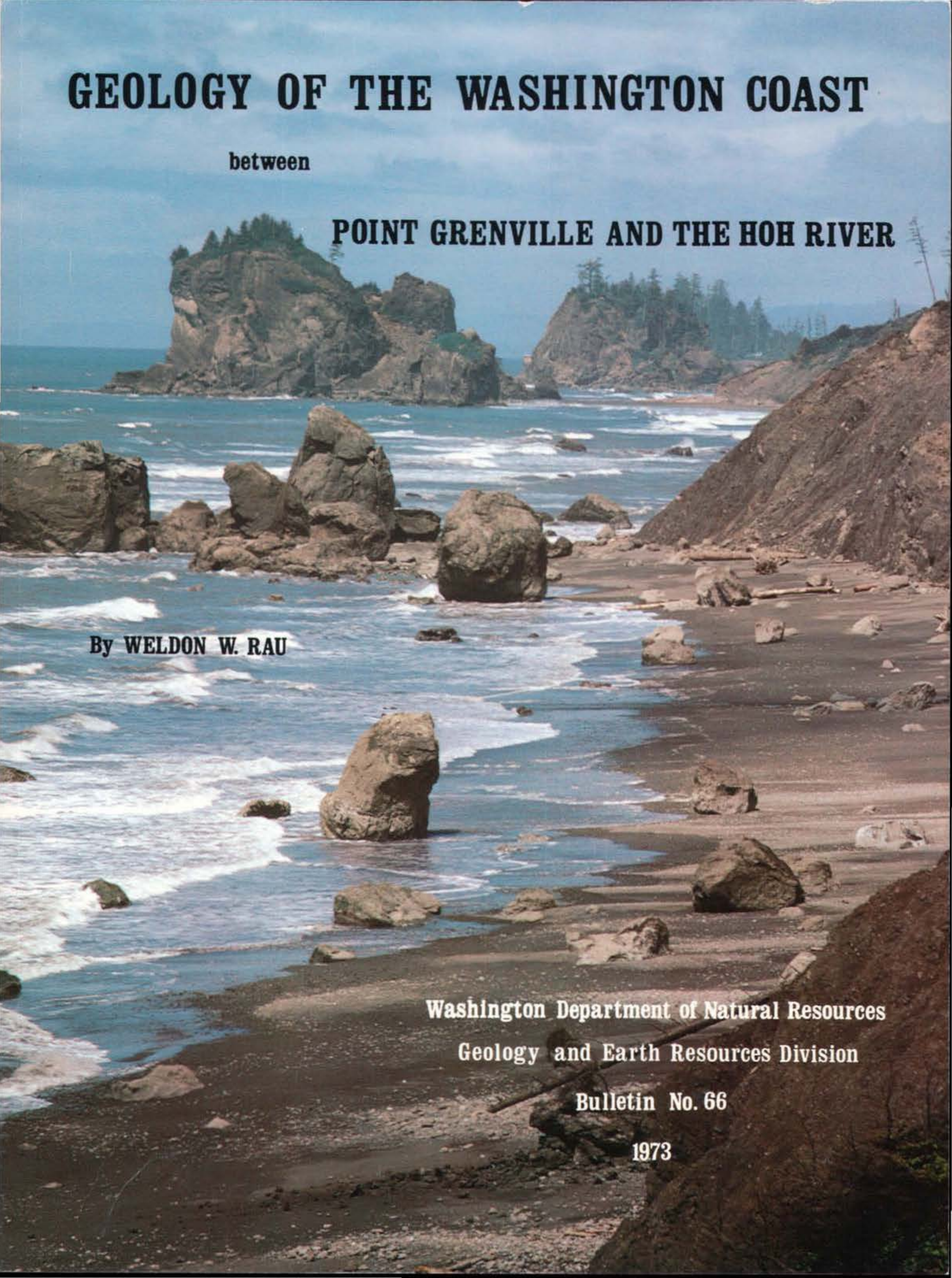
GEOLOGY OF THE WASHINGTON COAST

between

POINT GRENVILLE AND THE HOH RIVER



By WELDON W. RAU

Washington Department of Natural Resources

Geology and Earth Resources Division

Bulletin No. 66

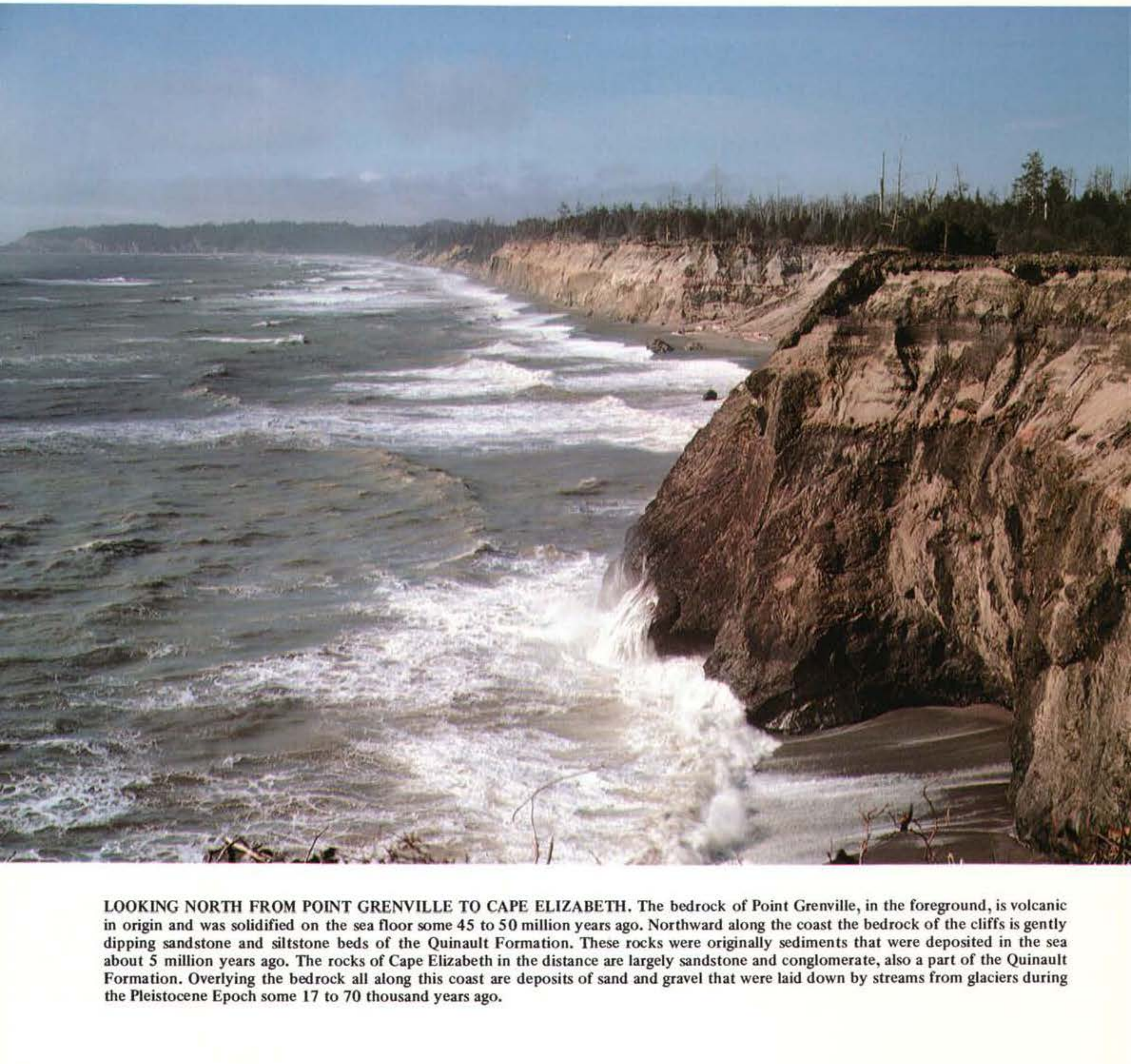
1973

COVER PHOTO

LOOKING NORTHWARD AT THE HOGSBACKS AREA. For nearly 2½ miles, the cliffs and promontories are composed of large resistant blocks of chaotically mixed sandstone and volcanic rocks set in a matrix of intensely broken and sheared siltstone. Little Hogsback, center, and Hogsback, in the distance, are very large resistant blocks of volcanic rocks that were left behind as the sea eroded the coastline eastward.

"From hence [Point Grenville], as we proceeded to the north the coast began to increase regularly in height . . . . The shores we passed this morning . . . were composed of low cliffs rising perpendicularly from a beach of sand or small stones; had many detached rocks of various romantic forms lying at a distance of about a mile . . . ."

Captain George Vancouver's description of the coastal area between Point Grenville and Destruction Island, April 28, 1792.



LOOKING NORTH FROM POINT GRENVILLE TO CAPE ELIZABETH. The bedrock of Point Grenville, in the foreground, is volcanic in origin and was solidified on the sea floor some 45 to 50 million years ago. Northward along the coast the bedrock of the cliffs is gently dipping sandstone and siltstone beds of the Quinault Formation. These rocks were originally sediments that were deposited in the sea about 5 million years ago. The rocks of Cape Elizabeth in the distance are largely sandstone and conglomerate, also a part of the Quinault Formation. Overlying the bedrock all along this coast are deposits of sand and gravel that were laid down by streams from glaciers during the Pleistocene Epoch some 17 to 70 thousand years ago.

STATE OF WASHINGTON

DEPARTMENT OF NATURAL RESOURCES

BERT L. COLE, Commissioner of Public Lands
DON LEE FRASER, Supervisor

GEOLOGY AND EARTH RESOURCES DIVISION

VAUGHN E. LIVINGSTON, JR., State Geologist

Bulletin No. 66

GEOLOGY OF THE WASHINGTON COAST

Between

Point Grenville and the Hoh River

Part I.—Rock Formations and Their Geologic History
Part II.—Geologic Observations and Interpretations Along Segments of the Coast

A review of the geologic processes and events responsible for the forming of the rock formations and deposits along the Washington coast

BY

WELDON W. RAU

Geologist

1973
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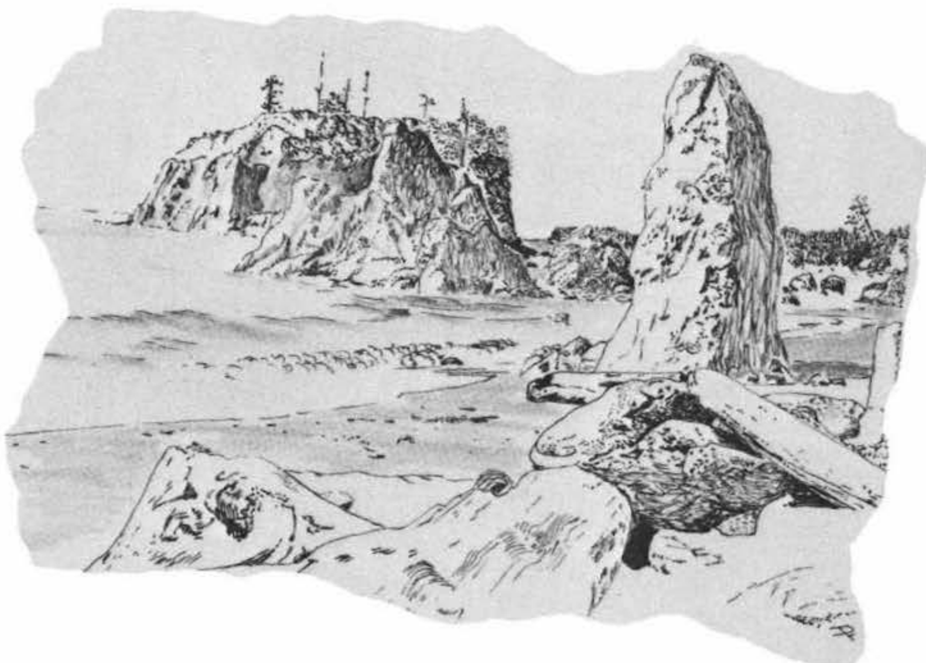

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FOREWORD

The picturesque rock formations so prominent along the Washington Coast have undoubtedly aroused the curiosity of many people. Needless to say, geologists have been particularly intrigued and challenged to learn about the origin and history of these geologic features.

This report summarizes known geologic facts, as well as theories applied by geologists in their attempt to unravel the geologic history of the rocks exposed in this part of Washington State. Although it is designed primarily for students and enthusiasts of the natural sciences, it nevertheless should be of general interest to many other readers. Those wishing to learn about a particular geologic feature or segment of the coast will find Part II especially informative. Furthermore, this section may well serve as a field guide for classes in geology. Finally, each illustration and caption tells a story in itself.

The report is an outgrowth of geologic mapping and technical studies that the Geology and Earth Resources Division is conducting along the coast and in adjacent inland areas to provide basic geologic data for future planning and for solutions to geologically related problems. The project is being conducted by Dr. Weldon W. Rau, a geologist on our staff for the past 13 years. He has devoted his entire professional career, including 10 years with the U.S. Geological Survey, to studying and writing about geology of the Pacific Northwest. He therefore is well qualified to present this geologic summary, which we hope will provide a better understanding and enjoyment of one of the natural areas of the Washington coast.

VAUGHN E. LIVINGSTON, JR.
Washington State Geologist

June 29, 1973

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Photography by the author unless otherwise indicated

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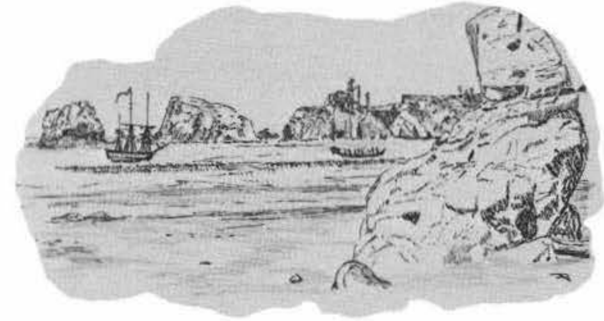


Although largely unaware of the geologic processes involved in the forming of the northwest coast of America, or "New Albion" as it was first called, the early coastal explorers nevertheless often were confronted with the results of these processes. The Spanish were the first to venture northward along this rugged coast, mainly in an attempt to protect their holdings in California from the possible southward migration of the Russian fur traders. Also, there was concern that a northwest passage might be discovered and thus bring more travel and settlement from the north.

Juan Perez, in command of the frigate Santiago in 1774, was probably the first European to record sight of any part of the Washington coast. While in these latitudes, he observed the high snow-covered mountains of the Olympics and referred to the highest peak as "El Cero de la Santa Rosalia."

The following year the Santiago, this time under the command of Bruno Heceta and with Juan Perez as second pilot, was accompanied to the northwest coast of America by the small schooner Sonora under the command of Bodega y Cuadra. During this expedition, observations of the tablelike Destruction Island were first made by Bodega and referred to as "Isla de Dolores." On July 13, 1775, the Sonora, eagerly seeking shelter, crossed over the dangerously shallow sandstone and conglomerate "Sonora Reef" between Point Grenville and Cape Elizabeth to anchor behind the conglomerate headland of Cape Elizabeth. The following day, seven men went ashore for wood and water, but met with ill fate and never returned to the Sonora. On the morning of July 14, 1775, from their anchorage south of the volcanic rocks of Point Grenville, Heceta and 23 additional men from the frigate Santiago made the first known safe landing of Europeans on this coast and claimed the land for Spain. They named the "roadstead" in which they anchored "rada de Bucareli," now Grenville Bay; and Bodega referred to Point Grenville to the north as "Punta de los Martires."

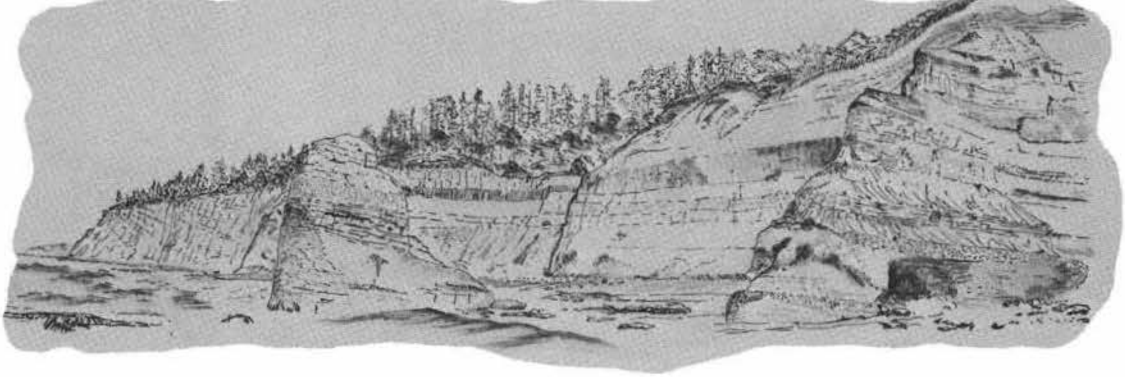
In the following years, exploration was conducted largely in the search of fur trading. Among these was the voyage of the "Imperial Eagle" (1786-87) commanded by Captain Charles William Barkley. His wife accompanied him on this voyage, and it is believed that she was the first European woman to visit the northwest coast. During this expedition, while anchored off Destruction Island, a small boat's crew of men were sent to investigate the river that is now called the Hoh, but they never returned. This prompted Barkley to name it Destruction River.

John Meares, during the summer of 1788, while on a trading expedition in the "Adventurer" from China, made a number of close-in observations of the Washington coast. He gave a rather graphic description of Destruction Island and was the first to record that name for the island. In addition, he applied the name "Queenhithe" to the large but indistinct indentation in the coastline inside Destruction Island. Although this name is no longer used, he was referring largely to the area covered by this report.

The first American expeditions to the "Northwest Coast" were in the ship "Columbia" under the command of Captain Robert Gray, in the years 1787-90 and again in 1790-93. During these voyages particular mention was made of the many offshore rocks along the north coast of Washington. Furthermore, they unmistakably noted Destruction Island, and referred to it as "Green Island."

Captain George Vancouver, in the sloop "Discovery" on a voyage of exploration and discovery for England, also sailed close in to the Washington coast during the spring of 1792. He accurately located and gave the present-day name to Point Grenville, and also accurately located Destruction Island. In addition, he vividly described many of the offshore rocks along the Washington coast. During the latter part of April, 1792, he met with Gray aboard the "Columbia" somewhere in the vicinity of Destruction Island, during which time Vancouver gained additional knowledge from Gray, particularly of the Straits of Juan de Fuca.

And so it was with these early visitors to the northwest coast of America—largely a challenge to discover and yet to survive the treacherous environment created to a great extent by geologic processes, some of which began many millions of years prior to their arrival. The following report discusses those geologic processes and events that are responsible for forming the rugged but picturesque present-day Washington Coast.



GEOLOGY OF THE WASHINGTON COAST
Between
Point Grenville and the Hoh River

By Weldon W. Rau

INTRODUCTION

Long before the Washington coast was viewed by Perez, Heceta, and Bodega y Cuadra, its beaches served as highways between Indian villages. Later the early settlers used them in much the same way. Today, however, the coast is a place where a variety of activities are pursued. Some visitors are content just to view the many scenes of natural beauty, perhaps take a short walk on the beach or, on occasion, observe the mighty force of winter storms being spent upon the sandy shores. Still others may be attracted by the colorful marine life of tide pools or the countless pieces of curiously shaped driftwood deposited high on the beach by winter storms.

Among these many visitors, some no doubt are also curious about the processes that formed the rock foundation for this unique and picturesque setting along Washington's part of our continent's western edge. What is the origin of rock strata that form cliffs and rocky beaches in many places along the coast? What were the forces that twisted and deformed many of these rock strata, and how were they generated? Where did the thick deposits of sand and gravel come from that are so common in many of the high cliffs, when were they deposited, and how did they get there? What do the fossils that are contained in some of the rocks reveal about the age of the rocks and about ancient environments? Although these and many other related geological questions are of particular interest to the geologist, very likely many others have also pondered at least some of these questions.

This publication, therefore, was prepared for the purpose of sharing some of the facts, theories, and concepts currently known to geologists or applied by them in their attempt to unravel the geologic history of the Washington coast and adjacent areas of the Olympic Peninsula. It is an outgrowth from comprehensive geologic studies now being conducted by the author for the purpose of collecting and interpreting basic data on the distribution and characteristics of the rock formations of the western part of the Olympic Peninsula.

The illustrations and accompanying captions alone tell a geologic story that many may find of interest. The text, in two parts, develops this story more fully.

Part I tells about the rock formations exposed along the coast and, in chronologic order, discusses the geologic events revealed by the formations. Included are comments on the general composition of the rock formations, their probable origin, and what they most likely have undergone since they were first formed. Part II describes less technically the geology of individual segments of the coast along a continuous traverse beginning at Point Grenville and extending northward to the Hoh River. Thus, the reader that is concerned only with a portion of this area can obtain general information about the rock formations and their geologic history locally without reading Part II in its entirety. However, some repetition is necessary as may be noted by those who do examine all of this part. For the reader desiring greater detail on certain related subjects, references are made to Part I, as well as additional, more technical publications.

All areas along the coast between Point Grenville and the Hoh River are accessible on foot with the exception of about half a mile along Pratt Cliff, where shear cliffs meet the ocean surf at all times. In many places tide conditions must be considered and several areas can only be reached during lowest tides. All of the coastal area south of the Olympic National Park boundary is part of the Quinault Indian Reservation and presently may be traversed only with the consent of the Quinault Tribal Council at Taholah.

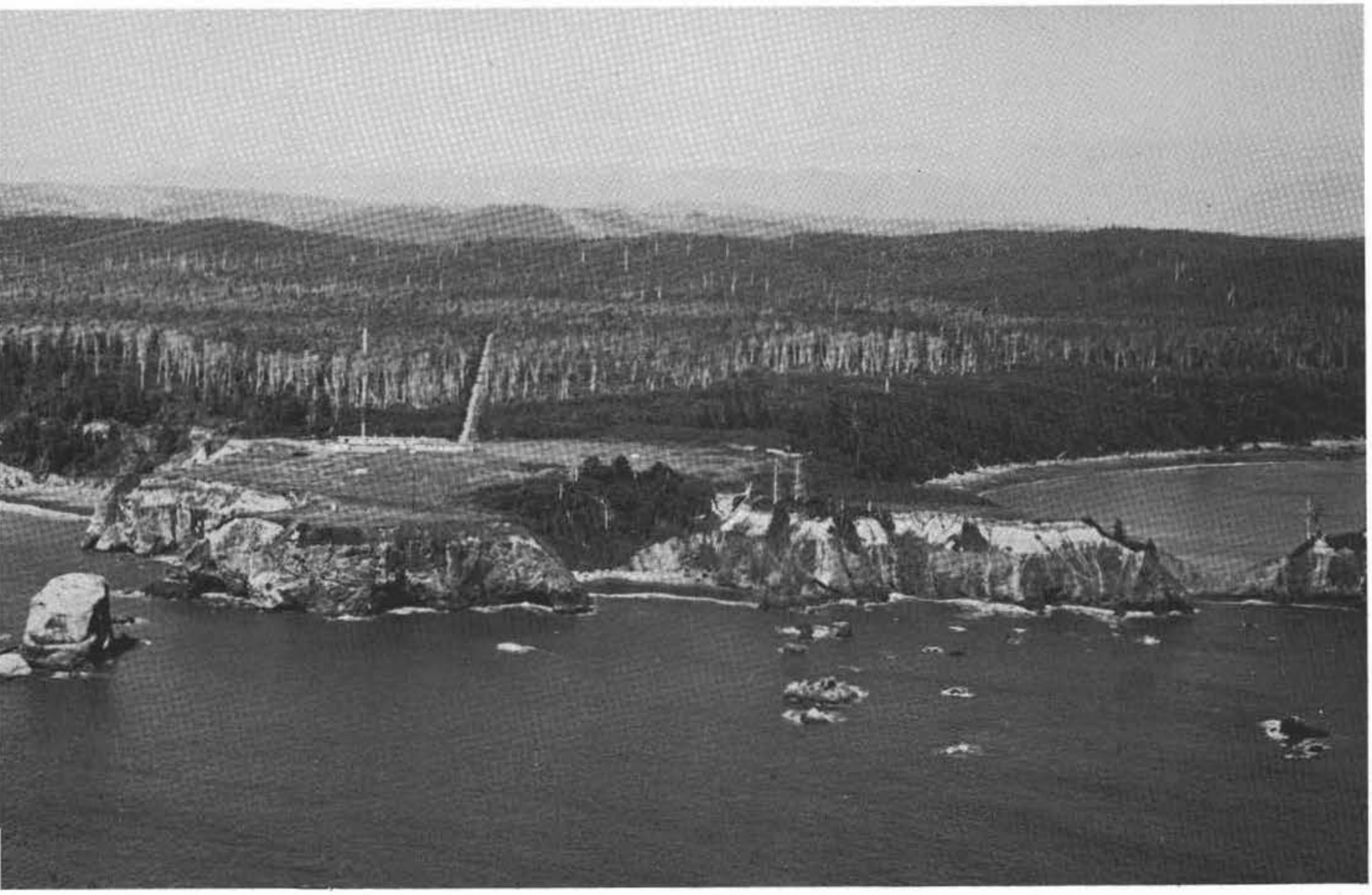
ACKNOWLEDGMENTS

The assistance and advice of, and discussions with, numerous colleagues have been invaluable to the writing of this report. Many published works have served either directly or indirectly as a source of background material, but, due to the nature of this report, not all have been cited specifically. Acknowledgments are here extended to these contributors.

Unpublished studies, including that of the late S. L. Glover, formerly of the Washington Division of Mines and Geology; a Master's thesis by E. M. Baldwin of the

University of Oregon; University of Washington student theses by J. L. Moore and by A. J. Koch; a Stanford University Ph. D. thesis by R. J. Stewart; and a University of Southern California Master's thesis by A. D. Horn have all been particularly useful sources of basic data and original concepts. Discussions during the past several years with P. D. Snavely, Jr., N. S. MacLeod, H. C. Wagner, and W. M. Cady of the U.S. Geological Survey; R. J. Stewart of the University of Washington; and A. D. Horn of North Seattle Community College have been most stimulating and helpful. Special thanks is extended to R. W. Tabor of the U.S. Geological Survey for his constructive review of the manuscript. Paleontological contributions of W. O. Addicott and the constructive suggestions concerning late Cenozoic deposits of D. R. Crandell, both of the U.S. Geological Survey, are greatly appreciated.

Many people of the communities of Pacific Beach, Moclips, Taholah, Queets, and Kalaloch have, through their assistance, contributed much to this report. The writer is particularly grateful for the assistance and historical information made available by Mr. and Mrs. George Bertrand of Queets, Mrs. Connie Fox of Pacific Beach, Mr. and Mrs. F. L. Dickinson and Mrs. Rella Binion of Kalaloch, and Mrs. C. H. Barlow of the Hoh River valley. The cooperation of the Quinault Tribal Council in granting access to the Reservation beaches, and the general assistance of many staff members of the Olympic National Park Service is greatly appreciated. The Mobil Oil Corporation, through the generous offer of J. R. Sprague, has supplied several technical services for which the writer extends his gratitude. Thanks are due to all staff members of the Geology and Earth Resources Division for their aid in individual ways in the preparation of this report. The capable assistance of G. D. Cloud during the summer months throughout the course of this study is gratefully acknowledged.



LOOKING EASTWARD AT POINT GRENVILLE. The bedrock of this major promontory is composed largely of volcanic material that was ejected onto the sea floor as lava, some 45 to 50 million years ago. Because this rock is more resistant to erosion than most other bedrock along the coast, it forms one of the more pronounced headlands along the Washington coast. It was behind this point, probably somewhere in the bay on the right, that Heceta anchored and from there made his historic landing. (Fig. 1)

PART I
Rock Formations and Their Geologic History

GENERAL STATEMENT

Rock formations along the Washington coast provide records of at least a latter part of the earth's history. Although these records are far from continuous, and in no one place are they all in a systematic sequence, the following discussion presents a "piecing together" of those available records in a systematic order from that of the oldest to the youngest rocks known along the coast between Point Grenville and the Hoh River. Generally, fewer details can be learned about the origin of older rocks than of those most recently deposited. Alteration or metamorphism from heat and pressure, as well as periods of erosion, have either obscured or completely erased many of the details of deposition or formation of the older rocks. However, those deposited or formed most recently are relatively unaltered and appear today much as they did when they were first deposited.

VOLCANIC ROCKS OF MIDDLE EOCENE AGE

The oldest rocks known along the coast between Point Grenville and the Hoh River are largely volcanic in origin with a few interbeds of marine siltstone. These rocks form most of Point Grenville and the nearby offshore stacks (fig. 1). Microfossils contained in the interbeds of marine siltstone indicate that these rocks were formed some 45 to 50 million years ago during middle Eocene time (fig. 2). The volcanic rocks are submarine lava flows that were ejected from within the earth onto the sea floor and there, in places, were incorporated with existing sediments or mud. Rapid cooling of the magma by sea water formed large amounts of noncrystalline glass. However, over millions of years much of this material has lost its glassiness. In other places, very fine-grained, dark colored basalt was formed. Furthermore, nearly all volcanic materials were highly shattered into small angular fragments, just as hot glass would be shattered if suddenly cooled in water. Now, however, these rocks are somewhat welded together and are referred to as "volcanic breccia." Many of the original cracks or fractures are now filled with veins of secondary light-colored minerals, much of which is calcite, or in places a zeolite mineral.

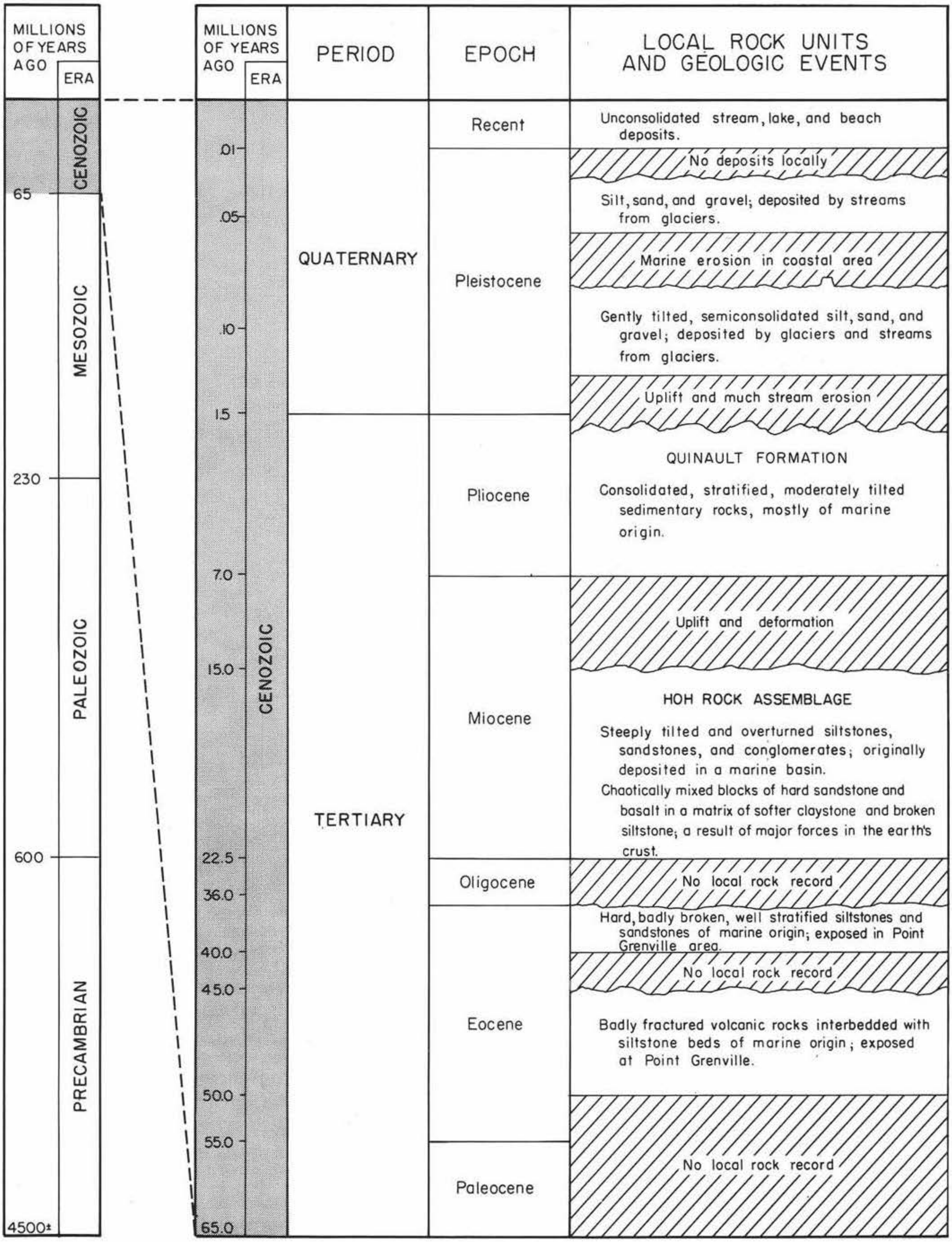
The muds, or sediments, that were incorporated in the volcanic rocks are today contorted beds or layers of siltstone. Other sedimentary beds may have been deposited between periods of volcanism. Most of these beds are calcareous and in some places they contain hard nodules or concretions that form irregular, resistant layers (fig. 31).

SEDIMENTARY ROCKS OF LATE EOCENE AGE

Highly broken, rhythmically bedded siltstones and sandstones outcrop immediately to the north of the main volcanic body of Point Grenville, on both the north and east shores of the point (fig. 3). They dip variably, but generally to the north and northeast. Microfossils indicate that these strata were deposited some 35 to 40 million years ago during late Eocene time. These rocks are therefore distinctly younger than the nearby middle Eocene siltstone interbeds of the volcanic rocks. Local relations between these two rock units are not clearly shown because of the limited exposures and because of structural complications. However, differences in the fossils indicate that a considerable amount of geologic record is missing between the two rock units. Faulting could have brought these rocks of different ages in juxtaposition or an unconformity may be represented, in which case a period of either nondeposition or erosion took place.

Rocks of late Eocene age appear to be restricted to the relatively small area near Point Grenville. Although other rocks along the coast between this area and the Hoh River are similar in appearance, none have produced fossils of late Eocene age; most are younger.

Late Eocene rocks of the Point Grenville area represent cyclic deposition in which fine-grained sediments, namely silts, were alternately deposited with coarse-grained sediments of sand. These sediments are now bedded siltstone and sandstone; and the microfossils indicate that deposition was well offshore in substantial depths of the ocean, perhaps at 1,000 feet or more, where water temperatures were relatively cold. Although these strata were deposited horizontally, or nearly so, on the sea floor as unconsolidated sediments sometime during late Eocene time, they have since been lithified, folded or tilted, and fractured by forces within the earth's crust.



GEOLOGIC TIME CHART. (Fig. 2)

DIPPING BEDS OF WELL-STRATIFIED SANDSTONE AND SILTSTONE exposed along the beach immediately east of Point Grenville. Fossils indicate these rocks are 35 to 40 million years old (late Eocene). (Fig. 3)

THE HOH ROCK ASSEMBLAGE

GENERAL DISCUSSION

Weaver (1937) originally applied the term Hoh Formation to many of the rocks found throughout much of the westernmost part of the Olympic Peninsula. Subsequent studies have found that these rocks not only are varied lithologically but are known to range greatly in age. Furthermore, they have undergone various amounts of tectonism from moderate folding and faulting to intense shearing and disarrangement of individual strata. Because these rocks are not a single mappable unit with a definable top and base, present-day workers no longer formally regard Weaver's rock assemblage as a formation.

Attempts have been made to subdivide these rocks into smaller mappable units. Glover (1940), for example, suggested that some of these rocks, largely the sandstone beds exposed in the vicinity of Browns Point and Destruction Island, be separated from Weaver's Hoh Formation and be referred to as the Browns Point Formation. However, recent studies of the extent of these rocks inland reveal that satisfactory boundaries are not easily mapped and, therefore, even these rocks do not constitute a well-defined formation.

Thus, in conformity with present-day usage of the term formation, the rocks that Weaver originally assigned to his Hoh Formation will be informally referred to in this report as the "Hoh rock assemblage."

Two major groups of rocks make up the Hoh rock assemblage between Point Grenville and the Hoh River. One group is a highly folded, steeply tilted sandstone and siltstone sequence. Good exposures of these rocks can be seen in the Browns Point-Starfish Point area (figs. 7 and 64). Although broken in places by faulting, generally they constitute a coherent sequence of sandstone and siltstone strata. The other group of rocks is called a "tectonic melange." These rocks are distinct from the first group in that they are a chaotic assemblage of siltstone, sandstone, conglomerate, and volcanic material. Such rocks are exposed in a number of places along the coast but are well exemplified in the cliffs for a distance of about 2½ miles immediately south of Raft River in the Hogsbacks area (fig. 4).

Although fossils are extremely rare in Hoh rocks, microfossils (Foraminifera) have been found in scattered places. Paleontologists have concluded that almost all collections represent an early to middle part of the Miocene Epoch and the containing rocks are therefore some 15 to 22 million years old (fig. 2). Rare isolated

EXTREMELY CONTORTED AND DISARRANGED MATERIALS OF THE HOH ROCK ASSEMBLAGE are exposed in the cliffs of the Hogsbacks area. Locally such deposits are called "smell muds" because of the petroleum odor that sometimes can be detected. Geologists refer to them as "tectonic melange," inferring that the chaotic mixture of resistant blocks of rock in soft silt and clay is the result of major deformation of the earth's crust. (Fig. 4)

collections may be slightly older—a late part of the Oligocene Epoch, in which case they may be as old as 25 to 30 million years.

The major collections of megafossils from Hoh rocks have come from the north side of the Hoh River about 1½ miles upstream from the mouth. Some of the more commonly occurring species from there were identified by Dr. Warren O. Addicott of the U.S. Geological Survey, and are listed below:

Gastropods:

Bruclarkia oregonensis (Conrad)
Cancellaria cf. *C. alaskensis* Clark
Crepidula aff. *C. rostralis* (Conrad)
Trochita? n. sp. Moore

Pelecypods:

Acila cf. *A. conradi* (Meek)
Diplodonta parilis (Conrad)
Glycymeris cf. *G. vancouverensis* Clark and Arnold
Solen cf. *S. curtus* Conrad
Tellina emacerata Conrad
Thracia schencki Clark
Spisula albaria (Conrad)
Vertipecten fucanus (Dall)

According to Dr. Addicott, these fossils also indicate an early or middle Miocene age. They further suggest a relatively shallow-water marine environment, possibly at water depths between 30 and 100 feet.

TURBIDITES OF THE HOH ROCKS

Many of the sandstone and siltstone strata of the Hoh rock assemblage, as typified by the rocks of the headlands and coves of the Browns Point-Starfish Point area, are known as turbidites, a type of sedimentary rock with a rather special and interesting depositional history. Although these beds are now steeply dipping and in many places are even overturned, originally they were deposited horizontally, or nearly so, on the sea floor as layers of sediments. They have since been lithified by pressure and mineralization. Furthermore, lateral forces applied over many millions of years on the earth's crust, probably have moved these rocks relatively eastward to their present place along our coast where they are seen today in a nearly vertical and, in places, overturned position.

As the term suggests, turbidites are sediments that originally settled out from turbid or muddy water; thus, a definite gradation of particle size usually occurs in each sequence of deposition. Each sequence probably was deposited in a relatively short period of time. The source of sediment for these deposits is believed to have been from the edge of an ocean basin, perhaps from the outer slope of some ancient continental shelf. Due possibly to earthquakes or the overweighting of a slope with sediments, large masses of unstable sediments were suddenly dislodged and moved downslope much like a landslide, except that many of these materials were placed in suspension in water to form a very large "cloud." Almost immediately redeposition or settling out of these sediments began to take place in a deeper part of the ocean basin. The coarsest materials were deposited first and nearest to their source. Therefore, these sediments formed

HOGSBACK, as it appears from the air and offshore. This very large block of resistant volcanic rock has been eroded from deposits of jumbled Hoh rock, similar to those deposits appearing in the cliffs in the background. Although today this block is nearly separated from the mainland, calculated erosional rates suggest that the cliffs of this area have receded eastward from the westernmost edge (foreground) of Hogsback to their present position, in about 200 years. (Fig. 5)

LOOKING SOUTHWEST NEAR BEACH TRAIL 4 at well-stratified, steeply dipping beds of siltstone and sandstone of the Hoh rock assemblage. Sedimentary structures indicate that the entire sequence is overturned. The youngest beds are on the right. (Fig. 7)

the base of each sequence of deposition. The very coarsest materials probably slid along the sea floor somewhat lubricated by water, perhaps more than actually being completely suspended. Typical examples of such coarse-grained beds form the main and prominent headland masses of both Browns Point and Starfish Point (fig. 65). These deposits of coarse-grained sand, grit, and, in places, even conglomerate are technically called "graywackes," because many of the individual grains or clasts are fragments of other rocks rather than individual mineral grains. In many of the graywacke sandstones seen along the coast, angular fragments of various sizes of dark-gray siltstone occur in a light-colored sand matrix. Most likely these siltstone fragments were ripped from siltstone beds on the sea floor as the turbidite "cloud" passed over. They then became incorporated in the coarse-grained part of the turbidite sequence.

Following the initial deposition of the coarse material of each turbidite sequence, fine-grained material gradually began to fall out of suspension. In many places, therefore, the strata display a grading of grain size from coarse-grained sandstone to fine-grained siltstone. The thickness of each sequence varies from that of a few inches to many feet. Frequently, a series of rhythmically bedded thin sandstone and siltstone strata were formed, some of which represent many small graded sandstone-to-siltstone se-

THE SOUTHERN PART OF BROWNS POINT. Sandstone bedrock is overlain by silt, sand, and fine gravel. These materials were deposited on the bedrock during the Pleistocene Epoch between some 17 and 70 thousand years ago. (Fig. 6)

quences. Others may be the result of pulsating currents that intermittently supplied coarse-grained material (sand) for a short period of time to an area otherwise normally receiving finer materials (silt and clay particles). Such rhythmically bedded strata can be seen in a steeply dipping position on the beach in the vicinity and at the foot of Beach Trail 4 (figs. 7 and 8).

Aside from the graywacke sandstone and interbedded finer siltstone beds, substantial thicknesses of massive siltstone may also occur in association with turbidite deposition. These deposits most likely represent relatively quiet and uniform periods of deposition, during which time only fine-grained particles settled out of suspension. Such fine-grained deposits are usually widespread, but because they are less resistant to erosion, they are more likely to be eroded and covered by debris, such as soil, sand, gravel, and vegetation. The low-lying cliffs and sand-covered beaches of many of the coves along the coast are underlain by such siltstone beds.

RHYTHMICALLY STRATIFIED SANDSTONE AND SILTSTONE BEDS exposed at Beach Trail 4. The original top of these beds faces to the left and therefore the beds are overturned. The generally level surface formed on the beveled ends of these beds represents an ancient elevated sea-level surface. Sands and gravels above were first deposited on this surface during a latter part of the Pleistocene Epoch some 70 thousand years ago. (Fig. 8)

Sedimentary Structures

Well-formed structures of sedimentation are excellently preserved in some turbidite sequences. "Flamelike" structures and "convolute" or contorted bedding are examples (fig. 9). These features were formed when unconsolidated sediments were either squeezed or wrinkled into overlying beds. Subsequent lateral movement of the entire bed, while still relatively soft, has bent these features mostly in the same direction. Other features are casts of "flutes" or small channels that were formed on the surface of a one-time muddy sea bottom. They are now preserved on the underside of what was an overlying sand bed. Such flute casts are common in turbidite sediments and are some of the features that not only indicate that the beds at Browns Point have been rotated beyond vertical to a slightly overturned position but also indicate the direction of currents during their formation. (Suggested technical reading on turbidite sedimentation: Bouma and Brouwer, 1964).

TECTONIC MELANGE OF THE HOH ROCK ASSEMBLAGE

Certain outcrops of the Hoh rock assemblage consist of chaotically mixed resistant blocks of rock set in a fine-grained matrix of softer rock materials much like peanuts in a "chunky-style" peanut butter (fig. 4). Locally these deposits are known as smell muds, because an odor of petroleum frequently can be detected. Technically these mixtures of rock are referred to as "tectonic melange" (mā′ lä nzh), implying that the jumbled condition is believed to be the result of major deformation of the earth's crust. Such materials (see cover photo) are well exposed in the cliffs for about 2½ miles along the Hogsback area (fig. 45). Here the hard blocks of rock ranging greatly in size consist variously of conglomerates, sandstones, well-stratified sandstone and siltstone, and, in places, altered volcanics. The softer, finer grained materials of the matrix are mostly clays and badly broken siltstone. The slumped condition of melange deposits in the Hogsbacks area, as well as in other coastal areas, attests to the extreme structural weakness of such deposits. This weakness is due largely to the expanding nature of many of the clay minerals after they have become moistened. Therefore, the periodic wetting of the base of the cliffs by ocean waves, together with much precipitation, makes coastal outcrops of the melange materials particularly vulnerable to slumping. Similar expanding materials have been encountered in many of the petroleum test wells drilled in the Ocean City area a few miles to the south, and in areas offshore. There, such deposits were referred to as "heaving shale." Because these materials tend to expand, the drill hole was often reduced in size or completely closed.

Some idea of the great amount of force involved in the formation of jumbled deposits of a tectonic melange can be realized by noting the very large size of some of

LOOKING AT THE EDGES OF SANDSTONE AND SILTSTONE STRATA that are dipping steeply away from the viewer. Because the flamelike structures, in the contorted layer extending across the central part of the picture, all point downward, the entire sequence of beds is upside down. Originally the irregular layer was deposited nearly flat like the others, but, while the material was still somewhat plastic, the weight of overlying beds (now seen below) caused this layer to be irregularly squeezed into the relatively soft overlying bed. The handle of the hammer lying on a bedding plane in the lower right is about 12 inches in length. (Fig. 9)

the resistant blocks incorporated in these deposits. A group of these blocks, some larger than houses, now rest on the beach at Boulder Point (fig. 10 and cover photo), where they were left after the fine-grained materials of the melange were eroded away by the sea. Furthermore, the promontories of Little Hogsback (fig. 49) and Hogsback (fig. 5), as well as the offshore rocks of Split Rock (fig. 48) and Willoughby Rock (fig. 34), are all huge resistant blocks, largely of volcanic origin, that were once incorporated in the melange but now are erosional remnants along the coast resting on the Continental Shelf.

Microfossils from some of the siltstones of the tectonic melange are known to have lived during early to middle Miocene time, some 15 to 22 million years ago (fig. 2). These fossils further indicate a deep marine depositional environment where temperatures were cold. Therefore, melange siltstones in which these fossils are found today were originally deposited as marine silts in an ocean basin somewhere below depths of the outer edge of a continental shelf, such as exists today well off the coast of Washington.

INTERPRETATIONS OF STRUCTURE IN THE HOH ROCK ASSEMBLAGE

General Discussion

The complicated structural patterns so apparent in many of the coastal outcrops of Hoh rocks no doubt have aroused the curiosity of many people. What conditions were these rocks subjected to in order to produce the chaotic mixtures of materials such as those in the cliffs of the Hogsbacks area? What forces were involved to tightly fold and place coherent sequences of sedimentary rocks in nearly vertical or overturned positions like those at Browns Point and on Destruction Island? Geologists' answers to these questions are not completely without reservations. However, geophysical and geologic studies of ocean floors in recent years have provided new fundamental concepts about the earth's crust. These theories, scientists now believe, are basic for logical explanations to many of the structural relations of the Hoh rock assemblage of the Washington coast, as well as the rocks of much of the Olympic Mountains.

LARGE RESISTANT BOULDERS AT BOULDER POINT. Over the years erosional processes have caused the cliffs of this area to recede eastward. Shown here are resistant blocks left behind from deposits of contorted Hoh rock. (Fig. 10)

Most early attempts to explain structural conditions of the Hoh rocks, particularly those of the jumbled melange rocks, were based simply on landsliding or slumping of structurally weak siltstone beds. This, however, did not adequately explain such problems as the large "exotic" boulders or blocks incorporated in the siltstone.

In recent years, Weissenborn and Snavely (1968) and Koch (1968), by using the same basic mechanism of gravity sliding, emphasized the magnitude of the force involved by suggesting that it took place on a tectonic or major crustal scale. They pointed out that these rocks may have been formed by gravity sliding of very large masses, possibly in combination with gravity thrusting or overriding of large blocks of rock in a submarine environment. Stewart (1971) suggested that melange deposits may represent major faulting and are materials brought together in shear zones created by differential movement between major segments of the earth's crust. Variations of the later concept are largely with respect to the specific type of faulting involved. Regardless of the mechanism of motion, it is now generally accepted that the chaotic condition of these rocks reflects major tectonism or movements of the earth's crust.

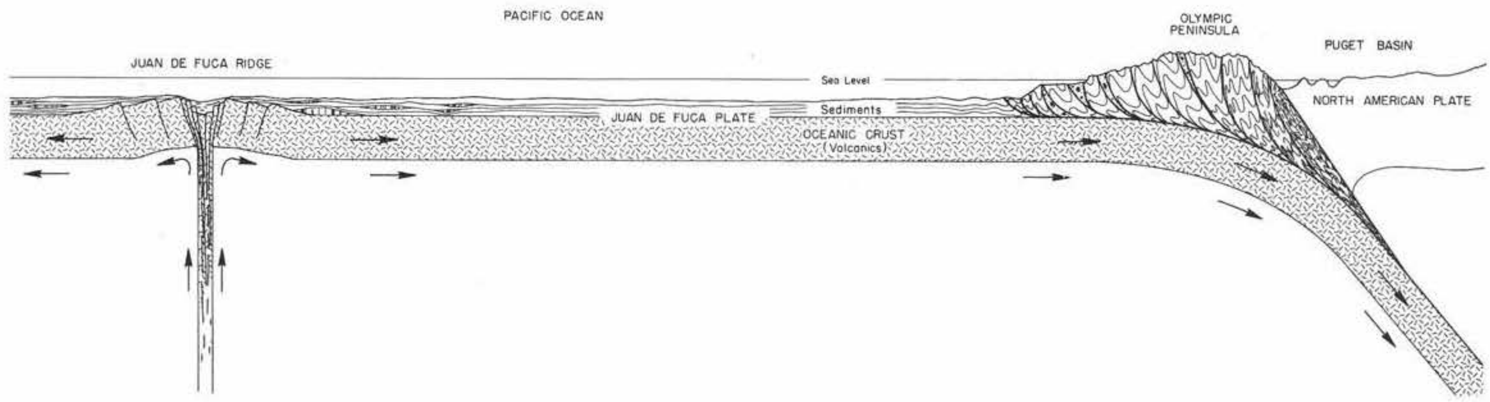
How and Why

Plate Tectonics–Sea Floor Spreading

Speculations on how, and to some extent why, these forces of tectonism were generated is also of interest to geologists. The new data about the ocean floor has aided greatly in the formulation of theories for possible answers to these questions. The relatively new concept known as "plate tectonics" is particularly significant. It generally maintains that the earth's outer crust consists of a series of large, somewhat mobile, plates (Matthews, 1973). This idea has evolved from a nearly forgotten theory proposed some sixty years ago and known as Continental Drift. Because the configuration of some of the continents appears as though they could be fitted together, for example, the east coast of South America and the west coast of Africa, some workers thought that the continents were together at one time but have since drifted apart. It was not until recent studies were made of the floor of the ocean basins that a mechanism was discovered explaining why continents may have moved apart. The available data of today strongly indicates that over millions of years sea floors have spread or expanded at various rates between one-half to over 2¼ inches a year in each direction from central ridges. The ridge in the Pacific extends in a northerly direction through much of the main part of the South Pacific and is known as the east Pacific Ridge (National Geographic Society, 1969). The axis of this and all ridges is a major fissure or crack in the earth's crust where volcanic materials are extruded and accreted periodically to the crust or sea floor, thus forcing the existing floor away both to the east and west from the ridge. Therefore, in a given plate, the farther away an individual volcanic unit is now from the ridge, the longer ago that unit was extruded from the ridge, and the older the unit should be.

Where two plates come in contact with each other from opposite directions, it is believed that the heaviest, usually the oceanic plate, underthrusts or slides beneath the other and the materials of the former are once again placed slowly back into the depths of the earth to become magma.

With respect to our Pacific Northwest, in the ocean basin some 250 miles off the Washington coast a ridge exists that, although offset considerably to the west, corresponds to a segment of the east Pacific Ridge. It is known as the Juan de Fuca Ridge (fig. 11). The present-day contact between the Juan de Fuca plate and the North American plate is believed to be immediately west of the Continental Shelf of the Pacific Northwest. However, some workers speculate that in the geologic past this contact was farther to the east relatively, perhaps somewhere between the present-day Olympic Peninsula and the Cascade range. During the millions of years that volcanic rock of the oceanic crust has moved away from the Juan de Fuca Ridge, probably at a rate of slightly more than 1 inch a year, marine sediments, such as the deep-water siltstones and sandstones of the Hoh rocks, were deposited and carried on the volcanic floor eastward toward the outer edge of the Juan de Fuca plate. Miocene rocks as young as 15 to 22 million years of age (Hoh rocks) are believed to have moved at least as far eastward as our present-day coast. Older rocks of the Eocene Epoch (36 to 55 million years of age) predominate even farther east in the eastern part of the Olympic Mountains. Therefore, according to this concept, the extensively folded rocks of the coastal area and the Olympic Mountains are believed to be sedimentary and volcanic rocks of the Juan de Fuca plate that were not thrust under the North American plate but instead were "skimmed off" the oceanic crust, foreshortened by crumpling and successive underthrusting, piled up, and accreted to the western edge of the North American plate. The present-day Olympic Mountains are believed to represent much of this "pile." Erosion by wave action has



A DIAGRAMMATIC SECTION showing how the structurally complex rocks of the Olympic Mountains and of the west coastal area may have been formed. Sediments, now lithified to rock such as the Hoh rocks, have been carried eastward, relative to the continent, on a thick oceanic crust of volcanic rock a few inches a year for millions of years. Where the heavier rocks of the Juan De Fuca plate met the lighter rocks of the North American plate, most of the rocks of the former moved beneath those of the continent and were dragged into the depths of the earth and were converted to magma. However, it is believed some of the materials were not thrust under the continent but were "skimmed off," foreshortened by crumpling and successive underthrusting, piled up, and accreted to the western edge of the North American plate. The present-day Olympic Mountains and complexly folded and faulted Hoh rocks along the coast are believed to represent the rocks of this "pile." (Fig. 11)

since beveled off the western part of this pile of complexly folded and sheared rock, leaving the Continental Shelf and the low-lying western coastal area of the Olympic Peninsula.

Listed below are selected references on plate tectonics and other subjects related to geologic structure along the Washington coast: Atwater, 1970; Dewey, 1972; Dewey and Bird, 1970; Dietz and Holden, 1970; McKee, 1972, p. 164-169; Phinney, 1968; Schiller, 1971; Silver, 1971; Stewart, 1970, 1971; Tabor, Cady, and Yeats, 1970.

Piercement Structures

The extremely distorted condition of some Hoh melange rocks may be the result of having been squeezed into, and in some places through, overlying strata of younger formations. Certain rocks when charged with liquids and gases under high pressure are known to have the ability to flow much like plastic. Therefore, where they are overloaded by another more rigid formation, the plastic material can be squeezed upward into areas of weakness in overlying, more rigid formations like putty into a crack. In so doing, the surrounding areas of more rigid materials become bent or dragged upward. In some cases, the plastic materials do not break completely through the overlying beds but simply dome them upward. Such structures are known to exist in a number of places in the world. For example, in the Gulf of Mexico coastal area, salt is the plastic material that is forced upward in the form of a "plug," thus producing salt domes.

The local occurrence of piercement structures is strongly supported by continuous seismic profiles recorded by various research groups in recent years over the Continental Shelf of Washington, Oregon and Vancouver Island. (Grim and Bennett, 1969; Snavely and MacLeod, 1971; Tiffin, Cameron, and Murray, 1972). Such records generally show, in cross section, geologic structures beneath traverse lines. In records from off the Washington coast such structures are well defined (fig. 12).

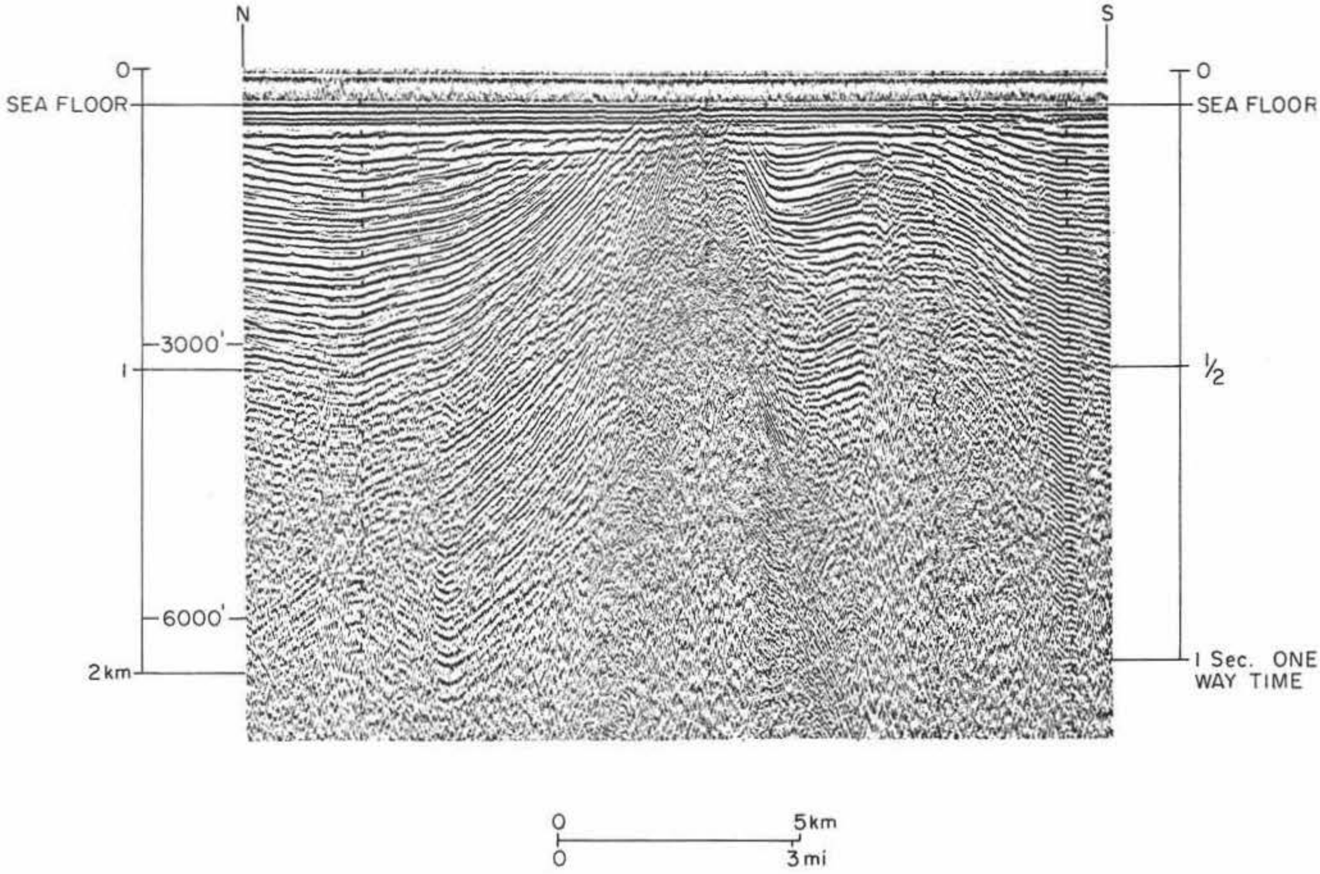
One of the better onshore examples of a possible piercement structure can be seen in the cliffs along the beach about three-quarters of a mile south of the mouth of Duck Creek and extending for one-quarter of a mile southward (fig. 29). There, dark-gray melange rocks are believed to have penetrated into the overlying lighter colored Quinault Formation (fig. 53).

THE QUINAULT FORMATION

GENERAL DESCRIPTION

Outcrops of the Quinault Formation, a series of sedimentary rocks largely of marine origin, are almost entirely confined to the Quinault Indian Reservation and are well exposed in many of the cliffs and on tidal benches between Point Grenville and the vicinity of the Raft River. The name Quinault (Quinaielt) was first applied to this group of rocks by Dr. Ralph Arnold, in 1906, in a published report on reconnaissance studies of the Olympic Peninsula. Although nowhere is the formation known to outcrop more than 3 miles inland, equivalent rocks are known in the subsurface of the Continental Shelf, extending at least 20 miles seaward and for a distance of at least 40 miles along the adjacent coast.

The limited onshore outcrop area of this formation is of particular interest to petroleum geologists because strata may be studied there that are otherwise essentially inaccessible on the adjacent Continental Shelf. Furthermore, the formation is generally regarded as one of the more favorable potential petroleum reservoirs off the Washington coast.



A CONTINUOUS SEISMIC PROFILE that was recorded along a shipboard traverse off the coast near Point Grenville. By means of sound reflections it shows the various subsurface layers beneath the sea floor and how they have been deformed by the upward motion of a pluglike structure shown in the center of the picture. Such features are known as "piercement structures." Photo, courtesy of Parke D. Snavely, U.S. Geological Survey. (Fig. 12)

The Quinault Formation is varied in composition ranging from fine-grained rocks, such as massive siltstones, to coarse-grained beds of sandstone and conglomerate. Both megafossils, mostly of clams and snails, and microscopic fossils (Foraminifera) are abundant in places within the Quinault Formation. A few of the more commonly known species of megafossils have been identified by Dr. Warren O. Addicott of the U.S. Geological Survey and are listed below:

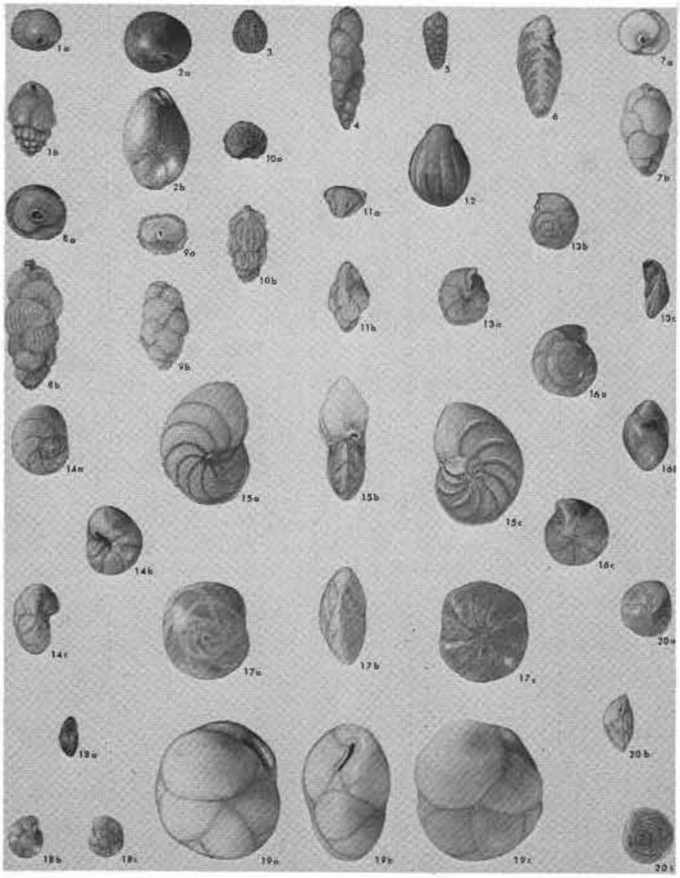
Gastropods:

- *Antiplanes perversa* (Gabb)
- *Mediargo mediocris* (Dall)
- *Nassarius andersoni* (Weaver)
- *Nucella* cf. *N. lamellosa* (Gmelin)
- *Trophonopsis* sp.

Pelecypods:

- *Lituyapecten* sp.
- *Lucinoma annulata* (Reeve)
- *Securella* sp.
- *Thyasira bisecta* (Conrad)

Some of the Foraminifera are shown and identified in figure 13 . Details on the Foraminifera of the Quinault Formation are discussed in another report (Rau, 1970). Fossils from the Quinault Formation indicate a Pliocene age and therefore, as shown in figure 2 , the Quinault Formation was deposited some 1.5 to 7 million years ago. These rocks are much younger than the Hoh rocks–the next oldest rock unit of the area. Figure 2 shows that no rocks are present to portray the considerable amount of geologic time between that of the middle part of the Miocene Epoch, represented by Hoh rocks, and the Pliocene Epoch, represented by the Quinault Formation. The local absence of rock strata to represent a period of geologic time that is known elsewhere is called an uncomformity. It indicates that the land was above the sea, and erosion rather than deposition was probably taking place during a latter part of the period of time not represented by rock formations. Additional rocks may have been deposited after the deposition of the Hoh rocks and prior to that of the Quinault Formation, but, if so, they were eroded away before the deposition of the Quinault Formation. Furthermore, much of the complicated folding and faulting (uplift and deformation) of the older Hoh rocks must have taken place during the time



MICROSCOPIC FOSSILS "Foraminifera," from the Quinault Formation. Fossils of this extremely varied organism are common in the Quinault Formation as well as in most other sedimentary rocks of marine origin. Conditions of deposition such as depth and the temperature of the water in which they lived can be estimated from such fossils. Furthermore, assemblages vary according to when they lived; and, therefore, they are useful indicators of geologic time. All specimens magnified about 25X and are identified below:

1. *Bulimina subacuminata* Cushman and R. E. Stewart
2. *Globobulimina auriculata* (Bailey)
3. *Oolina melo* d'Orbigny
4. *Virgulina californiensis ticensis* Cushman and Kleinpell
5. *Bolivina advena* Cushman
6. *Bolivina acuminata* Natland
7. *Uvigerina* cf. *U. hootsi* Rankin
8. *Uvigerina juncea* Cushman and Todd
9. *Uvigerina senticosa* Cushman
10. *Uvigerina subperegrina* Cushman and Kleinpell
11. *Angulogerina semitrigona* (Galloway and Wissler)
12. *Oolina borealis* Loeblich and Tappan
13. *Discorbis? columbiensis* Cushman
14. *Valvulineria malagaensis* Kleinpell
15. *Valvulineria washingtonensis* (Cushman and R. E. and K. C. Stewart)
16. *Eponides healdi* R. E. and K. C. Stewart
17. *Buccella inusitata* Andersen
18. *Rotalia* cf. *R. Garveyensis* Natland
19. *Cassidulina californica* Cushman and Hughes
20. *Epistominella pacifica* (Cushman)

(Fig. 13)

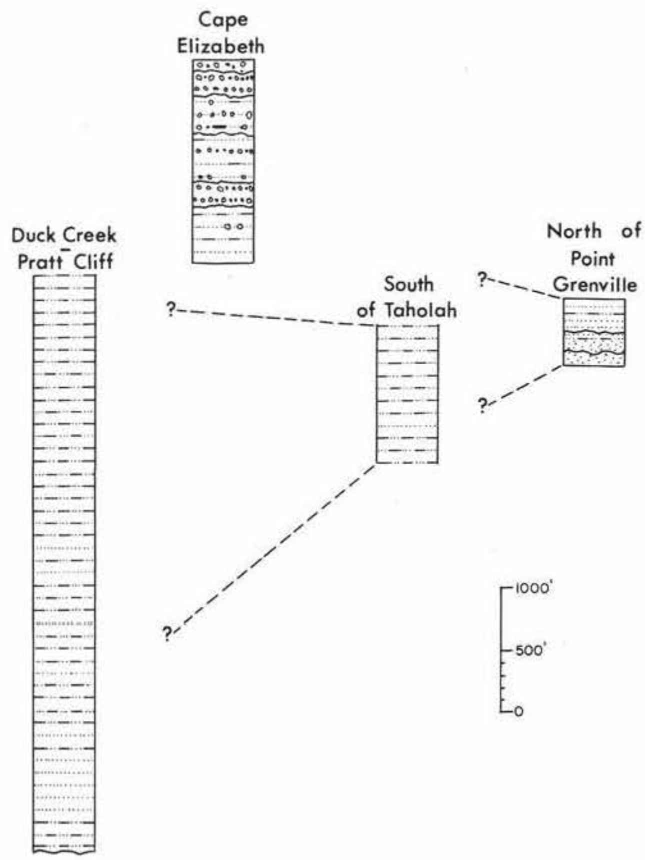
that is not represented by strata, because the younger Quinault Formation, although gently tilted and occasionally faulted, displays far less disturbance than do the Hoh rocks.

MAJOR SECTIONS OF CONTINUOUS STRATA

If those beds of the Quinault Formation exposed in the various outcrops along the coast were placed in their original, nearly horizontal position, the thickness would measure over 6,000 feet. Nowhere can the entire thickness of 6,000 feet be observed in one complete stratigraphic section, but major segments of the sequence can be seen in a tilted position in the four nearly continuous series of outcrops discussed below.

North of Point Grenville

The southernmost of these sections of strata is exposed in the nearly vertical cliffs that begin about one-quarter of a mile north of Point Grenville (fig. 29). From this point northward for nearly 1 mile, gently tilted beds, predominantly sandstone, are exposed in the nearly vertical cliffs beneath a cap of younger gravel (Frontispiece). These dipping beds are believed to represent a middle to upper part of the Quinault Formation (fig. 14).



CORRELATIONS of four major sections of the Quinault Formation. (Fig. 14)

CONTORTED BEDDING in the Quinault Formation exposed in the sea cliffs north of Point Grenville. When these beds were still unconsolidated, a thin silt layer was irregularly squeezed and contorted upward into an overlying massive sand body. Subsequent differential movement of the beds further contorted the silt layer. (Fig. 15)

Numerous, well defined, and, in many places, very large features of sedimentation, together with structural patterns that were formed shortly after deposition, are well preserved in this section (Horn, 1969). Many scour and fill structures may be seen at several horizons (fig. 30). They represent the periodic erosion of channels by local currents in semiconsolidated sediments. Most channels have been filled subsequently with angular, coarse conglomerate and grit, together with numerous shell fragments. Many other sedimentary structures may be seen, including flamelike structures, pulled-apart bedding, and other types of contorted bedding (fig. 15). Both large and microscopic fossils are common. These fossils, together with the various types of sedimentary structures, indicate that sedimentation most likely took place in a deltaic environment off the mouth of a major stream. Furthermore, the fossils suggest that water temperature during deposition was probably cool to cold, similar to that off our coast today.

South of Taholah

Northward for about 1 mile, a partially gravel-covered landslide area separates the first section from a second, nearly continuous sequence of northward-dipping beds of the Quinault Formation. The second section extends about half a mile northward and ends some three-quarters of a mile south of Taholah (fig. 29). These strata are distinct from those of the first section in that they are largely massive to faintly bedded siltstone, a generally finer grained rock than the sandstone beds of the first section. Microfossils are common and varied, indicating that they could have been deposited about the same time as those of the first section. However, final deposition most likely took place in a noticeably deeper marine environment than is indicated by the fossils of the first section, probably well below the outer edge of a continental shelf at water depths between 900 to 2,000 feet. Some of the micro-organisms actually lived at much shallower depths, but their shells were redeposited along with other sediments at the greater depth, together with the remains of those that actually lived at this greater depth.

CARBONIZED BRANCHES and other plant materials in massive sandstone of the Quinault Formation exposed on the beach near Cape Elizabeth. (Fig. 16)

CAPE ELIZABETH AREA. Looking northward at gently dipping sandstone and conglomerate beds of the Quinault Formation exposed between Cape Elizabeth, shown on the left, and the mouth of the Quinault River. Geologists conclude that the lowest of these strata were deposited in a very shallow marine environment, whereas the uppermost beds were laid down on land by streams and rivers. (Fig. 17)

Cape Elizabeth

A third, nearly continuous sequence of the Quinault Formation is exposed in the Cape Elizabeth area (fig. 29). Gently, southeastward-dipping beds of conglomerate, sandstone, and some siltstone form the high cliffs and tidal benches, extending from a place about a quarter of a mile north of the mouth of the Quinault River to Cape Elizabeth (fig. 17). Similar outcrops continue northward to a place about 1¼ miles north of Cape Elizabeth where they suddenly end in sharp contact with outcrops of older, dark-colored, jumbled Hoh rocks. The sequence of beds at Cape Elizabeth and vicinity forms about 1,600 feet of tilted, nearly continuous strata of the Quinault Formation. These beds are believed to represent an uppermost part of the formation (fig. 14). The basal one-third of this section, visible in the northernmost outcrops, is largely sandstone with beds of siltstone and some conglomerate. Grading upward, conglomerates become dominant in the upper two-thirds; and, extending from the Cape to the mouth of the Quinault River, the beds are largely irregular, lenticular deposits of conglomerate with some sandstone and minor amounts of siltstone. Much carbonaceous or plant material can be seen throughout the section, including large coalified branches, stumps, and even logs (fig. 16). Marine fossils are very rare and have been found only in the lower one-half of the section. Those present, however, are all indicative of very shallow, cool sea conditions.

Strata of Cape Elizabeth and vicinity most likely accumulated at first near the shore of a marine basin, probably not far from a delta of a major stream or streams. With the gradual filling of the sedimentary basin, water depths became less and less. In the final stages of deposition, an alternation of fluvial (stream) deposition and erosion by streams took place on land to form the lenticular and channeled deposition now visible as conglomerates and sandstones in the cliffs between Cape Elizabeth and the mouth of the Quinault River.

Duck Creek–Pratt Cliff

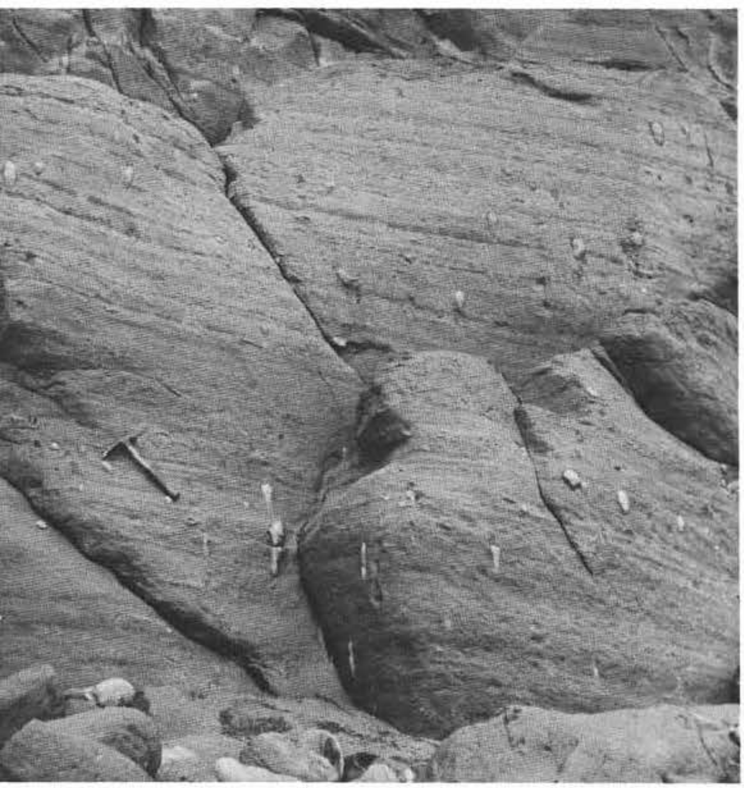
The thickest of the four major sections of the Quinault Formation is exposed in the area between the mouth of Duck Creek and a place about three-quarters of a mile north of Pratt Cliff (figs. 29 and 45). Although some of the strata are inaccessible at Pratt Cliff, a thickness of about 4,500 feet of nearly continuously exposed southeast-dipping strata form sea cliff and beach outcrops for a distance of nearly 2 miles. Beds exposed southward from the mouth of Duck Creek for about three-quarters of a mile are also a part of this section. However, structural relations, fossil content, and lithologic similarities indicate that they are essentially the same beds as those exposed immediately south of Pratt Cliff.

A CONTACT between the dark-colored jumbled Hoh rocks and the overlying lighter colored siltstone beds of the Quinault Formation, exposed in the cliff about three-fourths of a mile north of Pratt Cliff. (Fig. 18)

The base of the fourth and thickest section is clearly visible at the north end of its outcrop area (fig. 18). There, siltstone strata of the Quinault Formation rests unconformably on older, dark-colored and jumbled rocks of Hoh melange. The contact between the two units dips gently to the southeast. Lithologically the basal part of the section exposed north of Pratt Cliff is mostly well-bedded, sandy, fossiliferous siltstone, and in places thin-bedded, fine-grained sandstone. Concretionlike structures measuring from 4 to 8 inches in length are common, particularly in the sandstone beds of the area. Almost all are oriented with their long axis perpendicular to bedding planes (fig. 19). Pratt Cliff, although inaccessible, appears from nearby offshore to be uniformly dipping beds, largely of siltstone and possibly some sandstone (fig. 36). The remaining part of the section south of Pratt Cliff is mostly massive or bedded sandy siltstones containing scattered fossils. In many places throughout much of the lower part of the section in the Duck Creek area, bedding of individual strata appear to have been churned or disrupted before the sediments were consolidated (fig. 20).

Fossil Foraminifera indicate that the strata of the Duck Creek-Pratt Cliff section of the Quinault Formation most likely were deposited in cool water at depths between 400 and 1,000 feet.

ELONGATED CONCRETIONLIKE STRUCTURES in bedded sandstones of the Quinault Formation exposed in the cliffs north of Pratt Cliff. These structures may have been cavities that were formed by boring animals, perhaps clams, and then were filled with sediments with slightly more cementing material than the surrounding sand. (Fig. 19)



DISRUPTED BEDDING in siltstone of the Quinault Formation of the Duck Creek area. The burrowing of clams or other marine organisms, together with local slumping of individual beds on unstable submarine slopes before the formation was consolidated, may have been responsible for this phenomenon. (Fig. 20)

Tunnel Island Area

Although most of the Quinault Formation is represented in the four major sections previously discussed, an additional and sizeable series of discontinuous outcrops extend from Tunnel Island northward for a distance of over 1 mile. The sandstone strata exposed on Tunnel Island (fig. 24), in nearby sea stacks (fig. 25), and in the cliff immediately north of the mouth of the Raft River are all a part of the Quinault Formation. Northward to the end of the outcrop area, sandy siltstone beds are exposed in isolated areas in the cliffs and along the beach during low tide. Both megafossils and microfossils occurring in this series of outcrops suggest that the rocks belong to a lower part of the Quinault Formation, similar to those beds exposed immediately north of Pratt Cliff.

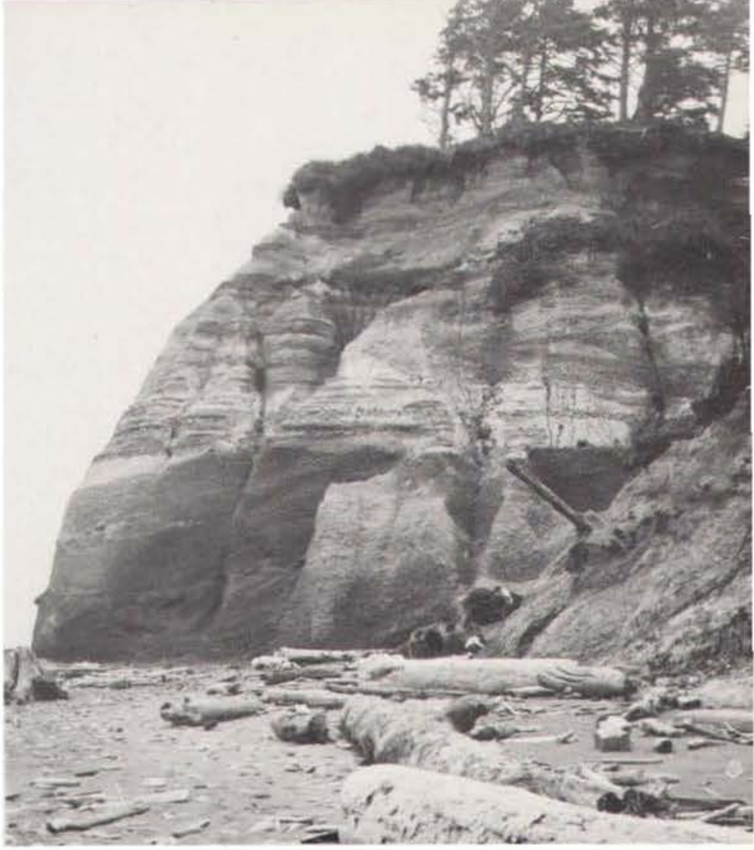
LATE CENOZOIC DEPOSITS

GENERAL DESCRIPTION

In almost all sea cliffs along the coast between Point Grenville and the Hoh River, nearly horizontal to gently dipping beds of semiconsolidated silt, sand, and gravel cover the underlying bedrock. In places the entire cliff is composed of these materials and may be more than 100 feet thick (figs. 22 and 55). Most, if not all, of these deposits probably were laid down during the last million and a half years or so–a period of time known to geologists as the Pleistocene Epoch (fig. 2).

A number of geologic events are rather well preserved in these relatively young deposits of silt, sand, and gravel. Preliminary studies of these as well as nearby deposits have made it possible to conclude various probabilities and even some facts about the local Pleistocene geologic history.

All materials contained in these deposits very likely were derived from bedrock outcrops of the Olympic Mountains. A large majority of the stones in the gravels are composed of graywacke sandstone. Individual pebbles contain abundant black siltstone chips set in a matrix of lighter colored sand grains, a lithology characteristic of many of the graywacke sandstone beds of Hoh rocks (fig. 21). Not more than 15 percent of the stones in these gravels are composed of other rock types, most of which are volcanic in origin and are much like those at outcrops in the Point Grenville area (see section on volcanic rocks of middle Eocene age). The few remaining stones are red argillites, phyllites, and cherts from the Olympic Mountains. Most of the sand and gravel was transported by streams and rivers and is known as "fluvial" deposits. In a few places some of the older materials may have been



TWO MAJOR SAND AND GRAVEL UNITS exposed in a sea cliff just south of Whale Creek. All materials were carved from the Olympic Mountains and transported to the coastal area by glaciers and streams from the glaciers during two different periods of time in the Pleistocene Epoch. The upper unit was probably deposited between 17 and 70 thousand or more years ago, whereas the lower unit was deposited prior to 70,000 years ago. The nearly horizontal contact separating the two units represents the trace of a now elevated wave-cut surface that was formed essentially at sea level, prior to the deposition of the overlying younger sand and gravel unit. (Fig. 22)

GRAYWACKE SANDSTONE BEACH PEBBLES, common on many of the local beaches, contain many fragments of various rock types. Note the conspicuous black, angular shale fragments in some of the pebbles. Their disc-shape is typical of beach pebbles. (Fig. 21)

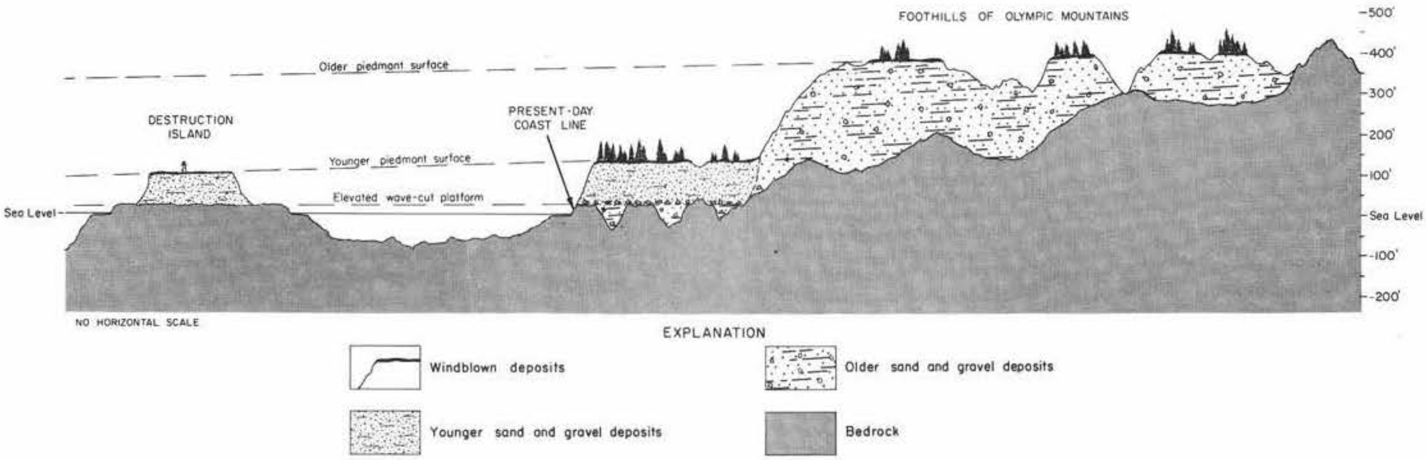
RED BEACH SANDS occur on many beaches along the coast. The color is caused by a concentration of small, 12-sided crystals of the mineral garnet. Because this mineral is relatively heavy, it, together with other heavy minerals, particularly the black magnetic mineral magnetite, tends to become concentrated by wave action as shown here near Hogsback. (Fig. 23)

SEASTACKS of sandstone north of Tunnel Island. These outcrops together with the sandstone of Tunnel Island and nearby cliffs north of the Raft River are all a lower part of the Quinault Formation. (Fig. 25)

deposited directly by glaciers. Such materials are called "till." In other places fine-grained deposits that contain large amounts of carbonized plant material were deposited in shallow lakes. These "lacustrine" deposits are well exposed in the low beach cliffs immediately north of Kalaloch (fig. 57).

The Pleistocene Epoch is commonly known as the "ice age." During this period of time, large areas of western Washington were glaciated on several occasions when average summer temperatures were about 10° F. colder than today. Periods of glaciation were separated by interglacial times when the climate was probably similar to that of today. Although major lobes of large ice sheets from Canada moved southward several times and covered much of the northern part of the Olympic Peninsula and the Puget Sound Lowland, only local alpine glaciers originating in the Olympic Mountains occupied the southwestern part of the Olympic Peninsula. The

TUNNEL ISLAND, off the mouth of the Raft River, is a relatively hard body of sandstone of the Quinault Formation. (Fig. 24)



IDEALIZED CROSS SECTION showing relations between major Pleistocene deposits and the land surfaces that were formed by periods of either erosion or deposition during the Pleistocene Epoch. Older deposits were thick and extended many miles seaward. Erosion by wave action followed, removing much of these materials from the present-day Continental Shelf. A second and thinner series of sand and gravel was brought down major stream valleys and deposited on the now uplifted wave-cut platform. These younger deposits also extended seaward, but less so than the older deposits. They have been eroded by wave action back to the present-day coastline, leaving Destruction Island as a remnant of the mainland that existed farther west a few thousand years ago. Following the deposition of the younger sand and gravel deposits and probably before much vegetation had developed, windblown silt and sand covered much of the coastal area to a depth of as much as 4 feet. (Fig. 26)

"Olympic" origin of these glaciers is shown by the kinds of rock debris laid down by the glaciers and the streams from the melting glaciers. Geologists have thus far concluded that the Olympic Mountains were occupied by glaciers at least four times. One or more of the older glaciers probably extended westward at least to our present-day coastline, particularly in the Hoh Valley area. However, the westward extent of the younger glacier was not as great. Even so, one of the last of the glaciers extended from the slopes of the Olympic Mountains westward to a point some 10 miles northeast of the Taholah-Point Grenville area, between 15,000 and 20,000 years ago.

ORIGIN OF SAND AND GRAVEL DEPOSITS

Most of the nearly horizontal semiconsolidated silt, sand, and gravel, visible in the cliffs between Point Grenville and the Hoh River, is rock debris that was brought down major valleys by streams and deposited along the coastal area probably 17,000 to 70,000 or more years ago. The uppermost surface of these deposits forms the broad, very gently westward-sloping surface that is conspicuous today in many places along the coast (fig. 1). This surface is known as a "piedmont alluvial plain." When first formed, it extended several miles farther westward than it does today, but much of it has since been removed by wave erosion back to the present coastline. The nearly flat surface on Destruction Island is the westernmost remnant of this piedmont surface (fig. 54).

Two major units of the sand and gravel deposits can be recognized readily along the coast between Point Grenville and the Hoh River. Outcrops of the older unit are confined to basal parts of some of the cliffs and are well exposed in three major areas: between Trail 5 and a point about one-half mile north of Beach Trail 7; from about three-quarters of a mile north of Abbey Island to near the Hoh River; and from about one-half mile south to nearly one-half mile north of the mouth of Whale Creek.

In some places stratification suggests that the older of the two deposits is slightly tilted whereas the overlying younger deposits appear nearly horizontal. This evidence suggests that slight warping of the older beds, as well as all strata below, took place before the overlying younger materials were deposited.

Ancient Wave-Cut Surface

The contact between the two major sand and gravel units is frequently marked by a layer of cobbles and large boulders (fig. 63). Their occurrence indicates that the older beds were eroded and beveled by the sea to form a wave-cut platform upon which the residual cobbles and boulders were left prior to the deposition of the overlying beds (fig. 26).

This surface is now elevated in places, relative to present-day sea level. Because the older deposits were laid down on a somewhat irregular bedrock surface, largely formed on the Hoh and Quinault Formations, the wave-cut surface in places also bevels across bedrock high areas. Therefore, the erosion that formed the wave-cut platform has removed all of the older sand and gravel deposits above most of the bedrock ridges or high places,

MODERN (PIDDOCK) CLAM BORINGS on the rock surface of a tide pool. Compare with fossil borings on uplifted tidal surface shown in figure 28. (Fig. 27)

but the older sand and gravel deposits still remain in valleys or low areas that existed on the bedrock surface. Thus, in areas where the bedrock surface stood relatively high, such as between Point Grenville and Cape Elizabeth and at Browns Point, the youngest or uppermost sand and gravel unit now rests directly on bedrock with no intervening older beds of sand and gravel. Furthermore, because the bedrock formations had differing resistance to wave erosion, rounded knobs or stacks were left in places along the coast above the main level of the wave-cut platform, just as Willoughby Rock and Split Rock stand above the sea-level bench being formed along the coast today.

Possibly the most convincing evidence that this uplifted erosional platform was formed at sea level is the abundance of rock clam borings still well preserved in its surface (fig. 28). These borings were made by the piddock clams, *pholadidea penita* (Conrad), a form of clam found today only in tidal areas (fig. 27). Borings, usually about 1½ inches in diameter, unmistakably of this origin, may be found in many places along the coast on this uplifted erosional platform at heights above today's sea level, varying from some 125 feet at Cape Elizabeth to just above high tide at the foot of Beach Trail 4.

CRUSTAL WARPING AND CHANGES IN SEA LEVEL

The earth's crust continued to buckle and warp throughout the Pleistocene Epoch just as it did during older geologic times. However, the results have been relatively minor and are confined mostly to broad warping and minor uplifting. The older beds of sand and gravel in places have been noticeably affected, but warping is hardly perceptible in a single outcrop of the younger beds of sand and gravel. Nevertheless, they too have been broadly downwarped. The axis of the downwarp lies in the Kalaloch area, where the old wave-cut platform lies below sea level and the top of the younger sand and gravel deposits (essentially the land surface of today at Kalaloch) is only some 50 feet above sea level. However, a few miles both to the north and south these surfaces are both noticeably higher.

Much of the vertical movement of the earth's surface relative to sea level during the Pleistocene is believed to have occurred largely as a result of depression and rebound caused by the weight of great thicknesses of ice on the continent. However, the relative vertical movement is further complicated by the fall or rise in sea level caused

FOSSIL (PIDDOCK) CLAM BORINGS preserved on an uplifted wave-cut surface of beveled sandstone strata exposed at the foot of Beach Trail 4—they were formed some 70,000 years ago during the Pleistocene Epoch. Compare with modern piddock borings common today in nearby tide pools, see figure 27. (Fig. 28)

by the formation or melting of the extensive continental ice sheets of the Pleistocene Epoch. The present-day elevated wave-cut platform separating the two sand and gravel units is one conspicuous example of sea level having been at a different relative position than it is today.

SUMMARY OF LATE CENOZOIC GEOLOGIC HISTORY

A period of emergence accompanied by moderate folding and faulting followed the deposition of the Pliocene Quinault Formation in the Washington coastal area of today. The Quinault Formation, as well as older rocks, was elevated well above sea level of that time and eroded by streams. A topography with considerable relief developed on these bedrock formations. Probably during early Pleistocene time, sea level along the Washington coast was lower than today because bedrock valleys formed at that time are known to be lower in places than the present-day sea level. However, these old valleys are now partially filled to present-day sea level, or higher, with sand and gravel deposits (fig. 26). Before this deposition began, however, sea level rose slightly so that the lower parts of the bedrock valleys were drowned to form shallow bays in which estuarine or bay sediments were formed. This was followed by much thicker and more extensive deposition of silt, sand, and gravel that was carried by the glaciers and the streams from melting glaciers. These materials probably were deposited some time prior to 70,000 years ago and blanketed the entire coastal area.

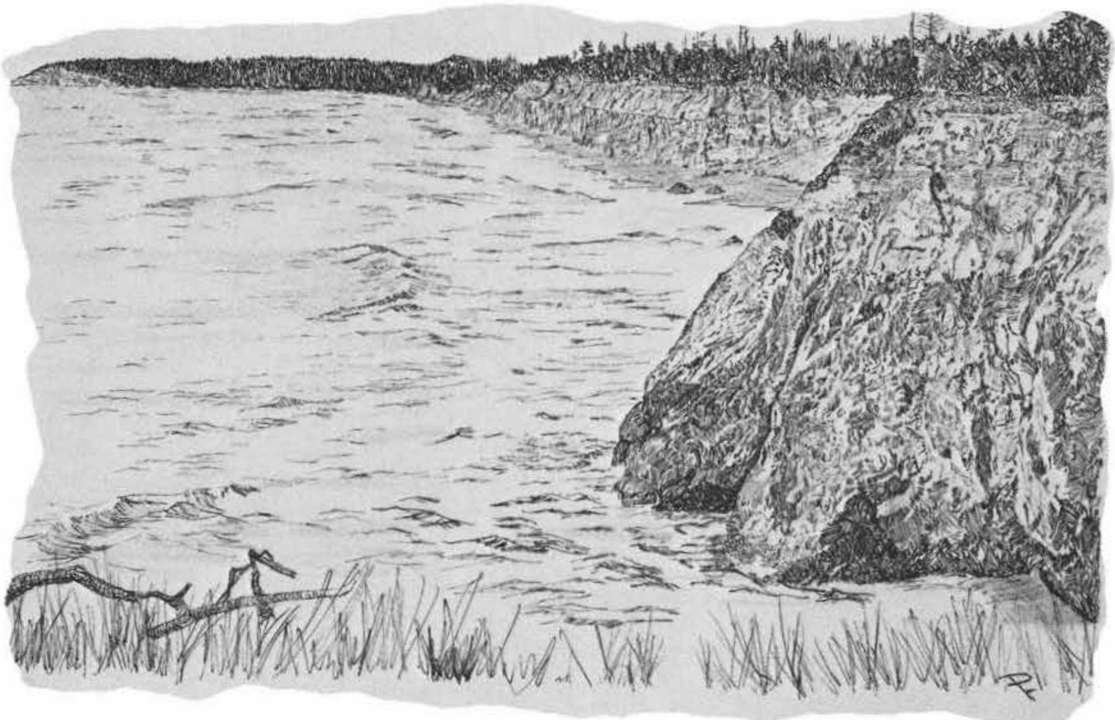
Remnants of the upper, nearly flat surface of these deposits can be seen today on top of some of the nearby foothills, particularly in the Taholah-Queets area, at an elevation of approximately 400 feet. This surface formed a broad piedmont plain with a very gentle seaward slope. At that time the coastline was many miles farther west than it is today.

Gentle warping of the earth's crust followed, together with a rise of sea level to a height of possibly 50 feet above present-day sea level. Waves cut a bench at that higher level, which extends eastward beyond the coastline of today to the western edge of the foothills. This marine erosion cut across ridges of the old bedrock and removed much of the earlier sand and gravel deposits, leaving undisturbed only those in the lower part of the old bedrock valleys. Beach deposits of residual boulders and cobbles were left strewn on the wave-cut platform.

Sea level was lowered once again to a point probably below that of today, leaving the wave-cut bench appreciably above sea level of that time. Stream deposits measuring more than 100 feet in thickness, together with some lake sediments, were deposited on this surface. Most of these sediments were brought down main valleys by melt water from alpine glaciers in the Olympic Mountains, probably 17,000 to 70,000 or more years ago. The top of these deposits formed another broad gently westward-sloping surface, some 200 feet lower than the older one, in the valleys, and over the wave-cut surface to the west. Well-preserved remnants of this lower surface form the top of Destruction Island and the generally 100- to 200-foot land surface immediately adjacent to much of the present-day coastline. At the time this surface was first formed, the coastline extended a number of miles farther to the west than it does today. Finally, fine-grained silt and clay, believed to have been carried and deposited by the wind, less than 17,000 years ago, blanketed all existing surfaces to a thickness of three or four feet. These materials form the yellow-colored sediments that are exposed today in the uppermost few feet of many of the cliffs along the coast.

Since the younger surface was formed, the sea has again eroded eastward a number of miles and formed another wave-cut bench essentially at present-day sea level. Thus, the coastline of today is, in places, as much as 200 feet below remnants of the youngest Pleistocene piedmont surface.

Very broad warping of the earth's crust has continued. Locally it has lowered the younger piedmont surface to within 50 feet of sea level near Kalaloch and elevated other areas to the north and south at least 150 feet above sea level. (Suggested technical reading about the Pleistocene in this and nearby areas: Baldwin, 1939; Crandell, 1964, 1965; Florer, 1972; Heusser, 1972; Moore, 1965.)



PART II

Geologic Observations and Interpretations Along Segments of the Coast

POINT GRENVILLE AREA

OLDER ROCKS

Point Grenville and the nearby sea stacks (fig. 1) are composed largely of volcanic rock, a material more resistant to erosion than most other rock formations along the coast. These rocks were formed many millions of years ago when hot magma was spewed onto an ocean floor from fractures in the earth's crust. The rapid cooling of the magma by sea water formed a highly fractured and glassylike igneous rock now poorly welded together with secondary minerals. These rocks are sometimes referred to as a "volcanic breccia." Some of the muds of the ocean floor were incorporated in the volcanic material and can now be seen, particularly on the southeast side of the point, as somewhat contorted and irregular beds of limy siltstone (fig. 31). Microscopic fossils from these siltstone beds indicate that they were deposited some 45 to 50 million years ago, in middle Eocene time (fig. 2). These fossils represent the oldest geologic record known in the rocks along the coast between this point and the Hoh River. Crustal movements have been nearly continuous, since the rocks of Point Grenville were formed, and therefore over the centuries they have become somewhat contorted. Today, these rocks are steeply tilted and form one of the major promontories along the Washington coast.

YOUNGER ROCK DEPOSITS

On top of the volcanic rock foundation of Point Grenville are deposits of nearly horizontal, poorly stratified, semiconsolidated sand and gravel. In places, they are at least 50 feet thick. These deposits are extensive in the coastal area and cover much of the older rock. They were deposited by the streams from glaciers that extended down the slopes of the Olympic Mountains during the Pleistocene Epoch, some 17 to 70 thousand or more years ago. Glaciers advanced several times into nearby areas, and during at least one advance they stood within some 5 miles of Point Grenville.

ANCIENT SEA LEVELS

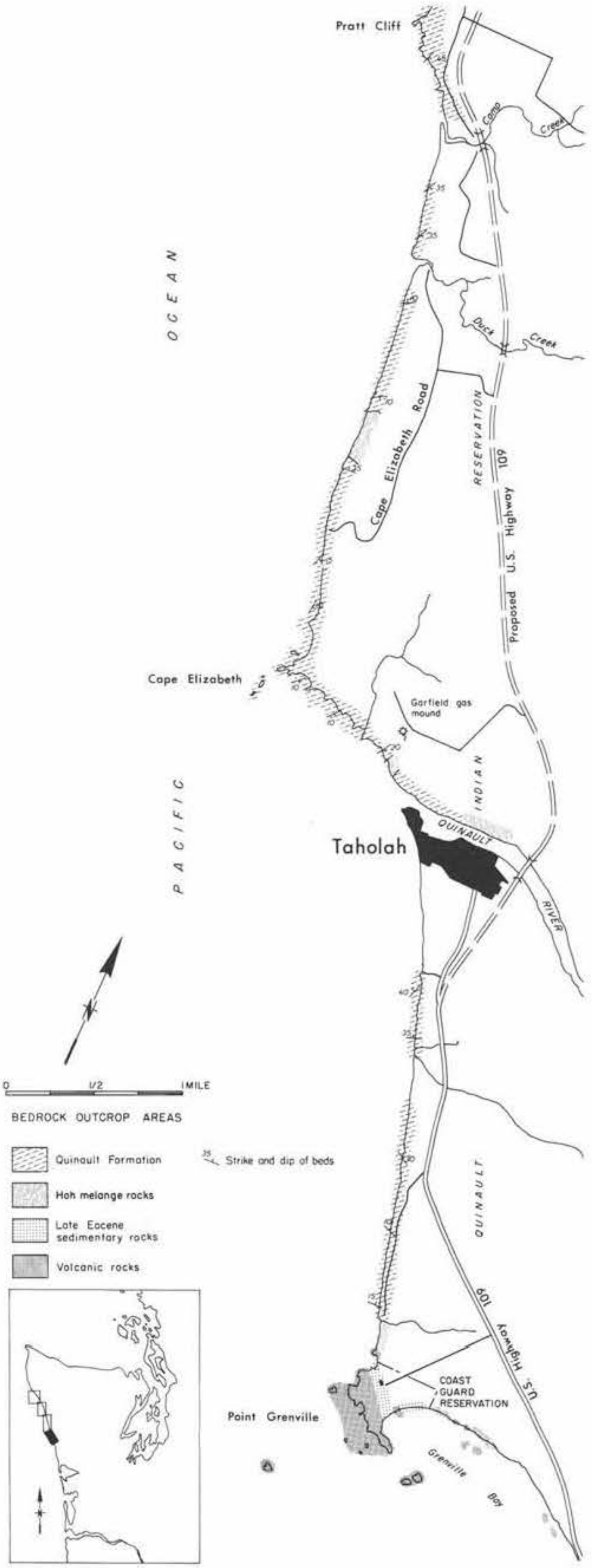
The uppermost, present-day, nearly flat surface on Point Grenville (fig. 1) slopes imperceptibly seaward, and, when first formed, extended seaward to sea level probably a number of miles to the west. Since then, some 17,000 or more years ago, wave action has eroded the coast eastward to its present-day position, leaving a wave-cut platform at essentially sea level of today. Evidence of an earlier wave-cut platform some 50 feet higher can be seen at the contact between the older rocks and the overlying sand and gravel. Borings formed by piddock clams, known to live only in tidal areas, are present on this uplifted bedrock surface at Point Grenville and many other places along the coast (fig. 28).

GRENVILLE BAY AREA

Eastward from Point Grenville, along Grenville Bay, bedrock is extensively broken and largely covered by landslide debris from overlying sand and gravel deposits. Those bedded sandstone and siltstone strata exposed for a few hundred yards immediately to the east of the main body of the Point Grenville volcanics are believed to have been deposited some 35 to 40 million years ago during late Eocene time (see Part I, Sedimentary rocks of late Eocene age). The remaining bedrock outcrops, consisting of conglomerates, sandstones, siltstones, and volcanic rocks, along the shore of Grenville Bay, are all tentatively referred to a much younger, although badly contorted, rock unit known as the Hoh rock assemblage (see Part I).

BETWEEN POINT GRENVILLE AND TAHOLAH

Northward from Point Grenville for at least a quarter of a mile (fig. 29) the cliffs are extensively slumped. In the first cove, immediately north of the main body of the Point Grenville volcanics, broken, well-bedded sandstones and siltstones of late Eocene age, similar to those exposed to the east in Grenville Bay, are exposed at the base of the slumped cliff.



POINT GRENVILLE TO PRATT CLIFF–Coastal Map. (Fig. 29)

JUMBLED ROCKS

The large volcanic boulders at the base of the small headland between the first and second coves are most likely resistant blocks from jumbled Hoh rocks. These and other similar deposits are sometimes referred to as a "tectonic melange" (see Part I, Tectonic melange of Hoh rock assemblage). They are comprised of broken and sheared claystone and siltstone in which resistant blocks, mostly of sandstone and volcanic rocks, are incorporated.

Apparently in recent years erosion by wave action has caused the boulders that form the base of this headland to move seaward, thus a landslide has formed in the overlying material. Note that the overlying sand and gravel deposits are dipping significantly to the east (fig. 35).

Northward from these boulders the cliffs of the second cove are also extensively slumped because they too are underlain by jumbled Hoh rocks. In places, where these deposits have been exposed to moisture, they have moved outward essentially as mudflows. Blocks of sandstone from the jumbled deposits can be seen in places at the base of the cliffs under the overlying slumped sand and gravel debris.

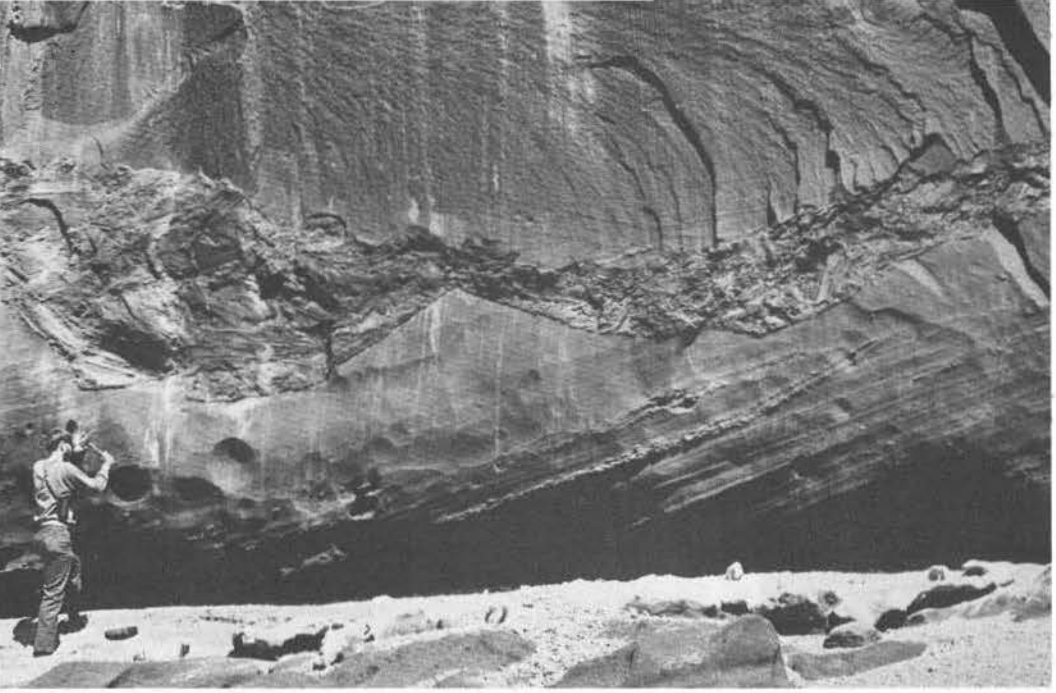
SANDSTONE STRATA OF THE QUINAULT FORMATION

An abrupt, nearly vertical cliff of sandstone forms the north edge of the second major cove some quarter of a mile north of the volcanics of Point Grenville (fig. 29). Here Hoh rocks are in fault contact with the gently dipping sandstone beds of the Quinault Formation. These sandstone beds were deposited in the sea during the Pliocene Epoch, about 7 to 1.5 million years ago (fig. 2). Because the Quinault Formation is much younger than the underlying rocks, its strata have undergone only moderate tilting compared to the highly folded and contorted older rocks. Sandstone and siltstone beds of the Quinault Formation are exposed in several major and continuous outcrops from this point northward to Taholah beneath a 50- to 100-foot thickness of the same relatively young sand and gravel deposit that caps Point Grenville.

The southernmost of these sections of continuous outcrops begins at this contact with Hoh rocks and extends northward for nearly 1 mile. The strata are mostly sandstones and are gently dipping in a northeastwardly direction. This sequence of beds is at least 500 feet thick.

Fossils and Sedimentary Features

A marine origin for these beds is indicated by the presence of fossil remains of marine organisms such as clams and snails, together with microscopic fossils of Foraminifera (fig. 13). Paleontologists have further determined from these fossils that the sandstone beds were deposited in relatively cool water. The geologic age (Pliocene) of these strata has also been determined by fossils.



CROSS SECTION OF SCOUR AND FILL STRUCTURES exposed in the sea cliffs of the Quinault Formation north of Point Grenville. The erosion of these and other channels represent a short break in the depositional record. They were subsequently filled rapidly with coarse rock debris from the formation. This was followed by the deposition of the overlying massive sand above. (Fig. 30)

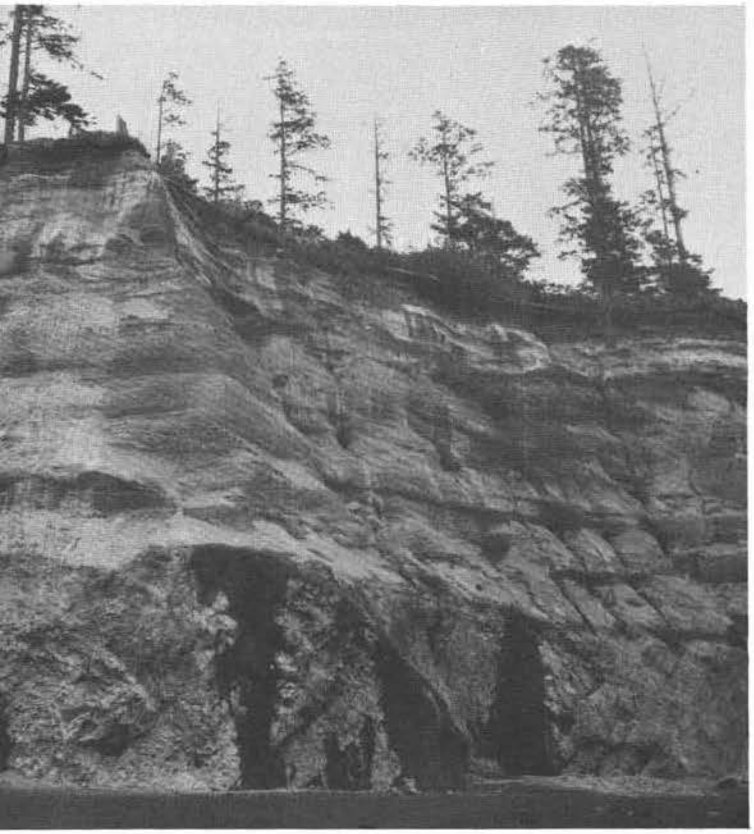
Particularly well-developed features of ancient sedimentation are excellently preserved in these strata. Evidence of alternating conditions of deposition and erosion by local currents can be seen at several levels. Cross sections of channels that were scoured by local currents while the sediments were still semiconsolidated are now seen filled with broken parts (sand, pebbles, and some shell fragments) of the Quinault Formation (fig. 30). Such conditions suggest an environment on or near a delta or similar setting where shifting deposits and channel scouring takes place. Many other sedimentary structures that were formed during or shortly after deposition also can be seen in these cliffs (fig. 15).

Landslide Area

Northward along this outcrop area the Quinault Formation becomes fine grained and thin bedded. At its northern end, a mile or so north of Point Grenville, the rocks are largely thin-bedded siltstone with only minor amounts of very thin beds of sandstone.

From this area northward for over a quarter of a mile, landslides are prevalent in both the Quinault Formation and overlying younger deposits of sand and gravel (fig. 33). Large rotated blocks of sand and gravel have moved out and downward from their original position. Trees and

SILTSTONE INTERBEDDED WITH VOLCANIC ROCKS at Point Grenville. The contorted light-colored layers are calcareous. Because they are generally harder than the surrounding materials, they weather out as irregular nodules. (Fig. 31)



MASSIVE SILTSTONE OF THE QUINAULT FORMATION (the darker colored basal part of the cliff) beneath a thickness of nearly 100 feet of late Pleistocene outwash sand and gravel, exposed in the cliffs about 1 mile south of Taholah. The contact between the two formations is an elevated wave-cut surface that was carved by the sea during the Pleistocene Epoch prior to the deposition of the overlying deposits over 70,000 years ago. (Fig. 32)

other vegetation on these blocks are now tilted, creating a "drunken forest." In places, siltstone of the Quinault Formation also can be seen in discontinuous outcrops at the base of the cliffs and on the beach at low tide. Slumping in this area is most likely due to the structural weakness of siltstone of the Quinault Formation that crops out in this particular area. Unstable conditions created along a continually eroding coastline make these relatively soft rocks somewhat susceptible to landsliding.

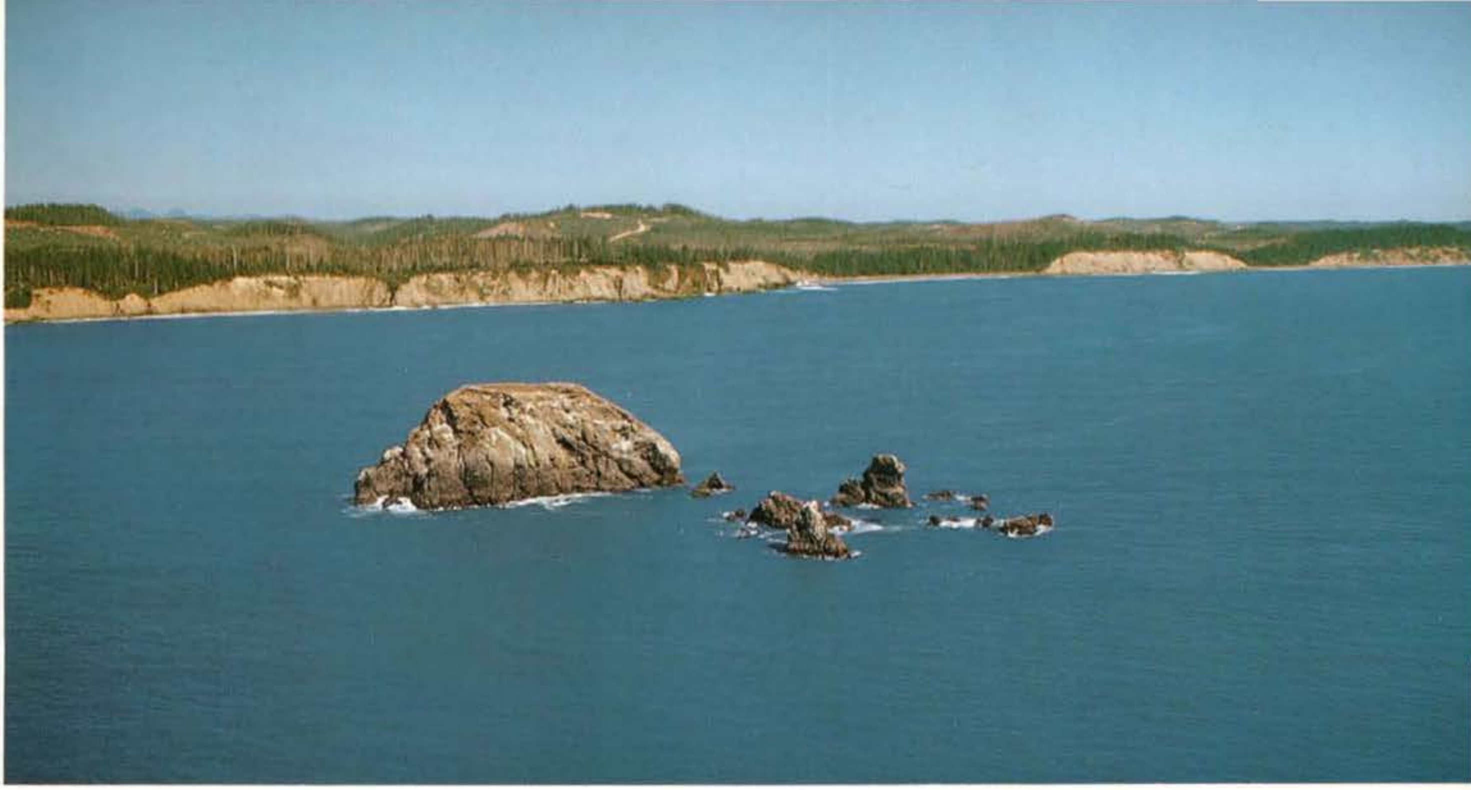
SAND AND GRAVEL OF THE ICE AGE

Along the next quarter of a mile or so northward to the mouth of a major stream (fig. 29), only deposits of sand and gravel are exposed in the sea cliffs. They are the same Pleistocene glaciofluvial materials that overlie the older bedrock along the coast from Point Grenville to this area.

SILTSTONE OF THE QUINAULT FORMATION

Continuing northward and ending abruptly about three-fourths of a mile south of Taholah, the Quinault Formation is again exposed almost continuously for nearly an additional one-half mile in the basal 50 feet of the cliffs (fig. 29). Here, the formation is largely massive to vaguely bedded siltstone and is gently tilted to the north (fig. 32). Occasionally beds of sandstone are present and fossil remains of clams and snails, together with tiny Foraminifera, are common. A total thickness of nearly 1,000 feet of continuous deposition is represented in this tilted sequence of sedimentary rocks. The fossils suggest to paleontologists that these strata were deposited in cold, fairly deep water (see Part I, The Quinault Formation, south of Taholah).

A MAJOR LANDSLIDE AREA about 1 mile north of Point Grenville. For nearly a quarter of a mile, large blocks of sand and gravel have moved seaward and rotated the land surface so that trees are variously tilted to form a "drunken forest." Structural weakness of underlying massive siltstone of the Quinault Formation is probably the cause of the landsliding in this area. (Fig. 33)



WILLOUGHBY ROCK, a resistant remnant of the Hoh rock assemblage, as it appears from the air. The Quinault Formation forms the high cliffs along the coastline. Pratt Cliff extends from the left to center; Camp Creek is in the wide low area; and the Duck Creek valley is the small low area on the right. (Fig. 34)

Sand and gravel deposits overlying the bedrock in places reach a thickness of nearly 100 feet. Locally, some 30 feet from the top of the cliff, a zone of silt can be seen that contains large amounts of plant material including remains of logs and stumps. These materials represent an intermittent period of lake or swamp (lacustrine) deposition. Wood samples from this bed were radiocarbon dated and found to be over 30,000 years old.

TAHOLAH SANDSPIT

From the north end of the Quinault Formation outcrop area to the Quinault River, a distance of nearly a mile, only Recent deposits of beach sand are exposed. The retention and further accumulation of these sediments has been aided by an artificial levee built some years ago.

A LANDSLIDE immediately north of Point Grenville in Pleistocene deposits of sand and gravel underlain by large volcanic boulders of Hoh rocks. Note that the normally horizontal Pleistocene strata are now dipping significantly to the east. The underlying boulders most likely moved seaward when they were undercut by erosion, enough to cause the overlying materials to be tilted eastward. (Fig. 35)

PRATT CLIFF, where gently southward-dipping strata of the Quinault Formation are well exposed but inaccessible from the beach. The nearly flat land surface on bedrock of the Quinault Formation represents an old uplifted wave-cut surface that was formed at sea level sometime during the Pleistocene Epoch. (Fig. 36)

JUMBLED HOH ROCKS in the low-lying area on the right in contact with a fault scarp formed on the more resistant, gently dipping sandstone and conglomerate beds of the Quinault Formation on the left. This outcrop is exposed along the coast about one-quarter of a mile north of the mouth of the Quinault River. (Fig. 37)

TAHOLAH TO CAPE ELIZABETH

NORTH SIDE OF QUINAULT RIVER AT TAHOLAH

North of the Quinault River, immediately across from the town of Taholah and eastward nearly to the highway bridge, Hoh rocks are exposed in scattered outcrops along the riverbank, and occasionally in the heavily vegetated bluffs above. In this area most of the outcrops appear to be resistant blocks of sandstone. They are most likely from deposits of intensely jumbled rock (see Part I, Tectonic melange of the Hoh rock assemblage).

Westward from these outcrops of Hoh rocks and across the river from Taholah, the younger Quinault Formation is again exposed in the low-lying cliffs for a distance of about one-half mile. Here, the formation is largely a massive siltstone, similar to that exposed in areas south of Taholah. Because this siltstone is structurally weak, a number of landslides have developed and therefore drunken forests are common in this area too. Young deposits of sand and gravel also overlie these outcrops of the Quinault Formation.

About a quarter of a mile northwest of the mouth of the Quinault River the Quinault Formation is in contact with the underlying dark-gray, slumped, and completely jumbled Hoh rocks. Here, the Hoh rocks are so broken and structurally weak that they are flowing outward much as a mudflow. Freshly broken pieces of siltstone from this outcrop usually produce a distinct petroliferous odor. The outcrop area of these rocks extends westward for about 200 yards where it ends abruptly against a nearly vertical north-trending fault scarp formed by more resistant and gently dipping beds of sandstone and conglomerate of the Quinault Formation (fig. 37).

GARFIELD GAS MOUND

The Garfield Gas Mound, one of the few natural gas seeps in Washington State, lies in the woods about one-quarter of a mile north of the beach near the mouth of the Quinault River. It measures several hundred feet in diameter and rises some 50 feet above the surrounding terrain. This mound has been built up, over the years, from the extrusion of mud from a small vent located near the top. Natural gas (largely methane) bubbles from this mud-filled vent. In 1913, two oil test wells were drilled nearby to depths of 560 feet and 820 feet, but no petroleum was produced. Equipment used in these operations can still be seen in the woods (fig. 38). The gas undoubtedly is derived from Hoh rocks, and may possibly be seeping up along the fault seen on the beach between Hoh rocks and the Quinault Formation to the west.

REMAINS OF A BOILER, used in connection with unsuccessful drilling operations for petroleum in 1913, located in the woods a short distance north of Taholah. Fire wood, badly rotted but still recognizable, is stacked nearby. Small amounts of gas still bubble from the wellhead a short distance away. (Fig. 38)

GENTLY DIPPING SANDSTONE AND CONGLOMERATE BEDS of the Quinault Formation exposed in the high vertical cliffs northward from Cape Elizabeth. (Fig. 39)

CONGLOMERATES OF THE QUINAULT FORMATION

Sandstone and conglomerate beds of the Quinault Formation are in fault contact with the small outcrop of jumbled Hoh rocks that is exposed along the coast just north of the mouth of the Quinault River (fig. 29). This gently southeastwardly dipping series of beds is some 1,600 feet thick. It is continuously exposed from the contact with Hoh rocks northwestward to and including Cape Elizabeth, forming the high cliffs and rocky beaches of this area (fig. 17). The sequence also extends northward up the coast forming particularly high cliffs for nearly 1¼ additional miles (fig. 39). At its northernmost extent the lower part of the sequence is also in fault contact with Hoh rocks. This large, continuously exposed sequence of the Quinault Formation is the youngest known part of the formation (fig. 14) and most likely was deposited during the latter part of the Pliocene Epoch, perhaps some 2 to 5 million years ago (fig. 2).

Along the beach north of the Quinault River and westward to the Cape, the formation is largely conglomerate with some sandstone and minor amounts of siltstone. The surfaces between these major rock types are frequently irregular or channeled, indicating a varying environment of shifting deposition and local current erosion. Much carbonaceous material occurs throughout the rocks. In places large concentrations of coalified limbs, logs, and even stumps can be seen (fig. 16). Marine fossils are extremely rare occurring mostly in rocks near the Cape and northward. The lack of marine fossils in the eastern (upper) part of this sequence suggests that the materials may well have been deposited on land but perhaps immediately adjacent to the sea. Marine fossils, although rare, in the middle and lower (northern) part of the sequence indicate deposition in the sea, but almost certainly in a very shallow environment, perhaps tidal or, in places, slightly deeper. Overall, this sequence of generally coarse sedimentary rocks probably represents the last stages of the gradual filling of a marine basin. The final beds probably were deposited by streams above sea level.

DIFFERENTIAL EROSION

Excellent examples of the effects of erosion by wave action and other agents on different rock types can be seen westward to and particularly at Cape Elizabeth. Resistant beds of gently dipping conglomerate form many ribs on the wave-cut tidal flats. Several minor promontories, largely of conglomerate, extend out from the general line of the cliffs. It is interesting to note the amount of change these promontories have undergone

SANDSTONE AND CONGLOMERATE CLIFFS of the Cape Elizabeth area. This photo was taken about 1900. (Courtesy of the Washington State Historical Society.) Compare with figure 41, the same view taken in 1972. (Fig. 40).

over the years. Figure 40 was photographed about 1900 in the Cape Elizabeth area, and figure 41 was taken from nearly the same place in 1972. Probably the most striking change at Cape Elizabeth over the past 70 years has been the development of a wide gap as seen today and shown in figure 43, from what used to be a large natural arch as shown in figure 44.

Remnants of resistant beds of Cape Elizabeth extend seaward in a southwesterly direction forming the offshore Sonora Reef. It was behind this sandstone and conglomerate reef that Cuadra on July 13, 1775 took precarious shelter in his small (36-foot-long) schooner, the Sonora.

RECENT UPLIFT

The cliffs are particularly high in the Cape Elizabeth area, reaching a height of some 200 feet in places. The same deposits of sand and gravel that occur along the coast to Point Grenville form the upper 30 to 50 feet in the cliffs of the Cape Elizabeth area. Today's generally flat land surface on top of these deposits some 200 feet above sea level was developed largely as a piedmont surface some 17,000 years ago. Here this surface is about 100 feet higher than it is in the area to the south. Furthermore, the trace of the old wave-cut surface, formed on bedrock and on which the sand and gravel now rests, is also higher in the cliffs of this area than to the south. Therefore, because both the depositional surface on top and the erosional surface below are higher locally, geologists conclude that over the past thousands of years these rocks have been elevated in the Cape Elizabeth area by the gentle warping of the earth's crust.

CAPE ELIZABETH TO DUCK CREEK

HIGH CLIFFS OF THE QUINAULT FORMATION

Northward from Cape Elizabeth for about 1¼ miles the Quinault Formation continues to outcrop in very high cliffs (fig. 39). Younger sand and gravel deposits above are relatively thin, in places only two or three feet thick.

Immediately north of the main promontory of Cape Elizabeth another sea arch has formed in a small sandstone and conglomerate point. Although today it is possible to walk upright through this arch, in 1900 only a small hole existed, barely large enough for crawling space. The nearby sea stack may well have been attached at one time to this point. Perhaps an arch existed here sometime in the past, also.

Northward, the sandstone and conglomerate beds of the Quinault Formation dip gently eastward into the cliffs. Sandstone becomes prevalent northward (down section) and some siltstone beds begin to appear. The several small headlands occurring in this area are relatively thin beds of resistant conglomerate and represent the lowest conglomerate beds in this part of the Quinault Formation.

About 1 mile north of Cape Elizabeth the Quinault Formation is largely siltstone and fine-grained sandstone. Major landslides have developed in these relatively incompetent rocks for a distance northward of nearly a quarter of a mile.

LOOKING NORTHWEST-WARD AT CAPE ELIZABETH, 1972. Erosion on these sandstone and conglomerate beds over a period of some 70 years has made a marked difference in this view (compare with figure 40). Note the changes in Cape Elizabeth in the background as well as the smaller point in the foreground. The gap in the nearby point did not exist in 1900. Furthermore, the main part of the adjacent cliffs appears to have receded noticeably landward. (Fig. 41)

JUMBLED DEPOSITS OF HOH ROCKS

Landslide outcrops of the Quinault Formation are terminated to the north at a fault contact between this formation and jumbled, darker colored, and older Hoh rocks (fig. 53). From this point northward for over a quarter of a mile, a completely chaotic mixture of broken and squeezed siltstone, together with blocks of more resistant rocks, form the slumped cliff outcrops (fig. 42). Bedded sandstone and siltstone, massive sandstone, and altered igneous rocks are common among the resistant blocks. Much slumping has occurred along the cliffs of this area. In places the materials have moved down the cliffs as mudflows. The many large boulders resting on the beach and the nearby offshore reefs are blocks that have resisted erosion, while the cliffs have receded eastward.

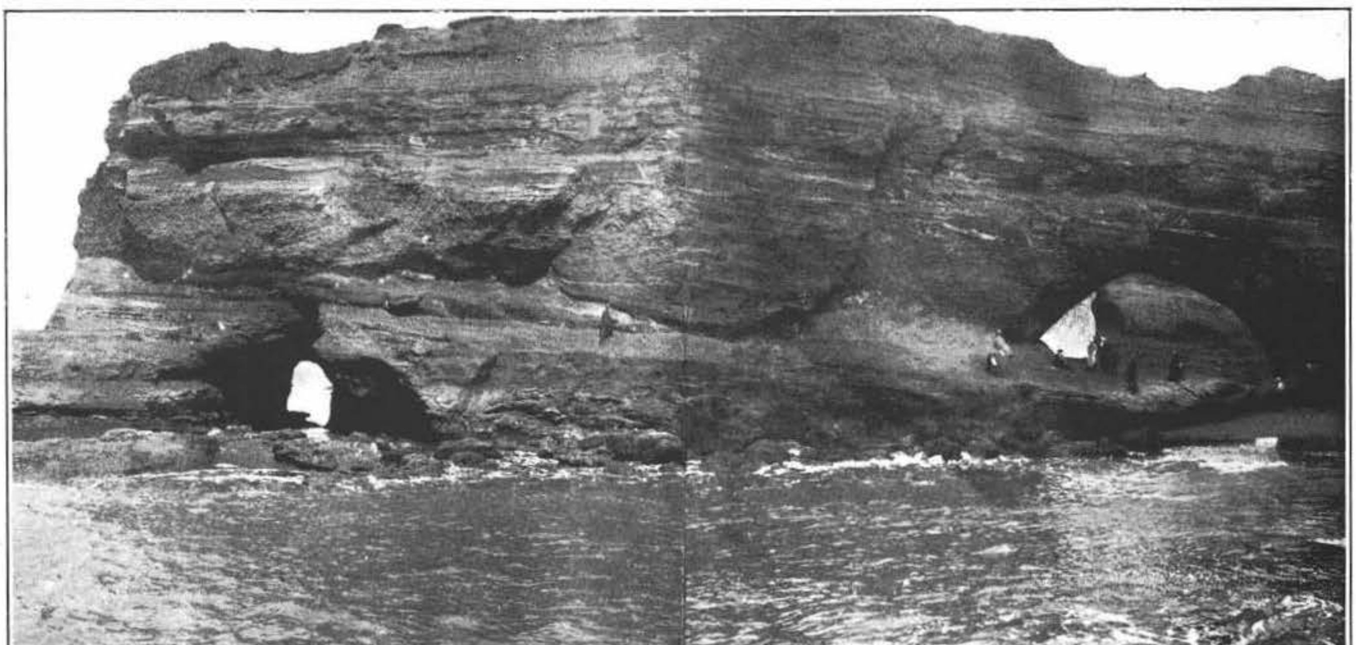
This outcrop area is of particular interest to geologists because it is believed to expose a geologic structure similar to many others that have been delineated recently by geophysical exploration offshore in the subsurface of the Continental Shelf (fig. 12). These structures are referred to as "piercement structures". The jumbled materials visible in this quarter of a mile of outcrop are believed to have been squeezed upward into the younger Quinault Formation, here exposed adjacent to Hoh rocks both to the north and south. Erosion has removed any of the younger formation that might have been domed over the "plug" of jumbled materials (see Part I, The Hoh rock assemblage, Piercement structures).

CONTORTED DEPOSITS OF HOH ROCKS about three-quarters of a mile south of Duck Creek. Note the contact between Hoh rocks and the more resistant and upturned sandstone beds of the Quinault Formation on the right. Disarranged Hoh rocks are believed to have been squeezed upward deforming the overlying Quinault Formation. (Fig. 42)

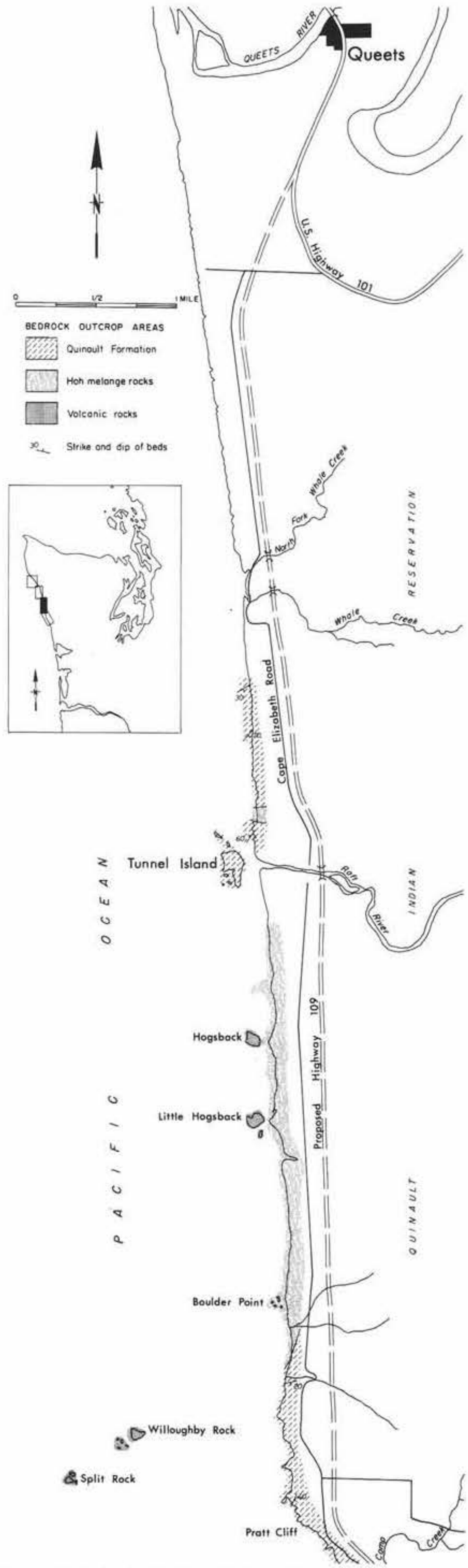
LOOKING NORTHWARD AT CAPE ELIZABETH, 1970. Since 1902, the large arch on the right in figure 44 has become a wide gap. Note the large boulder on the floor of the present-day gap, a remnant of the conglomerate roof of the old arch. (Fig. 43)

UPWARPED QUINAULT SILTSTONE, SOUTH OF DUCK CREEK

Siltstone beds of the Quinault Formation are continuously exposed in the cliffs northward from the jumbled Hoh rocks nearly to the mouth of Duck Creek, a distance of about three-quarters of a mile (fig. 29). The cliffs in the first few hundred yards northward of the Hoh deposits are badly slumped just as they are immediately south of the Hoh rocks. Northward to Duck Creek the Quinault Formation contains numerous fossils. Foraminifera are particularly abundant. In addition, many small sedimentary structures can be seen in individual beds which indicate much disruption or local churning of the sediments prior to consolidation (fig. 20). Most of this was likely accomplished by burrowing marine organisms. In traversing past these outcrops from south to north, note that the direction in which the strata are tilted changes from a south-southeast direction to an eastward direction; then, finally in the area immediately south of Duck Creek, the beds dip in a northerly direction. Structurally, in this distance of three-quarters of a mile, the traverse crosses an eastward plunging "anticline" (an upward arched fold) in the Quinault Formation, the top of which has been beveled or removed by erosion.



A VIEW TAKEN ABOUT 1902 looking northward at sandstone and conglomerate strata of Cape Elizabeth. Compare with present-day view shown in figure 43. Photo from Washington Geological Survey Bulletin no. 13. (Fig. 44)



PRATT CLIFF TO THE QUEETS RIVER–Coastal Map. (Fig. 45)

DUCK CREEK TO PRATT CLIFF

Immediately north of the mouth of Duck Creek, siltstone beds of the Quinault Formation crop out again and are continuously exposed in the cliffs nearly to Camp Creek (fig. 29). These strata all dip generally to the southeast some 35° and represent a thickness of over 1,000 feet of marine deposition that took place during the Pliocene Epoch, some 1.5 to 7 million years ago. This interval of sedimentary beds constitutes an upper part of a nearly 2-mile-long, almost continuously exposed section of the Quinault Formation, a total thickness that is estimated to be over 4,500 feet. With the exception of a covered interval at the mouth of Camp Creek, the formation is continually exposed along the coast to a point about three-quarters of a mile north of Pratt Cliff (fig. 45).

North of Camp Creek and extending to the south end of Pratt Cliff, siltstone beds are steeply dipping in a continuous sequence that measures more than 500 feet in thickness. These strata are similar to those exposed immediately south of Duck Creek. Most are massive to faintly bedded. Fossils are generally common and scattered throughout. In many places individual bedding has been disrupted by organisms as is apparent south of Duck Creek.

PRATT CLIFF

For a distance of nearly one-half mile the beach is inaccessible in the Pratt Cliff area (fig. 36). Even during low tide the surf pounds directly on these cliffs. Therefore, it is practically impossible to inspect these rocks closely. However, offshore observations from the air have verified that here too the rocks are largely siltstone and crop out to the top of the cliffs, some 100 feet in height. Furthermore, the strata uniformly dip rather steeply to the southeast in a similar direction as those exposed immediately to the south. Calculations indicate that some 1,400 feet of additional thickness of the Quinault Formation is represented in those tilted beds exposed in the Pratt Cliff area.

UPLIFTED WAVE-CUT TERRACE

From a distance, the Pratt Cliff area appears nearly flat. This surface is a remnant of an old wave-cut sea level surface formed during the Pleistocene Epoch at a time when sea level stood higher relatively than it does today. It may well be the same wave-cut surface that is visible in many other places along the coast, varying in height from nearly sea level at Browns Point to over 150 feet above present-day sea level in the Cape Elizabeth area. In most places, such as between Cape Elizabeth and Point Grenville, this surface is buried beneath sand and gravel deposits and only its trace can be seen in the cliffs at the contact of the older formations with the overlying sand and gravel. However, at Pratt Cliff, very little, if any, sand and gravel cover remains; and therefore the present-day surface is essentially the old Pleistocene wave-cut surface that was formed over 70,000 years ago. Variations in its height above the present-day sea level is thought to be due to slight warping of the earth's crust since the wave-cut surface was formed.

NORTH OF PRATT CLIFF

North of the inaccessible part of Pratt Cliff, the Quinault Formation is exposed in the sea cliffs for a distance of about three-quarters of a mile (fig. 45). This section of beach can be approached only from the north because of impassable Pratt Cliff and then only during low tide because of several headlands. In this interval the Quinault Formation also dips generally in a southeast direction. A thickness of some 900 feet of the formation is exposed in these cliffs and in tidal areas. Here, many of the beds are sandstone, varying from fine grained and thin bedded to medium grained and thick bedded. Sandstone is particularly prevalent in the middle and upper (southern) part of the section, whereas the lower or northern part is largely siltstone. Fossils are scattered throughout this sequence of beds and are particularly common in the lower or siltstone part.

Concretions or resistant nodules and irregular resistant layers are common in the upper or southern part of this sequence. A greater amount of calcium carbonate or limy material cements these structures and, therefore, they are more resistant to erosion than the surrounding sandstone.

Numerous pear-shaped resistant nodules can be seen in the sandstone beds of the central part of this traverse (fig. 19). These peculiar structures range from 4 to 8 inches in length and are always oriented with their long axis perpendicular to the bedding plane. All appear to have a central core of slightly harder and different colored material. They may have been cavities originally formed in the sand before consolidation, and perhaps were made by the burrowing of marine organisms. Subsequently, these cavities were filled with additional sediment before the formation became lithified. The greater resistance to weathering of these nodules is due to a cementing material left behind, possibly by the organism that formed the hole. This material has since penetrated outward to serve as a cementing agent in the surrounding areas.

Many of the individual beds, particularly in the siltstone part near the northern end of the outcrop area, as in the Duck Creek area, are disrupted or appear to have been churned by burrowing marine organisms (fig. 20).

The base of this major sequence of the Quinault Formation is well exposed in a low-lying cliff about three-quarters of a mile north of Pratt Cliff (fig. 18). Here the Quinault Formation is in contact with dark-gray colored chaotically mixed Hoh rocks. The actual contact is generally delineated by color contrast between the two rock units.

THE HOGSBACKS AREA

JUMBLED HOH ROCKS

One of the largest continuous outcrops of jumbled Hoh rocks to be seen along the Washington coast is exposed from the contact of the Quinault Formation, about three-quarters of a mile north of Pratt Cliff to within about one-half of a mile south of Raft River, a distance of some 2½ miles (cover photo and fig. 45). This outcrop is a classic example of the extreme effects of crustal deformation; the results are referred to as a "tectonic melange" (see Part I, Tectonic melange of Hoh rock assemblage). Here, much like the outcrop area of Hoh rocks exposed south of Duck Creek, the materials forming the cliff are a chaotic mixture of completely broken siltstone in which are set a variety of more resistant blocks (fig. 4). Such intensely jumbled rocks are generally believed to have been deformed into their present chaotic condition by major forces generated by the continued movement of large segments of the earth's crust. These forces have caused much folding, faulting, and jumbling, possibly, in part at least, by mass slumping of large segments of the sediments on the sea floor. These forces have continued periodically since the rock materials were deposited, and although not as active today as in the past, movement that is not always perceptible still goes on. Earthquakes locally felt on occasion are the result of sudden movements of the earth's crust, and serve to remind us that the earth's crust is indeed active.

Paleontologists have determined from microscopic fossils found in siltstones of these deposits that some of the sediments were deposited in a deep marine basin during a middle to early part of the Miocene Epoch, some 15 to 22 million years ago. Because this formation is so intensely broken and many of the clay minerals it contains tend to swell when they are moistened, it is particularly vulnerable to erosion by ocean waves during high tides and by winter storms. Much precipitation in this area further contributes to the erosion process.

Although resistant blocks are scattered throughout this 2½ miles of outcrop, a concentration of particularly large boulders have been eroded out of the melange and now rests on the beach at Boulder Point (fig. 10). A variety of rock types are present among these boulders, representing a number of different environments of origin. Many are altered sandstone and other sedimentary rocks and a few are volcanic in origin.

Willoughby Rock (fig. 34) and Split Rock (fig. 48), the two small islands a mile or so offshore from this area, are also very large resistant blocks that were once in the jumbled deposits of Hoh rocks. As the coastline receded slowly eastward, they were left behind, protruding above the general surface of the Continental Shelf, as well as present-day sea level.

LITTLE HOGSBACK

Northward to Little Hogsback, jumbled Hoh rocks are continuously exposed in the cliffs. At a point about one-quarter of a mile south of Little Hogsback, bedded sandstone and siltstone crop out that are more nearly intact than the deposits to the south, but nevertheless they are tightly folded and extremely contorted.

Like Willoughby Rock and Split Rock, Little Hogsback (fig. 49) is a particularly large block of relatively hard material that has been differentially eroded from the softer, less resistant clays and siltstones of the "melange" deposits. It, too, will soon be an isolated island. The rock of Little Hogsback is volcanic in origin, quite unlike the marine sedimentary rocks in which it was incorporated. A contact between well-bedded sedimentary rocks and volcanic rocks can be seen on the southeast side of Little Hogsback.

Immediately north of Little Hogsback, steeply dipping well-stratified sandstone, siltstone, and conglomerate are exposed on the beach and in the cliff (fig. 46).

Although very little unconsolidated sand and gravel overlies Hoh rocks immediately south of Little Hogsback, northward to the Raft River valley these deposits thicken to as much as 25 feet.

HOGSBACK

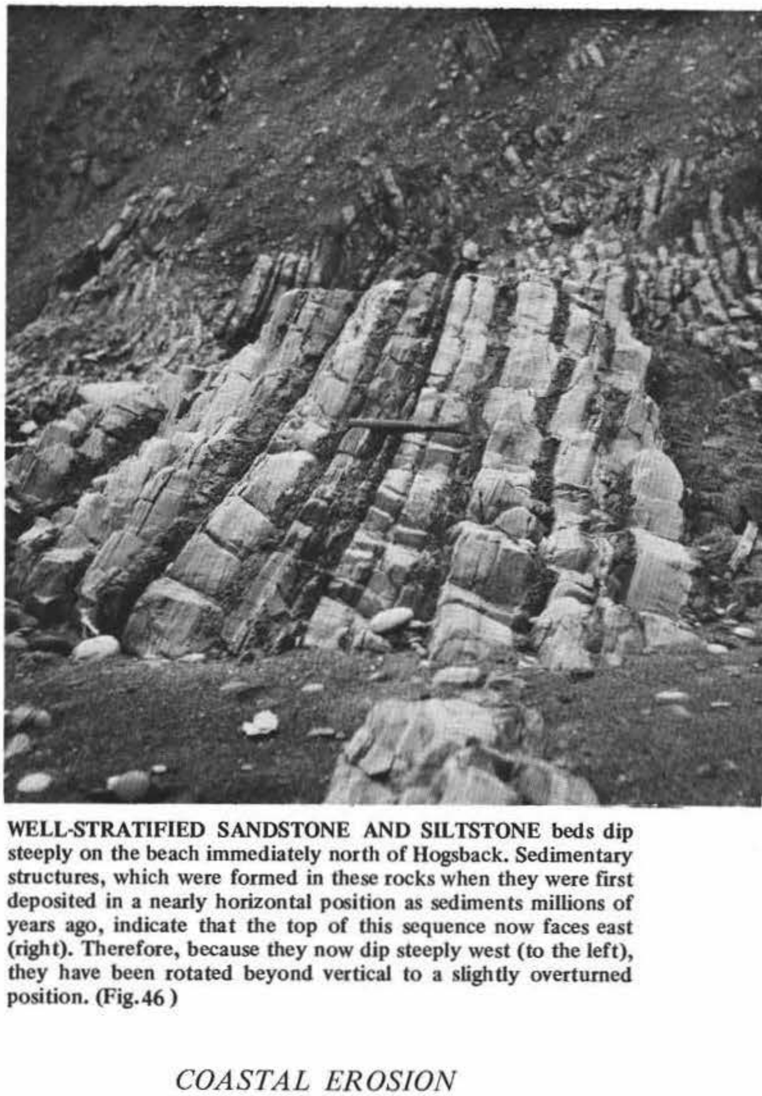
Jumbled Hoh rocks extend northward to the Hogsback, forming most of the cliffs of that area. A particularly large accumulation of resistant blocks eroded from the Hoh melange rests on the beach a short distance south of the Hogsback. These are also volcanic in origin and are largely breccia or angular fragments of volcanic materials that have been welded together.

Hogsback (fig. 5) also is welded brecciated volcanic fragments but, in addition, it contains some fragments of siltstone and other sedimentary rock types. A steeply dipping fault surface can be seen on the south side between the softer parts of the formation and the volcanic rock of Hogsback.

Mineralized Veins

Large veins of calcite are present in the volcanic rocks of Hogsback. In most cases, the mineral has crystallized in a form known as "nailhead spar." In addition, very small quartz crystals have formed on the surfaces of many of the calcite crystals. These quartz crystals can be identified by their six-sided elongated shape. Formation of these mineralized veins took place sometime after the volcanic "host" rock was fractured. Then, by the slow precipitation of calcium carbonate, these fractures were filled. In areas where well-formed crystals remain, the fractures never became completely filled with calcite. Apparently the last ground water to percolate through the crystal-coated cavities was rich in silica, some of which precipitated out of solution adding the coating of small quartz crystals.

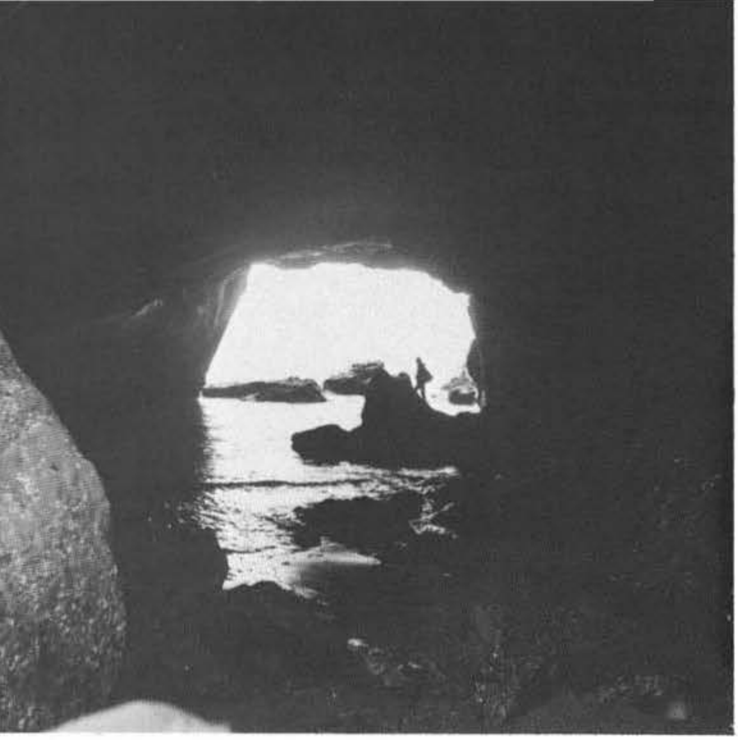
Jumbled Hoh rocks extend for about three-quarters of a mile northward from Hogsback, forming the lower part of the cliffs and tidal outcrops. Large sandstone blocks are common immediately north of Hogsback, and another large block of volcanic rock forms a stacklike feature a short distance beyond. Cliff outcrops of Hoh rocks end at the south edge of the Raft River valley, about one-quarter of a mile south of Tunnel Island.



WELL-STRATIFIED SANDSTONE AND SILTSTONE beds dip steeply on the beach immediately north of Hogsback. Sedimentary structures, which were formed in these rocks when they were first deposited in a nearly horizontal position as sediments millions of years ago, indicate that the top of this sequence now faces east (right). Therefore, because they now dip steeply west (to the left), they have been rotated beyond vertical to a slightly overturned position. (Fig. 46)

COASTAL EROSION

Natural processes of erosion have been active on this shoreline for many thousands of years and most likely will continue to be so for some time to come. Sea cliffs of jumbled Hoh rocks, like those in the Hogsbacks area, are particularly susceptible to wave action of the sea. Just how much and at what rate land is being eroded can be calculated by comparing original land surveys of 1902 with those made in recent years. A few hundred feet



LOOKING WESTWARD THROUGH THE TUNNEL BENEATH TUNNEL ISLAND. The erosive power of the sea has carved this passageway through a less resistant part of the sandstone of the island. (Fig. 47)

north of Hogsback (fig. 45), an east-west line between an established corner to the east and the edge of the cliff to the west measured 2,053 feet in length in 1902. That same line was surveyed in 1962 and found to be only 1,828 feet in length, a loss of 225 feet in 60 years. At that rate, the cliff recedes eastward about 375 feet in 100 years. Such a general rate of erosion is further indicated by the actual loss in acreage along the coast during the same period of time. Surveys show that one particular government lot contained 30.3 acres in 1902, whereas only 17.3 acres were left in 1962. Another adjacent lot was reduced from 33 acres to just a little over 20 acres. Based on the same rate of coastal erosion, it is therefore possible to estimate that a little over 200 years ago the coastline was probably about even with the western edge of Hogsback; and some 1,200 years ago the present-day offshore Willoughby Rock may have been part of the mainland.

RED BEACH SANDS

Although isolated patches of red-colored beach sands can be seen in many places along the coast, they are probably most prevalent along the 2½-mile-long Hogsbacks area (fig. 23). "Ruby Beach" to the north no doubt was so named because red sands are also common in that area. This reddish color is caused by the concentration of small "almandite" crystals, a type of red garnet, which is an entirely different mineral than the precious stone known as ruby. The garnet sand grains were originally individual dodecahedron (12-sided) crystals, but most of them have been abraded to a nearly spherical shape. This mineral is relatively heavy and tends to become concentrated in patches by wave action. Several other heavy minerals are frequently found in association with garnet sand. Most common is magnetite, a black-colored mineral that is readily attracted to a magnet. Other associated dark-colored minerals are ilmenite and hematite. In addition, grains of zircon, a heavy and very hard nonmagnetic mineral, are found in substantial amounts with the garnet. Zircon grains are very small, well-formed, clear, glassy crystals.

For many years it was thought that the only source of these garnet-bearing sands was sand and gravel deposits brought south from Canada by continental ice during the Pleistocene Epoch. However, many of the better concentrations of garnet along the coast are confined to areas where continental deposits have never been found, such as the Point Grenville-Hoh River area. Nevertheless, local glaciers originating in the Olympic Mountains did bring large amounts of sand and gravel to this area. These deposits are primarily sand and sandstone (graywacke) pebbles, much of which were removed from bedrock outcrops of Hoh rocks and other rocks of the Olympic Mountains. Recent studies have shown that these rocks do indeed contain garnets and are therefore now thought to be a major source for garnet and associated minerals found in this beach area.

It is interesting to note that at one time a considerable thickness of sand and gravel covered the Hoh rocks of the Hogsback area (see Part I, Late Cenozoic deposits). Presently, however, very little remains at the top of the cliffs. Most of the sand and gravel was removed when sea level stood at a relatively higher elevation and a flat wave-cut surface was carved on the Hoh rocks, the trace of which can be seen at the top of the cliffs of this area. During that period of erosion, heavy minerals were concentrated and deposited on that wave-cut platform. Today, the sea, at a lower level, is eroding the cliffs; and the heavy mineral concentrates are being lowered to present-day beach level and reconcentrated.

TUNNEL ISLAND

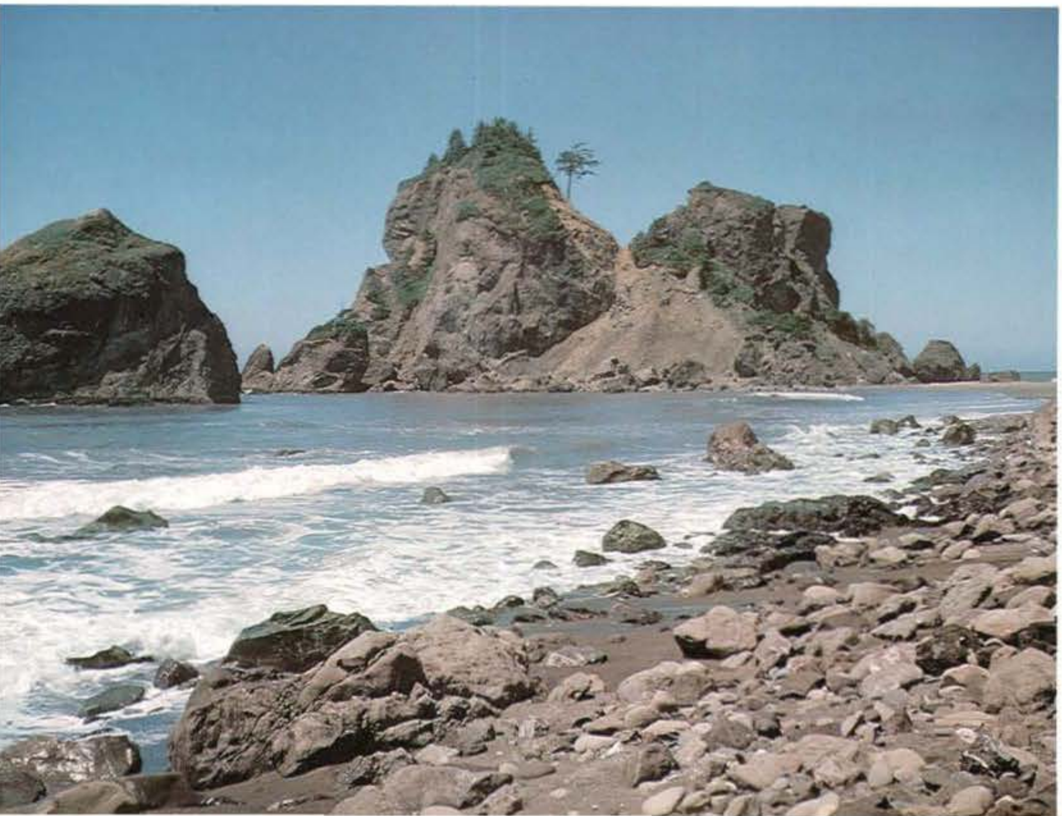
Tunnel Island (fig. 24) at the mouth of Raft River is accessible on foot during low tide, usually from the south side of the river. It consists of a relatively hard body of sandstone with a few less resistant strata of siltstone. Some very interesting erosional features have been formed largely by the differential effects of wave action on these rocks. Perhaps the most fascinating is the tunnel for which the island was named (fig. 47). From a relatively small entryway on the east side, the tunnel opens up into a large room beneath the island and extends to a fairly large opening on the west side. According to local residents, only in recent years has the eastern entryway broken through to form a true tunnel from what used to be a large sea cave with its only opening seaward. Wave action

SPLIT ROCK, a very large, relatively resistant erosional remnant from the Hoh rocks. It now rests on the Continental Shelf and protrudes as an island above the present-day sea level. (Fig. 48)

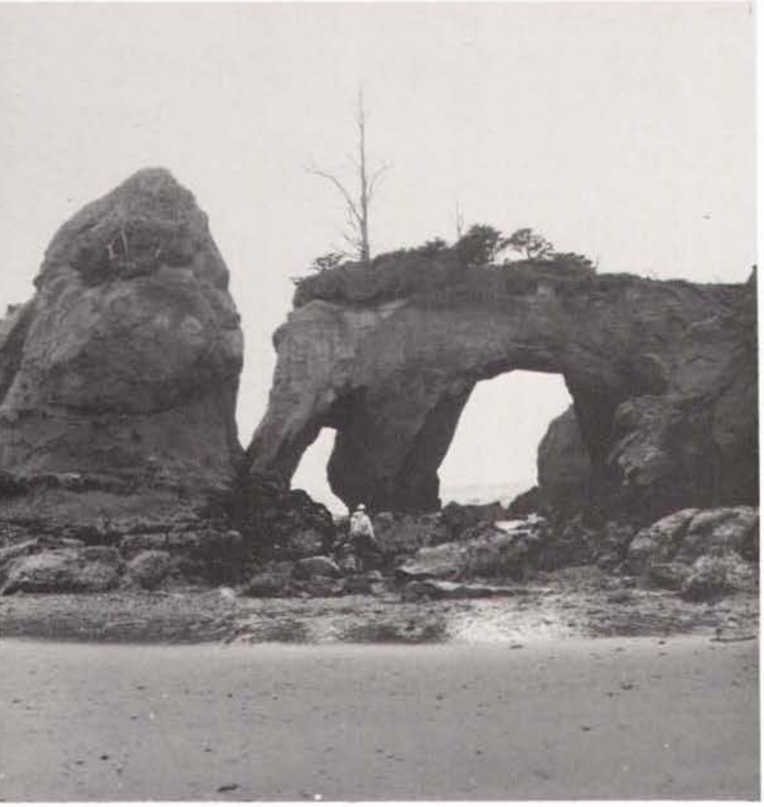
has further eroded a number of picturesque arches on the south end of the island, some of which form a shape resembling an elephant (fig. 50); and thus in the past the name "Elephant Island" has also been applied to this island.

The sandstone of Tunnel Island and the nearby sea stacks (fig. 25), together with the sandstone and siltstone in the cliffs and along the beach immediately north of Raft River, are all a lower part of the Quinault Formation.

Macerated carbonized wood fragments are common in much of the sandstone, suggesting that when the materials were deposited millions of years ago a source of vegetation was nearby. Concretions, or relatively hard nodules, are scattered throughout, some of which are formed around fossils. The most common among these fossils is the relatively large pectenlike clam known as *Lituyapecten* sp. (fig. 51). Microscopic fossils are particularly common in the sandy siltstone strata exposed



LITTLE HOGSBACK, like other nearby headlands and offshore rocks, is a volcanic relatively resistant mass from deposits of jumbled Hoh rock. Erosion processes of the sea have removed the finer and softer parts of the deposit and left Little Hogsback as a headland, connected to land only during low tides. (Fig. 49)



ELEPHANT ROCK, at the south end of Tunnel Island, is among a group of fascinating arches and seastacks that were differentially carved from sandstone by erosional processes of the sea. (Fig. 50)

largely at low tide. Together, all fossils indicate to paleontologists that the sediments of the containing rocks were deposited in the sea during an early part of the Pliocene Epoch, some 5 to 7 million years ago (fig. 2).

The younger overlying sand and gravel deposits of the Pleistocene Epoch, although relatively thin to the south of Raft River, are thicker northward reaching a thickness in places up to 50 feet.

RAFT RIVER TO WHALE CREEK

NORTHERNMOST OUTCROPS OF THE QUINAULT FORMATION

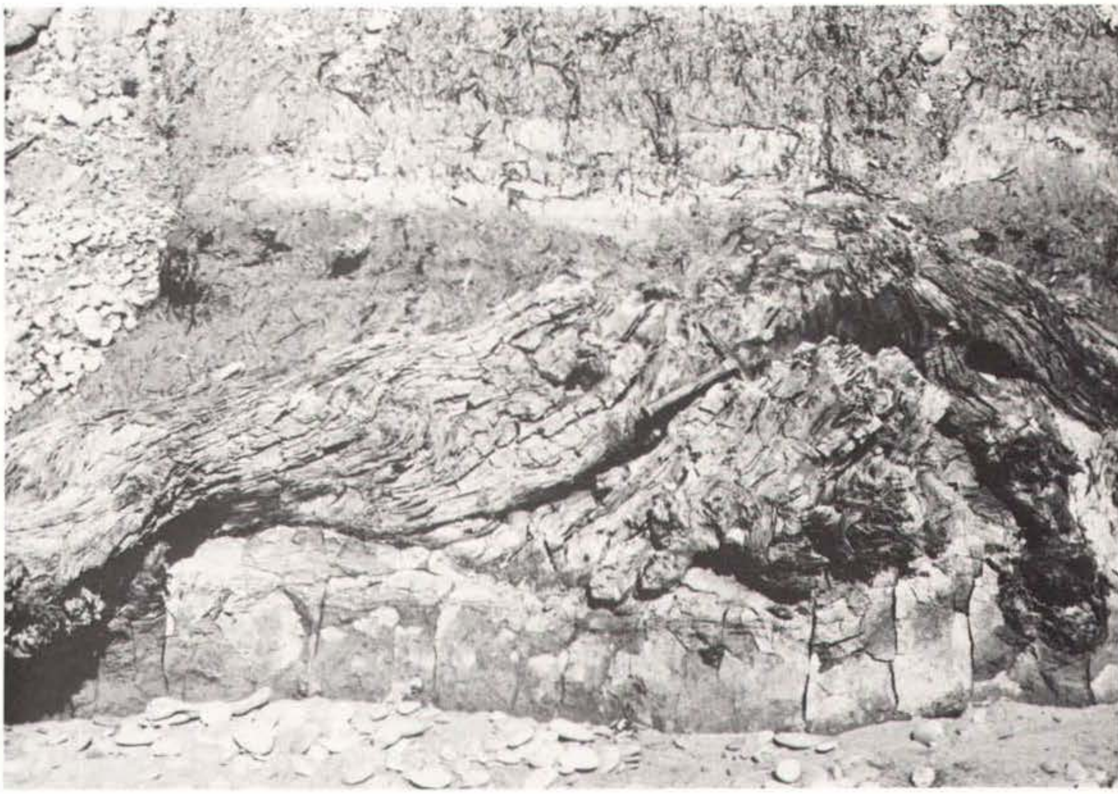
About one-quarter of a mile north of Raft River jumbled Hoh rocks are poorly exposed for a few hundred feet at the base of the cliff beneath landslide debris of sand and gravel. These Hoh rocks are similar to those seen in the Hogsbacks area and appear to be in fault contact with the younger Quinault Formation, both to the north and south. Structural relations, therefore, suggest that this small outcrop of badly jumbled rocks may well have been injected into the Quinault Formation in much the same way as Hoh rocks are believed to have been emplaced in an area south of Duck Creek. (See Part I, Hoh rock assemblage, Piercement structures).

For a distance of at least three-quarters of a mile northward, massive sandy siltstone of the Quinault Formation is poorly exposed in the bluffs beneath sand and gravel deposits and intermittently in low-tide outcrops. Landslides are common in this area and therefore the Quinault Formation is partially covered by slumped deposits of the overlying younger sand and gravel. Because the massive siltstones of the Quinault Formation are relatively soft and structurally weak, they too have slumped, forming a low-lying hummocky topography. Drunken forests are common in this area and indicate that the land surface was disrupted during the growth of these trees. Although the amount of sand covering the outcrops on the beach varies from time to time, on occasion the Quinault Formation is rather well exposed during low tide at the north end of this series of outcrops. It extends to a point about 1¼ miles north of Raft River and represents the northernmost outcrop of the formation known along the coast. Here the rocks are generally massive siltstone, but some display faint bedding that indicates the beds are steeply dipping northward.

OLDER DEPOSITS OF SAND AND GRAVEL

At the northernmost outcrop of the Quinault Formation, steeply dipping deposits of semiconsolidated gray-colored sand and gravel are in abrupt contact with steeply dipping siltstone beds of the Quinault Formation. In this area both the steeply dipping sand and gravel beds

A PECTENLIKE FOSSIL in the sandstone of Tunnel Island. This form is relatively common among the various larger fossils contained in the sandstone of Tunnel Island and nearby outcrops immediately to the north. (Fig. 51)



A DISTORTED TREE STUMP, surrounded by deposits of carbonaceous clay and silt, exposed at the base of the cliff about 1 mile north of Whale Creek. Radiometric dating of samples from this stump indicate that it is older than 30,000 years. Hammer in center of photo is about 12 inches in length. (Fig. 52)

and the Quinault Formation are overlain by the same nearly horizontal iron-stained sand and gravel deposits that can be seen in the upper part of most cliffs southward to Point Grenville. In this immediate area therefore, three distinct rock units are exposed: the bedrock Quinault Formation, older tilted sand and gravel beds, and the younger nearly horizontal deposits of sand and gravel (fig. 26; see Part I, Cenozoic deposits). Because both the Quinault Formation and the older of the two sand and gravel deposits are steeply tilted in this area, the folding and possibly faulting that deformed them took place after deposition of the latter, most likely in the Pleistocene Epoch but prior to the deposition of the younger horizontal and unaffected sand and gravel.

From here northward to a place about one-quarter of a mile north of the mouth of Whale Creek, both sand and gravel units are exposed in the cliffs and can be easily distinguished, mainly because the older unit is a dark-gray color at the base of the cliff and appears to dip decidedly in a west-northwest direction, whereas the younger overlying deposits are iron stained and are nearly horizontal (fig. 22).

The contact between these two deposits constitutes the same wave-cut surface that was carved by the sea on bedrock in other areas both to the south and north. However, in this area the bedrock surface was below the level of the wave cutting, and the surface was formed on the older sand and gravel unit that previously had covered the bedrock.

RECENT WARPING OF THE EARTH'S CRUST

Since the deposition of the younger sand and gravel deposits, broad warping has very gently tilted northward all deposits in the Whale Creek area. Therefore, the once horizontal contact (wave-cut surface) between the two deposits of sand and gravel is also gently tilted northward. South of Whale Creek the older deposits extend upward to a height of some 35 feet from the base of the cliffs; but they become less and less of the total height of the cliffs northward until finally about one-quarter of a mile north of Whale Creek the contact between the two sand and gravel units projects beneath the base of the cliffs. From that point northward to the Kalaloch area, the cliffs are composed entirely of the younger of the two sand and gravel deposits.

OLD WOOD REVEALS AGE OF DEPOSITS

From the northern end of the outcrop area of the Quinault Formation to Whale Creek and for some distance beyond, at least one major carbonaceous bed containing branches, stumps, and even small logs can be seen in the younger sand and gravel deposits (fig. 52). This bed is largely compressed vegetation and is known as peat, the beginning stages of coal. Radiometric dating of samples of this material show that it is more than 30,000 years old.

PIERCEMENT STRUCTURE between Cape Elizabeth and Duck Creek. The dark colored cliffs are composed of broken and contorted rocks of the Hoh rock assemblage. These materials are believed to have been squeezed upward into the lighter colored Quinault Formation seen here in the cliffs on each side. (Fig. 53)

DESTRUCTION ISLAND, once known as "Green Island" by some of the early explorers, has a foundation of steeply dipping sandstone strata of the Hoh rock assemblage. A thickness of some 50 feet of Pleistocene sand and gravel forms the uppermost part of the island. Its nearly flat surface is a western remnant of a broad plain that was formed on outwash deposits and extended westward from the present-day mainland to and beyond Destruction Island during the Pleistocene Epoch. (Fig. 54)

WHALE CREEK TO THE QUEETS RIVER

For about 3 miles northward from Whale Creek to nearly the mouth of the Queets River, iron-stained sand and gravel deposits are rather uniformly exposed in the some 80-foot-high cliffs (fig. 55). With the exception of the older beds at the base of the cliffs near Whale Creek, all of these materials were deposited during a late part of the Pleistocene Epoch, between 17,000 and possibly 70,000 or more years ago. They were originally removed by a late period of alpine glaciation from bedrock outcrops, mostly of sandstone (graywacke), exposed somewhere in the Olympic Mountains. These stones and sand and silt grains were farther transported by streams and rivers from the glacial fronts and deposited in the coastal area, forming a broad piedmont surface that extended westward from the foothills of the Olympics. At one time this piedmont surface (the present surface at the top of the cliffs) probably extended much farther westward. However, over the past thousands of years, the continual erosion by ocean waves has caused the coastline to recede eastward in places at the rate of as much as 375 feet every 100 years (see Part II, The Hogsbacks area, Coastal erosion). As a result, today's wave-cut surface, or beach level, is some 80 feet below the old piedmont whose very gently sloping surface, at one time, extended westward to sea level (see Part I, Cenozoic deposits).

Many features of sedimentation can be seen in these cliffs. For the most part, the various beds of sand and gravel appear nearly horizontal. However, locally, others display cross bedding, a pattern indicating rapid deposition at different slopes and directions, as would be expected at the edge of a delta or along the edge of a steeply sloping river bank (fig. 56). Evidence of much channeling by streams, or the local eroding instead of depositing of materials, can be seen in places. These features all indicate that during the melting of the glaciers numerous streams and rivers flowed over much of the area continually changing channels, depositing in places for a time, and then shifting and perhaps eroding for a time in another place.

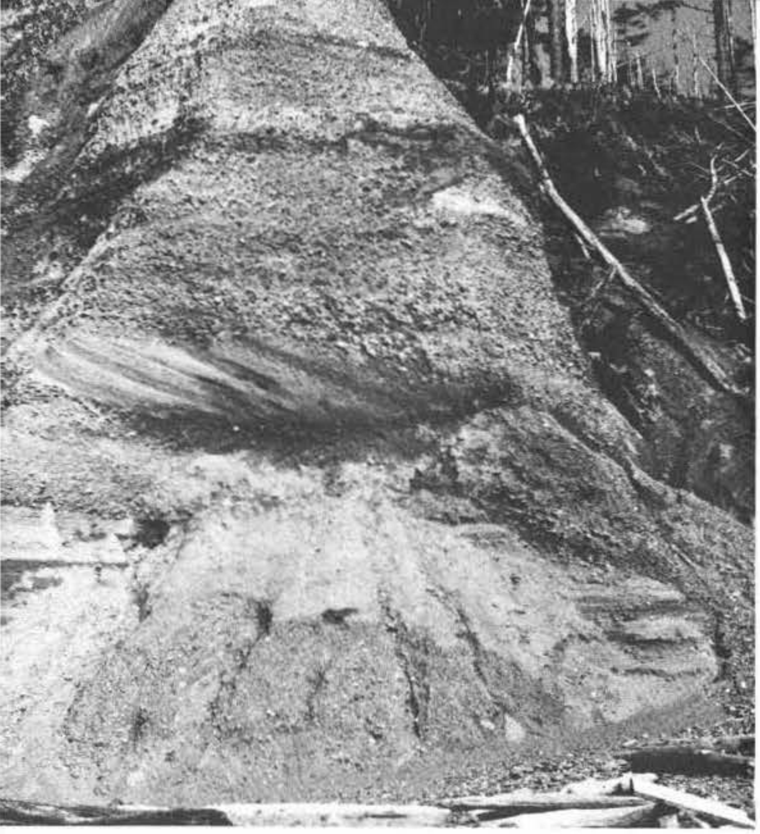
Although these deposits appear to be nearly horizontal, they dip slightly northward. This gentle tilt is perhaps best observed by following the dark-colored carbonaceous clay and wood layer seen only a few feet below the top of the cliff near Whale Creek. It gradually appears lower and lower in the cliffs northward from Whale Creek until finally the layer extends beneath the level of the base of the cliff. This carbonaceous bed represents a local impounding of water, such as a shallow lake or a swamp in which only fine-grained sediments were deposited together with the vegetation that grew in and around the impoundment. The bed, therefore, was formed originally in a horizontal plane.

Erosion by springs and surface streams has serrated the high, nearly vertical cliffs that form the otherwise straight coastline for nearly 3 miles between Whale Creek and the Queets River valley.

MOUTH OF QUEETS RIVER VALLEY

The position of the actual mouth of the Queets River has changed over the years as the sea slowly eroded the coastline eastward. At one time the river flowed along the south side of its valley from the town of Queets to nearly the present-day coastline. There, the river turned northward and followed along a west bank, marked today only by the east edge of the low-lying gravel spit extending across much of the mouth of the present-day valley.

LOOKING NORTHWARD FROM WHALE CREEK at the nearly straight coastline to the Queets River. The cliffs are semiconsolidated silts, sands, and gravels deposited by streams from melting valley glaciers that extended westward from the Olympic Mountains during the Pleistocene Epoch. Most of these deposits probably were laid down between 17 and 70 thousand years ago. (Fig. 55)



CROSS STRATIFICATION in beds of sand and fine gravel exposed about one-fourth of a mile north of Whale Creek. This pattern indicates rapid deposition at the edge of a delta or along the edge of a steeply sloping river bar. (Fig. 56)

At different times in the past the river entered the sea at various places through the spit. One channel, possibly the oldest, extended northward about one-half mile north of the present mouth before reaching the sea. This old channel is now a small elongated pond isolated from the river and sea behind the northernmost part of the old spit.

QUEETS RIVER TO KALALOCH

PLEISTOCENE DEPOSITS

The same unit of late Pleistocene sand and gravel that crops out south of the Queets River also forms much of the low-lying bluffs between the Queets River and Kalaloch. In this area, no more than 50 feet of the uppermost part of this deposit of sand and gravel is exposed above beach level. The upper surface of the gravel gradually appears lower in the bank northward to Kalaloch where only about 8 feet of the uppermost part of the unit is exposed in the lower part of the bank. The upper part of the bank between the Queets River and Kalaloch is largely silt and clay. These latter deposits become thicker northward from the Queets River, and at Kalaloch most of the 30-foot-high bank is composed of silt and clay materials.

The relatively low position of the old piedmont surface (essentially present-day land surface) some 30 feet above sea level may be the result of a broad downwarp of the earth's surface in the Kalaloch area. Further evidence for such a downwarp is the low position of both the top of the sand and gravel deposit near sea level and the Pleistocene wave-cut surface apparently beneath sea level. Accumulations of fine-grained sediments of silt and carbonaceous clay in the Kalaloch area began some 70,000 years ago and have continued essentially to Recent time. This relatively low-lying area was a rather marshy region, receiving only very fine-grained sediments from sluggish streams. Much vegetation probably grew in and around numerous shallow bodies of water. Eventually this vegetation became incorporated in the accumulating fine-grained sediments to form layers of carbonaceous silt and clay now exposed in the banks of the Kalaloch area.

BEACH DEPOSITS OF TODAY

Most deposits along the upper part of the beach are gravels, whereas sand occurs largely in the low-tide areas along much of this part of the coastline. These materials obviously are derived from the older deposits of the adjacent cliffs. Wave action has winnowed the fine materials from the coarse gravels and deposited them farther seaward. Pebbles of the gravels are very largely sandstone but a few are white quartz, red chert, and dense volcanic rock. The sandstone of the pebbles is sometimes referred to as a "graywacke sandstone" (see Part I, Turbidites of the Hoh rocks). Numerous angular fragments of dense dark-gray siltstone can be seen in many of the pebbles (fig. 21). All sand and gravel deposits, which form the bluffs of this area and are the source of the present-day beach deposits, were brought to nearby areas by glaciers during the Pleistocene Epoch (fig. 2), from bedrock outcrops in the Olympic Mountains. These materials were then further distributed and deposited in the immediate area by streams from the melting glaciers to form the deposit now visible in the cliffs. In recent years they have been removed from the cliffs, reshaped, and distributed along the beach by wave action of the present-day sea. The shapes and arrangements of these pebbles are typical of ocean beach deposits. Most of them are somewhat flattened or disclike in shape, and in many places wave action has arranged them in an imbricate or shinglelike manner. This arrangement is sometimes referred to as "beach shingle."

KALALOCH AREA

BEDROCK OUTCROPS

The offshore Kalaloch rocks (fig. 58), together with outcrops in and near the mouth of Kalaloch Creek, are all a part of the Hoh rock assemblage. Based on the depositional history of these rocks, geologists refer to them as "turbidites" (see Part I, Turbidites of the Hoh rocks). Kalaloch is the southernmost area of outcrop of such rocks along the coast. Although structurally complex, they are not completely disarranged as are the "melange" Hoh rocks that are exposed in places to the south (see Part I, Tectonic melange of the Hoh rock assemblage). Turbidite outcrops display sequences of sedimentation that are still intact, and, in places, individual strata can be traced along the beach. The beds dip eastward and have been overturned with the younger strata to the west. Many of these rocks are basically sandstones and conglomerates, but because they contain many fragments of other rocks as well as individual mineral grains, geologists refer to them as "graywackes." Dark-gray siltstone chips are frequently the most conspicuous rock type. Graywacke beds, similar to those that form the turbidite sequences at Kalaloch, are the bedrock source for many of the local present-day beach sand and gravel deposits.

Similar bedrock is much more extensively exposed in several of the headlands immediately to the north of Kalaloch. More detail is presented about these sedimentary rocks in a following discussion on the Browns Point and Starfish Point area.

LOOKING EASTERLY AT THE KALALOCH ROCKS with the community of Kalaloch in the background. These rocks are the southernmost beds of sandstone and conglomerate of the Hoh rock assemblage that crop out along the coast. (Fig. 58)

UNCONSOLIDATED MATERIALS

The low-lying bluffs between Kalaloch and Browns Point to the north are composed almost entirely of silt and clay. Several beds are highly carbonaceous and, in places, contain large pieces of carbonized wood (fig. 57).

HIGHLY CARBONACEOUS CLAY BEDS exposed in the bluffs north of Kalaloch. These deposits were laid down during the latter part of the Pleistocene Epoch in a swamp environment where clays were mixed with much plant material. In places, concentrations of this vegetation have been converted to "peat," the beginning stages of coal. Studies recently made of these beds indicate that the strata vary in age from about 17,000 to greater than 48,000 years. (Fig. 57)

These beds, as well as those to the south of Kalaloch, are composed of materials that were deposited in swamps or shallow ponds, the uppermost of which represents one of the last geologic events to take place in this area. Recent detailed studies reveal that the lowest beds exposed locally in the cliff may have been deposited some 70,000 years ago, whereas the uppermost carbonaceous beds are about 17,000 years old (Florer, 1972; Heusser, 1972).

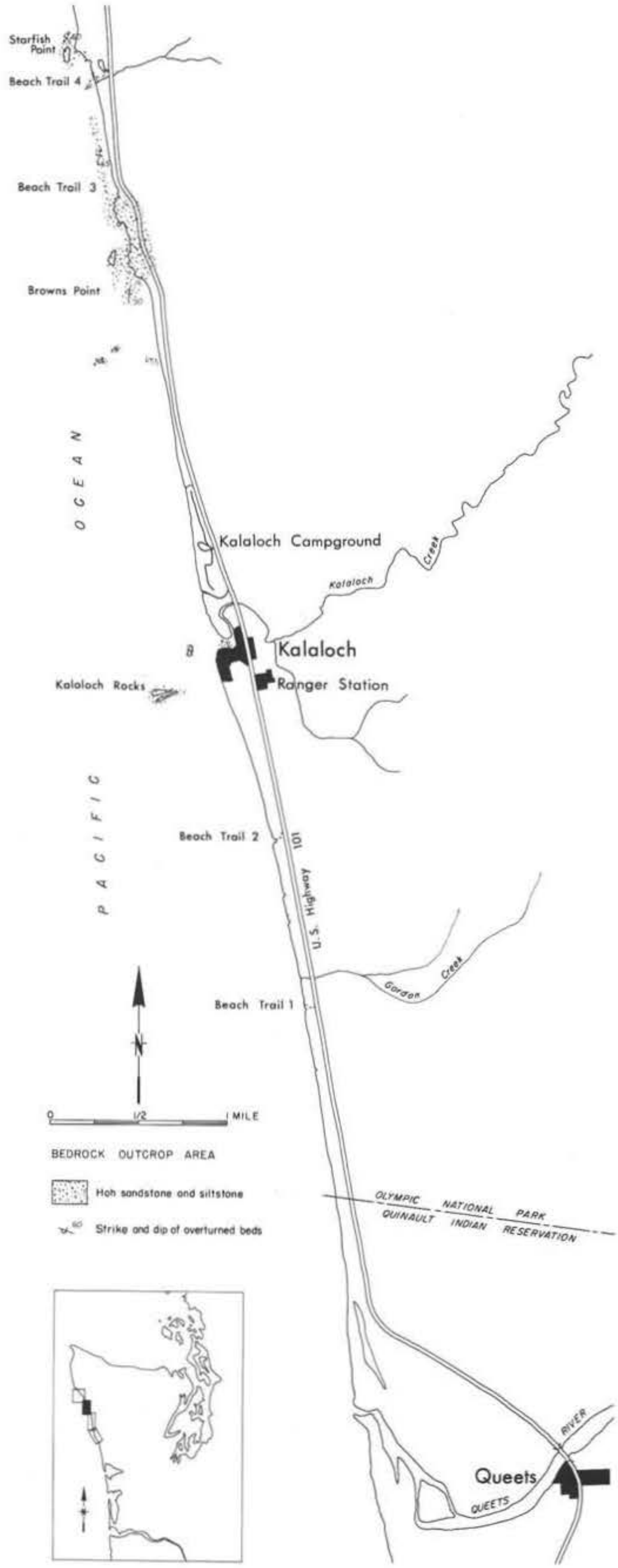
Patches of red-colored sand frequently occur on the beaches of the Kalaloch area (fig. 23). The individual grains are small crystals of garnet. Because this mineral is relatively heavy, it has been concentrated in patches by wave action (see Part II, Hogsbacks area, Red Beach sands).

BROWNS POINT–STARFISH POINT AREA

BROWNS POINT–BEACH TRAIL 3 AREA

Bedrock

About 2 miles north of Kalaloch and in the vicinity of Beach Trail 3 (fig. 59), a major series of bedrock outcrops form the headland known as Browns Point (fig. 6). These rocks, together with those exposed in the vicinity of Starfish Point near Beach Trail 4 (figs. 7 and 65), constitute one of the major coastal outcrop areas of Hoh rocks between Point Grenville and the Hoh River. Locally these strata have been called the Browns Point Formation by some geologists. However, recent studies reveal that they cannot be easily mapped as a separate rock unit in the foothills of the Olympic Mountains to the east and north. Therefore, in this report these strata are still regarded as a part of the Hoh rock assemblage.



QUEETS RIVER TO BEACH TRAIL 4–Coastal Map. (Fig. 59)

In the Browns Point-Starfish Point area Hoh rocks are composed of a series of steeply eastward-dipping massive to thin-bedded sandstones and siltstones representing a nearly continuously exposed sequence of sedimentary strata, measuring nearly 2,000 feet in thickness. Although the beds dip eastward some 40° to 65° from horizontal, sedimentary structures (fig. 9), particularly abundant and well formed in this area, indicate that the youngest beds of the sequence are to the west. Therefore all beds have been rotated beyond vertical to an overturned position. According to paleontologists, the few fossils that have been found in these rocks indicate that they were deposited some 15 to 22 million years ago in a deep ocean basin somewhere west of our present-day coastline (see Part I, Interpretations of structure in the Hoh rock assemblage). Furthermore, many of these strata were formed by the settling of sediments from turbid waters created largely by the repeated slumping of large masses of sediments. Geologists therefore refer to these sedimentary rocks as "turbidites." The resulting deposits are basically a series of bedded sandstone and siltstone in which a grading of grain size occurs from sand-size sediments of sandstone to silt-size particles in siltstone. The numerous beds of sandstone and siltstone exposed locally represent a repetition of many similar events of deposition.

Thick units of predominantly siltstone laminated with only an occasional thin bed of sandstone represent periods of normal deposition, interrupted by infrequent and short periods of coarse-grain deposition. Examples of such deposition can be seen at times when the beach is cleaned of sand in the saddle between the Browns Point headland and the high-tide area (see Part I, Turbidites of the Hoh rocks).

Numerous northwest-trending faults in the rock can be easily traced, particularly in the low-tide outcrops at Beach Trail 3 and immediately to the north. Displacements on most of these faults are only a few feet and almost all show left lateral movement (the north side of a fracture has moved west relative to the south side). Because these faults usually cut at a decided angle across the bedding, the amount of displacement can be determined if the same strata or sequence of strata is recognized on each side of a fault.

Unconsolidated Deposits

Bedrock in the Browns Point area is overlain by deposits of silt and sand with some 5 to 10 feet of thickness of fine gravel near the base (fig. 64). Several highly carbonaceous layers, representing swamplike deposits, can also be seen. These unconsolidated deposits were laid down during the latter part of the Pleistocene Epoch (fig. 2) and are a continuation of those exposed in the banks of the Kalaloch area. However, in places, a somewhat greater thickness is visible at Browns Point than at Kalaloch.

The contact between younger materials and the underlying Hoh rocks is roughly a horizontal plane about 20 feet above high tide. Its trace can be seen well in the vicinity of the small natural arch along the upper part of the beach (fig. 60). The roof of this arch is composed of fine gravel and represents about the level of the contact. The surface on bedrock at this level represents an old wave-cut bench that was carved during Pleistocene time, prior to the deposition of the overlying silt, sand, and gravel, some 70,000 or more years ago. Although here the surface is on bedrock, it is believed to be the same surface that was carved on old sand and gravel deposits to the south in the Whale Creek area (see Part II, Raft River to Whale Creek, Older deposits of sand and gravel). Due to downwarping, this surface lies below high-tide level at Kalaloch and therefore cannot be seen in that area. Note the numerous old "pholad" or rock clam borings in many places on this surface in the Browns Point area–evidence that this surface at one time occupied a low-tide position with respect to sea level of that time. In places bedrock was not completely reduced to sea level and therefore it stood above the old wave-cut level as offshore rocks or sharp promontories. The westernmost high point of Browns Point and much of the inland area to the east of Browns Point are places that stood above sea level at that time.

LOOKING NORTHWARD IN THE BROWNS POINT AREA. Note the roughly horizontal profile as indicated by a dashed line, some 20 feet above beach level, that cuts across steeply dipping sandstone beds of the Hoh rock assemblage. This level represents an elevated wave-cut surface that was carved by the sea during the Pleistocene Epoch. Sand and gravel materials were deposited subsequently on this surface but now are being removed by erosion. The roof and overlying materials of the small natural arch, visible on the right, are some of the Pleistocene deposits that have not yet been removed. (Fig. 60)

From Beach Trail 3 to Beach Trail 4 sandstone and siltstone beds of the Hoh rocks are exposed in the low-tide area and at the base of the cliff. Old pholad borings are also very common in these rocks about 10 feet above the high-tide level. A thickness of 8 to 10 feet of crudely bedded gravel is present in the banks immediately above the bedrock surface. These gravels may well have been deposited as beach gravels on the old wave-cut beach. Sand and silt beds overlie the gravels and form the upper part of the bluffs.

BEACH TRAIL 4

At the end of Beach Trail 4, steeply eastward-dipping, well-bedded Hoh sandstones are exposed in the basal part of the cliffs and uppermost part of the beach (fig. 8). These strata, like those to the south in the Browns Point area, are typical turbidite sedimentary rocks, and, because the original top of these strata also faces west, they too have been tilted to an overturned position. A south-western extension of these beds is usually well exposed at low tide (fig. 7). Note how wave action has more deeply eroded the softer siltstone beds, leaving the coarser more resistant sandstone strata as ridges.

A continuation from the south of the younger deposits of silt, sand, and gravel also overlies the bedrock in this area. Their thickness increases northward to at least 80 feet in the Beach Trail 4 area. Again, the old wave-cut surface, which was carved on Hoh rocks during the Pleistocene time, is the contact between bedrock and the younger deposits some 10 to 20 feet above present-day high-tide level. Ancient rock clam borings that were formed when the tidewater once covered this area are abundant at the foot of Beach Trail 4 (fig.28).

STARFISH POINT

The major headland immediately north of Beach Trail 4, sometimes referred to as Starfish Point (fig. 59), is another rather extensive outcrop of Hoh rocks (fig. 65). Lithologically, it is similar to the coarse-grained sandstone that forms the prominent headland to the south at Browns Point. However, Starfish Point rock is probably stratigraphically above and represents the basal or initial part of another large sequence of turbidite deposition. Note the numerous dark-colored siltstone fragments scattered through much of this sandstone. These and other rock fragments make up a large part of this rock, and therefore geologists also classify it as a graywacke sandstone (see Part I, Turbidities of the Hoh rocks).

Differential erosion by wave action has shaped this and other rocks of the area. Because of its massiveness and coarse-grained texture, Starfish Point stands more resistant to wave action than the adjacent poorly exposed finer grained and better stratified rocks.

STARFISH POINT TO BEACH TRAIL 5

Another Hoh sequence of sandstone and siltstone is partially exposed in the basal part of the cliffs between Starfish Point and Beach Trail 5. A few outcrops of some of the more resistant sandstone beds are also visible at low tide. These strata are somewhat structurally complex, particularly those near Beach Trail 5. All beds are overturned and generally dip to the southeast.

At Beach Trail 5 and for a few hundred feet to the south, most of the rock is massive pebbly siltstone. These beds are among the very few along the coast where fossils have been found in Hoh rocks. Definitive collections of Foraminifera have been made here from the siltstone and a few megafossils from the nearby sandstones. These fossils indicate to paleontologists that the beds were deposited in a moderately deep marine environment some 15 to 22 million years ago during early Miocene time (fig. 2).

Overlying Pleistocene deposits of sand and silt form much of the sloping bluffs of the area between Starfish Point and Beach Trail 5, but they are only poorly exposed because of the vegetation cover. Note at least one highly carbonaceous layer well above a sand layer. Its presence indicates swamp or shallow pondlike deposition.

DESTRUCTION ISLAND

Destruction Island, about 3½ miles offshore, is the largest island off the coast of Oregon and Washington and the first one north of the Farallon Islands of the San Francisco area. Its distinctive flat-top shape served as an unmistakable reference to the early coastal explorers. It was first named "Isla de Dolores" by Bodega y Cuadra. Others referred to it as "Green Island," because of its dense cover of green foliage. Later Meares transferred the name of "Destruction" to the island from the river, so named by Barkley, the presently named Hoh River. Aside from its fascinating historical background. Destruction Island is also one of the more interesting places geologically along the Washington coast. It represents the westernmost major bedrock outcrop exposed above sea level in this local area.

BEDROCK

The foundation or bedrock of the island and surrounding low-tide reefs is very similar to the bedrock exposed in the Browns Point-Starfish Point area. Most strata are massive to thick-bedded graywacke sandstone and, like the Browns Point-Starfish Point strata, represent typical turbidite deposition of the Hoh rock assemblage (fig. 54).

Structurally the beds are dipping steeply to nearly vertical and in places are even slightly overturned. Because the less resistant thin siltstone layers have been more deeply eroded, the thick more resistant sandstone beds stand out prominently and can be easily traced along the island and to the nearby reefs. From the air, these beds can be seen to form a horseshoe-shaped pattern. Large and well-formed sedimentary structures (fig. 61) indicate that the original upper surfaces of all strata face toward the center of this pattern. Therefore, these beds were not only downfolded to form a "syncline" but also rotated up on end so that today a beveled end of this nearly vertically plunging structure forms the bedrock foundation of the island.

SAND AND GRAVEL DEPOSITS

In much the same way as at Browns Point and Starfish Point, nearly horizontal, relatively unconsolidated sand and gravel deposits overlie the hard sandstone Hoh beds and form the upper 50 feet or so of Destruction Island. The contact between the two units forms a generally horizontal plane only a few feet above the present-day sea level. This surface can be discerned slightly above the high-tide level from the mainland, particularly from the Kalaloch area where it may be seen prominently on the southwest end of the island. It represents the same wave-cut surface visible in the Browns Point-Starfish Point area just a few feet above the high-tide level. As in the latter area, this surface was carved by the sea during the Pleistocene Epoch prior to the deposition of the overlying sand and gravel. The flat-top surface so prominent on Destruction Island is a westernmost remnant of the old piedmont surface that was essentially completed some 17,000 years ago during the final stages of outwash deposition from a late period of glaciation. On the mainland, this surface constitutes the present-day land surface adjacent to much of the coast of this area. From places along the coast the upper surface of Destruction Island can be visually projected to a similar relatively level surface on parts of the mainland. This projected line slopes very gently seaward and, somewhere to the west, intersects present-day sea level. Wherever the sea level stood at the close of the Pleistocene Epoch (possibly even lower than today), the sea has eroded the land from there eastward to our present-day coastline. Destruction Island, having a particularly resistant foundation, has not yet given way to the forces of the sea.

COASTAL EROSION RATE

The rate at which the coastline migrates eastward due to erosion, leaving Destruction Island behind, can be estimated from a comparison of old land surveys with those made in recent years. In the Hogsbacks area about 15 miles to the south, records indicate an eastward recession of the cliffs of some 225 feet in a 60-year period (see Part II, Hogsbacks area; Coastal erosion). This is equal to a rate of 375 feet every 100 years. Although the rocks of that area are particularly susceptible to erosion, nevertheless the unconsolidated sands and gravels of Destruction Island and the adjacent mainland area also are easily cut by the sea. Except for local resistant headlands and islands, such as Browns Point and Destruction Island, the gross configuration of the shoreline is generally straight. Therefore, erosion must have been reasonably uniform along most of the coastline of this area. Assuming a conservative rate of 300-feet eastward recession of the cliffs every 100 years, Destruction Island, now about 3½ miles offshore, would have been a part of the mainland some 6,000 years ago.

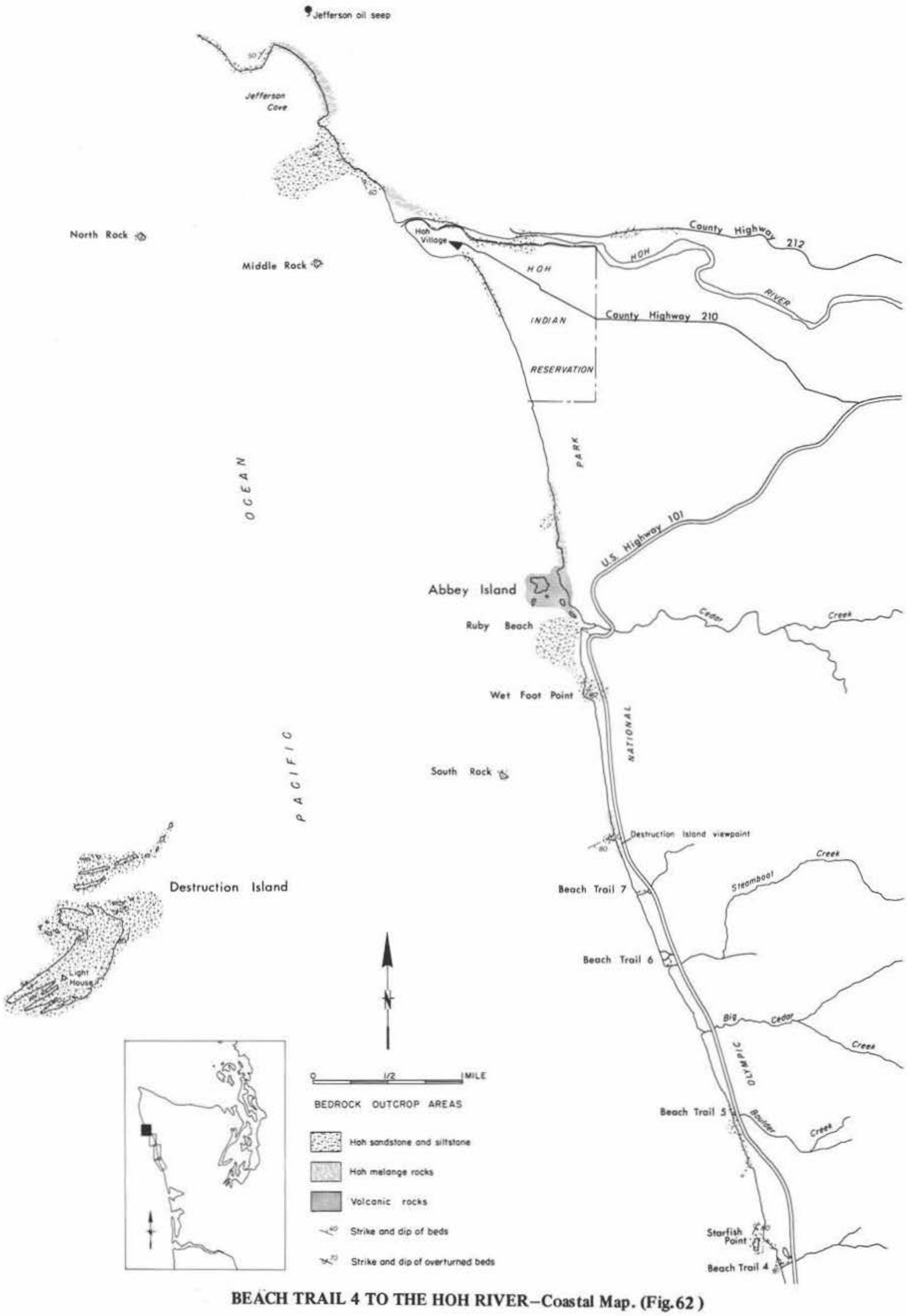
WELL-FORMED GROOVE CASTS preserved on the bottom side of a nearly vertically dipping sandstone bed on Destruction Island. Shown here is the impression of grooves that were made by the dragging of objects across the ancient muddy sea floor. The siltstone bed on which the grooves were originally made has been eroded away exposing the cast or impression of the grooves on the underside of the overlying sandstone bed, now standing in a nearly vertical position. (Fig.61)

BEACH TRAILS 5 TO 7

SAND AND GRAVEL CLIFFS

Sand and gravel deposits are very well exposed for a distance of nearly 2 miles from Beach Trail 5 to a short distance beyond Beach Trail 7 (fig. 62). With the exception of a few poorly exposed outcrops of jumbled deposits of Hoh rocks, all of the cliffs of this area are composed of clay, silt, sand, and gravel, most of which are believed to have been deposited during the Pleistocene Epoch.

Two major divisions of Pleistocene deposits can be easily recognized in this area. The younger of the two is a continuation of those sand and gravel deposits exposed above bedrock immediately to the south. The older unit, first appearing here at the base of the cliffs a short distance north of Beach Trail 5, is comparable to deposits



BEACH TRAIL 4 TO THE HOH RIVER–Coastal Map. (Fig. 62)

at the base of the cliffs in the Whale Creek area some 12 miles to the south (see Part II, Raft River to Whale Creek, Older deposits of sand and gravel). However, between the Whale Creek area and Beach Trail 5 only the younger of the two units is exposed.

From Beach Trail 5 northward, the contact between the two units is sharply marked by a layer of large boulders and cobbles (fig. 63). Furthermore, the lower unit usually is darker colored and in places parallel bedding is tilted, whereas parallel bedding appears nearly horizontal in the upper unit.

Both deposits are composed largely of sand and gravel. Clay is common in places in the lower unit. Some silt beds occur in the upper unit and they contain much plant material, including large pieces of wood. Some of this wood has been found to be older than 48,000 years. A similar conclusion was reached on wood from the upper unit in the Whale Creek area to the south.

Gravels of both units are very largely graywacke sandstones with minor amounts of red chert, argillite, and volcanic rock. All were derived from rock formations of the Olympic Mountains and were carried by alpine glaciers to the foothills, then farther transported to the coastal area by numerous streams and rivers during the Pleistocene Epoch. In places some of the materials of the lower unit may have been deposited directly from glaciers with very little, if any, transport by streams. These deposits display no sorting or stratification, with materials varying in size from clay particles to large boulders. Such materials occur, in places, at the base of the cliffs northward to the Hoh River, and thus suggest that at one time ice extended down the Hoh valley at least as far west as the present-day coastline. Particularly good examples of these deposits are exposed at the foot of Beach Trail 7 and in places northward for about one-third of a mile (fig. 66).

Similar to geologic relations in the Whale Creek area, the contact between the two units is the trace of an old wave-cut surface that was carved by the sea during the Pleistocene Epoch, and prior to the deposition of the upper unit. The large cobbles and boulders so common along the contact north of Beach Trail 5 are residual materials left behind when the surface was a tidal bench essentially at sea level. The large size of some of these boulders further suggests that they, as well as some of the materials removed, were most likely transported directly by ice rather than streams. Boulders that have been removed from the old wave-cut surface and redeposited at a lower level of the present-day wave-cut surface can be seen during low tide a short distance north of Trail 5 and on the beach at Trail 6 (fig. 67). Particularly large boulders are also present in the streambed adjacent to Beach Trail 7.

Northward from the first appearance of the lower sand and gravel unit, a short distance north of Beach Trail 5, the boulder contact is seen progressively higher in the cliff. At Beach Trail 7 about 1½ miles northward, it is over 35 feet above the high-tide level. Therefore, this surface dips gently southward, whereas in the Whale Creek area it dips gently northward. Thus, between these two areas, some 12 miles apart, it appears the earth's surface has been broadly downwarped some time after the wave-cut surface was formed.

SANDSTONE BLOCKS OF HOH MELANGE

In an area north of Beach Trail 6 and immediately south of Trail 7, a number of sandstone blocks are scattered on the beach and others are protruding from the basal part of the vegetated cliffs. These blocks are most likely residual materials that were left behind as the sea eroded structurally complex and chaotically mixed deposits of Hoh rocks (see Part I, Tectonic melange of the

TWO MAJOR UNITS OF SAND AND GRAVEL exposed in the cliffs immediately north of Beach Trail 6. The cobble and boulder studded, nearly horizontal contact between the two deposits represents the trace of a now elevated wave-cut surface that was developed on the lower unit prior to the deposition of the younger or upper deposits, some 70 thousand or more years ago. (Fig. 63)

STEEPLY DIPPING SANDSTONE STRATA of the Hoh rock assemblage at Browns Point. These beds have been tilted beyond vertical to a slightly overturned position so that the original top of each bed now faces west (left). (Fig. 64)

Hoh rock assemblage). Such materials are well exposed to the south in the Hogsbacks area and also between Cape Elizabeth and Duck Creek. In these latter areas the relatively soft, finer grained matrix materials in which sandstone blocks occur are well exposed. However, between Beach Trails 6 and 7 vegetation masks much of the low-lying outcrop area, and only in small isolated places can the soft matrix materials be seen at the base of the cliffs.

Note the distinct green color of many of the sandstone blocks. This is due to an abundance of glauconite, a green colored mineral that is known to form on the bottom of the sea, thus indicating that these sandstones are indeed marine in origin.

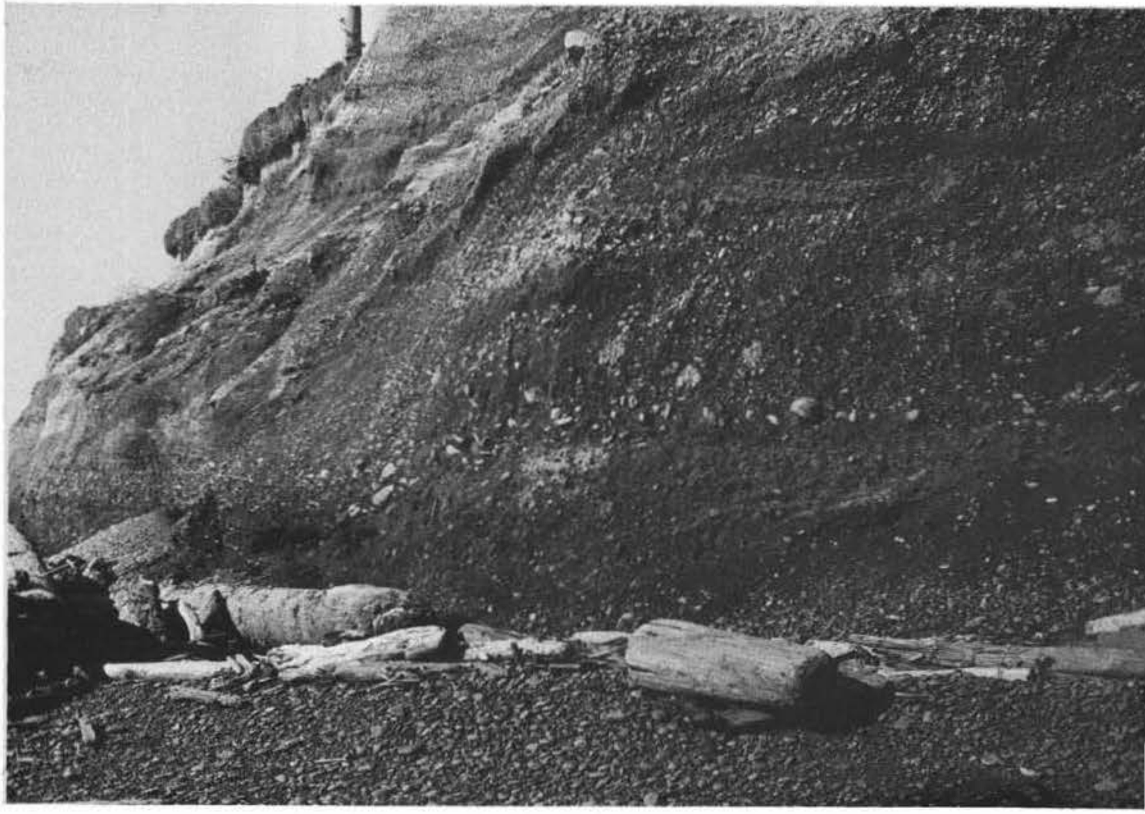
STARFISH POINT, just north of Beach Trail 4, is relatively resistant sandstone and conglomerate of the Hoh rock assemblage. (Fig. 65)

BEACH TRAIL 7 TO RUBY BEACH

Both the younger and the older deposits of sand and gravel are well exposed in the high cliffs that extend northward for about one-third of a mile from Beach Trail 7. In the vicinity of the highway sign for Destruction Island, the straight coastline is broken by a small sandstone point that protrudes from beneath the sand and gravel. This massive sandstone is another small outcrop of Hoh rocks. These strata are dipping steeply to the southeast and are several hundred feet thick. Intensely sheared Hoh siltstone is sometimes exposed for a short distance both to the north and south at the base of the cliffs. Similar materials are present but very poorly exposed at the base of much of the heavily vegetated sloping bluffs that extend northward from the sandstone point for about one mile to Wet Foot Point (fig. 62). Because badly broken and unctuous Hoh siltstone beds are relatively incompetent or weak, they are particularly vulnerable to erosion and furthermore serve as a poor foundation for the overlying sand and gravel deposits. Therefore, for nearly a mile much slumping has occurred, modifying the cliffs to sloping surfaces where vegetation can grow more easily than on the nearly vertical cliffs to the south.

Foraminifera from siltstone beds exposed at the base of the cliff immediately below the Destruction Island viewpoint sign are similar to those known from the Beach Trail 5 area (see Part II, Starfish Point to Beach Trail 5). They, too, indicate that the strata in which they occur were originally deposited in the sea during early Miocene time some 15 to 22 million years ago.

South Rock (fig. 68), the prominent offshore stack about three-quarters of a mile to the west of this area, is a resistant Hoh sandstone remnant. It is similar to the sandstone that forms the point immediately north of the Destruction Island viewpoint sign.

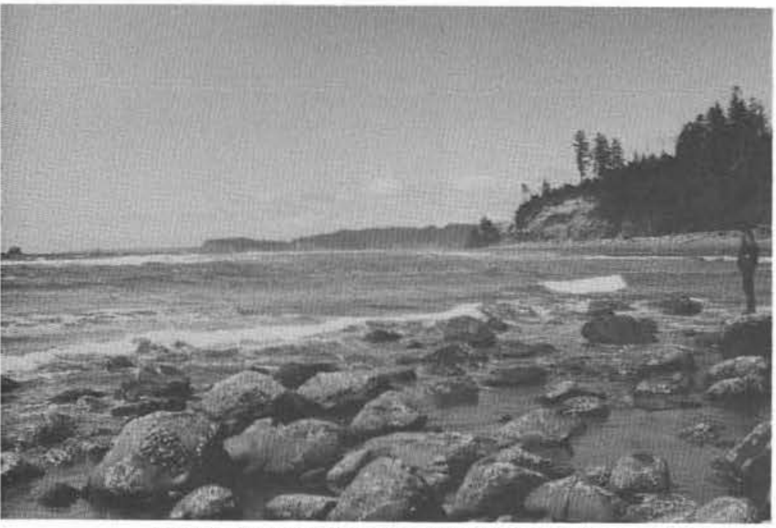


UNSTRATIFIED DEPOSITS of clay, silt, sand, gravel, and boulders exposed in the base of the cliff at Beach Trail 7. The completely unsorted condition of such materials suggests little if any stratification by water, and therefore they were very likely deposited directly by glaciers. (Fig. 66)

RUBY BEACH–ABBEY ISLAND

BEDROCK

Extending from Wet Foot Point, immediately south of Ruby Beach (fig. 62), northward to nearly the mouth of Cedar Creek, a distance of about one-half a mile, massive, badly fractured sandstone is exposed in the lower 50 feet of the cliffs and in both onshore and offshore stacks and low rocks. These are also outcrops of Hoh rocks. In places the sandstone is very coarse grained, consisting of grit-sized pebbles. White chert or quartz pebbles are particularly noticeable. As are most of the Hoh standstones, these strata are composed of many



A BOULDER-STREWN BEACH NEAR BEACH TRAIL 6. As the sea erodes the coastline eastward, boulders were redeposited here from an ancient, now elevated beach level. The boulder-studded trace of this old elevated beach surface is visible in the adjacent cliffs of this area. (Fig. 67)

fragments of various rock types and are therefore classified as graywacke sandstone.

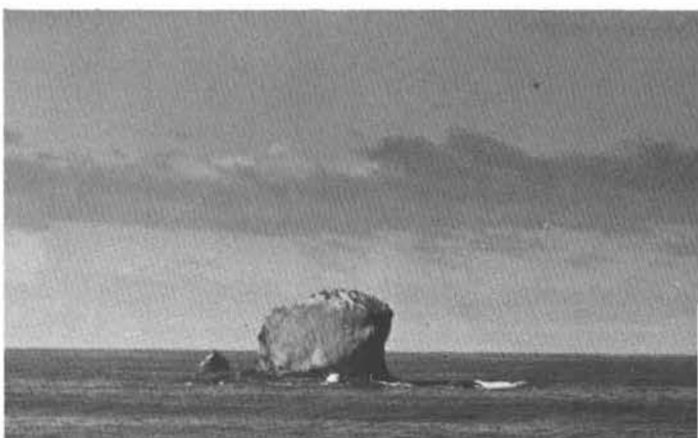
In this area Hoh rocks have undergone considerable deformation and have been highly fractured. Most of the fractures have since been filled with secondary minerals, largely calcite, forming thin white veins.

A somewhat different rock type is exposed north of the mouth of Cedar Creek in beach stacks, in the base of the cliff, and on Abbey Island (fig. 71). Here, the rocks are primarily volcanic in origin although many clasts of sedimentary rocks can be found within them. Generally, the rocks of this area are classified as "volcanic breccia" (fig. 69). Most likely they were formed when volcanic materials were ejected onto the sea floor where they cooled rapidly, forming much angular volcanic rubble that, in turn, was incorporated with sediments already on the sea floor. All of these materials have since been welded together by heat, pressure, and secondary mineralization. Some of the rock types that can be seen in this agglomerated rock unit are various volcanic rocks including volcanic glass, amygdaloidal and vesicular basalt and tuff, together with clasts of sedimentary rocks including white, green, and red chert, argillite, and sandstone. Some time following the consolidation of this rock unit, it was fractured, but subsequently it has been recemented with secondary minerals, largely calcite, much like the sandstone of Ruby Beach. Numerous thin white veins can therefore be seen in rocks of Abbey Island as well as other nearby outcrops.

Structural and stratigraphic relations of Hoh rocks in the Ruby Beach-Abbey Island area are very complex. Attempts by geologists to unravel details of the geologic history of these rocks have been based largely on conjecture and conclusions are therefore hypothetical. It is apparent that Hoh rocks of this area have undergone considerable deformation. The presence of volcanic rocks in an unknown relation with an otherwise sedimentary section suggests that crustal movement may have brought these two different rock types in juxtaposition. Some geologists, therefore, postulate that a major fracture or fault zone may pass through this area. Others suggest that the bedrock of this area represents huge blocks of contorted resistant rock within a "melange" or mixture of rocks (see Part I, Tectonic melange of the Hoh rock assemblage). On the latter basis, the rocks of this area can be compared with those of the Hogsbacks area, where large resistant blocks, mostly of sandstone and volcanic material, are set in a matrix of relatively soft, contorted clay and siltstone (see Part II, The Hogsbacks area). Regardless of how the Ruby Beach-Abbey Island bedrock became structurally complex, it is apparent that these rocks have undergone much deformation from great amounts of force, and that a history of considerable crustal movement during the past 20 million years or so is represented in rocks of this area.

SAND AND GRAVEL DEPOSITS

In most of the Ruby Beach-Abbey Island area bedrock extends upward in the cliffs between 30 and 60 feet above beach level. The generally level line formed on

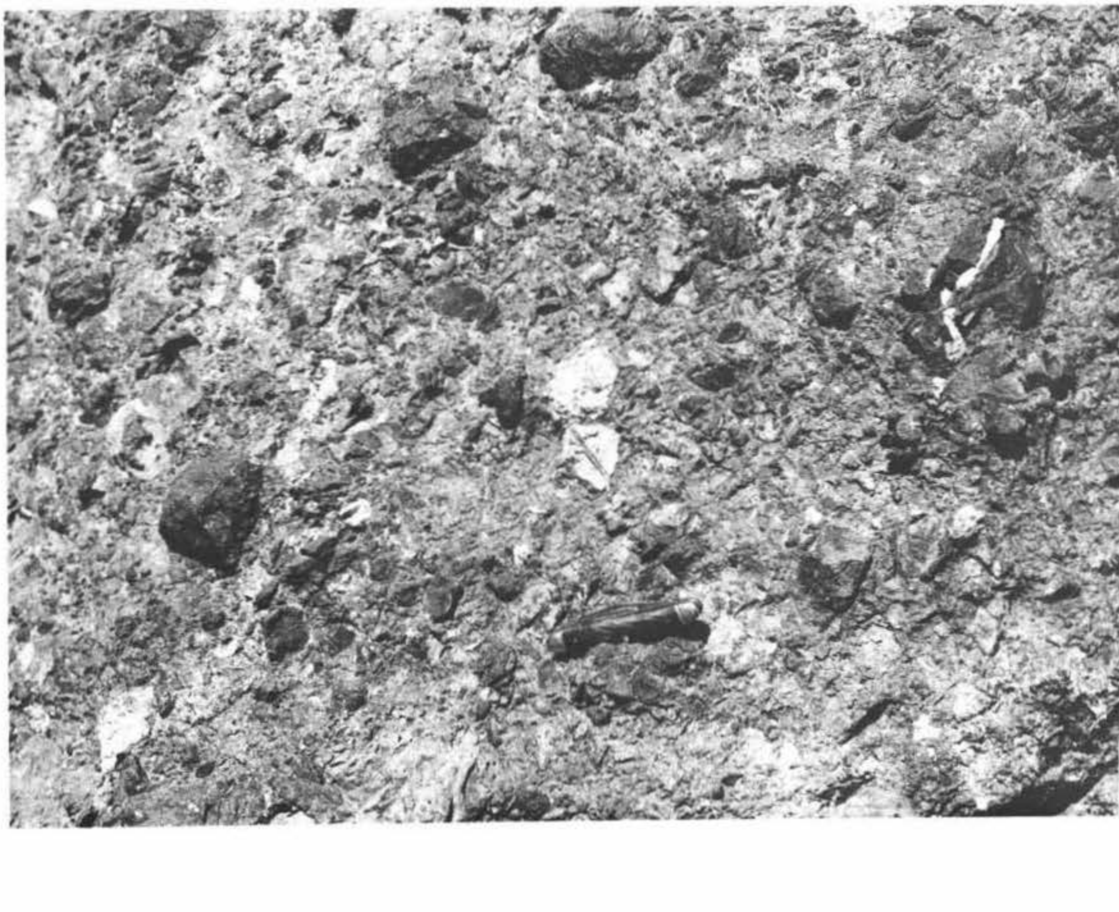


SOUTH ROCK, a sandstone erosional remnant from Hoh rocks about three-quarters of a mile offshore between Beach Trail 7 and Ruby Beach. (Fig. 68)

top of bedrock represents the trace of the Pleistocene wave-cut surface that also occurs in many places to the south. Ancient piddock clam borings, essentially identical to those found today only at tidal level, can be seen on this surface on the south side of Abbey Island some 50 feet above present-day sea level. Bedrock knobs that stand above the old elevated level were offshore stacks or promontories of land during that time. Outwash sand and gravels, distributed by streams from glaciers of the Pleistocene Epoch, cover the old wave-cut surface and form the remainder of the cliffs, which in this area, measure over 100 feet in height. Some of these deposits also form an upper part of Abbey Island.

sand and gravel of late Cenozoic age (fig. 70). The highly fractured and structurally complex outcrops of Hoh rocks of the Ruby Beach-Abbey Island area extend northward from the volcanic rocks of Abbey Island for over half a mile. Various rock types are exposed in the lower 50 feet or so of the cliffs and in several large low-tide outcrops. They include both highly sheared siltstone and large bodies of massive broken sandstone. Siltstone outcrops are similar to the intensely sheared and jumbled Hoh rocks that are exposed in several places to the south (see Part II, The Hogsbacks area), and the sandstones are comparable to those of the Ruby Beach area.

The trace of the ancient wave-cut surface, visible in the Ruby Beach area and many other places to the south, is also seen here at the top of the bedrock some 50 feet above the beach. Sand and gravel deposits of late Pleistocene age overlie bedrock and, in places, are at least 100 feet thick.



BEDROCK OF ABBEY ISLAND. It consists mostly of angular fragments of volcanic material and some sedimentary rock, all of which are welded together to form a solid rock mass. Such material is called volcanic breccia. (Fig. 69)

The name "Ruby Beach" is derived from reddish-colored patches of sand that are particularly prevalent in this area. This color is due to concentrations of individual crystals of the relatively heavy, red-colored mineral, garnet (see Part II, Hogsbacks area, Red beach sand).

ABBEY ISLAND TO THE HOH RIVER

For a distance of neary 2½ miles northward from Abbey Island to the Hoh River, high cliffs, in many places towering over 150 feet above the beach, expose both bedrock of Hoh rocks and large continuous outcrops of

At the north end of the bedrock outcrops, about one-half of a mile north of Abbey Island, a dark gray semiconsolidated mixture of clay, sand, and boulders is exposed in the lower part of the cliffs. These materials most likely were deposited directly from glacial ice with very little, if any, reworking by streams from the glaciers. A few hundred feet to the north, these poorly sorted materials are overlain by typical lakebed deposits of fine-grained gray, thin-bedded silts and clays. Outcrops of these well-stratified sediments continue northward for a considerable distance. From the relations seen in this immediate area it appears that the poorly sorted materials were deposited directly from a glacier into a body of water, perhaps a lake. Subsequently, normal lake deposition of fine materials resumed and at least partially buried the glacially derived deposits. In this same area a thickness of some 20 feet of orange-colored sands overlie the gray-colored sediments. A few cobbles are scattered along the trace of the nearly horizontal upper surface of these orange-colored sands, marking the continuation of the old wave-cut surface that, to the south, was formed on the bedrock of Hoh rocks. All sand and gravel above this line of cobbles was deposited by streams flowing from one of the last of the Pleistocene glaciers to occupy nearby valleys to the east.

Northward for overhalf a mile to a place about 1¼ miles north of Abbey Island, the cliffs are prominently broken with landslides. Extremely large areas of the upper sand and gravel unit are slumped downward and rotated away from the scarp that has been formed several hundred feet inland from the coastline. Drunken forests are prevalent in this large area, indicating movement of the surface during the life span of the trees. This slumping most likely has resulted from movement of large masses of sand and gravel on the underlying soft, somewhat greasy, laminated clay and silt unit, part of which is exposed immediately to the south of the slumped area.

To the north of this large area of landslides, the cliffs, towering nearly 150 feet above the beach, display relatively undisturbed deposits of Pleistocene silt, sand, and gravel. Here the trace of the Pleistocene wave-cut surface is well marked by a line of boulders some 50 feet above the beach. Fine-grained, well-laminated, gray-colored materials, similar to those at the base of the cliffs south of the landslide area, also form the base of these cliffs. They are overlain by very colorful, reddish-orange, parallel and cross-laminated sands (fig. 72), materials that were probably formed as beach or dunelike deposits during the Pleistocene Epoch. These sands extend upward to the line of boulders and cobbles that separates them from later Pleistocene glaciofluvial materials above. In places these latter deposits measure nearly 100 feet in thickness.

Both units above and below the boulder layer are well displayed in the ciffs northward for nearly three-quarters of a mile. Toward the north, the boulder layer gradually rises in height above the beach to an elevation of at least 75 feet. However, the total height of the cliff becomes less to the north because, in this area, the land surface has been lowered by erosion to form the south side of the Hoh valley. Therefore, the thickness of outcrop of the upper unit has been reduced. Farther north all of the upper unit has been removed and only a part of the lower unit remains. In the northernmost area of these deposits, about half a mile south of the Hoh Indian village, only beds of the lower laminated gray silt and clay are left to form the low-lying bluffs. The gradual but noticeable rise northward in the height of the trace of the boulder-covered wave-cut surface indicates that since it was first formed sometime during the late Pleistocene it, as well as the materials beneath, have been slightly upwarped.

Present-day beach deposits in much of the area between Abbey Island and the Hoh River are continually replenished from the Pleistocene materials of the adjacent cliffs. They have been moderately reworked by wave

LOOKING NORTHWARD FROM THE ABBEY ISLAND AREA. In places, contorted Hoh rocks crop out at the base of the cliffs beneath thick deposits of sand and gravel of the Pleistocene Epoch. (Fig. 70)

ABBEY ISLAND with Hoh Head in the distance. The basal part of the island is largely volcanic rock with some included fragments of sedimentary rock. Bedrock materials are overlain by sand and gravel deposits, some 50 feet thick. (Fig. 71)

action of winter storms; the finer fractions of the deposits including fine pebbles, sand, and silt have been removed and deposited farther seaward.

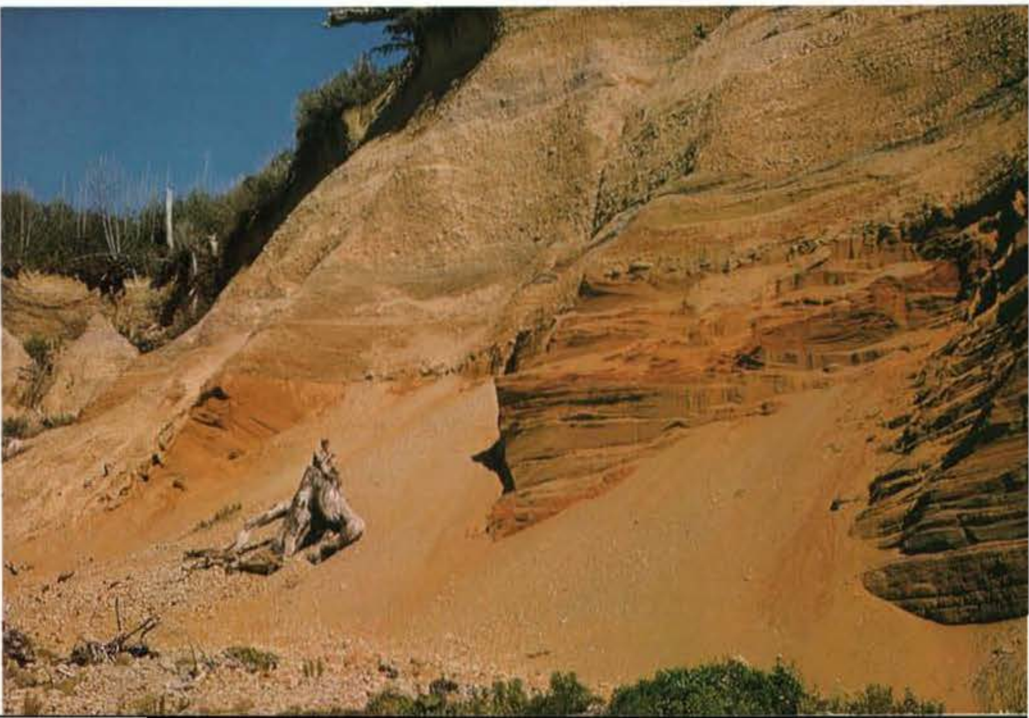
HOH RIVER AREA

In the low-lying bluffs, for a distance of about one-half of a mile south of the Hoh Indian village, Hoh rocks are poorly exposed in a few isolated outcrops beneath deposits of sand and gravel. Erosional remnants of sandstone boulders are scattered on the beach in this area. Here, as in the Abbey Island area, Hoh rocks are structurally complex. Thin-bedded sandstone and siltstone strata are well exposed immediately south of the village where the complexity of the structure is particularly apparent. Additional outcrops of Hoh rocks, mostly massive graywacke sandstones, are present on both sides of the Hoh River.

One of the few outcrop areas where marine fossils are known to occur in Hoh rocks is located about 1½ miles upstream on the north side of the river. A few of the more common species known from there have been identified by Dr. Warren O. Addicott of the U.S. Geological Survey and are listed on page 6 . According to Dr. Addicott, these fossils lived in a relatively shallow marine environment, possibly at depths between 30 and 100 feet during the Miocene Epoch (see Geologic time chart, fig. 2).

In the same vicinity a major oil and gas test well was drilled in 1965 to a depth of 5,015 feet. According to information from well logs, much of it was drilled in sandstone and some beds of siltstone. Significant gas was encountered, particularly near the bottom of the hole, but in subcommercial quantities. This, however, was not the first attempt at petroleum production in the Hoh River

COLORFUL DEPOSITS OF SAND AND GRAVEL exposed in the cliffs about one mile south of the Hoh River. Beach and dunelike deposits are represented in the lower unit of sand, whereas the gravels in the upper part of the cliff probably were deposited by streams. The nearly horizontal line of cobbles and boulders separating the two deposits represents the trace of an elevated wave-cut sea level surface that was formed on the lower deposits sometime during the Pleistocene Epoch. (Fig. 72)



area. At least eleven shallow wells, for which there are records, were drilled in an area about 1½ miles northeast of the mouth of the Hoh River in the vicinity of the Jefferson oil seep (fig. 60). Most of these wells were drilled to a depth of less than 1,000 feet. Although none produced commercial quantities of oil or gas, shows of petroleum were recorded in nearly all. Two eras of drilling took place near here, the earliest of which started in 1913. At that time the drilling equipment was brought in from ships through the surf at Jefferson Cove, and then dragged up the bluffs to the drilling site a mile or so inland. The second period of drilling began in the early 1930's, during which time slightly deeper wells were drilled. The deepest penetrated 2,155 feet of Hoh rocks. Another well was drilled in the 1930's near the Lacy oil seep, some five miles northeast of the mouth of the Hoh River, but without commercial success. In 1948, a major company drilled to a depth of 5,600 feet on the south side of the Hoh River, some 3 miles upstream from its mouth. Again, however, only minor shows of gas were reported.

Thus, the lower Hoh River area has had a history of considerable petroleum exploration, most of which was prompted by the presence of several oil seeps. Remaining evidence of these days of exploration optimism can still be seen on maps and highway signs where the name "Oil City" is used to refer to a platted, but essentially nonexistent, community near the mouth of the Hoh River.

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