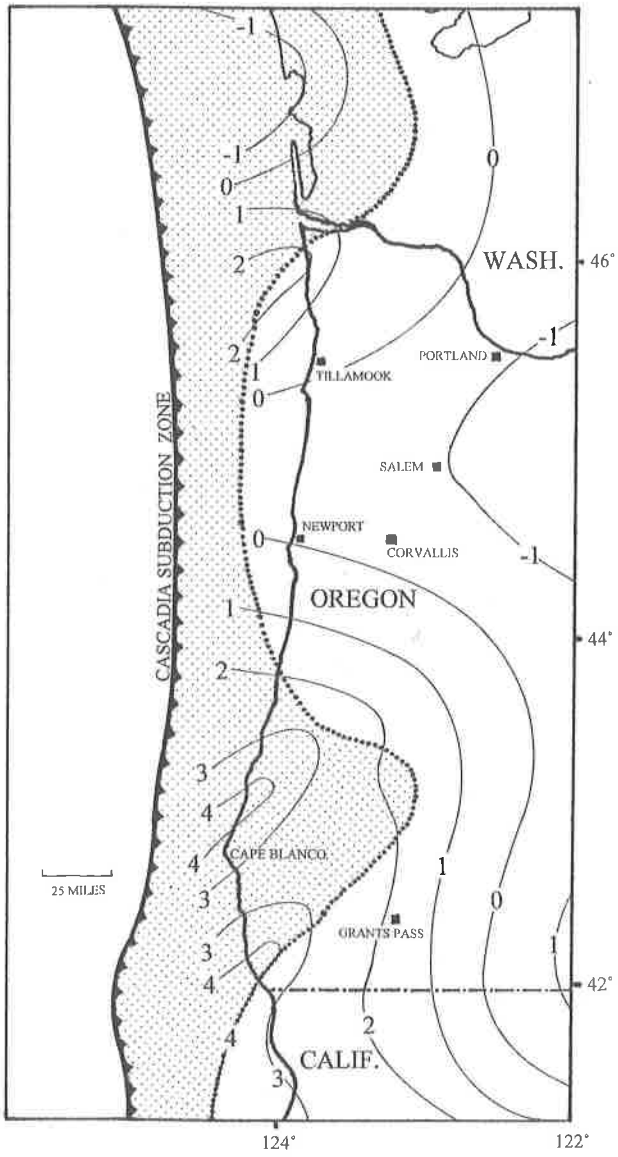
Clockwise rotation was generated by oblique plate subduction, extension, and dextral shear. Wells concluded that dextral shear was responsible for 40 percent of the rotation and that extension in the Basin and Range was responsible for the remainder. Today the north-northwest movement of the Pacific plate with respect to North America results in right lateral (dextral) shear. With dextral shear, strike-slip faults move sideways past each other, and the block beyond the viewer shifts to the right.

Folding and faulting of the province are an integral part of plate accretion. Structurally the Coast Range is a pair of large, in-line crustal folds with a north-south axis and many smaller wrinkles across the flanks. In Washington, the Willapa Hills is a broad regional fold anchored by volcanics at the core, which continues south into Columbia and Tillamook counties in Oregon, where it domes into



Structure maps of the coast mountains illustrate the northwest and northeast pattern of faults, the large Willapa Hills-Nehalem folds, and the Tyee basin. (After Niem and Niem, 1985; Niem, et al., 1992; 1994; Snavely and Wells, 1991, 1996) the low Nehalem arch and Tillamook highlands. South of Newport, the upfold inverts to the Elkton syncline or Tyee basin that reaches into the Klamath Mountains.

Uplift of the Coast Range in the Cenozoic brought diminishing marine sediments and increasing terrestrial deposits. In a broad view, the western coastal margin is rising, while the eastern border and the Willamette Valley are either subsiding or are only being minimally elevated.



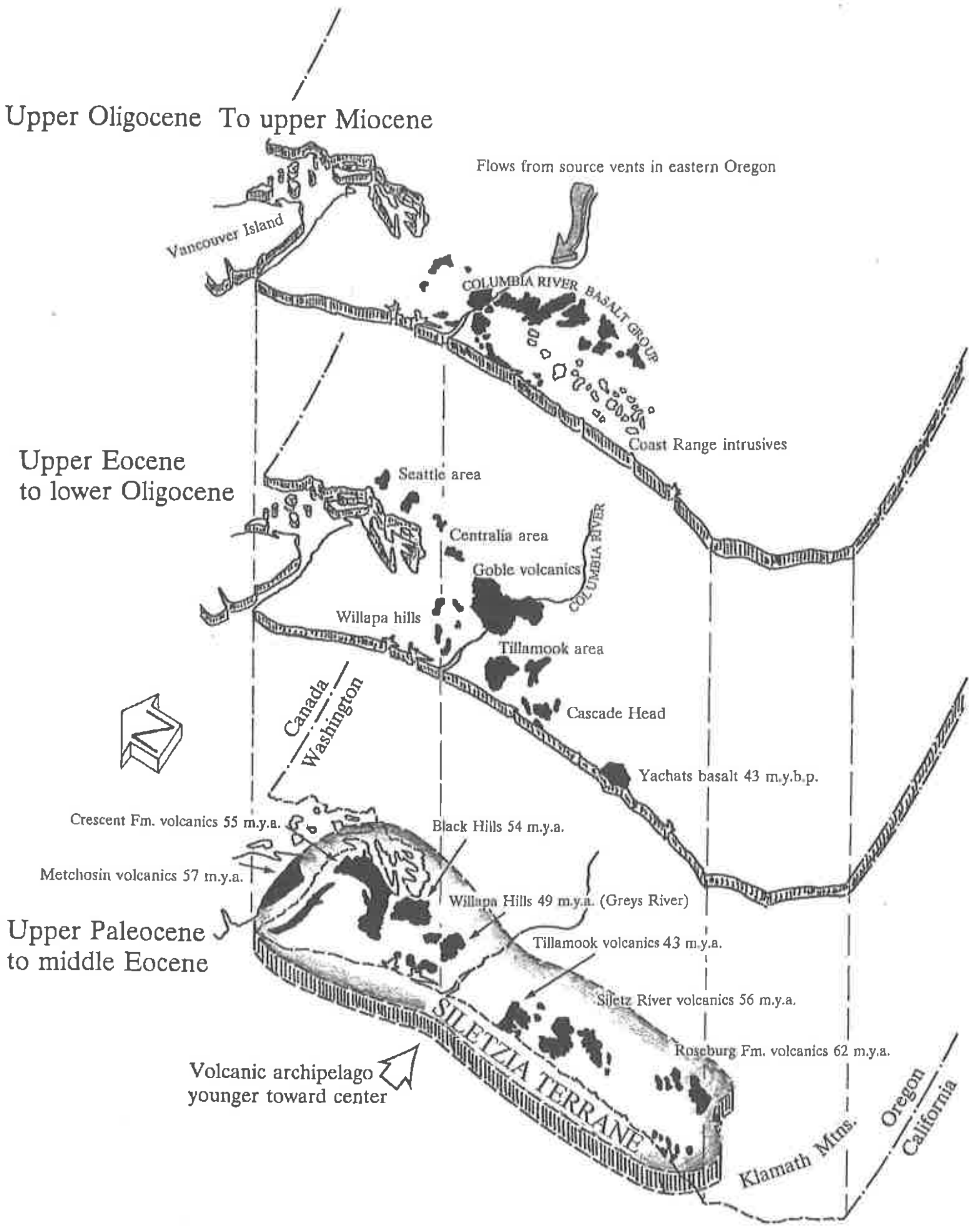
This map shows the apparent rate of uplift along the Pacific coast expressed in millimeters per year. The north-south discrepancies in elevation are a function of interseismic strain accumulating along the subduction boundary between the two plates. In juxtaposition with areas along the Cascadia subduction zone that demonstrate the greatest amounts of accumulated strain, the northern and southern portions of the coast have the highest magnitudes of latitudinal uplift (shaded area). (After Kelsey, et al., 1994; Komar, 1992; Mitchell, et al., 1994; Savage, 1983; Vincent, 1989; Vincent, et al., 1989)

Uplift can be measured by leveling surveys and tide records. Surveys along two axes—latitudinally north-south along the coast and longitudinally east-west from the coast inland to the Willamette Valley—yield data on uplift of the land relative to sea level. When geodetic data from 1987 and 1988 was compared to that taken between 1930 and 1941, it became apparent that a central depression lies between Newport and Tillamook. Higher elevations at the north and south margins are interpreted as evidence of interseismic elastic (temporary) strain causing a bulge between the Juan de Fuca and North American plates. The differences can be seen when assessing rates recorded at Astoria, which is rising only slightly faster than sea level, in comparison to those at Newport which is essentially static. The most profound elevation has been recorded at Cape Blanco.

Paul Komar has pointed out that measuring land submergence or emergence along a coast must take into consideration that the standard itself—sea level—fluctuates. The present-day melting of glaciers and polar ice caps yields a global sea level rise of about one-sixteenth inch a year. By comparing data from tide gauges and rates of tectonic elevation along the Oregon coast, he determined that the northern and southern portions are rising faster than global sea level, while the central region is being submerged, a conclusion that is analogous with the findings of others.

Paleocene-Eocene Coastal marine basins

The oldest rocks at the core of the Coast Range block (Siletzia terrane) are early Tertiary basalts. Because of their variable age, texture, mineralogy, and distribution, they have been mapped individually as the Metchosin of Vancouver Island, the Crescent in Washington, and the Siletz River and Roseburg in Oregon. Both the Siletz River and the Roseburg formational names have been applied to the Eocene volcanics in southern Oregon, but ongoing discussions between Alan and Wendy Niem and others led to the conclusion that the basalts are continuous, thus giving preference to the Siletz River designation. The Siletz River at the southern extreme and

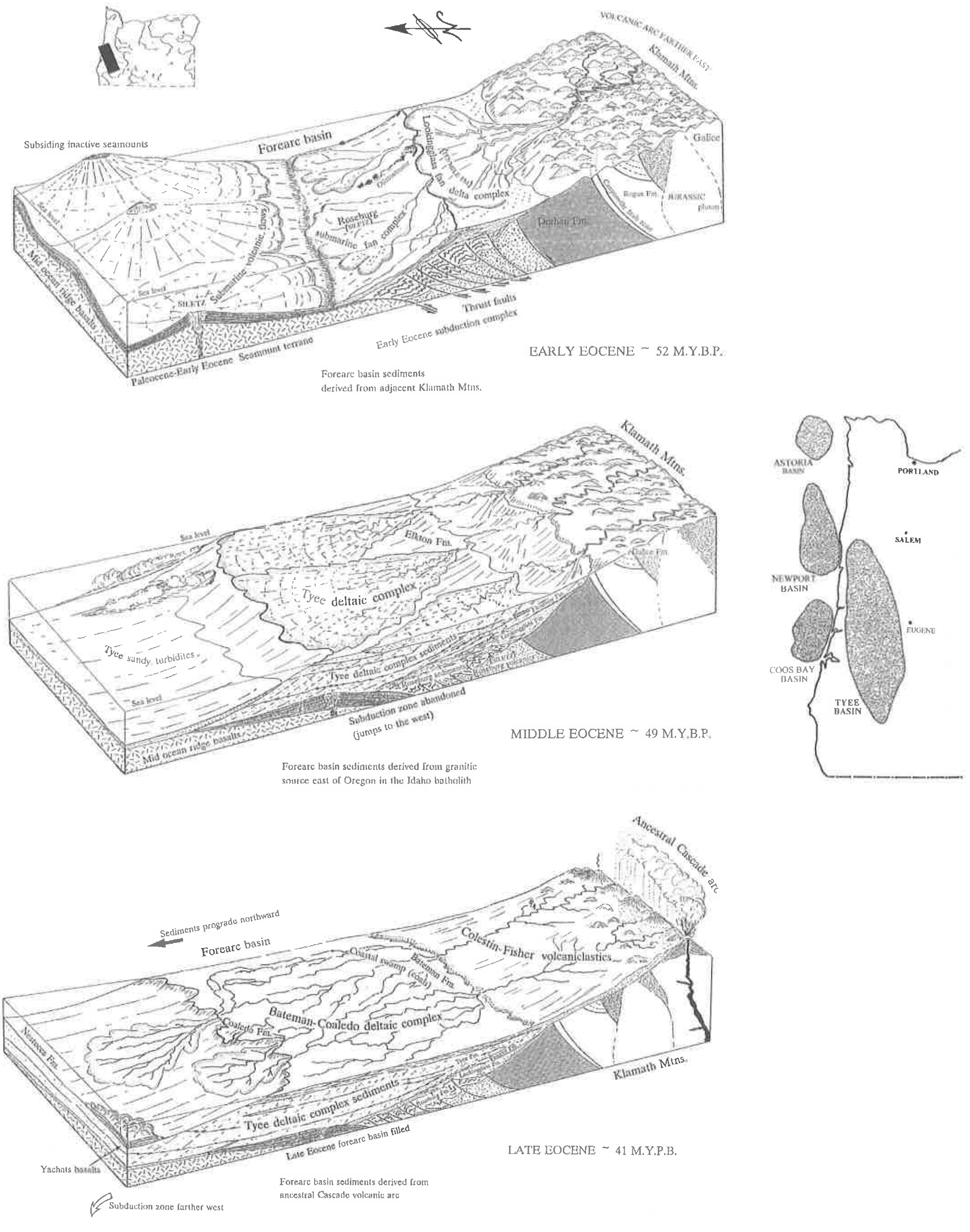


Throughout the Coast Range, Cenozoic volcanism and intrusions emplaced many of the present-day rugged mountains and headlands. Eocene to Oligocene dikes and sills of the Tillamook volcanics, the basalts of Cascade Head, and the Yachats Basalt are older than the Miocene Columbia River lavas from eastern Oregon. (After Armentrout and Suek, 1985; Baldwin, 1976; Christiansen and Yeats, 1992; Niem, et al., 1994; Wells, et al., 2009)

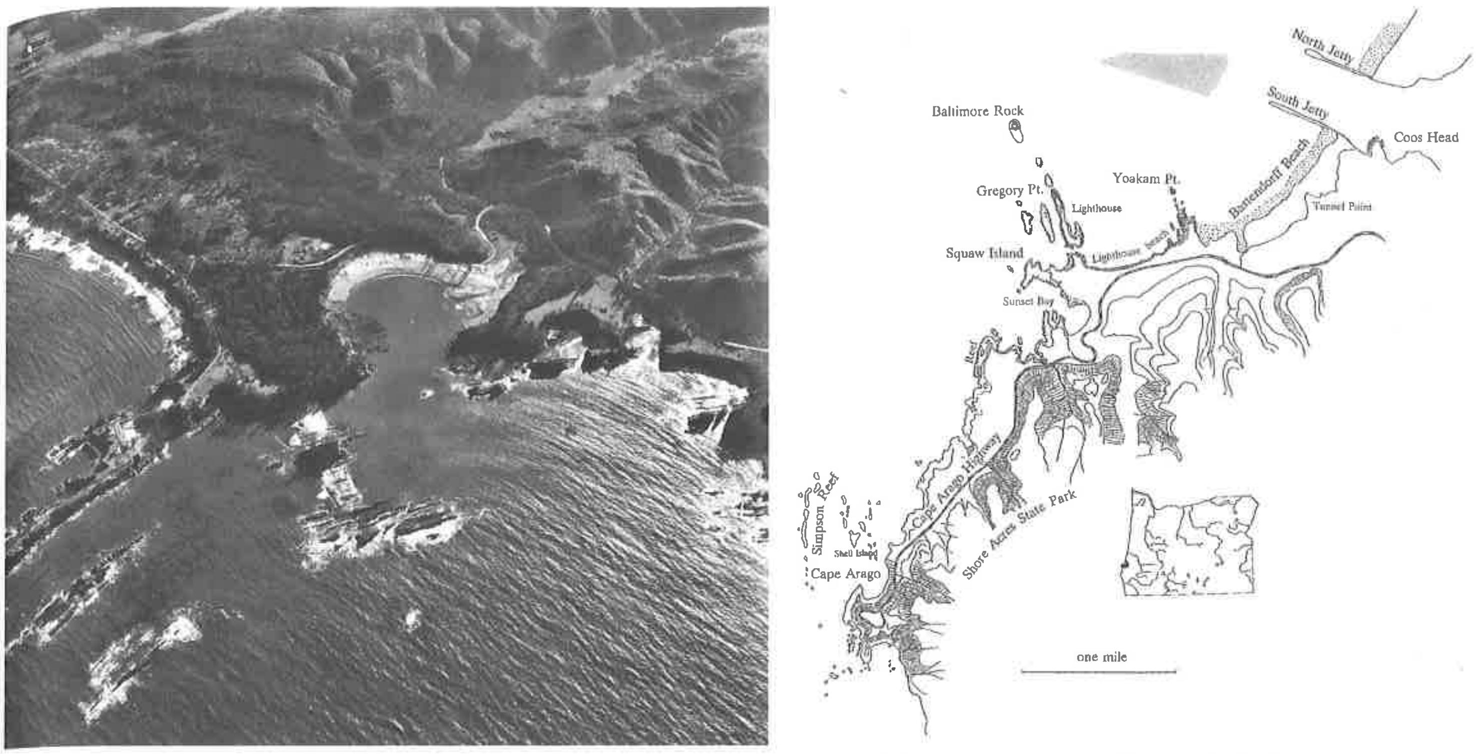
the Metchosin in the north are the oldest, while formations in the middle are up to 10 million years younger. Common to all of these, breccias (angular fragments) and elliptical bodies called pillows (because of their size and shape) formed during submarine eruptions.

By the middle Eocene, the Siletzia platform had subsided into a 400-mile-long forearc basin, which was the repository of massive deep-sea fans and deltaic sediments before uplift brought about a shallowing and eventual closure of the seaway by the late Miocene. Ewart Baldwin's Tertiary stratigraphy and nomenclature of southwest Oregon strata underwent a major revision by In-Chang Ryu and Alan and Wendy Niem in the 1990s, when many new names were proposed, others redefined, and several dropped.

The older Siletz River volcanics were blanketed by fluvial (stream) and marine deposits of the Lookingglass (Tenmile), Flournoy (White Tail Ridge), and Tyee formations. Cherts, metamorphics, and heavy minerals within these sediments indicate sources in the Klamath Mountains and western Idaho. Megafossils (mollusks) and microfossils (ostracods, foraminifera, and coccoliths) typify what were moderate water depths of an inner to



Renewed subsidence 50 million years ago pushed the early Eocene seaway from Cape Blanco northward beyond Newport and brought an influx of characteristic Tyee sandstones and mudstones. But sediments of the middle to late Eocene Elkton, Bateman, and Coaledo Formations, transported by inland streams, were limited to the southwestern forearc region near Coos Bay. Derived from the emerging Western Cascade range and the northern Klamath Mountains, approximately 2,500 feet of dark Elkton mudstones entomb an upper slope fauna of mollusks and microfossils. (After Baldwin, 1974; Brouwers, et al., 1995; Christiansen and Yeats, 1992; Heller and Ryberg, 1983; Orr and Orr, 2009; Ryberg, 1984; Ryu, Niem, and Niem, 1992; Snavely and Wells, 1991)



Sunset Bay in the foreground, Gregory Point and Lighthouse Beach in the center, Bastendorff Beach at the top, and Simpson Reef offshore are cut into silts and sandstones of the Coaledo Formation (Photo courtesy W. Robertson).

middle shelf during Siletz River time. Deposited by an advancing sea, deep-water Lookingglass (Tenmile) slope deposits, carried by turbidity currents, grade upward to a shelf setting as the depression filled. During Flournoy time, the retreating seaway was restricted to the area between Coos Bay and Newport. Conglomerates, pebbly sandstones, and siltstones point to stream systems, shallow water, and nonmarine coal beds along the margins of the Flournoy basin.

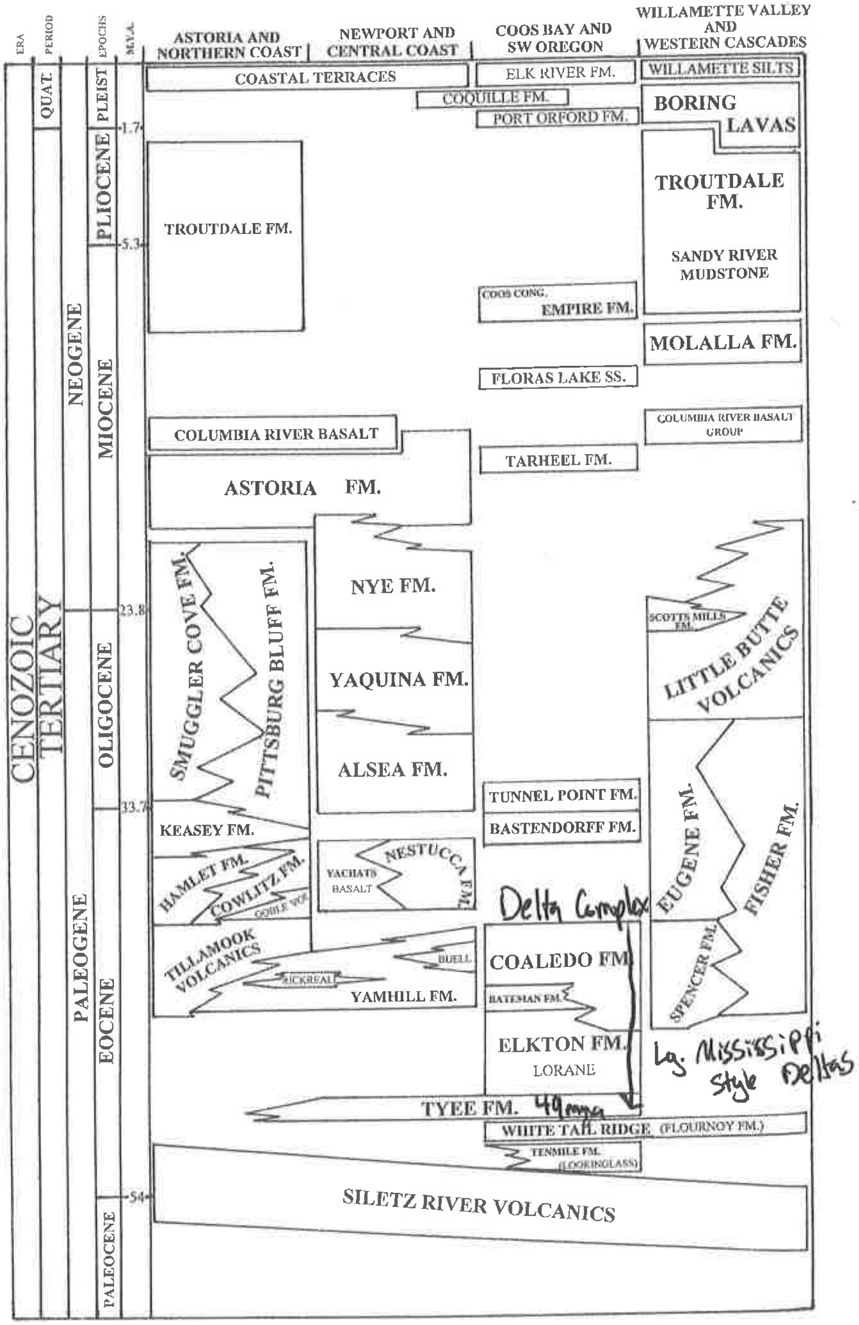
Distinguished by an abundance of muscovite mica flakes, the 6,000-foot-thick Tyee Formation overlies the Flournoy. Tyee sediments, carried by rivers coming off the Klamaths, built a north-trending delta that merges with deep-water turbidites toward the north. Huge submarine fans of the Tyee lap onto and cover the Siletz River volcanic seamount high. Bathyal microfossils (foraminifera) are present, but overall Tyee faunas are meager because of rapid deposition and the overwhelming volumes of sediment.

The Elkton basin, in turn, is covered by advancing fans of the Bateman with tropical foraminiferal microfossils and the distinctive Eocene shoreline clam *Venericardia*. Shoaling by Coaledo time is reflected in the coarse sands of an immense delta in the Coos Bay basin, layered with the remains of plants that grew on a swampy shore or in estuaries. Where sandstones of the coal-bearing Coaledo Formation have been deeply eroded at Cape Arago, Yoakam Point, and Gregory Point, the strata are honeycombed with sea caves. Offshore from Cape Arago, Simpson reef is a remnant of Coaledo sandstones and silts originally continuous with the headland.

At Coos Bay, swamps, wide coastal plains, and a shallow continental shelf delineate the third and final late Eocene phase of marine sedimentation. Explosive eruptions of the early Western Cascades were the primary source for the ash and pyroclastics of the Tunnel Point Formation overlying the Bastendorff shales. Thin-shelled delicate mollusks and microfossils in Bastendorff deposits are evidence of bathyal depths open to the ocean, well away from the shore, whereas Tunnel Point sandstones were part of a marine embayment. Once a sharp promontory that projected south of the entrance to Coos Bay, Tunnel Point had a natural channel and cave carved through before the cliff partially collapsed.

Following deposition of the Tyee submarine fan, the shoreline retreated progressively to the north and west, reflecting an overall pattern of uplift and the creation of small basins between Newport and Astoria. Along the central coast, Yamhill silts, sands, muds, and volcanic ash were distributed in the deeper offshore, while tropical mollusks, microfossils, and plants, layered within Buell and Rickreall limestone lenses, inhabited the fringes of seamounts and volcanic islands. Sills and sedimentary rocks of the middle Eocene Tillamook Volcanics, which interfinger with the Yamhill Formation, form the basement core of the northern Coast Range anticline.

Above the Yamhill, the bathyal Nestucca Formation lacks planktonic (open ocean) microfossils, an indication that deposition took place in an isolated marine embayment, separated from the ocean by a barrier of offshore islands or by the highlands of Yachats Basalt and Cascade Head. The Nestucca interfingers with nearly horizontal submarine flows of the Yachats Basalt, erupted from volcanoes lining a shallow coastal shelf. Over 2,000 feet thick in



Tertiary stratigraphy of the Oregon Coast Range province. (After Addicott, 1964; Armentrout, ed., 1981; Armentrout, et al., 1983; Baldwin, 1950, 1974; Molenaar, 1985; Niem, Niem, and Snavely, 1992; Niem, et al., 1994; Orr and Orr, 2009; Prothero, ed., 2001, 2003; Ryu, Niem, and Niem, 1992) places, the Yachats has been interpreted as a small field of seamounts scraped off the subducting Farallon plate. This basalt forms resistant promontories at Sea Lion Caves, Heceta Head, and Cape Perpetua. The Eocene basalts that armor Cascade Head are slightly older. Proposal Rock, now a tree-covered island, was part of Cascade Head before being cut away from the mainland.

In the Nehalem basin, strata of the Hamlet, Cowlitz, and Keasey formations represent swamps, spreading deltas, and deep marine troughs. The high-energy pocket beach conditions of the Hamlet merge into the deep marine Cowlitz delta, which consists of micaceous and feldspar-rich sandstones with abundant upper shelf invertebrates, trace fossils, and microfossils. In sharp contrast, the overlying Keasey Formation, from a continental slope at depths of 1,500 feet or more, preserves unusually delicate fossils such as crinoids, thin-shelled mollusks, corals, sea urchins, and plants.

Cooling, which occurred worldwide throughout the Cenozoic, continues today. Climate changes from the middle Eocene and into the Oligocene triggered two episodes of extinction when warm tropical faunas were replaced by temperate forms. Diversity of invertebrates reached a maximum during the tropical Cowlitz interval, preceding a dramatic regional late Eocene demise. A second extinction occurred when Keasey invertebrates and plants were replaced by the cool-water faunas of the Oligocene to early Miocene Pittsburg Bluff and Eugene formations.

Oligocene

Shoreline Embayments and Deltas

Covering a relatively short time span from 34 to 24 million years before the present, the Oligocene was an epoch when marine sedimentation was limited to embayments along the central and north coast. Strata are typified by siltstones and muds of the Alsea, Yaquina, and Nye formations in the central region, and by the Smuggler Cove and Pittsburg Bluff formations toward the north.

Near Newport, abundant ash, silts, and sands of the Alsea and Yaquina are reflective of an open-ocean, cool-water upper bathyal shelf shoaling to a coastal plain. The Yaquina may have been derived from the underlying Tyee Formation and Eocene basalts, but the persistence of ash and pumice suggests sources from ongoing Western Cascade eruptions.

The Nye Mudstone, spanning the Oligocene to Miocene epochs, overlies the Yaquina in the Newport basin. The Nye thins toward the north, where it may have shoaled against a broad Yaquina delta, however, a cold water bathyal interval reaching 2,000 feet is reflected by the presence of deep-water microfossils. Both formations are famous for their whale and seal remains, fish scales, and shark teeth.

In Clatsop County, the Oligocene Epoch was marked by shallow seas with growing deltas, brackish estuaries, and offshore deeper shelf and slope sands and silts of the Smuggler Cove and Pittsburg Bluff formations. Initially designated as the Oswald West Mudstone, the Smuggler Cove is best known for its trace fossils of tracks, trails, and burrows. The formation reflects cold water, continental slope conditions below 1,000 feet.

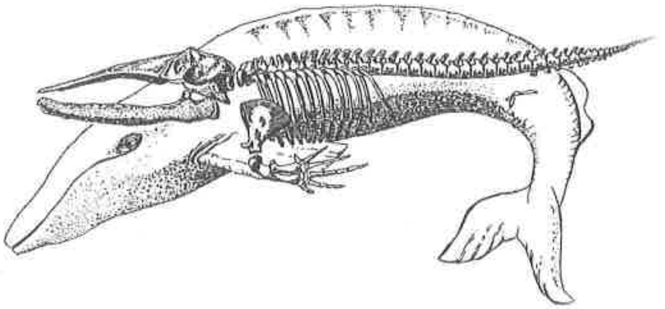
Originally regarded as Eocene, the Pittsburg Bluff was assigned to the Oligocene in 1915 before its current placement spanning the Eocene-Oligocene-Miocene boundaries. The most definitive works on these rocks are by Ellen Moore of Oregon State University, who detailed the paleontology and stratigraphy. Even though there are few species overall, mollusks and other invertebrates in the Pittsburg Bluff are abundant, depicting a remarkable range of settings from upper continental shelf, to intertidal, and even terrestrial. Since many of the shells are broken but show little beach wear, Moore surmised that they had been transported some distance by storms before deposition. Fluvial channels and deltas of the Scappoose Formation have been revised and mapped as facies of the upper Pittsburg Bluff by the Niems.

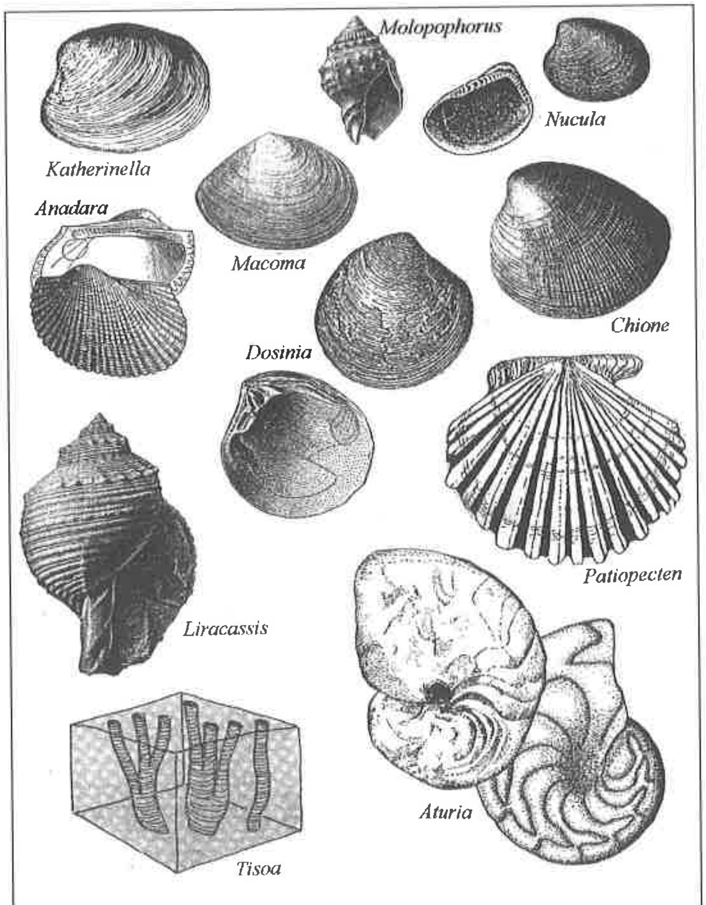
Miocene

Fluctuating Oceans

During the latest Oligocene to early middle Miocene, regional uplift shifted the shoreline close to its present position, and marine waters occupied only narrow inlets at Astoria, Newport, and Coos Bay. Deposition continued uninterrupted as the Western Cascades showered ash directly into the ocean, where currents carried the debris into deeper waters.

Middle Miocene strata on the southwest coast were unknown until 1949, at which time mollusk-bearing sandstones were brought to the surface and piled in a disposal area during U.S. Army Corps dredging operations in the Coos Bay channel. The fossils were inspected by Ewart Baldwin and his student Ellen Moore, who determined they were of Miocene age. In 1966, John Armentrout, also Baldwin's student, discovered similar fossiliferous outcrops near Pigeon Point. Naming them the Tarheel Formation, he surmised that the sandstones were deposited in warm to temperate water at shallow to moderate depths up to 180 feet.





Marine central coast invertebrates. (After Dall, 1909; Gabb, 1869; Zittel, 1913.)

The Oregon coast is famous for its fossils from the Miocene Astoria Formation, which are continuously exposed in eroding sea cliffs. In addition to shells, bone fragments of the primitive baleen whale *Cophocetus* (above) are often encountered. (After Moore, 2000, 2002; Niem and Niem, 1985; Orr and Orr, 2009)

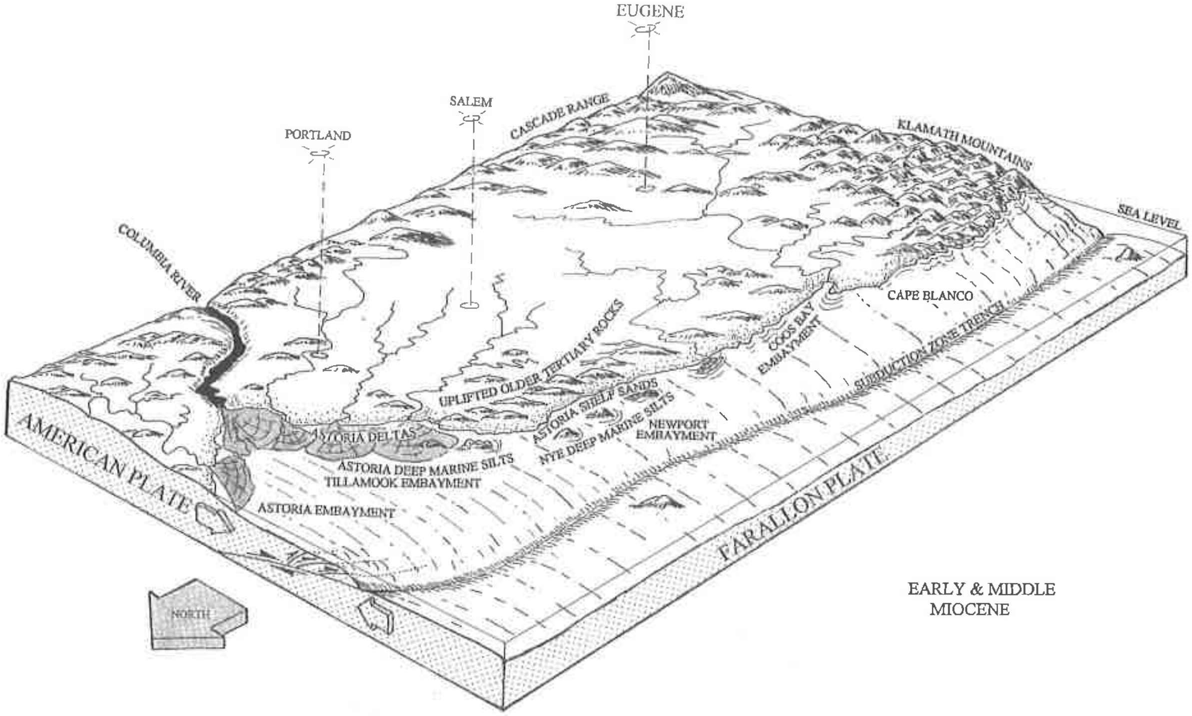
Above the Tarheel, the fossil-rich Empire Formation stretches to Cape Blanco, and at South Slough it is exposed around Coos Head. When he visited Coos Bay, William Dall of the Smithsonian Institution obtained Empire mollusks and marine vertebrate fossils that he described and illustrated in 1902. Armentrout reassessed the invertebrate fauna over 60 years later, concluding that the late Miocene climate and calm estuary were close to the environment of today.

Part of the same formation, the Coos Conglomerate at Fossil Point was described in 1896 by Joseph Diller, who recognized the small patch of less than one acre as the most fossiliferous anywhere along the coast. The lens was a narrow submarine channel cut into upper layers of the Empire Formation in which shallow water mollusks and the remains of whales, seals, walrus, and fish collected.

At Cape Blanco, the Empire was assigned to the middle Miocene until a gap or unconformity was noted within the strata. When Warren Addicott of the U.S.G.S. subsequently divided the formation, he designated the lower section as the Sandstone of Floras Lake, retaining the name Empire for the upper portion. South of Bandon, the state's only known marine diatomite, that projects well out onto the continental shelf, was mapped as a facies of the Empire Formation by Jerry Fowler of Oregon State University and coauthors in 1971.

On the central and northwest coast, fossiliferous sandstones and siltstones of the middle Miocene Astoria Formation are well exposed. The Astoria has not lacked for attention since the first examination of fossils in 1848 by Timothy Conrad of the New York Geological Survey. Astoria shales were formally named by Thomas Condon in 1880 and described by Joseph Diller in 1896. Ellen Moore's research on the Astoria has produced many publications as have Parke Snavely's mapping and descriptions of the strata at Newport, and Wendy and Alan Niem's work on the Astoria, Tillamook, and Nehalem basins.

The diverse warm-temperate fauna of the Astoria Formation includes corals, barnacles, bryozoa, brachiopods, and crabs, along with 97 species and

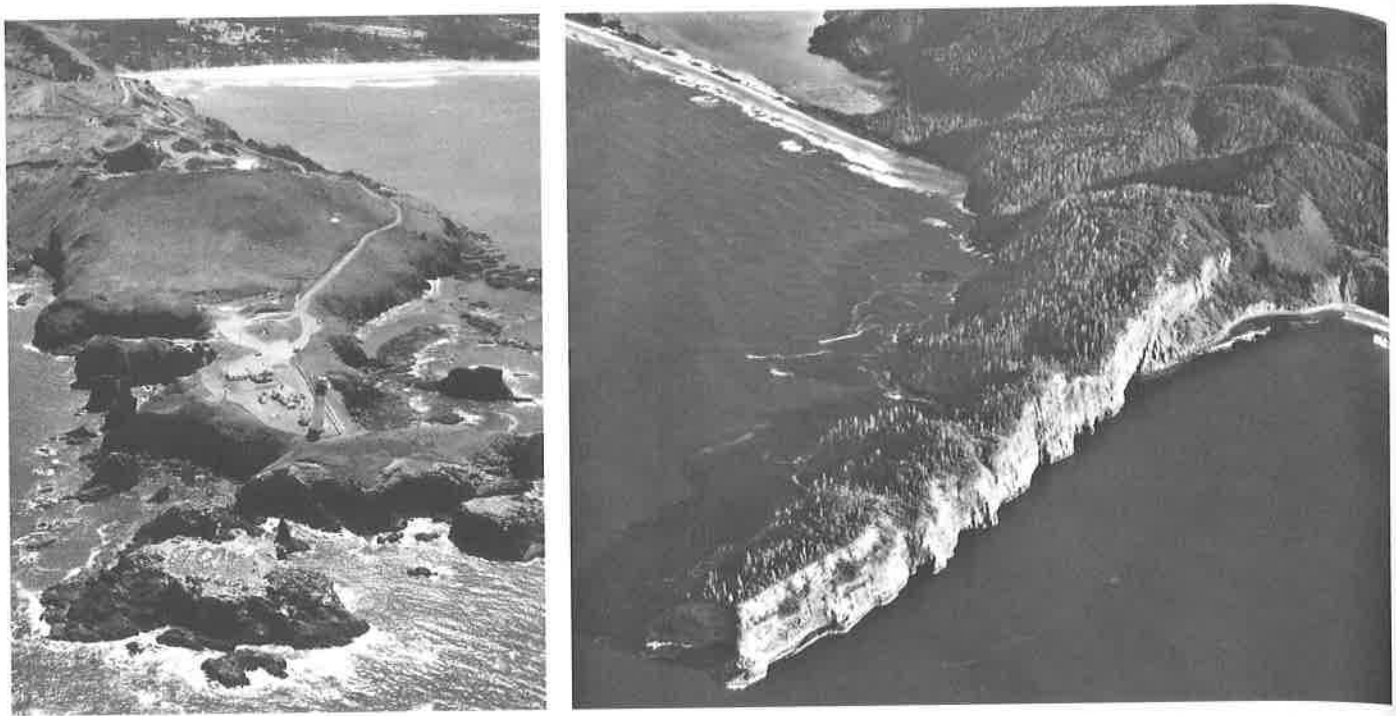


By Miocene time, marine sedimentation was confined to areas close to the present-day shore. (After Orr and Orr, 2009)

73 genera of mollusks, as is characteristic of organisms living on a soft muddy seafloor and continental shelf at depths of 500 feet. Astoria sediments are also the repository of an extraordinary collection of vertebrate bones, shark teeth, and reptilian (turtles) fragments. Even occasional ungulates (hoofed mammals) were washed into the seaway.

Concurrent with deposition of the Astoria Formation, areas of the north and central coast were invaded by Columbia River lavas from eastern Oregon. The flows, sills, and dikes were initially mapped and interpreted by Parke Snavely and others as having erupted from local volcanic vents, but the striking paleomagnetic, chemical, and mineralogical similarities between the basalts making up most promontories between Seal Rock, Oregon, and Grays Harbor, Washington, to those of the Columbia River Group were an enigma until Marvin Beeson demonstrated that both were derived from the same magma source beneath the Grande

Now adjacent to the mainland, Elephant Rock is an elongate invasive sill of Miocene Columbia River basalts at Seal Rock State Park south of Newport. During high interglacial sea levels of the Pleistocene, it would have been an isolated sea stack. (Photo courtesy Oregon Department of Geology and Mineral Industries)



Projecting offshore, Yaquina Head (left) north of Newport and the dramatic promontory of Cape Lookout (right) at Netarts Bay are Miocene Columbia River basalts. Both features are outstanding examples of inverted topography. In such cases, dense fast-moving lavas filled estuaries, but after the softer sediments were eroded away, the resistant basalts remained as elongate headlands, cast in stone. (Photos courtesy Oregon Department of Geology and Mineral Industries and Oregon State Highway Department).

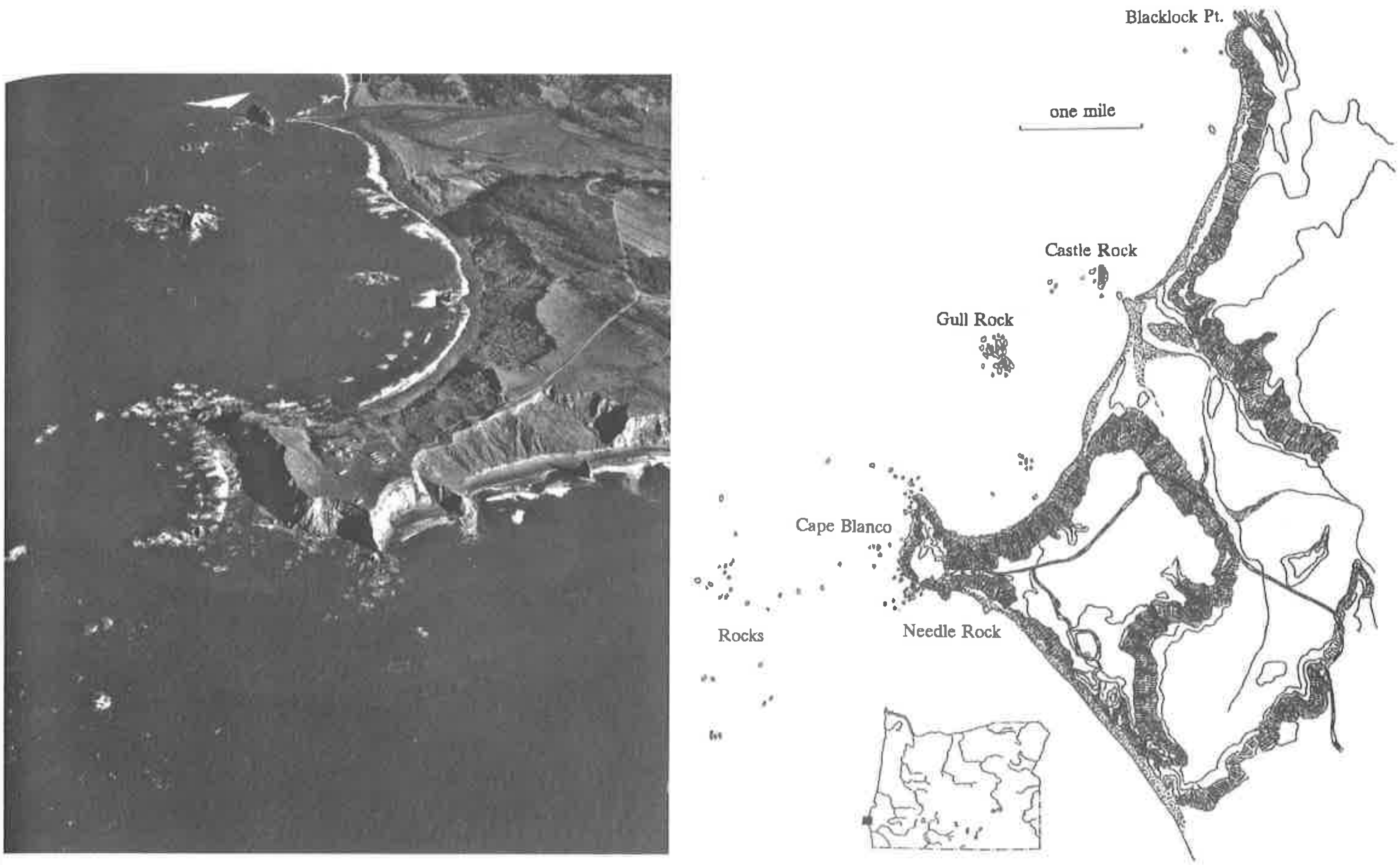
Ronde Valley of Baker County. Voluminous floods of lavas flowed westward along a broad Columbia River paleochannel, through a gap in the Cascade Range, and into the Willamette Valley. Advancing seaward to pond up in marine bays and estuaries, the dense flows penetrated deeply into the soft, soupy sediments. Geophysical transects across the coastal exposures reveal that the basalts are rootless, which further supports a distant origin rather than a local volcanic source.

Outcropping as far as 120 miles south of the entrance to the Columbia River, the Miocene basalts terminated at Seal Rock, close to the same latitude they reached in the Willamette Valley. Yaquina Head, Cape Foulweather, Cape Lookout, Cape Meares, Neahkahnie Mountain, Cape Falcon, and Tillamook Head are all headlands of resistant Columbia River basalts. Most of the offshore stacks, islands, and arches are vestiges of the same flows. These features have been isolated from the mainland by erosion as have Arch Cape and Haystack Rock offshore at Cannon Beach. Pillar Rock, Pyramid Rock, and Three Arch Rocks located near Cape Meares have been cut back as well.

Pliocene-Pleistocene Glaciers and Ocean Waters

There are few confirmed Pliocene sediments in western Oregon as this was a comparatively short time when much of the area was above sea level and erosion predominated. Pliocene gravels of the Troutdale Formation, with Precambrian cobbles derived from well up in the northern Rockies, are encountered intermittently in the Columbia River channel.

Global cooling characterized the Pleistocene or Ice Ages, starting around 2 million years ago. In the Pacific Northwest, continental glaciers from Canada reached into northern Washington, but only ice caps appeared along the crests of the Oregon Cascades. Glaciation, which tied up water as ice, initiated a profound lowering of sea levels worldwide, while in Oregon it brought a widening of the coastal plain and a rapid down-cutting of estuaries and stream valleys. At the termination of the last glacial phase 11,000 years ago, which brought a reversal of Arctic-like conditions, a warming climate melted ice caps that, in turn, elevated ocean levels, submerged the coastline, and created vast new habitats for marine invertebrates.



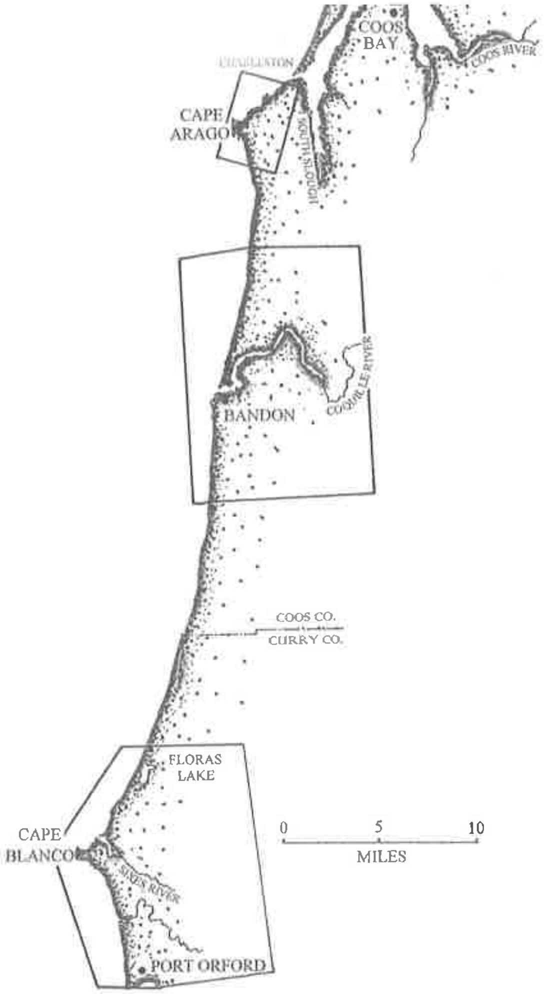
Clearly visible here, the Cape Blanco terrace has undergone the most rapid uplift of any coastal feature in Oregon. This distinct promontory, noted on maps of early explorers, is the state's most westerly point. Named the White Cape in the 16th Century, it is a complex of durable Jurassic Otter Point conglomerates covered by Eocene mudstones and the Miocene Empire Formation. (Photo courtesy U.S. Forest Service).

Although Pleistocene marine fossils are comparatively rare in Oregon, mollusks are prevalent in terrace deposits at Cape Blanco, which takes its name from the white shells that litter the cliffs. Invertebrates in the Port Orford and Elk River formations at Cape Blanco and in the Coquille Formation at Bandon some 20 miles to the northeast were described by Warren Addicott. He characterized the climate as slightly cooler than at present and surmised that the shallow-water conditions differed little from those of the modern offshore. Many of the species inhabiting the region today are similar to those of the Pleistocene.

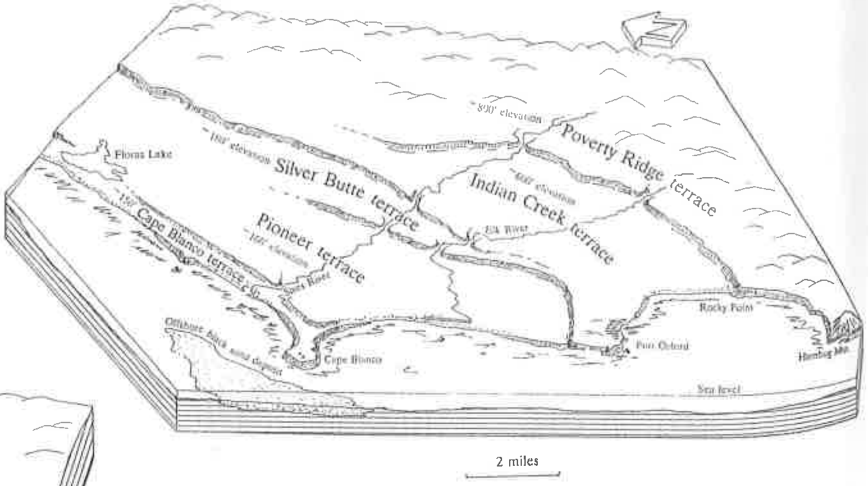
Elevated Terraces

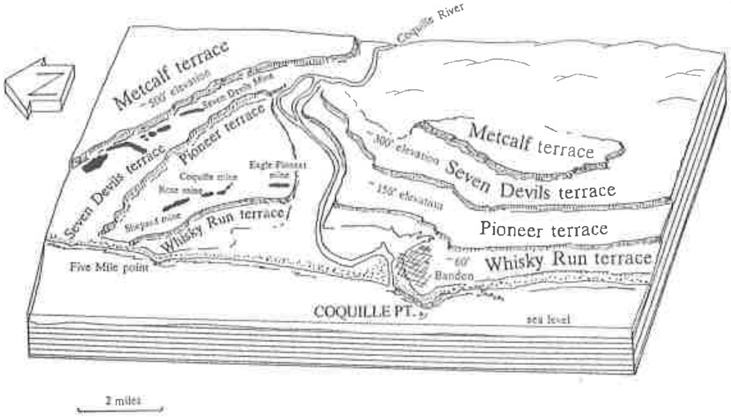
Along much of the Pacific Northwest coast, a series of stair-step terraces form discontinuous elevated surfaces that chronicle erosion, uplift, and deformation. The oldest terraces are inland, whereas the younger late Pleistocene surfaces are found near sea level. Buried by up to 20 feet of beach gravel and sand, the lower terraces are better preserved than the higher ones. Separated by headlands or bays, the individual surfaces are difficult to correlate because the rates of uplift vary considerably from place to place, and the surfaces have been altered by deformation, faulting, and erosion.

The number of recognized marine platforms has been refined and revised since they were first mapped in 1945 by Allan Griggs of the U.S.G.S. Northward from Coquille Point, the Whisky Run, Pioneer, and Seven Devils terraces were named by Griggs, while the oldest Metcalf was described by John Adams of the Geological Survey of Canada. In his classic 1984 overview paper, Adams calculated the magnitude of uplift and tilting for the Silver Butte, Indian Creek, and Poverty Ridge terraces that lie inland from the Pioneer terrace at Cape Blanco. In 1969 Richard Janda of the U.S.G.S. identified most of the terraces at Cape Blanco, and some 20



The most extensive, highest, and best-preserved terraces are at Cape Arago (photo, top), Coquille Point, and Cape Blanco. In the photograph of Cape Arago, the stair-step configuration can easily be seen. (After Adams, 1984; Brockheim, Kelsey, and Marshall, 1992; Griggs, 1945; Janda, 1969; Kelsey, 1990; McInelly and Kelsey, 1990; Muhs, et al., 1990; photo courtesy U.S. Forest Service)





years later Harvey Kelsey described the youngest level here. From a height of 150 to 190 feet above sea level in southern Oregon, the lengthy Pioneer decreases to 60 feet at Tillamook.

In 1990, Galan McInelly and Harvey Kelsey recognized and mapped the Arago Peak terrace at Cape Arago, and in 1996 Kelsey named and described six new platforms, the Newport and Wakonda at Yaquina Head, the Yachats and Crestview at Waldport, and the Fern Ridge and Alder Grove at Alsea Bay on the central coast. These range from sea level to almost 800 feet in elevation and extend approximately three miles inland. Based on the depth of the soils, the oldest at Alsea and Yaquina bays were estimated in excess of 200,000 years old, while the youngest terrace at Newport is closer to 80,000 years.

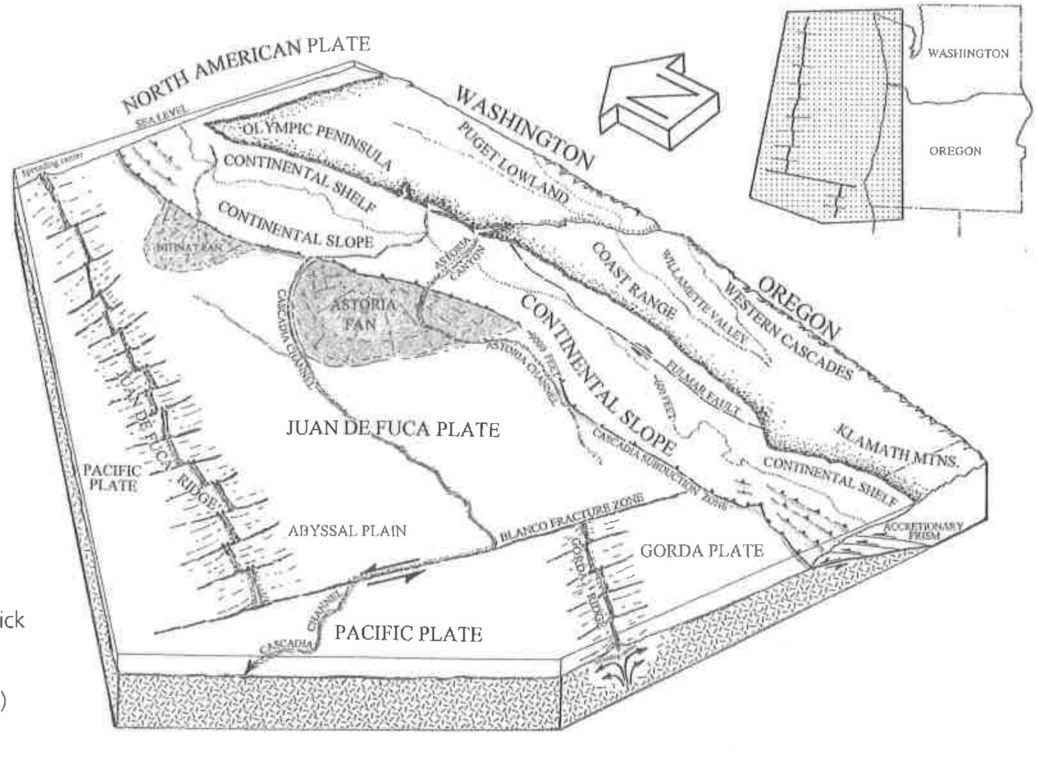
Varying interpretations have been proposed for the observed elevations and tilting of marine terraces. Contrary to earlier descriptions, there are no clear regional trends or orientations to the tilted surfaces. Recent mapping has shown that the three lowest (youngest) surfaces at Cape Banco tilt landward, and the two higher ones seaward. While elevation is seen as due to subduction, tilting and the rate of elevation may be the product of local folding and deformation. Identifying and comparing the distribution of strike-slip faults and folds, Kelsey found that most of the platforms had been uplifted at the comparatively low rate of 4 to 12 inches every 1,000 years throughout the past 125,000 years. Near the folds and faults, however, the elevation was faster, approaching three feet every 1,000 years.

Multiple techniques are used to date and correlate terraces. One method is to measure uranium /thorium radioactive decay from the calcite in fossil shells. Another calculates the chemical changes that amino acids undergo in an animal shell after it dies, commonly employing the thick-shelled clams *Saxidomus* and *Mya*. Using this method, Daniel Muhs inferred dates for the Cape Blanco terrace at 80,000 years, the Whisky Run at 83,000 years, the Pioneer around 100,000 years, the Seven Devils at 124,000 years, and the Metcalf terrace at 230,000 years. A third procedure for distinguishing one terrace from another compares and matches the successions of soils that developed on top of each.

Continental Margin

Topography of the offshore shelf and slope

The Oregon coastal province does not stop at the beach but extends out onto the continental shelf that dips gently seaward to 600 feet and to the lower slope that descends to abyssal seafloor depths of



The Oregon submarine landscape of deep canyons, ridges, plains, faults, and a thick sedimentary covering is more intricate than that onshore. (After Kulm and Fowler, 1974)

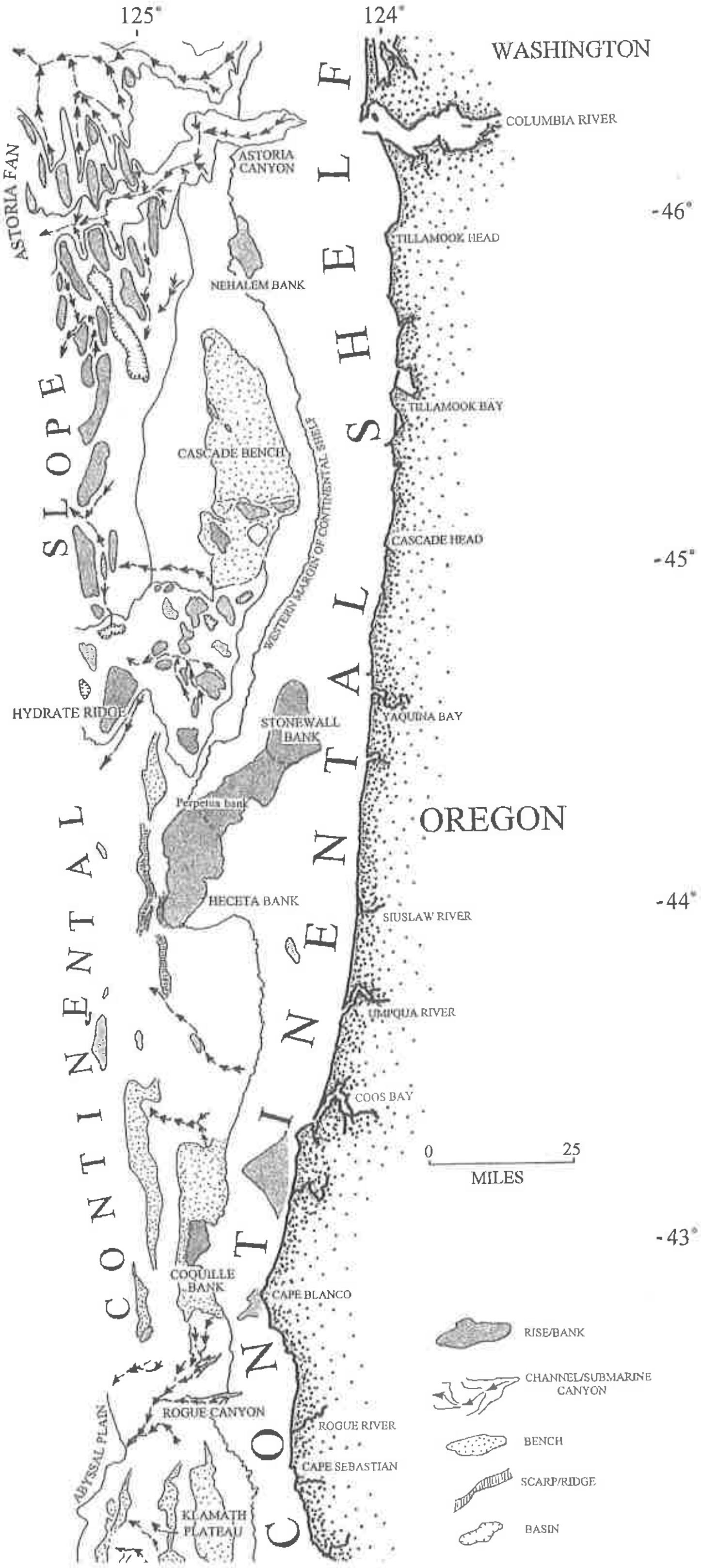
9,000 feet. The offshore topography is mantled by sand and muds, producing flat areas that are folded and broken by banks, ridges, basins, channels, and canyons. The combined width of the shelf and slope varies from approximately 70 miles off Astoria to 40 miles off Cape Blanco. Shelf and slope geology is closely linked with onshore patterns and processes, and the Oregon margin consists mainly of the same Eocene through Pleistocene formations as those exposed in the Coast Range.

With an east-west gradient of only 6 to 10 feet per mile, the nearly horizontal continental shelf is broken by the prominent fault-bounded Nehalem, Stonewall, Perpetua, Heceta, and Coquille banks. These topographic features are capped by Miocene through Pleistocene mudstones, sandstones, and clays.

The upper continental slope drops from 600 to 5,000 feet and is distinguished by benches, low hills, and canyons. The longest Cascade bench—a level platform with steep sides—lies between Cascade Head and Tillamook Bay at depths of 2,000 feet. A similar feature between Cape Sebastian and the California border at 1,500 to 2,000 feet deep is a seaward continuation of the Klamath plateau.

From the edge of the shelf, deep-sea canyons crossing the slope serve as conduits for dispersing sediments to the lower slope and abyssal sea floor. Northwest of the mouth of the Columbia River, the 1,200-mile-long Cascadia channel that eventually cuts the Cape Blanco fracture zone is the longest such feature in the Pacific basin. Off the mouth of the Columbia River, the Astoria Canyon projects westward from the outer shelf across the Astoria fan before reaching the base of the slope at 9,000 feet, at which point it splits into two directions. Adjacent to the mouth of the Rogue River, the Rogue Canyon follows a westerly pathway to abyssal depths.

An analysis of heavy mineral suites in offshore deposits shows that the dominant Pliocene sources were the Klamath Mountains and British Columbia,

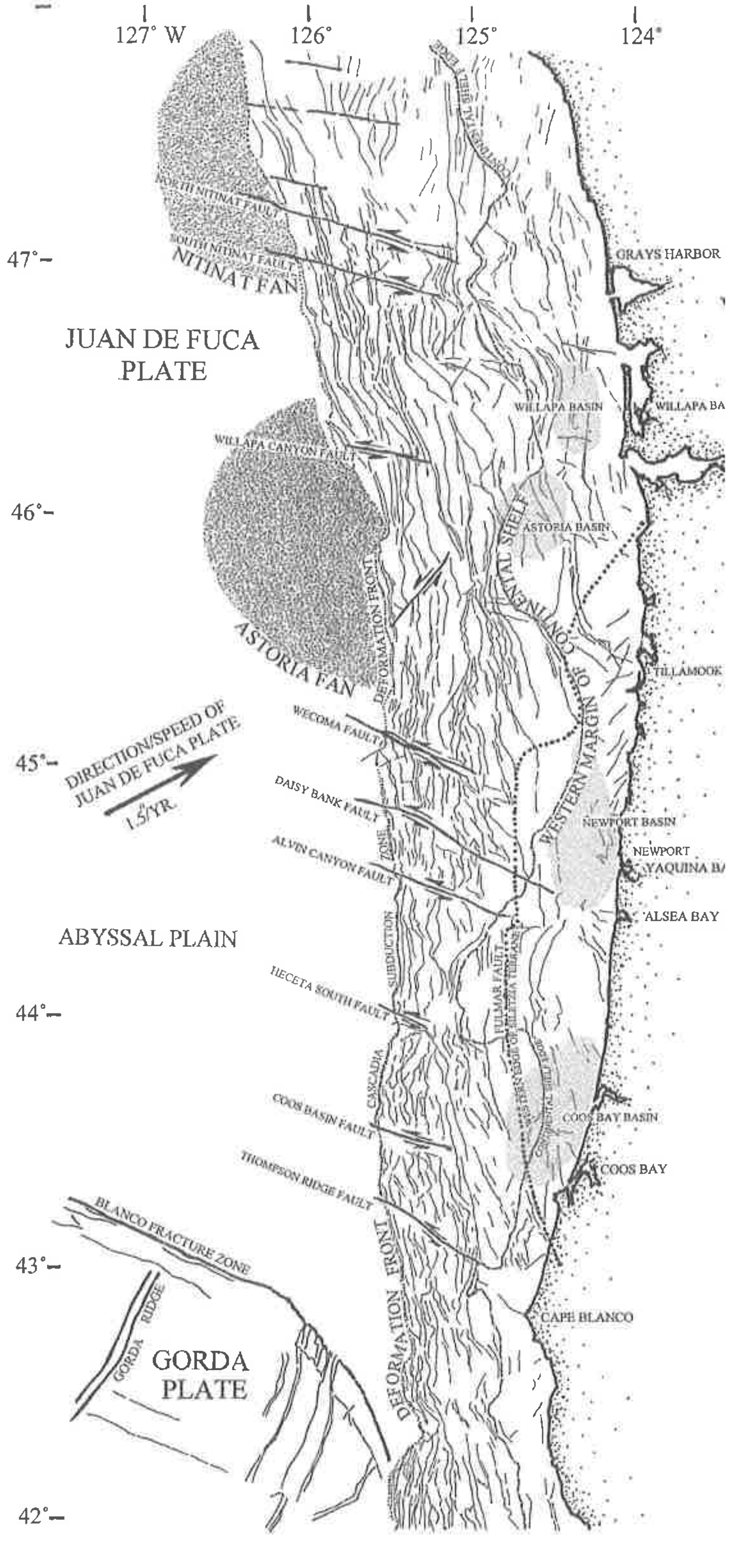


Twenty miles off Yaquina Bay, Stonewall Bank lies in water less than 120 feet deep, and Heceta Bank, west of the mouth of the Siuslaw River, rises to within 360 feet of the surface. Coquille Bank, a shoal approximately three miles wide and eight miles long between Coos Bay and Cape Blanco, exhibits 198 feet of relief. Beneath Heceta Bank a lengthy basalt ridge, buried in the accretionary wedge, marks the western edge of the Eocene Siletzia oceanic terrane. The banks may have resulted when eastward-migrating seamounts "plowed" beneath the continental slope and shelf to bulge up on the seafloor during subduction. The volcanic ridges are presently buried beneath the banks. (After Fleming and Tréhu, 1999; Kulm and Fowler, 1974; von Huene, 2008) however, that changed around 2 million years ago with an influx of fine-to-medium-grained sandy turbidites from the Columbia River. Exiting through the Astoria and Willapa canyons, the sediments constructed the Astoria fan that covers more than 3,500 square miles and is somewhat larger than the Nitinat fan off the Washington Olympic Peninsula.

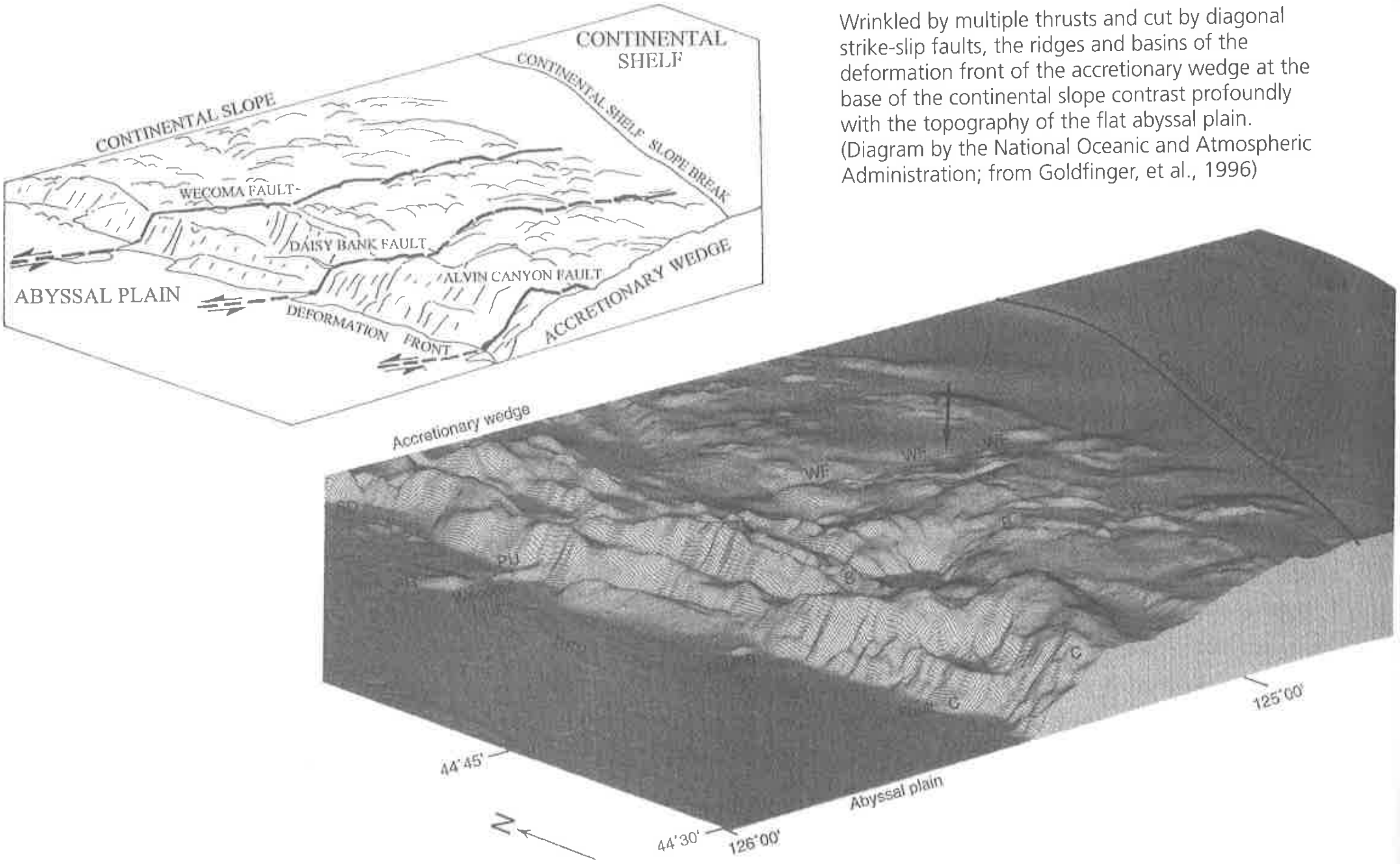
Between the base of the slope and the abyssal plain, the Cascadia subduction trench is the focal point of Oregon's offshore geology. Largely obscured by thicknesses of sediments, the long narrow depression lies at the boundary between the Juan de Fuca and North American plates and runs from Cape Mendocino, California, to Vancouver Island. The Juan de Fuca and Gorda slabs are moving east-northeast into the subduction trench at the rate of one and one-half inches a year.

One by-product of the subduction process is a thick accretionary prism (wedge) of sediment and crust, which was peeled off the top of the Juan de Fuca plate, to become the leading edge of the continent. This mélange has been highly compressed and sheared by thousands of low-angle north-south thrust faults creating long, overlapping anticlinal ridges and intervening synclinal basins that parallel the shoreline. The broad zone of intense faulting reaches from the Cascade subduction zone (deformation front) to the base of the continental shelf. Thrust faults, where the overlying or upper plate has moved up and over the lower block, are the result of extreme crustal shortening or telescoping.

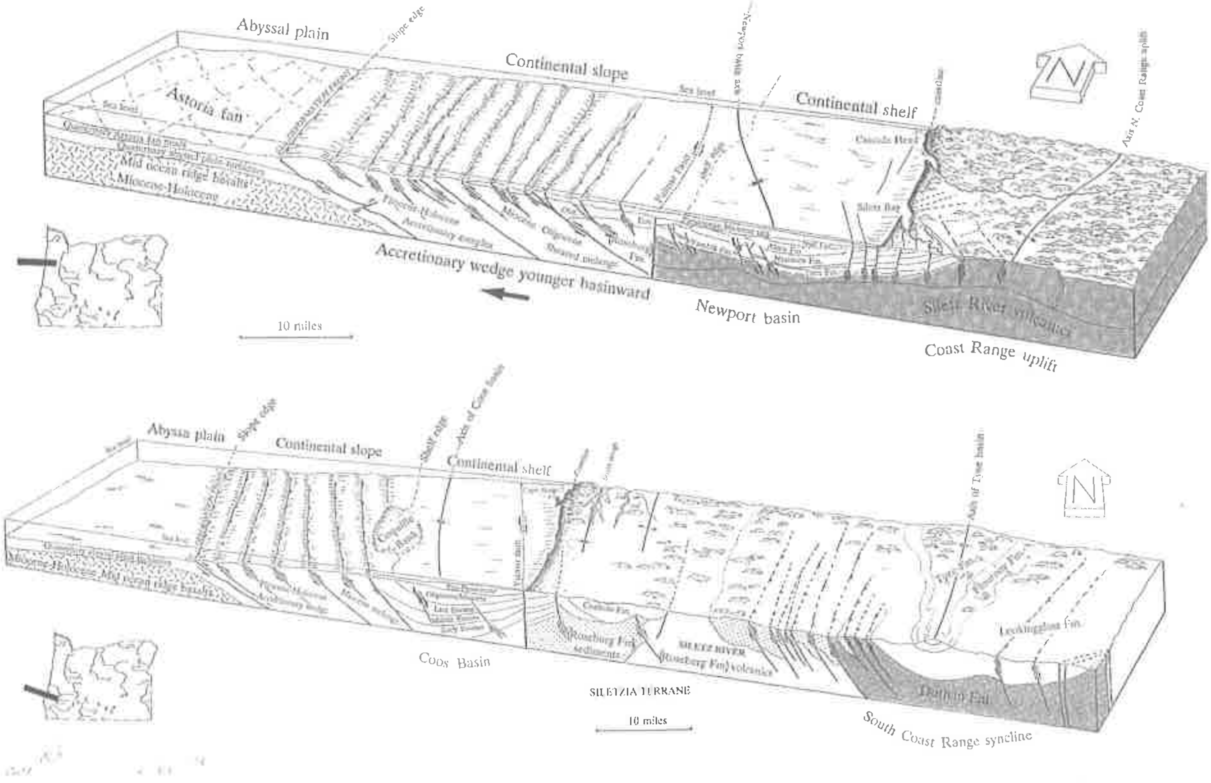
The abyssal plain is a wide nearly horizontal to gently sloping, deep-sea floor, where the older topography is covered by thin layers of marine sediment. Intersecting the abyssal plain, the Juan de Fuca and Gorda plates are bounded by lengthy mid-ocean ridges and fracture zones. At spreading centers along the Juan de Fuca and Gorda ridges, cooling sheets of lava create new oceanic crust. Vents along the Juan de Fuca ridge, releasing hydrogen sulfide, host rich communities of giant clams



Prominent features of the offshore are west-northwest-trending strike-slip faults (arrows) that run from the abyssal plain across the deformation front and shelf toward the coast. Between 20 to 70 miles in length, at least nine faults from Cape Blanco to the central Washington coast offset both the Juan de Fuca and North American plates and the accretionary prism. Dated at 650,000 to 300,000 years ago, these shear structures define the boundaries of elongate blocks, which are rotating clockwise, driven by the oblique subduction of the Juan de Fuca plate (long dark arrow). The most notable of these are the Wecoma, the Daisy Bank, and the Alvin Canyon faults. At the base of the continental slope, the intersection of the Wecoma fault with the deformation front is marked by a complex of bulges or fault pop-ups with a pronounced indentation in the slope. (After Couch, 1979; Goldfinger, et al., 1996, 1997; Kelsey, et al., 1996; McNeill, et al., 2000; Yeats, et al., 1998)



Wrinkled by multiple thrusts and cut by diagonal strike-slip faults, the ridges and basins of the deformation front of the accretionary wedge at the base of the continental slope contrast profoundly with the topography of the flat abyssal plain. (Diagram by the National Oceanic and Atmospheric Administration; from Goldfinger, et al., 1996)



Imbricate sheets of deformed Tertiary sedimentary and basaltic rocks lie at the foundation of the shoreline, shelf, and slope off Newport and Cape Arago. (After Baldwin, 1976; Snavely and Wells, 1996) and tube worms living in a symbiotic relationship with bacteria.

The Juan de Fuca and Gorda ridges are offset by wide sheared zones of the Blanco and Mendocino transform faults that move laterally past each other and that are generally perpendicular to the ocean ridges. Projecting in a westerly direction from southern Oregon and northern California, the Blanco and Mendocino faults are the sites of frequent earthquakes. The Blanco transform fault separates the Juan de Fuca and Pacific plates.

Geohazards

Typical of an active tectonic margin, the coastal province has been beset by earthquakes, tsunamis, erosion, landslides, and flooding of considerable magnitude throughout its geologic past. Such natural processes are only termed hazardous when human life or property is threatened, but the physical dynamics combined with inadequate land-use planning and population pressures have fostered circumstances of higher-than-normal risks.

Earthquakes

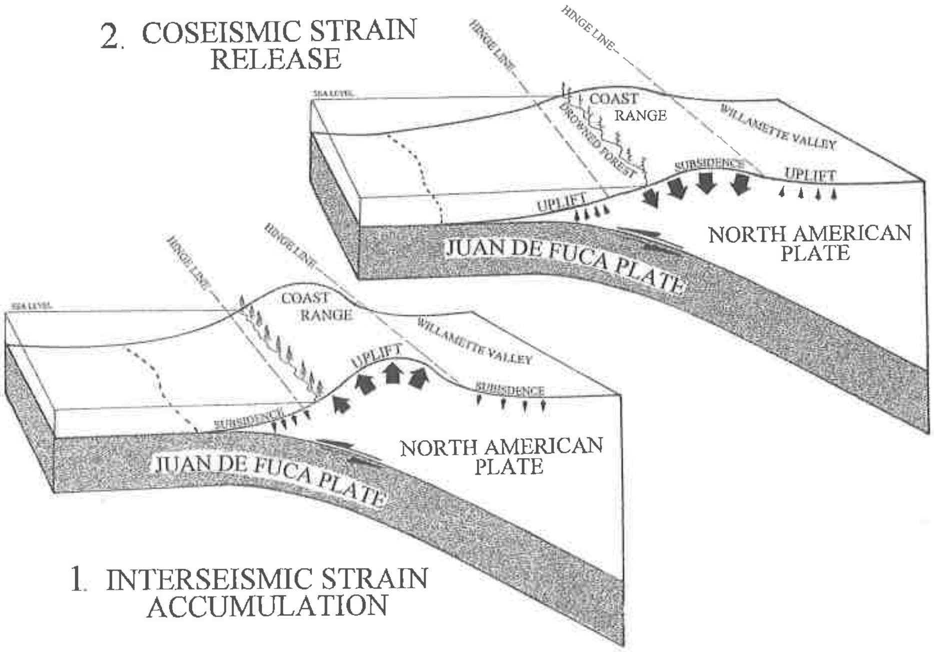
Sources and causes

Episodes of earthquakes are not new to the Pacific Northwest, and most are now being systematically documented through geologic verification of the actual events. Of particular concern is the periodicity of large quakes along the Cascadia subduction zone, coupled with the fact that it has the lowest incidence of documented seismicity of any subduction system worldwide.

Massive earthquakes occur offshore along the Cascadia subduction area at the interface between the Juan de Fuca plate and the North American plates. If the lower subducting slab adheres to the overlying plate, they bind up and lock. As subduction proceeds and stress steadily increases, interseismic strain accumulates, and the distal edge of the North American plate bulges upward. If the bond along the subduction surface fails suddenly, the release of coseismic strain initiates an earthquake and rapid subsidence of the uplifted area.

Faced with a rising coast, which is a sign that strain is building between locked plates, geologists' efforts revolve around understanding the apparent lack of historic megathrust (subduction) quakes. Explanations include aseismic creep, where ongoing slip relieves the pressure, or crustal shortening of the forearc basin by clockwise rotation. Faulting and folding may also absorb large amounts of plate convergence, lessening earthquake intensity. Current research favors a model where interseismic (elastic) strain on the locked plate interface is released at periodic intervals.

In contrast to the locked zone model, other theories maintain that high temperatures may diminish friction and stress along parts of the plate interface. The thick slab of accreted volcanics (Siletzia) along



Tied to subduction, the earthquake cycle for Oregon proposes that during an interseismic period of low activity, lasting hundreds of years, strain accumulating at the interface between the Juan de Fuca and North American plates causes coastal uplift. When the strain is released, an earthquake, rapid subsidence of the coastal region, and a tsunami drowning the area take place simultaneously (coseismic). (After Kelsey et al., 1996; Mitchell, et al., 1994; McNeill, et al., 1998) the central Oregon margin might act like a thermal blanket to confine heat to the interface between the two plates and thus reduce friction.

While gaps of seismic activity on the order of 300 to 1,000 years may occur between major quakes, interseismic strain alone might not account for these extended lapses. In 1996, John Adams correlated and dated 13 turbidite sequences from deep-sea piston cores in the Cascadia channel using volcanic ash from the 7,700-year-old Mt. Mazama eruption as a marker horizon. Following the eruption, turbidity currents, with ash-laden sediments, were dispersed from the mouth of the Columbia River into the channel. An examination of the successive thin clay layers atop the turbidites led him to speculate, that since they were deposited on average every 600 years, the swiftly-moving currents were triggered by strong Cascadia subduction zone earthquakes, which show the same periodicity.

Chris Goldfinger, a researcher at Oregon State University, offers evidence that the gaps between subduction quakes occur because the different segments of the Cascadia zone may act independently of each other. In his chronology, 19 quakes of magnitude 9.0 have ruptured along the entire zone, while those of magnitude 8.0 took place on shorter portions. Also examining turbidite frequencies, he assessed the 10,000-year history of subduction events to estimate that southern Oregon and northern California have experienced megaquakes every 250 years, central Oregon about every 450 years, and northern Oregon and Washington every 500 years. Because the quakes may occur in clusters, the question to be asked is whether the present-day hiatus is part of a grouping within a short time frame, or whether the state is experiencing a 1,000-year gap. The last major quake around 1700 A.D. was in the vicinity of northern Oregon and southern Washington.

In 2008, Anne Tréhu reported that in 2004 and 2007 two earthquakes of magnitude 4.9 and 4.8 and at depths between five to ten miles occurred offshore from central Oregon. Such seismicity along the Juan de Fuca-North American plate boundary may represent slippage on a weak portion of the Cascadia subduction zone. Further work by Tréhu relates seismic activity to deeply subducted seamounts (volcanoes).

Seismologists are presently struggling to determine the probability of when the next quake will strike, where it will take place, and what the magnitude will be. A comparison to subduction systems elsewhere shows striking similarities between the Cascadia zone and that of south-central Chile, which suffered a 9.5 magnitude event in 1960. Buried under tsunami debris, Chilean coastal areas were subjected to as much as six feet of coseismic subsidence.

Historic earthquakes

Oregon's historic record of earthquakes is minimal, going back only 175 years, but evidence of catastrophic Holocene seismic activity has been found in lowland sediments. In 1987 Brian Atwater of the U.S.G.S. was the first to use bog stratigraphy to demonstrate that earthquakes, tsunamis, and subsidence occurred simultaneously (coseismically) and repeatedly along the Pacific Northwest coast. Using shallow cores from tidal areas and bays, he identified marsh and soil layers covered by sandy tsunami deposits as signs of a sudden down-dropping. Preserved in an upright position, drowned trees also point to the rapidity of the subsidence.

In light of Atwater's discovery, dozens of coastal subsidence sites from British Columbia to northern California have now been identified. Thin tsunami sand layers over paleomarsh settings have been documented from 12 estuaries between the Columbia and the Sixes River. Each of the bays may have experienced multiple events, but the timing and number of the megaquakes, or whether subsidence at some of the sites was the product of local faulting in conjunction with subduction zone earthquakes, is unclear.

A quake in the Siletz River valley 5,500 years ago is the oldest dated in Oregon. Changes in microfossil assemblages prior to the quake and after submergence substantiate extensive paleoenvironmental alterations at South Slough in Coos County. Four separate marsh-sand transitional phases at Netarts Bay that took place over the past 3,000 years show similar changes. Cycles of episodic coastal submergence in the Alsea Bay estuary have been chronicled by Curt Peterson and Mark Darienzo at Portland State University, who concluded that coseismic subsidence is the only explanation for peat-burial sequences.

Mapping by the Oregon Department of Geology and Mineral Industries has predicted likely scenarios for inland reaches (run-up heights) of tsunami waves. Its conclusions show that many coastal communities are much more vulnerable than previously realized. In this photo, Cannon Beach, at sea level, lies completely unprotected from waves. Haystack Rock is offshore, and the Ecola State Park landslide area is in the center back just in front of Tillamook Head. DOGAMI hopes to complete its mapping south to Bandon by 2018. (Photo taken in 1965; courtesy Oregon State Archives)

Tsunamis

The sudden displacement of the ocean floor can trigger ocean waves called tsunamis that are catastrophic in scale. Not to be confused with wind-generated waves or lunar tides, tsunamis can travel up to 600 miles per hour, appearing as low, broad waves in the open ocean and piling up as high as 100 feet when the wave encounters shallower water. A succession of destructive waves from a single earthquake may last for several hours.

Since a seismometer was installed in 1971 at the Hatfield Marine Science Center in Newport, only three minor tsunamis have been recorded. In one case, the groups of waves caused by an earthquake in northern Japan lasted up to two days. The largest tsunamis to reach the Oregon coast were in March, 1964, and May, 1968. Generated by the 1964 earthquake in Alaska, waves tossed logs and debris onto beaches, across highways, and into nearby buildings. At one point, the water level dropped extensively, exposing vast areas of the upper shelf before cascading back. Although property damage in Oregon was light, four children sleeping at Beverly Beach State Park were drowned. The town of Seaside was badly damaged, and the bridge at Cannon Beach was displaced 1,000 feet inland.

Submarine landslides could also generate tsunamis. Brian McAdoo of Vassar College and Phil Watts, a private consultant, reported in 2004 that cohesive sediments, which built high escarpments offshore from Siletz Bay, pose a significant potential for initiating strong tsunamis in the event of slope failures.

Coastal Processes

The first explorers to the Oregon coast encountered hidden shoals and offshore rocks, shifting bars, fog, storms, and treacherous currents, and as late as 1951 the U.S. Coast Pilot warned of "dangers too numerous for description." Today these elements still play a dominant role in shaping what Paul

Komar characterizes as one of the highest wave-energy climates in the world.

Inventories of ocean processes and hazards compiled in the 1970s by Jim Stembridge, a resource specialist, have been updated and augmented by Paul Komar's ongoing research. Jonathan Allan and Robert Witter at DOGAMI and Peter Ruggiero at Oregon State University are currently examining the impact of climate changes on Pacific Northwest shoreline erosion and flooding.

Reducing the beaches, terraces, and headlands

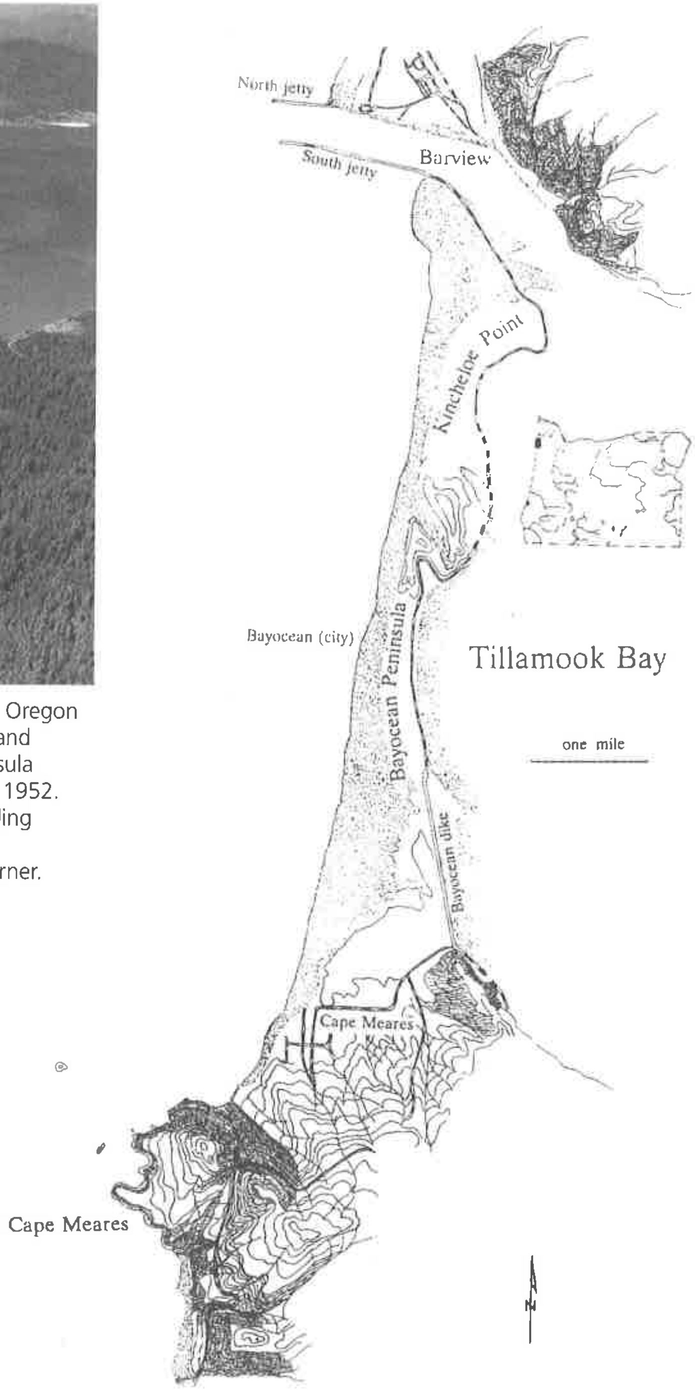
Waves, prevailing winds, tides, climate, currents, and sea levels are all working to modify the coastal morphology. While the sandy areas are being rapidly reduced, the level terraces and protruding bluffs are also being steadily diminished. Erosive processes are tied to cycles of a turbulent wintertime ocean that contrasts with moderate summers conditions.

Paul Komar's first introduction to coastal processes came during visits to Lake Michigan, where he saw homes, that had been undercut by erosion, slide into the surf. At Scripps Institute of Oceanography, he completed a PhD on the longshore transport of sand by currents and waves. After joining the Oceanography Department at Oregon State University in 1970, Komar concentrated on western coastal geomorphology and evolution, although his interests expanded to other countries. His 1997 book *The Northwest Coast* provides an invaluable and readable account of coastal Oregon and Washington. Maintaining an office at OSU since retiring in 1998, Komar is currently working on global climates and sea level changes. (Photo courtesy P. Komar)

A forceful November surf, on reaching the beach, strips away sand and distributes it offshore in submerged bars, restoring it during the summer months. Overall, the amount of sand moved north

During the 1982 to 1983 El Niño, Alsea Spit was reduced dramatically when the longshore movement of sand shifted the channel leading into the bay northward (top, left). This action continued for three years, bringing losses to houses on top of the spit (bottom, left). On-going erosion has similarly threatened housing on Siletz Spit (right), cutting away at its width. Rip-rap will protect the houses only until the next onset of high storm waves. (Photos courtesy Oregon Department of Geology and Mineral Industries)

Tillamook Spit was the site of the city of Bayocean, advertised as "The Queen of Oregon Resorts." Houses, streets, a natatorium, and the beginnings of a hotel, grocery, and bowling alley were erected in 1912, but erosion opened three gaps in the peninsula bringing an end to hopes for a stable settlement. The last of the residents left in 1952. Several years later the Army Corps of Engineers diked the breach to protect eroding farmland and constructed the south jetty in 1974. In the photograph, Bayocean peninsula and the jetty are in the center, and Cape Meares is in the lower left corner. (Photo courtesy Oregon Department of Geology and Mineral Industries)

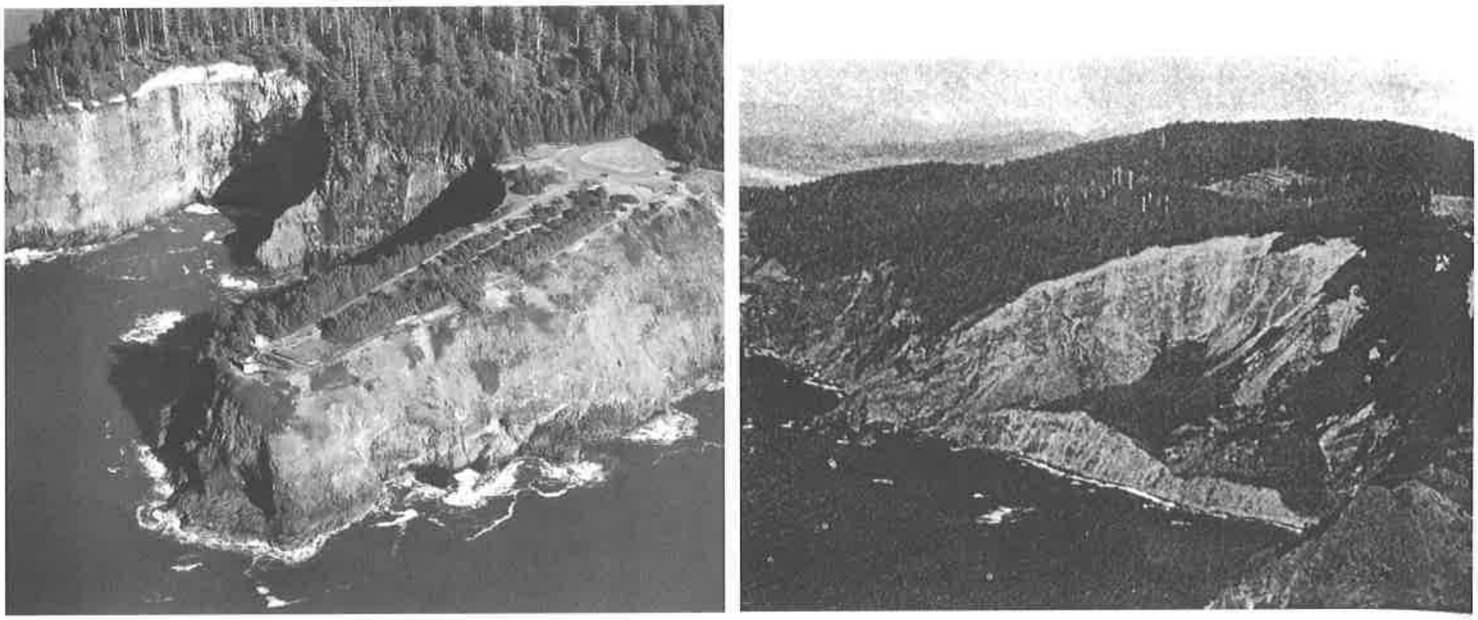


is about the same as that carried south, and the zero net drift is due to projecting volcanic headlands that trap and prevent it from being removed. Isolated between the rock barriers, each of the pocket beaches contains its own stock of sand within what Komar terms beach cells.

Except where sand is confined by headlands, the waves and currents shape it into elongate north-south peninsulas called spits, which parallel the general orientation of the beach. Characterized as "Here today, gone tomorrow," the transitory nature of sand spits makes them particularly vulnerable to erosion, while their scenic location makes them attractive to builders. Situated between the bay and ocean, the fragile environment of sand spits is easily unbalanced when the natural pattern of waves and currents is altered by jetty construction, by the placement of rip-rap, or by roadways.

The location of a mile-long jetty on the north side of Tillamook Bay by the Army Corps of Engineers in 1917 is one of the most notorious examples of human activity initiating sand spit erosion. Constricting the natural channel, the jetty caused sand to accumulate and gaps to appear through the south end of Tillamook Spit. The community of Bayocean, placed at a midway point, was doomed and even the village at Cape Meares was threatened. With completion of the jetty, the beach disappeared at the rate of six feet a year from the 1930s to 1940s.

Cliffs seem comparatively durable, but, in reality, they are subject to degradation by rock falls,



Headlands such as the 1,000-foot-high basalt monolith at Cape Meares (above left) appear deceptively durable, but, as with other coastal promontories, it is being steadily diminished by rockfalls. Boulders line the toe of a landslide that slumped off the face. A spectacular slump on Cascade Head (above right) carried over 20 acres of rock and terrace debris down to the ocean, as waves dissect the promontory itself. (Photos courtesy Oregon State Highway Department and Oregon Department of Geology and Mineral Industries)

landslides, and undercutting. Waves, attacking and removing the lower strata of bluffs and terraces, expose them to over-steepening and slumping. The composition and structure of the rocks, the groundwater, rainfall, and waves all play roles in the differing rates of erosion.

Because of their level surface, marine terraces are especially favorable spots for the placement of highways, parks, communities, and homes, but a variety of factors such as wave run-up, a small beach, or high sea levels lead to erosion and retreat. Beverly Beach in Lincoln County is a particularly visible case in which the cliff is open to the surf. Above the terrace, Highway 101 is not protected by the narrow strip of sand at the base, and the road had to be moved inland several times when the coastline retrograded. Between 1940 and 1980, as much as 50 feet of the cliff was lost, and since then another 30 feet has been cut away.

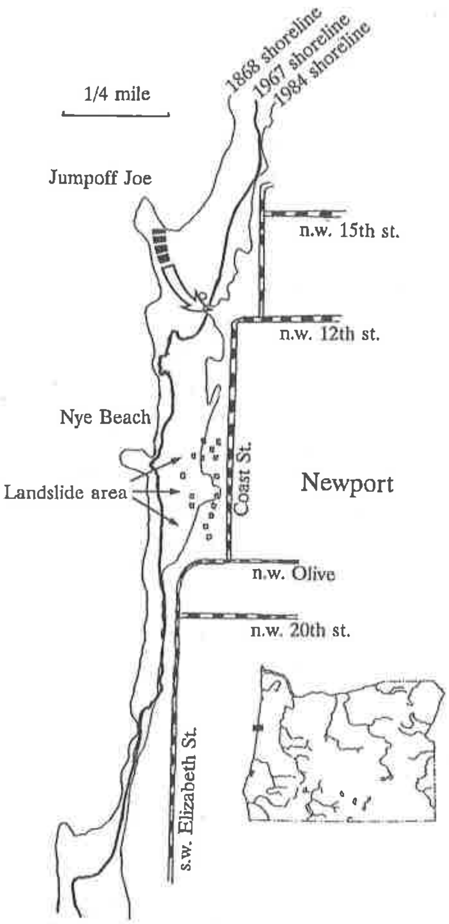
Paul Komar relates the measures taken when a 39-home condominium complex was to be situated at Jump-Off Joe. Approved by the Newport Planning Department in 1964 and substantiated by a geotechnical report from the firm Shannon and Wilson, stabilization was to be accomplished by the installation of a drainfield and seawall and by decreasing the angle of the slope. Even after additional problems came to light, construction began in 1982. Slumping and sliding occurred almost immediately, many of the units were never completed or sold, and the builders filed for bankruptcy.

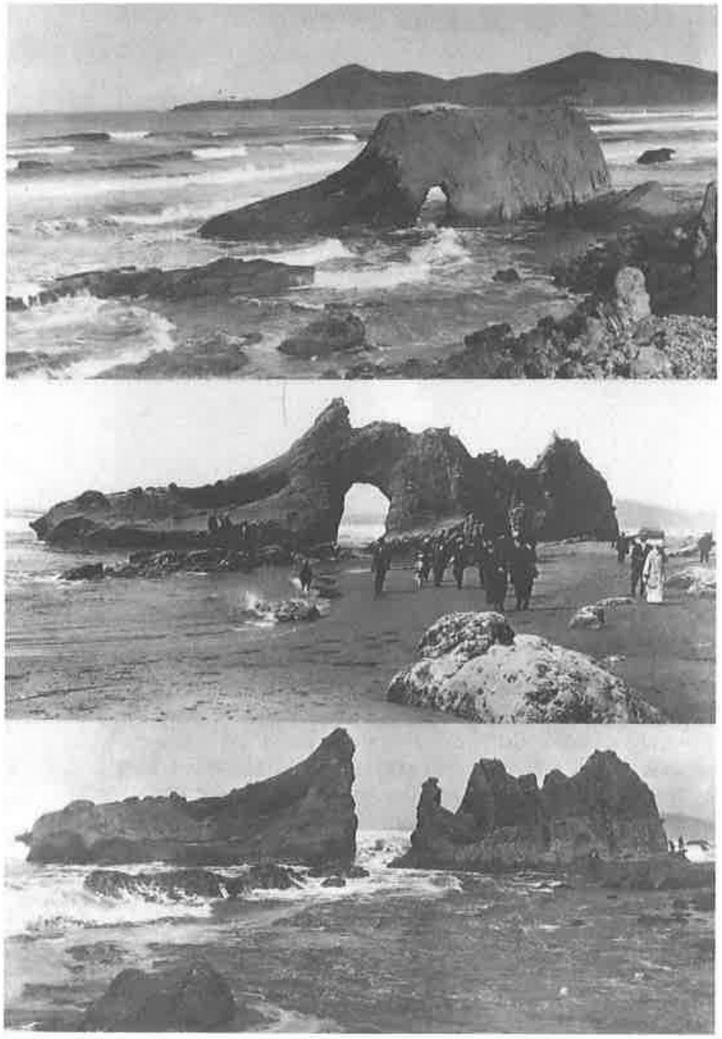
Based on DOGAMI landslide maps and reports, which show much of the coast as hazard-prone, Newport officials proposed code changes to assure that buildings can be moved and that deeds disclose specific risks. Opposition to the new code came from builders and property owners fearing loss of sales, reduced property values, lawsuits, and increased construction costs.

Landslides

Earthflows are common in sedimentary rocks of the coastal mountains, while debris flows are more frequent along steep stream gradients. Large earthflows are deep-seated and occur when blocks, covering several acres, move downslope. By contrast, debris flows are water-saturated, rapid, shallow, and generally activated by heavy rains to move as a muddy slurry.

North of Florence, the soft clay-rich Astoria, Nye, and Nestucca formations are responsible for many historic and present-day earthflows. The Astoria Formation is particularly susceptible, and, after heavy March rains in 2007, deep fissures appeared,





Newport has seen a remarkable combination of slumping, storm wave erosion, and landsliding that demolished the peninsula at Jump-Off Joe (above right) and moved the strand at Nye Beach inland as much as seven feet a year. The promontory and adjacent cliff are composed of poorly consolidated, seaward-dipping Astoria Formation and Nye Mudstones, topped by a terrace. Adjacent to Jump-Off Joe on 14th Street (left), an active slump block undercut housing in 1982. (The photos of Jump-Off Joe were taken in 1880, 1915, and 1926; courtesy Oregon Department of Geology and Mineral Industries)

A 1982 evaluation by John Gentile, then at Oregon State University, pinpointed 153 prehistoric and present-day slides within a one-and-one-half-mile-wide strip between Roads End and Yachats in Lincoln County. The most susceptible unit was the clay-rich Nye Mudstone underlying marine terraces. Erosion of the Nestucca, Astoria, and Nye formations is particularly evident in this county, which is additionally subsiding relative to sea level. (Photo at Roads End; courtesy J. Orr)

spreading mud and rock across Astoria city streets. Just a few years earlier a slide of spectacular proportions threatened the The Capes housing development near Netarts Bay. In this case, a Holocene paleovalley fill of the Astoria Formation was reactivated by El Nino storms. Ancient and recent slides at Ecola State Park and Silver Point near Cannon Beach sent a mass of Astoria debris downslope and into the sea at both localities.

Clatsop, Columbia, and Tillamook counties experience winter landslides on a regular basis, but no one spot is more notorious than the Wilson River Highway. Here rainfall averages 100 inches a year, and catastrophic slope failures in steep exposures of Eocene Tillamook basalts interlayered with sedimentary rocks repeatedly cover the highway and even dam the river. In 1991, after 500,000 cubic yards of rock and soil cascaded downslope, the road was closed for nearly two months. This was one of the largest earthflows in recent history.

Debris flows in rugged mountainous areas involve a similar set of characteristics. Where soft, loosely consolidated strata becomes water-saturated, the hillside moves more or less continuously in waves as a viscous mass. Hummocky surfaces, tilted trees, small ponds, and swampy depressions

Extensive clear-cuts and roadbuilding on Neahkahnie Mountain adjacent to Oswald West State Park (summit trees) expose the steep slopes to landslides (Photo courtesy Oregon Department of Transportation) are all signs of such activity. Major storms in 1996 activated over 350 debris flows in tributaries along the Umpqua River in Douglas County, and the Clatskanie region in Columbia County experienced a similar devastation in December, 2008. Long identified on DOGAMI maps and known to forestry officials as posing extremely hazardous conditions, the highway near Clatskanie was overwhelmed with rubble, mud, and debris that moved downhill from Oregon State University clear-cuts after heavy rains. The water was dammed into a lake that broke loose to bury homes and roadways. Although there was over $12 million in damage, no one was injured. A similar slide here in 1933 killed four people.

While precipitous topography and a high rate of precipitation were the main contributors to Pleistocene slope movements in the southern Coast Range, University of Oregon professor Joshua Roering concluded that other factors may have played a role. By mapping the geometric curvature, gradient, and distribution of large landslides active between 18,000 to 40,000 years ago, he found that they were deep-seated (thick), pervasive, and long-lived. Most occurred in the failure-prone soft siltstone and sandstone layers of the Tyee Formation, and he estimates that there are hundreds if not thousands of large paleo-landslides and lakes with similar origins in this region.

Loosened Tyee debris was responsible for the landslide-created Triangle Lake near Blachly, for Loon Lake near Scottsburg, and for the lake basin at Sitkum in Lane County. Dammed during the Pleistocene, most are only remnants of what were formerly much larger bodies of water, which have since filled in with alluvium. In December, 1975, Drift Creek in the Alsea River watershed was impounded by a thick mass of Tyee material that covered 40 acres. This was one of the largest movements in the state, involving reactivation of an ancient slide and creating a dam that that impounded Ayers Lake. Road building and logging of the slope preceded the failure.

Flooding

In a province bordered by the ocean, with widespread wetlands, estuaries, tributary streams, and heavy precipitation, flooding is an annual phenomenon, most frequent during the winter months. Many factors such as topography, logging, and obstruction of the channel can cause rivers to rise. During wet seasons runoff is rapid, and peak flows are short. Records since the mid-1800s, listed in the invaluable Oregon weather book by George Taylor of Oregon State University and Raymond Hatton from Central Oregon Community College, show flooding and peak discharges of coastal rivers almost always follow rain on snowpack.

Ocean flooding is brought on by storm conditions that result in tidal surges and fluctuating currents. When ocean water piles up against the beach and backs into estuaries, low-lying areas are inundated. If heavy runoff and a high surf collide, the results may be calamitous.

Natural Resources

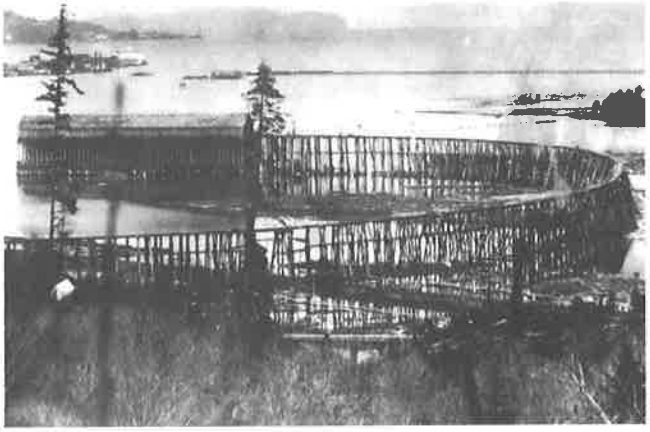
Coal

Although coal seams are widely scattered, there have been only two productive regions, one in the Newport-Beaver Hill basin and the other at Eden Ridge, both in Coos County. Mining in the Coaledo Formation at Newport-Beaver Hill near Coos Bay began in 1855, whereas Tyee sediments at Eden Ridge south of Powers were not examined extensively until the 1950s. Coal from this field in the rugged southeastern corner of the county has a greater heat value but extraction was more difficult. Most of Oregon's coal is high in ash and ranked as sub-bituminous, making commercial exploitation unlikely. At Coos Bay, production reached its peak year in 1904, and in 1985 the potentially dangerous shafts and portals were sealed and covered as a safety measure, closing the Oregon coal mining era.

Oil and Gas

The great thickness of Cenozoic sediments in the Coast Range have been viewed as potential sources of hydrocarbons since the first holes were drilled, but the results were disappointing. Gas shows, but no oil, were encountered in prospects near Bandon as early as 1913, and exploration in the offshore over the next 40 years was equally unsatisfactory.

Discovery of the state's first commercial gas field in 1979 near Mist in Columbia County is credited to Wes Bruer, consulting geologist for Reichold Energy Corporation. A 1950 graduate of Oregon State



Oregon's coal mining era was relatively brief, and all production took place in Coos County. The upper photo shows the remaining wooden pillars at Empire, where the rail line ran coal out from the Libby Mine in the Newport-Beaver Hill district to be loaded on ships. Few traces are left of the mine entrance in this district, seen in the 1905 photograph (right). (Photos courtesy Oregon Department of Geology and Mineral Industries)

University, Bruer spent many years investigating Oregon's oil and gas potential. To date, 18 wells in the Mist field have produced 65 billion cubic feet of gas. Most of the reservoirs are fault traps within a larger anticline, where hydrocarbons are present in sandstones of the upper Eocene Cowlitz Formation. Today the depleted Mist field is being used to store imported gas.

Likely porous hydrocarbon reservoir sands are those deposited in high energy upper upper shelf environments. Fine-grained sedimentary rocks of the Cowlitz, Yamhill, Coaledo, Spencer, Eugene, Yaquina, and Astoria formations meet these conditions to some extent, but the presence of clays and zeolite minerals plugs the sandstones. In February, 2010, the Oregon legislature passed a bill banning oil and gas drilling within the three miles off the coast.

About 60 miles offshore from Newport, seismic profiles taken by Ann Tréhu at Oregon State University in 1989 show evidence of widespread gas hydrates along the margin of the accretionary wedge. Gas hydrates occur when cold methane gas is locked into a lattice of water in an ice-like mixture, and Hydrate Ridge is especially rich in the hydrocarbons. As with the hydrothermal vents along the Juan de Fuca ridge, there are similar colonies of worms and clams living off the hydrogen sulfide in a symbiosis with bacteria.

Gold

An assortment of economic minerals occur in black sands from Cape Blanco to Cape Arago. Concentrated at the mouths to rivers and on elevated terraces, the sands were conveyed from high in the Coast Range by Pleistocene streams. Sorted by the winnowing action of the waves, the heavier gold, platinum, chromite, magnetite, garnet, and zircon grains are deposited along the beach, whereas the lighter quartz, feldspar, and mica are carried out onto the continental shelf. As indicated by the black color of the sands, the Jurassic Galice Formation, intruded by small granitic dikes, was the host rock.

The discovery of gold in 1852 north of the Coquille River sparked the settlement of Randolph, a boom town of tents, stores, and saloons. The placers at Whiskey Run failed to pay, and mining was abandoned after a storm destroyed most of the operations two years later. Miners attempted to tunnel into black sand lenses of the older terraces, but the 50-to-60-foot covering of loose material above the layers and the extremely fine-grain of the minerals made recovery difficult. North of there, deposits of gold, platinum, and chromite were accessed by tunnels into the Pioneer terrace, but the Seven Devils or Last Chance Mine saw only brief activity before closing after World War II.

Production amounts from beach placers in Coos and Curry counties were never systematically reported, but $60,000 in gold and platinum—around $2 million in today's dollars—is estimated to have been mined between 1903 and 1929.

In 1988, federal and state agencies examined the Oregon shelf for economic deposits of metalliferous black sands, but only limited amounts were found.

Surface and Groundwater

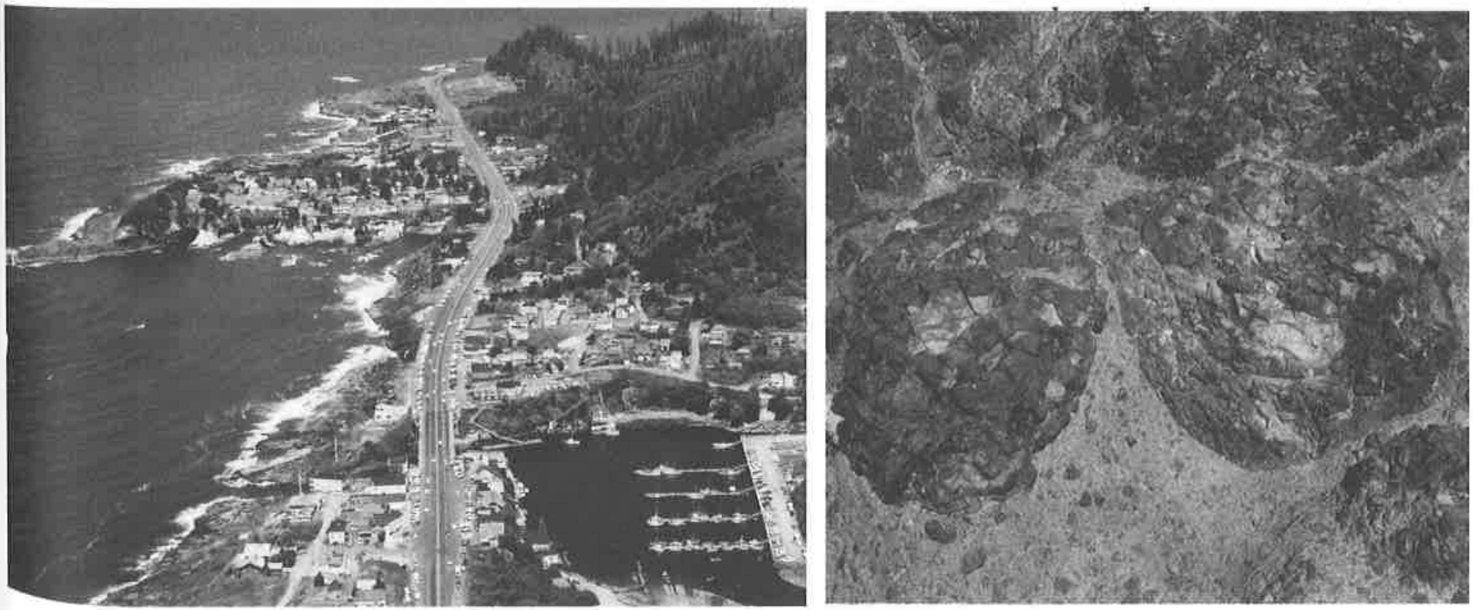
Surface and groundwater resources in the Coast Range are marginal, although the province experiences greater precipitation and stream runoff than elsewhere in Oregon and even more than in most areas of the United States. The streams that drain the western slopes have modest watersheds and flows diminish greatly during the late summer when demand is highest. Surface amounts are augmented by Pacific storms and groundwater springs originating from Tertiary lavas.

Groundwater percolates through gravel and sand along river floodplains, in marine terraces, and in dune aquifers, but the quantity is low and generally only sufficient for domestic needs. The underlying Tertiary sediments have equally low yields, and wells drilled into these layers often produce saline water that has a bad taste or odor. Elevated marine terraces provide a better supply, but, as with dunes or where Tertiary rocks are encountered, the quality may be poor, high in salt and mineral content, or polluted by septic systems.

Historically, the diversion of water for industry, municipalities, and agriculture has come through pumping from streams or lakes, but increasing demands and a decrease in levels have forced users to try other means. Consequently, dunal aquifers have been targeted. Rumored to contain unlimited quantities of water, dune reservoirs are recharged directly by precipitation and discharged through springs or into small lakes. In actuality, over-pumping can pull deep brackish water up into the aquifer. Wells have only a brief life span of five-to-seven-years and frequently must be abandoned. Resorting to dunal aquifers in 2000, Coos County completed a 20-well system that draws water from beneath the Oregon Dunes National Recreation Area. Other coastal communities suffer similar problems.

Geologic Highlights

Long famous for its scenery, the Oregon coast provides a combination of pleasing beaches, dramatic headlands, sea stacks, and high terraces interspersed with quiet coves and immense sand fields. For travelers along the coast, vistas appear around each curve to rival those in the Cascades. Flat marine terraces dominate from Cape Blanco to Coos Bay.



The harbor and spouting horn at Depoe Bay are among the most visited attractions on the coast. Spherical basalt pillows are common in the Columbia River lavas, which compose the rocky landscape, including the wall that protects the picturesque inner harbor. (Photos courtesy Oregon Department of Geology and Mineral Industries and Oregon State Highway Department)

Ever-changing sand dunes, secluded lakes, and dense forests come together at Cleawox Lake (foreground), Woahink Lake (upper center), and Siltcoos Lake (upper right). (Photo courtesy Oregon State Highway Department)

Towering dunes stretch from Coos Bay to Florence, and north of there volcanic cliffs are home to marine birds and sea mammals. From Tillamook Bay to the Columbia River, the rough coastline is interspersed with arcuate coves and sandspits, which end at Clatsop Plains.

As James Stovall frequently remarked to his geology classes at the University of Oregon, the Devil nominally owns much of the coastal real estate. Devils Elbow, Devils Punchbowl, and Devils Lake are among some of the more scenic spots. Many of the imaginative names were given because of unusual rock configurations or other physical features.

Caves and Trenches

Rocks, cut by fractures and faults and exposed to pounding surf, have been eroded into caves, long straight trenches, or tunnels. If the roof collapses, as happened at Depoe Bay and the Devils Punchbowl, a spout, churn, or punchbowl may result. During high tide and on windy days, waves force their way through an opening cut into fractured and faulted Columbia River basalts at Depoe Bay to erupt upward, sending a spray of water high into the air. At Devils Punchbowl State Park, two adjacent sea caves, eroded into the Astoria Formation, collapsed to form a pit. During high tides or stormy conditions, sea water foams and froths as in a boiling pot.

Along the south central coast, Devils Churn, Cooks Chasm, Devils Elbow, and Sea Lion Caves are deep erosional cuts into Yachats Basalt where the roof has fallen in along a trench. The tunnel at Devils Elbow is 600 feet long and home to a noisy and smelly population of marine mammals. At Sea Lion Caves, the openings at the intersection of a system of fractures are visible in the ceiling. The southern part of the tunnel is below sea level, while the public viewing area is in the northern section.

Sand dunes and freshwater lakes

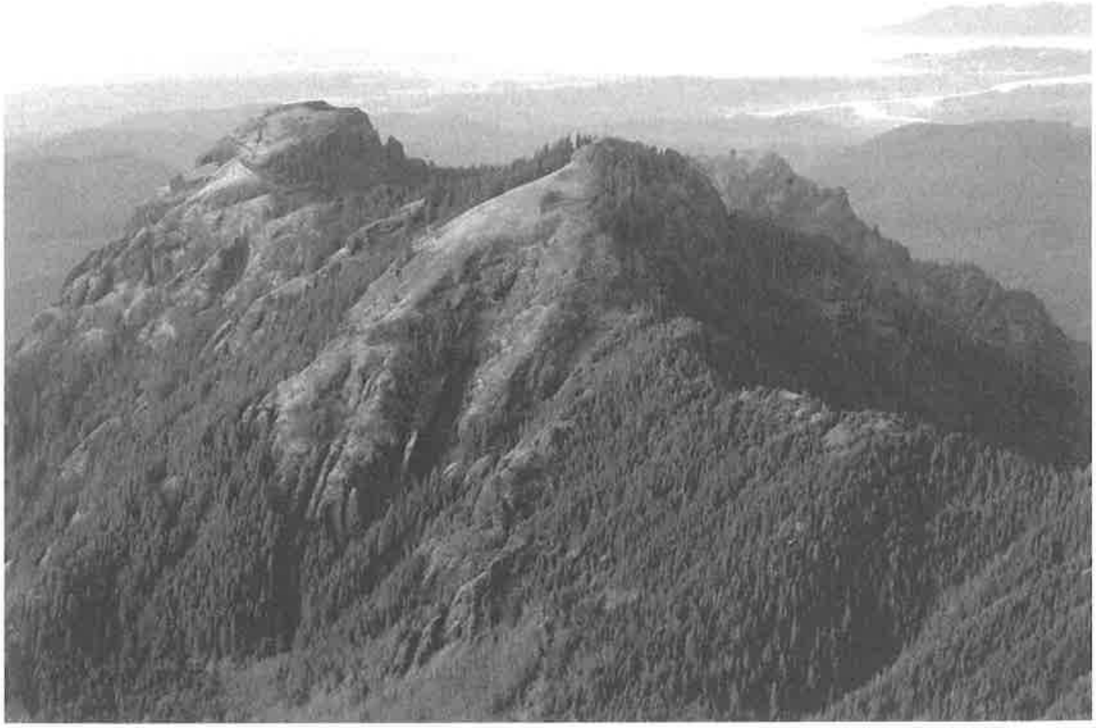
Impressive lengthy sand dunes cover almost half of the Oregon shoreline and about one-third of Washington's. Of these, the 31,566-acre Oregon Dunes National Recreation Area from Coos Bay to Florence is the longest at 50 miles. The field averages two miles in width, and many of the dunes reach 180 feet in height.

Within the recreational area, a chain of freshwater dunal lakes are the youngest and perhaps most ephemeral of the features. These bodies of water were impounded when streams were blocked by sand advancing inland or by sediments choking the valleys. At 3,164 acres, Siltcoos Lake is similar in size to nearby Woahink, Tahkenitch, and Tenmile, making them among Oregon's largest within the dunes. Devils Lake, at 678 acres, is the only freshwater lake of any size on the central coast. Even though they encompass less than 10 acres, Clear Lake near Roseburg and the similarly named Clear Lake north of Florence are the two deepest reaching 119 feet and 80 feet respectively. Dunal lakes vary considerably in elevation. The surface of Siltcoos Lake is five feet above and that of Woahink 38 feet below sea level. The lakes are fed by small streams, rainfall, and groundwater, and the interface between fresh and salt water in the subsurface gives them an exceedingly fragile environment. Particularly susceptible to pollution, they have been deleteriously impacted by all-terrain vehicles, logging, septic fields, housing, and pumping for municipal and industrial water supplies.

From Tillamook Head to the Columbia River, Clatsop Plains is a strip of dunes about a mile wide and 17 miles long, dropping from 100 feet in elevation to sea level. The Plains accumulated during the Holocene, when sand built up along the marine shoreline, which lay east of where it is now. As in-filling continued, the sand extended the coast westward. Dunal ridges run parallel to the shore for miles, marking the position of the beachfront from the transgressing sea. Within the elongate depressions, lakes are supplied by groundwater, and most are independent of local streams.

Coastal Mountains

A familiar shape on the skyline east of Seaside, the high twin peaks of Saddle Mountain were first noted and named by John Wilkes of the U.S. Exploring Expedition in 1841. Composed of Columbia River



Probably the most extreme example of inverted topography in Oregon, Saddle Mountain exhibits vertical dikes hundreds of feet long, pillows from underwater volcanic eruptions, and breccias. (Photo courtesy K. Sayce; flown by pilot Frank Wolfe)

The 4,097-foot-high Marys Peak is the highest in the Coast Range. Capped by a resistant 1,000-foot-thick sill of medium-grained gabbro that intruded Eocene sandstones of the Tyee Formation, the mountain is cut by the Kings Valley fault. The magnificent view from Marys Peak encompasses the Willamette Valley and Cascade volcanoes to the east and the intruded sills of Flat Mountain and Green Peak to the south. Westward, the Coast Range and Pacific Ocean stretch to the horizon. (Photo courtesy U.S. Forest Service)

basalts, the mountain and surrounding forests are now part of Saddle Mountain State Park. A climb to the top provides scenes of the Cascades, Mount St. Helens, the Columbia River, and the city of Astoria on the Pacific Ocean.