THE GEOLOGY OF A PORTION OF
THE SKAGIT DELTA AREA
SKAGIT COUNTY, WASHINGTON

by

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A Thesis submitted in partial
fulfilment of the requirements
for the degree of

MASTER OF SCIENCE

in the Department

of

GEOLOGY

We accept this thesis as conforming
to the required standards

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1962

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ABSTRACT

Northwest-southeast Miocene uplift with subsequent erosion has bared rocks of Paleozoic, Mesozoic and Cenozoic ages in the western Skagit Delta region. Pleistocene glaciation followed by recent alluviation has buried much of the bedrock leaving rock exposures only on islands in Skagit Bay or as low hills projecting through the alluvium.

A low-grade metamorphosed sequence of graywacke, conglomerate, breccia, argillite, and spilite, all of probable Paleozoic age, make up the oldest rocks of the area.

Mesozoic rocks, composed of graywacke and argillite, crop out in hills northwest and southeast of the town of La Conner. The contact between Paleozoic and Mesozoic rocks is not exposed but an unconformity is believed to separate the two. No fossils were found in either sequence. Because Paleozoic(?) and Mesozoic(?) rocks can not be correlated with any other known units, new names have been assigned by the writer. The Paleozoic(?) sequence is called the Goat Island Formation and the Mesozoic(?) sequence is called the La Conner Formation.

Along the North Fork of the Skagit River a conglomerate sequence with interbedded sandstones and siltstones makes up disconnected, low, tree covered hills. Lithologically this sequence can be divided into two formations separated by a probable unconformity. Microfossils in the upper unit indicate a Lower

Tertiary age but definite correlation with described units in other areas is not possible. The lower formation is here designated the Delta Rocks Formation while the upper is called the Ika Formation.

Serpentinites make up the whole of Goat Island and adjacent parts of Fidalgo Island. On southern Fidalgo Island another serpentinite encloses an unusual hydrothermal vein containing calcite, celestite, and strontianite. These ultrabasic rocks are considered part of the Fidalgo Formation and are of probable Triassic age.

A small outcrop of marine Pleistocene occurs at the east end of Goat Island and contains an assemblage of invertebrates. Vashon till and outwash cover most of Fidalgo Island and Pleasant Ridge.

Pre-Tertiary deformation has been intense with both Paleozoic and Mesozoic sequences folded, sheared and faulted. Cenozoic deformation has been restricted to Miocene concentric folding. Axes of both pre-Tertiary and Tertiary folding are aligned essentially east-west.

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INTRODUCTION

LOCATION AND ACCESS

This report describes the geology of an area of about 45 square miles, located in Western Skagit County, northwestern Washington, about 20 miles due south of Bellingham and 40 miles south of the Canada-United States border. The area is bordered on the east by Skagit Delta alluvium, on the north by alluvium and glacial debris, while to the west and south it is delimited by Skagit Bay. La Conner, a town of about 600 population lies close to the geographical center of the map area.

Most of the mainland and southern Fidalgo Island are readily accessible by road, but many of the outcrops occurring along the coast can be visited only on foot and at low tide.

The islands of Skagit Bay, comprising the western portion of the map area, can be reached only by boat and then only with some difficulty. Skagit Bay, when whipped by southerly winds, can become unpleasantly rough, and hazardous for a small boat. Shoal areas and mud flats are navigation hazards, even for shallow draft outboard vessels. At low tide it is not possible to cross most of the mud flat areas, hence Ika, Whitman and Martha Islands are inaccessible at low water. Other difficulties arise at high tide. Several islands, in particular Hope and Seal Rocks, are partially bordered by wave cut benches, which are barely water covered at high tide. The unwary navigator can easily lose a shear pin or even hole his boat unless he approaches these islands with considerable caution.

PREVIOUS GEOLOGICAL WORK

McLellan (1927) in his work on the San Juan Islands briefly describes the rocks of the northern end of Fidalgo Island, some six miles northwest of the area described in this report. More recently W.R.Danner, while doing detailed geology in the San Juan Islands, has had occasion to visit the area. Various publications of the "Washington Division of Mines and Geology," and predecessor agencies, refer to different aspects of the general region without much specific reference to this particular area. Included are publications by: Bretz (1913, 1920); Cambell (1953); Daly (1912); Glover (1935, 1947) and Willis (1898).

Landis (1929) reported on the strontium occurrence at the southeast end of Fidalgo Island. Sceva (1950) discussed the geology and ground water resources of the Skagit Delta.

FIELD WORK

Field work was started in December 1960 and continued at intermittent intervals through November 1961. Field data for the eastern portion of the area was plotted on U.S. Geological Survey topographic sheets with a scale of 2 inches equal one mile. The western part was plotted on topographic sheets of scale one inch equal one mile. Although lacking recent cultural changes, these maps were found generally adequate and accurate.

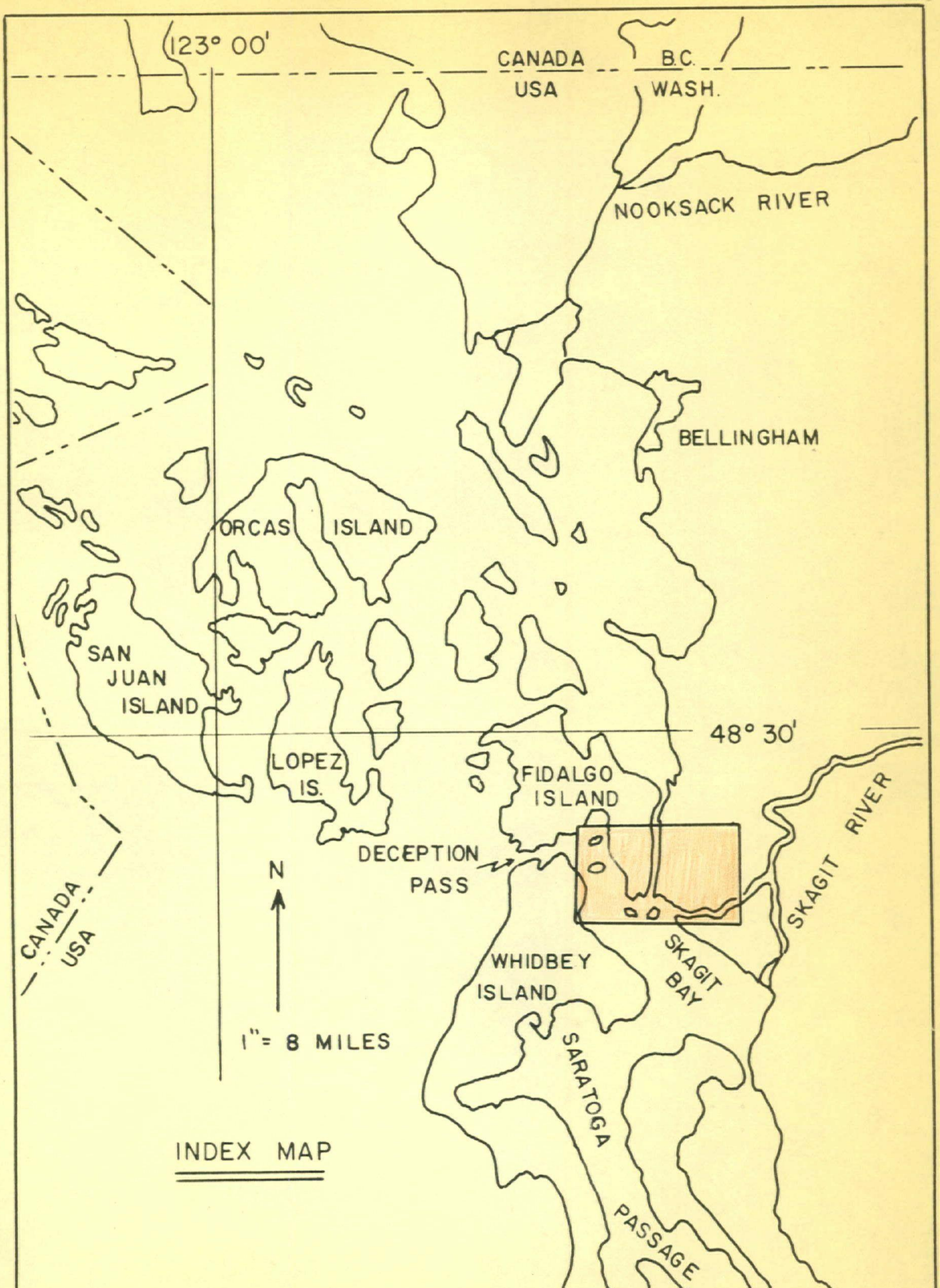

123° 00'
CANADA
USA
B.C.
WASH.
NOOKSACK RIVER
BELLINGHAM
ORCAS ISLAND
SAN JUAN ISLAND
LOPEZ IS.
48° 30'
FIDALGO ISLAND
DECEPTION PASS
SKAGIT RIVER
SKAGIT BAY
WHIDBEY ISLAND
SARATOGA PASSAGE
CANADA
USA
N
1" = 8 MILES
INDEX MAP

PLATE 2

ACKNOWLEDGMENTS

Several people offered considerable assistance during the preparation of this report. Mr. Alastair Sinclair offered much constructive criticism and made many helpful suggestions. Dr. Glen Rouse of the Botany Department was of indispensible help with methods, identification and presentation of the paleo-botanical data. Dr. P.A.Dehnel, of the zoology department, kindly identified the marine Pleistocene invertebrates. Special thanks are due Dr. W.R.Danner under whose supervision this thesis was written. Dr. Danner offered much helpful advice both in the laboratory and the field.

GEOGRAPHY

SURFACE FEATURES

The entire map area is topographically low, with elevations ranging from sea level to a maximum height of 440 feet on Ika Island. Flat and immensely fertile river alluvium of the Skagit Delta covers the western portion of the map area. Skagit Bay and bordering mud flats comprise the western part of the area. The North Fork of the Skagit River flows westward through the southern part of the map area. Bedrock projects through the alluvium as rounded hills and in Skagit Bay forms steep-sided islands.

MAINLAND

On the mainland, bedrock occurs along the North Fork of the Skagit River and northward along Pleasant Ridge, mostly as low, rolling hills with maximum elevations of 100 to 150 feet. All hills are surrounded by alluvium, the surface of which slopes gently from sea level near Fish Town to about 10 feet above sea level at the eastern border of the map area. Except where cleared for agricultural purposes, vegetation on the hills is dense, and includes conifers, deciduous trees and under brush. The west and south sides of these hills are often marked by vertical to near vertical, 20 to 30 foot high cliffs.

Much of the town of La Conner is built on and around bedrock hills rising to similar elevations as those along the Skagit River. These are occasionally steep-sided and are densely covered with vegetation except where cleared by man.

Within the map area, Fidalgo Island can be divided into two distinct geographical districts: (a) A southeast promentory bordering Swinomish Slough and (b) the remainder of the island north of the promentory. The northern and western parts of the island form a rolling upland surface, attaining an average elevation of 100 to 300 feet but shorelines are bordered by 50 to 75 foot high bluffs. The upland surface contains several closed depressions. Thick forest and underbrush cover the island.

Some of the most rugged terrain within the map area lies at the southeast end of Fidalgo Island. Relief is approximately 400 feet with numerous steep slopes and cliffs, especially

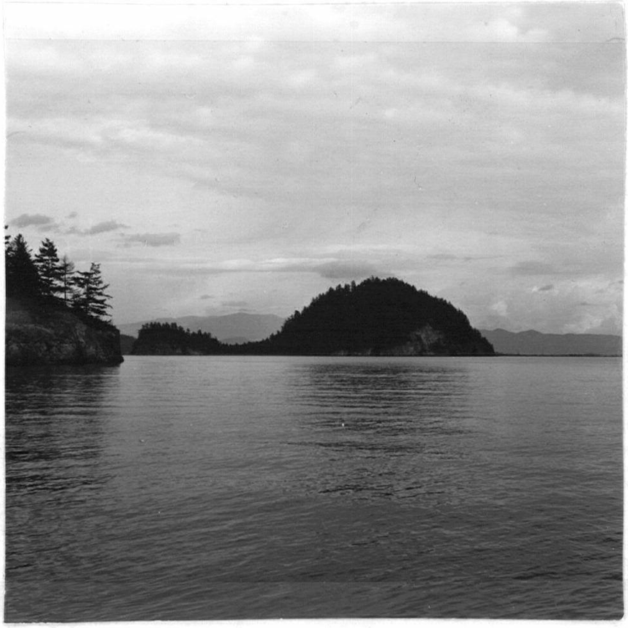


Figure 1. View east toward Ika Island. Notice opposed dips. West end of Goat Island to left.

Figure 2. Southwest side of Ika Island. Contact between Delta Rocks Formation (below) and Ika Formation (above) lies half way up slope. Both units dip north (left).

around the margin. The area is heavily covered with second growth timber and underbrush. Several overgrown logging roads are present, and the remains of two abandoned sawmills indicate former extensive logging operations.

In the northwest corner of the map area a sandspit connects Fidalgo and Kiket Islands. Kiket Island has an area of about 80 acres and a maximum elevation of 160 feet. Vegetation is thick except on the eastern and western extremities of the island. A private road traverses the island from east to west.

IKA ISLAND

Ika Island has an area of 115 acres, and with the exception of a permanent 32 acre salt water swamp, has a steep, precipitous land surface. It is topographically asymmetrical with a northern high point of 155 feet and a southern high of 440 feet separated by a saddle less than 30 feet high. Soil cover is thin over most of the island but vegetation is thick except on vertical rock faces. These tend to be separated by benches covered with a thick tangle of vegetation. The Island is completely surrounded by mud flats and is accessible only at high tide.

GOAT ISLAND

Goat Island, covering 109 acres, lies adjacent to the Swinomish Ship Channel, consequently its north side can be reached by boat at any time. It is lowest at the west end, gradually rising to its maximum elevation of 225 feet at the northeast edge. The island is steep-sided, being bounded on the east, north and south by cliffs of varying height. The only route of convenient access to its top is from the west. During the second World War Goat Island was the home of a small army detachment, based in what was called Fort Whitman. Subsequently the Fort was abandoned and vegetation overgrew the cleared areas making ground traverses difficult. Numerous barbed wire entanglements are still present and can be hazardous. Goat Island, now the property of the Washington State Game Department, is set aside as a game preserve.

BALD ISLAND

Bald Island, located near the mouth of the North Fork of the Skagit River covers 12.5 acres with a maximum height of 103 feet. It is a rounded grass and tree covered knob, used by its owners for cattle grazing.

MARTHA AND WHITMAN ISLANDS

Martha and Whitman Islands, arbitrarily named by the author in lieu of official names, are two adjacent rocky knobs, each about an acre in extent, lying north of Goat Island. Martha Island is about 35 feet high, barren of trees or shrubs but supports some grass in fractures or depressions. Whitman Island, perhaps 50 feet high, is almost circular and bounded by almost vertical cliffs. Both islands are surrounded by mud flats which are exposed at low tide.

SEAL ROCKS

Seal Rocks is a group of shoal rock areas in the middle of Skagit Bay. A seaward sloping rocky terrace surrounds the "Rocks" which are more or less uncovered at low tide but largely awash at high, so are a definite menace to closely passing vessels. A navigation beacon is installed at the highest point of Seal Rocks. Vegetation is limited to lichens, moss and grasses.

DEADMAN AND LITTLE DEADMAN ISLANDS

Deadman and Little Deadman Island, located between Goat and Hope Islands, are respectively, six and three acres in area. Except for size they are similar and both support a flora of conifers and underbrush. Both are fairly steep-sided but access to their summits is easy. Deadman Island rises to 50 feet while Little Deadman is perhaps one-half that. A number of large eagle nests were observed in the few trees of Little Deadman Island.

HOPE ISLAND

Except for Fidalgo Island, Hope Island is the largest island within the map area, having an area of about 180 acres and an east-west dimension of nearly one mile. It is almost flat-topped with average elevation of about 125 feet but near the east end is more than 160 feet above sea-level. The island is mostly bounded by steep cliffs which at the southwest and west end plunge at high angles into deep water. Much of the north, east and southeast shores are bordered by sand beaches. Care must be exercised in landing on the southern and eastern shores because of large boulders and irregularities on the rocky terrace bordering these portions of the Island. The cove on the north shore appears to have only a gradually shallowing sandy bottom making landing a "wet-boot" affair but with no danger to boat or motor. Except at the extreme west end, which is largely grass covered, the Island is forested with a dense growth of conifers and thick underbrush. Hope Island is State property and a part of Deception Pass State Park.

SKAGIT ISLAND

Lying to the north of Hope Island, Skagit Island is a mound-like rock rising to 110 feet and covering 26 acres. It is bounded by near vertical cliffs dropping down to a narrow, rocky, wave-cut terrace. Access to the Island summit is possible only at the northeast end where a small sandy beach allows a boat landing and where cliffs are lacking. Except for the grass covered southwest end the Island is conifer and brush covered. Along with Hope Island, Skagit Island is a part of Deception Pass State Park.

DELTA ROCKS

Delta Rocks is a collective term for a small group of rocky knolls south of the mouth of the North Fork of the Skagit

River and the only outcrop south of the Skagit River within the map area. This outcrop is separated from diked dry land by one-half mile of salt water swamp, impassable at high tide. Even at low water hip boots are necessary because of the soggy, unpredictable surface. The maximum elevation at Delta Rocks is 86 feet.

McGINN ISLAND

Across Swinomish Slough from the southeast tip of Fidalgo Island is situated a small island of 38 acres. Known as McGinn Island, and tied to the Skagit Delta by a sand bar, it forms the east border of "Hole-in-the-Wall", or southern entrance to the Swinomish Ship Channel. The island is heavily forested and is the site of several private homes. A quarry has been opened in its north side.

CLIMATE

The climate within the map area is equitable and mild. Average precipitation on the Skagit Delta is 36 inches, with the greatest rainfall in Decemher and the least in July. Prevailing winds are from the southwest, and though these may attain considerable force over Skagit Bay, winds over the delta are rarely strong. Temperatures are moderate with winter lows seldom below 30°F and summer highs rarely above 80°F.

VEGETATION

Hilly areas have been logged in times past and are now densely covered with secondary growth timber which, among the evergreens includes Douglas Fir, Grand Fir, Cedar and Hemlock. In the more recently logged areas willow, wild cherry, western birch, dogwood, cottonwood, alder and big leaf maple are common.

Shrub vegetation includes stinging nettles, Oregon grape, blackberry, salmon berry, salal, wild rose and buck-brush.

The "flatlands" made up almost entirely of Skagit River alluvium is exceptionally rich and intensively farmed. Major crops are grains of various sorts, especially oats with a record 175 bushels per acre. Other crops include hay, hops, vegetables and sugar beets, as well as much of the cabbage, turnip beet and cauliflower seed used in the United States.

CULTURE

The Skagit Delta Country has long been occupied by several different Indian tribes. The time of arrival of the first indians is unknown but presumably they have been in the area for several thousands of years. A site in eastern Washington was occupied about 8,000 years ago and it seems reasonable to assume that occupation west of the Cascades was essentially contemporaneous. The moist climatic conditions of Western Washington are not, however, conducive to preservation of cultural sites.

Evidence for recent indian occupancy is very striking within the map area. Many of the hills and lowlands along the Skagit River are mantled with human-created debris, especially clam and mussel shells, which make up impure, man-made coquinas up to 3 feet thick. Presumably these middens were the garbage dumps for adjacent indian villages. A most striking example of this is on Swinomish Slough across the river from La Conner where an entire flat meadow surface is built on a shell base. Another occurrance is near the mouth of the Skagit River on the north shore. Excavations by an archealogical team penetrated more than 3 feet of shell and interbedded soil materials without reaching a base. Because a cover of large conifers covers this latter site, its age must be at least several hundred years. Within the past year an indian skeleton was uncovered in burial position from this area.

The first known visit of a white man to the area was by Lt. Joseph Whidbey, commander of HMS Chatham, accompanying the George Vancouver expedition which explored Puget Sound in 1792. Whidbey first sailed north through Saratoga Passage to the vicinity of the mouth of the Skagit River. Several weeks later, in June 1792, he discovered the true nature of Deception Pass when he traversed it from west to east, again penetrating to the region of the Skagit Delta.

During the next 50 years the inevitable western cycle of trappers and traders, followed by settlers, was enacted in the Puget Sound Country. By the middle of the 19th century the rich farmlands of the Skagit Delta were attracting homesteaders while the waters of Skagit Bay, somewhat later, attracted commercial fishermen.

La Conner, the only town within the map area, is a settlement of about 600 persons. It was first settled in 1867 as a fishing and agricultural village and fulfills a similar role today.

The surrounding country is almost completely agricultural and supplied by a closely spaced network of roads. Much of the farmland is on reclaimed salt tide marsh, with the waters of Skagit Bay and the Skagit River being held back by a complex pattern of dikes.

WATER SUPPLY AND DRAINAGE

The major drainage feature of the area is the North Fork of the Skagit which is the principal distributary of the Skagit River. Drainage area of the west flowing Skagit River is 3,060 square miles of which 400 square miles are in Canada. The average discharge of the river is 16,260 cubic feet per second and is maintained at a rather steady flow by a series of upstream dams and reservoirs.

Because the regional water table is only slightly above

Figure 3. South end of Swinomish Channel, between Fidalgo and McGinn Islands

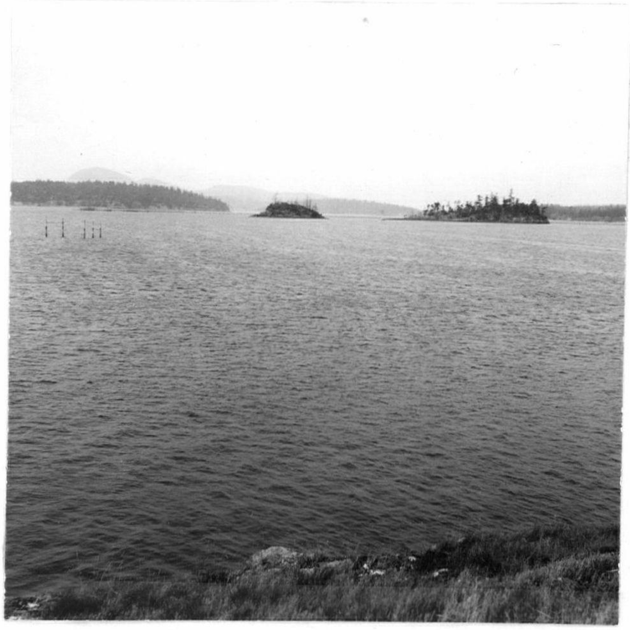


Figure 4. View north up Skagit Bay. Hope Island to left, Little Deadman Island center, Deadman Island right.

sea-level, ground water is found at shallow depths over the entire Skagit Delta. Lenses of sand and gravel, the principal aquifers are capable of producing large quantities of water. Wells 40 to 70 feet deep pump 125 to 600 gallons per minute. These are pump yields and often below their theoretical potential. (Sceva, 1950).

Deep wells, below 110 feet, and those near the margin of the delta penetrate only fine-grained sediments and consequently are poor producers. Recharge of aquifers is thought to be principally from precipitation with small amounts contributed locally by the Skagit River.

As of 1950 only seven water analyses had been run of ground waters on the Skagit Delta and these gave diverse results. Total hardness ranged from high to low; two water samples were very high in bicarbonates. Most ground water from the delta requires no treatment for domestic use, but locally it is high in iron or carbonaceous material which requires chemical treatment for removal.

Pleasant Ridge, composed of undifferentiated Pleistocene sediments, and capped by Vashon till contains several perched water tables. These, while usually adequate for domestic use, are too local and restricted for the heavier pumping required for stock use. Wells, penetrating to depths of 100 to 200 feet, supply sufficient quantities of water for stock and domestic use from sand or gravel lenses lying below the regional water table. Two logged wells are located within the map area and are named below. A water analysis for one well is also tabulated. Data from Sceva (1950).

Well 5H-1 - West side Pleasant Ridge.

Ground level, 90'; T.D. 112'; Bit 4"; Casing 112'; depth to producing zone 90'; Thickness of producing interval, 22'; Producing interval rock type, fine-grained sand; Date drilled, 1946; Water use, domestic and stock purposes.

Sample Description	Thickness	Depth
Alluvium and till of Vashon age:		
Soil and hardpan	50	50
Pleistocene Deposits, undifferentiated:		
Sand	30	80
Clay	10	90
Sand, fine-grained, water bearing	22	112

Chemical Analysis of water, well 5H-1 (U.S.Navy)

Parts per Million

Iron, Fe	0.05
Bicarbonate, HCO_3	358.0
Sulfate, SO_4	20.0
Chloride, Cl	6.0
Fluoride, F	0.2
Nitrate, NO_3	18.0
Hardness as $CaCO_3$ total	320.0
non-carbonate	190.0

Well 9H-1 - Southeast end of Pleasant Ridge.

Ground level, 25'; T.D. 60'; Bit, 6"; Casing length 60'; Date drilled, 1944; Use of water, domestic.

No analyses, but water is known to be high in iron.

Figure 5. View south down Skagit Bay. Seal Rocks, right; Goat Island, center; Fidalgo Island, left.

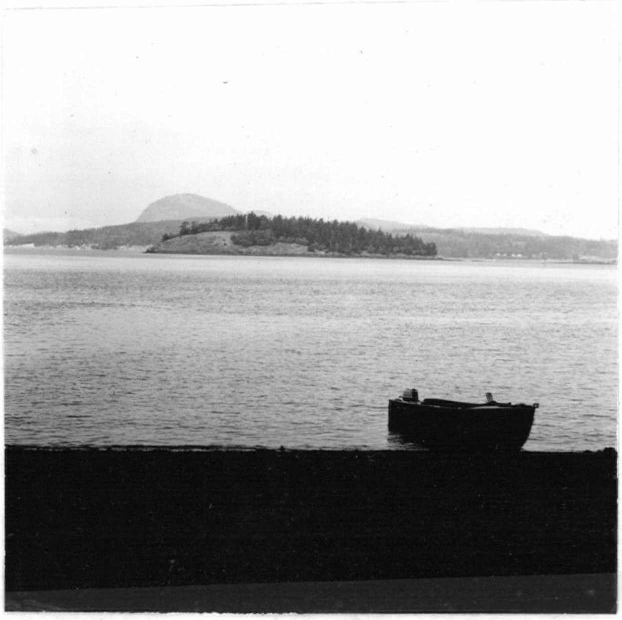


Figure 6. Skagit Island from north shore of Hope Island.

As regards water supply from wells drilled on Fidalgo Island or other areas of pre-Tertiary rocks the results are less predictable. Most holes are from 6 to 60 feet in depth and provide an adequate source of domestic water. Presumably this water is extracted from fractures because surface outcrop suggest there is no effective porosity or permeability in pre-Tertiary rocks.

Another minor source of water for dwelling use, is by catch basins and cisterns. People who use, or have used, this system report it provides more than an adequate supply of fresh, soft rain water.

The smaller islands have no significant surface drainage and to the writer's knowledge no wells have been drilled on them. The army, when occupying Goat Island, piped fresh water from the mainland.

An almost unlimited quantity of fresh water is available within the area covered by this report. Only a very small percentage of available ground water is being utilized and a much greater supply could be obtained without appreciable watertable drawn down.

In the unlikely event ground water supplies became inadequate, water could be diverted from the Skagit River. With purification this would be satisfactory for all domestic and stock purposes.

GEOLOGY

GENERAL FEATURES

The western Skagit Delta area is underlain by rocks of Paleozoic(?), Mesozoic(?) and Cenozoic ages. Included are igneous, sedimentary and low-grade metamorphic rocks.

Low grade, regionally metamorphosed Paleozoic(?) sedimentary rocks are exposed in the southwest part of the map area. This is a sequence composed of graywacke, phyllites, conglomerates, breccias, slates and interbedded volcanic rocks. Deformation has been intense and the rocks are highly deformed.

Mesozoic(?) rocks, essentially graywacke and phyllite, crop out in a northwest-southeast belt extending from Skagit and Kiket Islands in the northwest to a hill north of Dodge Valley in the southeast part of the map area.

Volcanic rocks, largely spilites, occur at the very southeast end of Hope Island and crop out at spotty intervals southward to the region just west of La Conner. Alteration is intense and caticlastic deformation is present at the Hope Island outcrop. A flow-breccia of similar material crops at the northwest end of Ika Island. The Paleozoic(?) and Mesozoic(?) sequences with contained volcanic rocks are called the Goat Island Formation and La Conner formations respectively.

Poorly sorted Tertiary conglomerates with interbedded sandstones and siltstones are present in the south portion of the map area. These sedimentary rocks have been preserved in an essentially east-west trending syncline. Identifiable macrofossils were not found but analysis of finer-grained portions of the sequence revealed the presence of plant microfossils, especially spores and pollen. An early Tertiary age is suggested by this assemblage, but it is not possible to conclusively equate this sequence with described rocks from other areas. However on the basis of lithology it is possible to subdivide these rocks into two formations separated by a probable unconformity. The older is called the Delta Rocks formation while the younger is termed the Ika Formation.

Pleistocene deposits are represented by abundant though discontinuous outwash and till units. These are the deposits of the last stage of Pleistocene glaciation (Vashon). A limited suite of marine invertebrate remains were found in Pleistocene outwash or beach deposits at the east end of Hope Island.

Ultrabasic intrusive rocks make up Hope Island and adjacent parts of Fidalgo Island. A similar ultrabasic rock, with a contained hydrothermal vein of strontium minerals, occurs at the southeast end of Fidalgo Island. These ultrabasic intrusions, now serpentinite, are assigned to the Fidalgo Formation of McLellan (1927).

Skagit River alluvium constitutes the youngest and aerially the largest lithologic unit of the western Skagit

Delta area. The entire Skagit Delta is composed of alluvium deposited since the Pleistocene by the west flowing Skagit River. The Delta is in the process of being built westward and is gradually tieing many of the islands to the mainland.

Following is a table of formations.

TABLE OF FORMATIONS

SEDIMENTARY-VOLCANIC ROCKS

ERA	PERIOD	NAME	LITHOLOGY
Cenozoic	Quaternary-Recent	- - -	Skagit delta alluvium and beach deposits
	Pleistocene	- - -	Glacial till and outwash. Some marine deposits
	Eocene(?)	Ika Formation	Conglomerate with interbedded sandstones and siltstones. Much carbonaceous material.
	Paleocene(?) Eocene(?)	Delta Rocks Formation	Conglomerate composed largely of metamorphic rocks
Mesozoic(?)	- - - - - -	La Conner Formation	Graywacke, argillite, argillaceous limestone nodules.
Paleozoic(?)	- - - - - -	Goat Island Formation	Graywacke, conglomerate, breccia, argillite, pillow lavas, spilite.

INTRUSIVE ROCKS

ERA	PERIOD	NAME	LITHOLOGY
Mesozoic(?)	Upper Triassic(?)	Fidalgo Formation	Ultrabasic intrusions, serpentinite, celestite-strontianite vein.

PRE-UPPER CRETACEOUS SEDIMENTARY ROCKS

OCCURRENCE

The pre-Upper Cretaceous rocks of the Skagit Bay area are an unfossiliferous sequence of graywackes with thin layers of interbedded slates, argillites and conglomerates. Outcrops occur in hills surrounded by recent deltaic deposits or as islands in Skagit Bay. Where subjected to wave erosion cliffs are prominent and are frequently marked by differential erosion along cleavage or bedding planes.

The writer is unable to assign definite ages to the pre-Upper Cretaceous sedimentary rocks of the Skagit Bay area, or to correlate them with rocks described from other areas. They will be discussed according to a broad and tentative two-fold division as outlined in the following section on stratigraphy.

STRATIGRAPHY

On a lithologic basis, using especially color, grain size, degree of deformation, presence or absence of volcanic rocks, and content of calcite, the pre-upper Cretaceous sedimentary rocks have been divided into two broad groups, tentatively considered Paleozoic and Mesozoic. The two groups will be considered independently; this will be followed by a resume of similarities and differences which led to the present sub-division. A discussion of structure has been deferred to a later chapter so the entire geologic column can be discussed as an entity.

PALEOZOIC(?) - GOAT ISLAND FORMATION

The sequence, here considered Paleozoic in age, crops out at Seal Rocks, on Goat Island, the southeast end of Fidalgo Island, McGinn Island, several small hills south of La Conner, Bald Island and at the northwest end of Ika Island where it is exposed below late Cretaceous or Tertiary sediments. The best exposures of this sequence are seen along the margins of Goat Island, consequently the Unit is, in this report, named the Goat Island Formation.

The predominant rock type is thin-bedded graywacke but included are prominent interbeds of pebble conglomerate which locally reach boulder size. Argillite is common and slate with poorly developed cleavage is rare. Volcanic rocks occur within the sequence at several different localities.

Color on weathered outcrop is usually buff to greenish gray. Fresh surfaces are various shades of green to gray or even black. The rocks are highly indurated, resistant and have no porosity or permeability. Silicification is common, especially prominent as ramifying veinlets and often quartz and calcite occur intergrown within the same veinlet. West of Swinomish Slough, on Southern Fidalgo Island, in fine-grained graywacke, intense silicification occurs in the form of numerous, closely spaced quartz veinlets parallel to shearing. Although calcite is common in these rocks, limestone and calcareous nodules appear to be absent.

Deformation is everywhere intense as indicated by isoclinal folds, cleavage and folded cleavage (See section on Structure). Because of the well-developed cleavage normally present which obscures contacts, correlation of units could not be made. Where cleavage is less pronounced individual rock units pinch out or intertongue laterally with other units over short lateral distances.

Fine-Grained Rocks

In thin-section, phyllite shows the effects of strong shearing with most of the silt-size quartz grains broken or fractured and invariably strained. Fine-grained quartz fragments are in places drawn into thin layers parallel to shear. Calcite, the only other important constituent appears to be largely secondary, the result of matrix alteration. A few small grains of a water-clear, negative relief, very low birefringent mineral occurs with the quartz and is probably secondary albite. The matrix, making up probably 90 per cent of the rock is an argillaceous, clay-like mass appearing brown to opaque in plane light. This "clay" matrix has been strongly sheared and is wrapped around the larger grains.

Figure 7. Folded graywacke on Skagit Island

Figure 8. Faulting in sheared graywacke. Northeast striking fault offset by northwest striking fault. Southeast Fidalgo Island

Medium-Grained Rocks

Medium-grained portions of the graywacke sequence are characterized by quartz, feldspar and/or rock fragments set in an indurated argillaceous matrix. Shearing is normally very evident.

Quartz commonly constitutes 40 per cent of the rock, occurring mainly as angular, fractured grains, up to 1 mm in maximum dimension. Indistinct quartz grain boundaries which grade into the matrix are the rule, and are partially the result of small vermicular growths of chlorite and quartz. Commonly the quartz appears to "feather" out into the matrix. Secondary growths of quartz, as rims on grains, were not observed.

Sodic plagioclase, ranging from albite to oligoclase, makes up from 1 to 10 per cent of these rocks. Plagioclase grains are highly corroded and altered to calcite, chlorite, sericite and/or epidote. Orthoclase, if present, is very inconspicuous and unimportant.

Chert is a common constituent and is present in most specimens though in varying amounts, and in places is as high as 10 per cent. It invariably occurs as rounded, elongated grains with the same marginal alteration as the quartz.

Rock fragments, for the most part altered basic volcanics, are common in parts of the sequence. Where present, they are usually elongated, sometimes strongly so, in a plane parallel to cleavage. Where rock fragments are predominant a diminution of feldspar is noticeable.

Coarse clastic fragments are set in a tough, indurated, predominately argillaceous matrix containing small fragments of quartz and feldspar. Authigenesis has resulted in the formation locally of biotite, sericite, chlorite, and calcite. Detrital epidote is rarely present. Pyrite is present as small euhedral crystals distributed randomly throughout the matrix.

Coarse-Grained Rocks

The conglomeratic portion of the sequence is similar in all respects to the sand size graywacke except for the size of fragments. Considerable variation is present in pebble dimensions with 3 mm representing an average diameter. Pebbles are usually sub-rounded to rounded and if shearing has occurred they are elongated in plane of shearing. Quartzites and phyllites are the most abundant pebble material though greenstone pebbles are not uncommon. The original quartzite was impure as indicated by secondary sericite, formed from intergranular, clay-size detrital material.

On southeast Fidalgo Island a number of sub-rounded boulders (up to 25 cm) of greenstone are conspicuous. These tend to be isolated and associated only with pebble conglomerates. The matrix appears to be largely a mass of varying size quartz and plagioclase grains set in a consolidated argillaceous base similar to that previously described.

Estimating the ratio of matrix to larger grains seems futile because of the apparent gradation in grain size from

Figure 9. Photomicrograph of Paleozoic(?) sheared graywacke. Plane light, x 10.

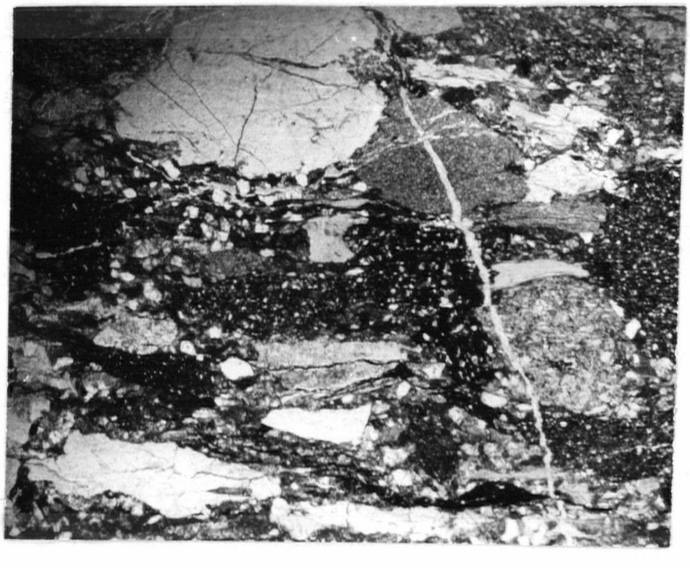


Figure 10. Photomicrography of sheared Paleozoic pebble conglomerate. Pebbles of quartzite, phyllite and greenstone. Plane light, x 10

sub-microscopic to pebbles 3 or 4 mm in diameter. Greenstone boulders are notably larger than the average pebble of the conglomerate.

MESOZOIC(?) - LA CONNER FORMATION

Rocks considered Mesozoic underlie Skagit and Kiket Island, the hills in and around La Conner and the hills west of Pleasant Ridge. These rocks markedly resemble a rock sequence croping out on the south side of Lopez Island in the San Juan Island Archipelago which McLellan (1927) considered Carboniferous and correlatable with the Leech River Group of southern Vancouver Island. Subsequently Danner (personal communication) has found Cretaceous foraminifera associated with interbedded pillow lavas.

However the Mesozoic(?) of Skagit Bay can not be confidently correlated rocks of Lopez Island hence a local formational name is applied. Because the best Mesozoic(?) exposures occur in road cuts at either end of the new bridge across Swinomish Slough, immediately west of LaConner, the writer has called the unit the La Conner Formation.

The predominant color of this group of rocks is dark gray or black; the greenish hues of the Paleozoic(?) sequence are nowhere present. Although a few pebble layers were observed the thick pebble conglomerates and large boulders noted in the Paleozoic(?) rocks were not found.

Deformation of the Mesozoic(?) group has been strong as evidenced by recumbent folding. Rock cleavage is not so widespread nor so strongly developed as in the Paleozoic(?) rocks.

Argillaceous limestone nodules are present on Skagit and Kiket Island. Quartz and calcite veinlets are locally common but calcite seems a much less abundant constituent of the rock matrix itself. No volcanics were found associated with this sequence of rocks.

In contrast to the rather thin-bedded nature of the Paleozoic(?) sequence, the Mesozoic(?) rocks are more massive and blocky, frequently with no evidence of bedding. Even where bedding is visible lateral correlation is not possible. Abrupt lateral lithologic changes are characteristic and beds lens with amazing frequency.

The graywacke is made up of quartz, plagioclase, rock fragments and matrix with small or minor amounts of accessories and secondary minerals. Quartz grains are angular, up to 3 mm in maximum dimension, and invariably show resorbed borders, where replacement by chlorite and matrix material has taken place. Albite and oligoclase appear in sub-rounded grains, or in laths up to 0.5 mm in length. They show considerable resorption and invariably are altered in varying degrees to sericite, chlorite and/or calcite. In one thin-section a few very small hornblende grains were observed.

Chert is not abundant, occurs rarely in grains over 0.5 mm in length, and is generally fairly well-rounded. Rock fragments, largely slate chips, with an average maximum dimension of 2 to 4 cm, are very conspicuous.

An indurated argillaceous matrix is always present, but is not dominant, as is the case in Paleozoic rocks. Ten to 20 per cent is a common average while it may be in excess of 50 per cent in older rocks.

Limestone nodules may be up to two feet in thickness and perhaps twice that in long dimensions. They are composed of a fine-grained, homogeneous, argillaceous limestone. Pyrite cubes are randomly and sparsely distributed and are usually bordered by secondary fibrous chalcedony. Occasional concentrations of pyrite were observed at intersections of microscopic veinlets. In one thin-section, circular areas, up to 1 mm in diameter, composed of somewhat purer carbonate suggest residual remains of foraminifera. Another thin-section shows a possible crinoid stem. Preservation is so poor in both cases that definite identification cannot be made.

Primary Structures

Graded Beds are sedimentation units characterized by a gradation in grain size from coarse to fine, upward from the base of the unit. These are comparatively common in the Mesozoic sequence and are typically marked by a light-colored silt that grades upward into a fine-grained, dark-colored argillite. Graded beds observed in the graywacke of the map area range in thickness from 1 to 20 cm.

They are generally considered to be the end product of material settling through quiet bottom water which allows the coarse material to settle first followed by the fine constituents. Consequently they are considered to be among the best criteria for establishing vertical stratigraphic orientation.

Penecontemporaneous Slump Structure is defined as small scale deformation such as folding, faulting and brecciation which commonly occurs in fine-grained sediments at or immediately below the land surface or sea bottom.

In several localities small scale folding and faulting occurs in thin shale beds less than 3 mm thick. These microstructures are seldom found well developed and are deformed to varying degrees by movements following compaction.

Channeling occurs locally and on a very small scale. Channels are usually filled with fine sand in an argillite portion of the sequence, though occasionally channels and enclosing rock are somewhat more coarse-grained.

SUMMARY OF PRE-TERTIARY STRATIGRAPHY

Danner (1960) divided the graywackes of the Pacific eugeosyncline into two general suites as follows:

> "The first 'suite' includes rocks of the Devonian through early Jurassic Age. It is characterised by marine basic volcanics, breccias, black graywacke, siltstone, ribbon cherts and lenses of limestone. With few exceptions the limestones are the only fossiliferous rocks and provide the sole means of establishing the stratigraphic sequence.

Figure 11. Graywacke cut by multitude of ramifying quartz veinlets. South side of Kiket Island.

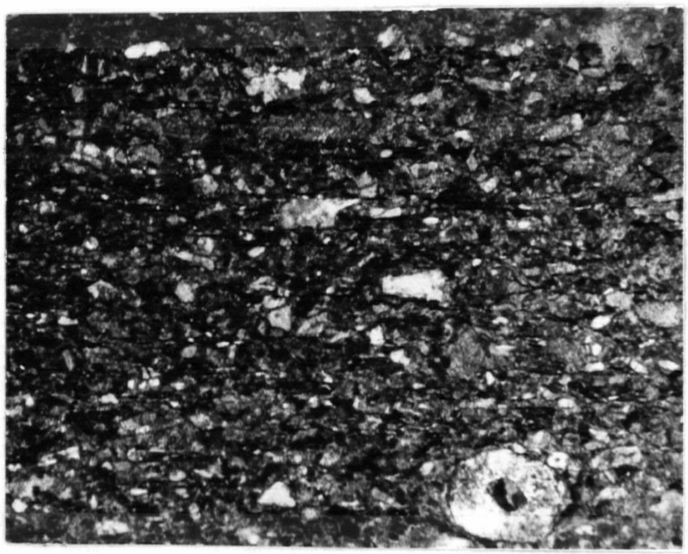


Figure 12. Photomicrograph of Mesozoic(?) argillaceous limestone nodule. Possible crinoid columnal at lower right. Plane light, x 10

A second eugeosynclinal 'suite' includes marine rocks of Jurassic to Oligocene age and is characterized by thick sequences of marine graywacke, slate, chip breccias, basic volcanic rocks, graywacke siltstone, and argillites. Ribbon chert forms a very minor part of the sequence and limestone is rare. Fossils are scarce in these rocks and many formations of unknown age probably belong to this 'suite'".

A summary of the differences between the Paleozoic(?) and Mesozoic(?) sedimentary rocks of the Skagit Bay area are tabulated below:

Characteristic	Group 1, Goat Island Formation (Paleozoic?)	Group 2, La Conner Formation (Mesozoic?)
Color	Shades of green to gray	Dark gray to black
Grain Size	Frequently coarse, conglomeratic	Deficient in conglomerate
Deformation	Very intense	Less intense
Limestone	None	Calcareous nodules
Volcanics	Some present	Absent
Rock fragments	Volcanic, argillite, quartzite	Usually slate but minor part of rock
Matrix	Commonly major part of of rock	Commonly minor part of rock
Calcite	Common	Common but generally less abundant than in Paleozoic(?)
Bedding	Thin-bedded	Thick-bedded

Rocks here considered Mesozoic are similar in outcrop appearance and thin-section to the Carter Point Formation of southern Lummi Island (Calkins, 1959). Calkins considered the Carter Point Formation to be Mesozoic in age on the basis of similarity in lithology to the Nooksack Group of the Cascade Mountain Foothills. Since Calkin's work, support was given for a Mesozoic age by the finding of a Mesozoic ammonite on an outcrop of Carter Point. Positive identification of the specimen has not yet been made (Danner, personal communication). Limestone, characteristically interbedded with Paleozoic graywackes, commonly contains fossils giving evidence of age. The group here considered Paleozoic contains no limestone but this may be an accident of poor exposure.

In the writer's opinion the gross characteristics of rocks in the report area can be broadly applied to subdivide the pre-Tertiary into two groups. Further these two groups can be generally equated with the two 'suites' of Danner. Consequently the writer tentatively refers his Mesozoic group to the first 'suite' of Danner and his Mesozoic to the second 'suite'.

It can be forcibly and logically argued that a lithologic correlation of this nature has little validity. The area is small, outcrops are admittedly sparce and commonly highly weathered. Varying degrees of deformation not readily apparent in the field may give the same rocks different aspects. Sampling and thin-section distribution may not be truly representative.

To these and other arguments the writer can but only agree. However the lithologic characteristics are the only criteria available, and in the absence of better evidence the proposed two-fold subdivision is presented as most probable.

Figure 13. Photomicrograph of Mesozoic sheared graywacke. Composed largely of quartz and argillite fragments. Plane light, x 10

Figure 14. Photomicrograph of Mesozoic feldspathic graywacke, Plane light, x 10

ORIGIN

The first recorded use of the term graywacke was in 1789 when Lasuis working in the Harz Mountains described a graywacke as a "sandstone made up of fragmental granite debris". By 1808 Jameson was emphasizing the importance of a "clay-slate" matrix. The end of the 19th century saw Bailey (1898) defining graywacke as a sandstone "containing grains of many different minerals and small fragments of rocks, united by a cement of the composition of many slates".

Twenhofel (1926) suggested that graywacke be considered the ferromagnesian equivalent of arkose but this has not been widely accepted. Pettijohn (1943) considered a graywacke to be a microbreccia with the following characteristics: (1) large, angular detrital quartz and feldspar grains, (2) a clay matrix, (3) a dark color, (4) tough and well indurated, (5) presence of rock fragments, (6) presence of macroscopic structure, and (7) characteristic rock associations.

In this paper the writer elects to use the classification of sedimentary rocks proposed by Pettijohn (1957). In this classification a graywacke is defined as a clastic rock with a variable angular quartz grain content, usually less than 75 per cent and varying quantities of feldspar and/or rock fragments. The coarse-grained fragments are set in a detrital, argillaceous matrix composing at least 15 per cent of the indurated rock. If the matrix is less than 15 per cent of the total the rock becomes a subgraywacke. The prefix "feldspathic" indicates a graywacke with more feldspar than rock fragments and the prefix "lithic" indicates the converse. Accessory minerals may be present and varying degrees of alteration are invariably present.

Graywackes are thought to be formed principally in deep water while the clastic material itself is the product of incomplete sorting and weathering. Genetically, graywackes indicate the following:
(1) nature of the source rock, (2) a tectonically active area, (3) a source area of considerable relief, (4) rapid transportation of clastic material and (5) deposition in deep water.

The thin-bedded and graded nature of graywacke suggest a pulsating and intermittent sediment supply. Sand and silt are deposited on a delta front or on the continental margin. These deposits may become unstable and if dislodged will travel down slope as a turbidity current. As this mass of water and suspended material levels out on the sea floor the speed decreases and deposition commences, large constituents first followed by progressively smaller grains. Consequently the common occurrence of graded bedding in a graywacke sequence is typical and to be expected.

The "trigger" necessary to start a turbidity current may be either tectonic, as in an earthquake shock, or climatic in the way of storm waves and sea turbulance.

Source area of graywacke in the Skagit Delta country is unknown but presumably it was a predominately metamorphic and volcanic terrain. The lack of fossils, the graded bedding, the lack of ripple marks and cross-bedding, and the carbonaceous nature of the rocks suggest a restricted marine basin of accumulation which was too deep and too toxic to permit marine life to survive.

VOLCANIC ROCKS

OCCURRENCE

Volcanic rocks are quantitatively unimportant within the map area. Small outcrops occur at 5 different locations. All volcanic exposures are highly weathered, making classification difficult and lending themselves only to the field term greenstone.

Greenstone crops out on the southeast end of Hope Island, on Deadman and Little Deadman Islands, along a stretch of shoreline west of the entrance to Swinomish Channel, on several hills south of La Conner and at a very small outcrop of unknown extent on the northeast side of Goat Island. A breccia, with both larger fragments and matrix composed of volcanic material, immediately underlies the Tertiary-pre-Tertiary unconformity at the northwest end of Ika Island.

The volcanic rocks are resistant to erosion, forming prominent cliffs where exposed to wave action, or as small promentories.

Field Description

In outcrop the occurrences of greenstone have many similar features. Generally they weather to a dull green color though in places they are buff to rusty brown, probably as a result of oxidation of iron. Freshly broken surfaces show an aphanitic texture and are, typically a dull, dark green color. West of the entrance to Swinomish Channel the greenstones are slickensided with a polished smear of reddish hematite(?) on the polished surfaces.

The only mineral identifiable in hand specimen is pyrite, which was observed as small cubes in a few specimens. Secondary quartz veining is common locally. To a lesser degree calcite veining is present and is occasionally associated with quartz veins.

Pillow lavas were noted at one location west of the entrance to Swinomish Channel (southeast end of Fidalgo Island). The pillows are poorly developed, but show a consistent size of about $1\frac{1}{2}$ feet in diameter. No vesicular or amygdaloidal structure was observed.

Two of the greenstone exposures, namely those on Hope Island and southeast Fidalgo Island, are in fault contact with ultrabasic intrusions. Fractures are abundant, in places healed by veinlets of quartz and/or calcite. West of Swinomish Channel an interbedded sedimentary unit is now a highly sheared, intensively folded phyllite.

Volcanic rocks on Deadman and Little Deadman Islands, as well as those south of La Conner have experienced less mechanical deformation, are more homogeneous in texture and color, are somewhat less fractured, and are less intensely slickensided than those associated with ultrabasic rocks.

Volcanic and sedimentary rocks were not observed in direct contact although in places they crop out within 10 to 15 feet of each other. Possibly the volcanics of Hope Island and the area west of Swinomish Channel are faulted into contact with sediments but it is also possible the two are intercalated; the true relationship being obscured firstly by regional deformation and low grade metamorphism, and secondly by deformation brought about by ultrabasic intrusion. Volcanic rocks of Deadman and Little Deadman Islands are isolated by the waters of Skagit Bay so contact relations with other rocks is obscured. However, volcanic rocks situated south of La Conner appear to be interbedded in the graywacke sequence. Although exact relations are uncertain, alternate outcrops of greenstone and graywacke strongly suggest an interbedded relationship.

PETROGRAPHY

All the volcanic rocks are intensely altered as indicated by a brief petrographic description of some typical specimens from different locations.

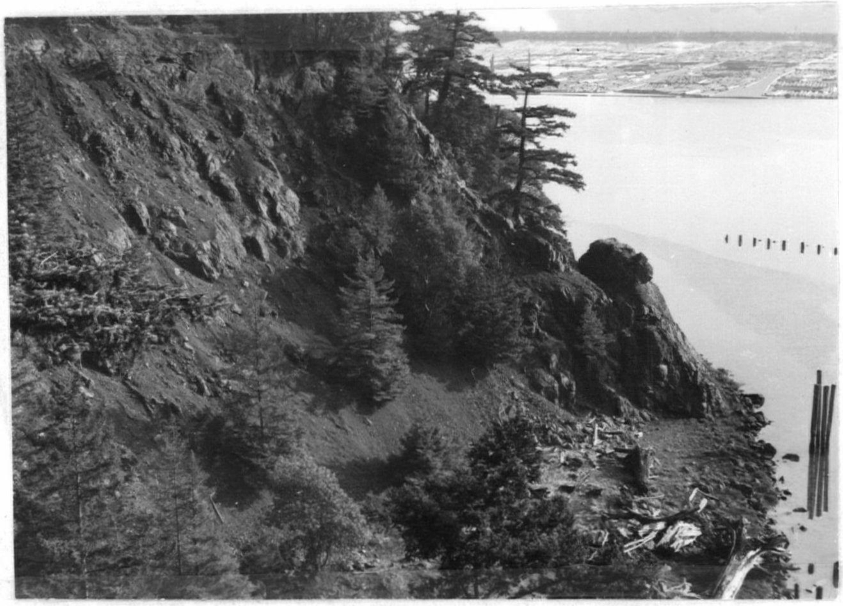


Figure 15. Spilite volcanic rocks dipping steeply toward the observer. Southeast end of Fidalgo Island.

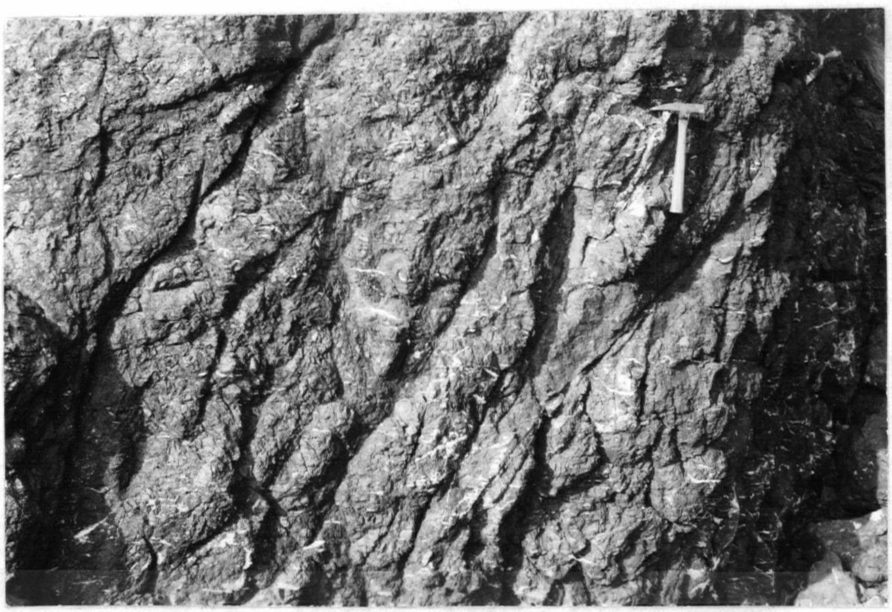


Figure 16. Poorly developed pillow lavas at southeast end of Fidalgo Island. Sequence right side up.

Little Deadman Island

The volcanic rock from Little Dead Man Island is very fine-grained and exhibits a felty texture. Radial growths of highly altered plagioclase microlites display a variolitic texture. Extinction angles and low negative relief of plagioclase microlites indicate an albitic composition. Plagioclase is largely replaced by chlorite and other clay minerals along cleavage surfaces and borders. Locally calcite replaces plagioclase but the overall pervading alteration, creating a gray matte effect, is saussuritization. Pyroxene is almost entirely replaced by chlorite, actinolite and calcite. Chlorite also occurs as discrete, pale yellow-green grains. In addition to directly replacing plagioclase, calcite occurs in small veinlets transecting the rock. Epidote is present in minor amounts, generally as discrete grains of very small size.

Volcanic rocks South of La Conner

In a greenstone outcrop south of La Conner the alteration is similar to that described for Deadman and Little Deadman Islands. Saussuritization is very intense, and chlorite is now an exceptionally prominent part of the section. Plagioclase is albite, and is commonly replaced along cleavage planes and borders by chlorite. Many of the plagioclases appear to grade into the matrix when examined under high power. The original pyroxenes are totally unidentifiable as they have been largely replaced by a pale green, weakly pleochroic actinolite. Calcite is not particularly prominent but locally occurs with feldspar as a decomposition product. A mineral, not present in most of the volcanic rocks is pyrite which is disseminated in rather large amounts through some of the specimens. The grains are for the most part idiomorphic but some show varying degrees of rounding due to corrosion. Several very small grains (0.1 mm) of a watery clear mineral with pronounced negative relief and low first order colors were seen in thin-section. Possibly this is albite or a zeolite.

The outstanding microscopic characteristic of volcanic rocks not associated with ultrabasic rocks is the high degree of alteration; especially saussuritization, chloritization and to a lesser extent, carbonatization and uralitization of pyroxene.

Volcanic Rocks from Hope Island

A specimen from the southeast end of Hope Island exhibits similar properties as those previously discussed but has a cataclastic texture, presumably the result of physical breakage within a fault zone. Plagioclase microlites are slightly less altered. Use of the microlite extinction curve indicates they are no more than $Ab_{95}An_{5}$ and are probably albite or sodic oligoclase. Pyroxenes are almost totally replaced by a pale green, weakly pleochroic amphibole, probably actinolite. Strongly pleochroic, reddish-brown biotite, occurs in association with chlorite, mainly interstitial to but partly pseudomorphic

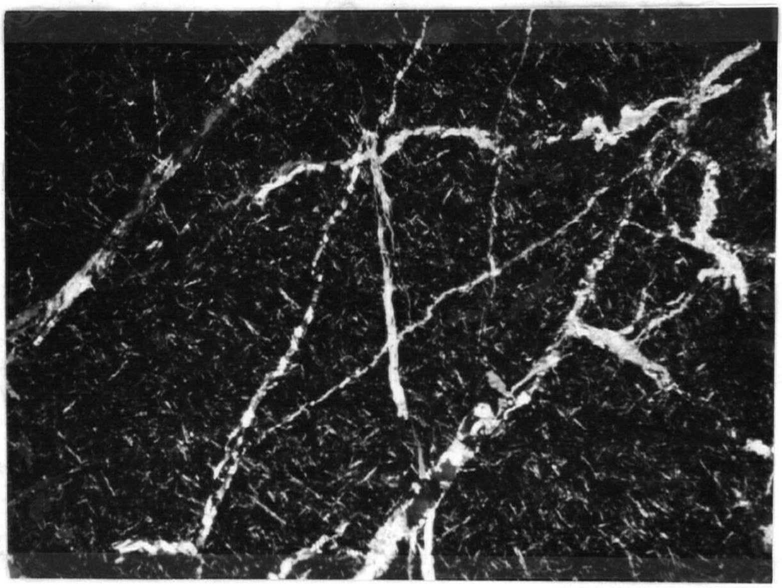


Figure 17. Photomicrograph of spilite showing high degree of saussuritization. Numerous quartz veinlets are characteristic. Cross-nicols, x10.

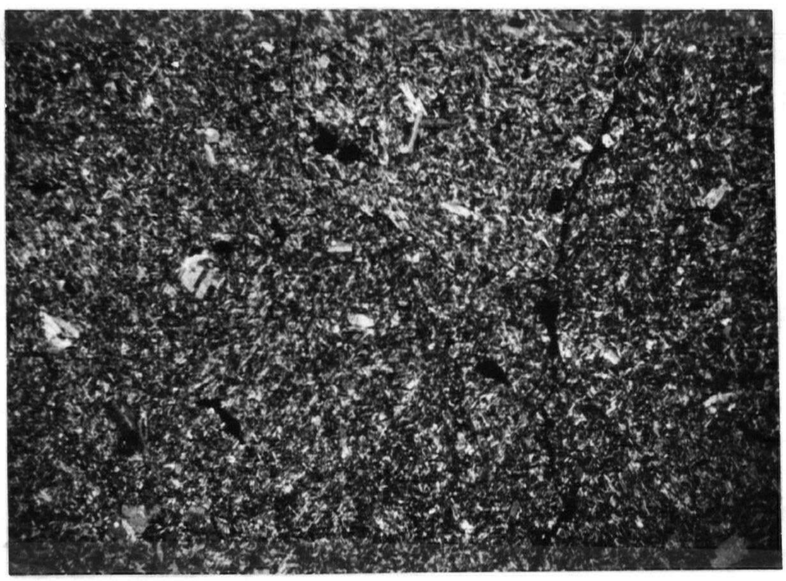


Figure 18. Photomicrograph of microporphyritic spilite from flow breccia on Ika Island. Cross nicols, x 10

after pyroxene. Magnetite-illmenite is moderately common. Epidote is rare. Chlorite appears to be one of the latest minerals to form as its replacement of biotite is widespread if not complete. Possibly deformation occurred following the alteration process for some actinolite grains are bent.

Volcanic rocks from Southern Fidalgo Island

Specimens from west of Swinomish Channel are similar to those of Hope Island. Plagioclases are lath-like, highly altered and appear to range from albite to soda oligoclase. Pyroxenes are strongly uralitized. Chlorite is very abundant, not only in vermicular growths throughout most of the plagioclases but also as flat plates up to 0.2 mm in maximum dimension. Calcite seems to occur mostly in secondary veinlets, often associated with quartz. The chlorite appears to be the final alteration product as it is invading and corroding the margins of the quartz found in the veinlets. Sericite is locally present in small amounts, commonly associated with calcite in the veinlets.

Principal alteration in these latter rocks appears to be chloritization, uralitization, minor carbonitization, and very minor and local sericitization.

Summary of Greenstone Petrology

Alteration of volcanic rocks both independent from and associated with ultrabasic intrusion is similar. However, in rocks not associated with ultrabasics saussuritization is quite intense while in the others it is much less prominent. It must be borne in mind that this division of volcanic rocks into those associated with intrusions and those independent of ultrabasic intrusions may be more apparent than real, and quite possibly has no significance. Outcrops are not adequate to properly evaluate this.

In summary the outstanding alteration these volcanic rocks have undergone is "propylitization", which is generally regarded as the replacement of pre-existing minerals by carbonates, epidote, secondary quartz and calcite. Other minerals that may be formed though usually of less importance are pyrite, zeolite, albite and sericite.

Volcanic Breccia

A volcanic breccia crops out at the northwest end of Ika Island. It is a buff-weathering breccia, extending to near the crest of the northern hill and composed of angular fragments of volcanic rock up to 3 cm in maximum dimension. Fragments range downward to microscopic sized particles. Freshly broken surfaces are a dark yellow-green, somewhat lighter in color than the greenstones described previously.

Plagioclase is albite in the form of lath-like microlites set in a felty matrix of finer-grained feldspar and uralitized pyroxene with minor chlorite and calcite. A few larger laths, up to 1.5 mm in length give the rock a microporpyritic texture. Chlorite is very common, both as wormlike growths and flat plates. Sericite is present in small amounts as a replacement of plagioclase. Pyrite is present, enclosed in a sheath of limonite. Limonite is further distributed in discrete grains and small irregular masses throughout the rock. The matrix is formed of the same volcanic material as the larger fragments although locally, small irregular blebs of secondary quartz have formed between fragments.

In all essential features the volcanic rock comprising this breccia is comparable to those described previously. The strong angularity of fragments, the lack of a distinctive matrix and the tendency for fragments to weld together making the boundaries obscure in thin section suggests it is not a water layed breccia. Probably its origin can be explained in one of the following ways.

(1) Flow breccia formed by the fragmentation of the surface of a still moving but solidifying lava flow. Because the hardened surface is incapable of yielding plastically with the still fluid interior it tends to break up into angular fragments which are carried along until flow motion finally comes to a halt.

(2) Autobreccia caused by escape of small quantities of gas simultáneously throughout the flow which is usually caused by relief of confining pressure with resultant rapid vesiculation and spalling along fractures. This usually results in a rock showing a vesicular porosity of 10 to 15 per cent.

Because this specimen shows no vesiculation, no evidence of water transport, sharp unworn fragmental edges and an apparent fusion of fragments, it is suggested this is a volcanic flow breccia.

ORIGIN

The A.G.I. Glossary of Geology defines a spilite as a basaltic rock with albitic feldspars. Albite is usually accompanied by autometamorphic minerals, or minerals characteristic of low grade metamorphosed greenstones, such as chlorite, calcite, epidote, chalcedonic silica or quartz, actinolite, and others.

Thin section study of the volcanic rocks of the Skagit Delta area suggest they fulfill the definition given above. However the mineral assemblage does not necessarily indicate an autometamorphic origin as the above definition would suggest. Spilitic rocks, regardless of their geographical occurrence or their geological age have certain characteristics and associations in common (Park, Waters and others):

(1) Virtually always associated with marine rocks.

(2) Virtually always occur in the eugeosynclinal phase of an orogenic belt.

(3) Commonly show pillow structure (though this is not absolutely necessary nor are all pillow lavas spilitic).

(4) Commonly associated with graywackes and bedded cherts.

(5) Commonly associated with ultrabasic intrusions though there may be no common genetic relation. The intrusions are usually a later phase than the spilites, though some over lapping of the two may occur.

(6) A general lack of olivine.

(7) Compared to basalt all spilites are high in Na_2O, moderately high in TiO_2, somewhat low in Al_2O_3, CaO and MgO, and very low in K_2O.

Field and petrographic study indicates the volcanic rocks of the map area have properties and associations characteristic of the first six criteria. No chemical analyses are available so the chemical composition is not known. However, the predominance of albite indicates high soda content, the absence of orthoclase and of basic plagioclases indicates a lack of potash and lime, while the presence of minor amounts of ilmenite indicates the presence of TiO_2. Consequently, on the basis of mineral assemblage, association and chemistry, it appears that the greenstones of Skagit Bay may be considered spilites.

The origin of spilites has long been a controversial problem and is still far from settled. The two most satisfactory theories are:

(1) Origin from a primary spilitic magma and

(2) Origin by subsequent metasomatism and alteration of plagioclases in an original olivine or tholeiitic basalt.

The first theory is substantiated by textural studies, If igneous rock textures have any genetic meaning at all, some spilites are definitely primary and form as the result of crystallization from a spilitic magma.

A second theory presumes that the original lava was a tholeiitic basalt, as suggested by the almost exclusive association with olivine deficient rocks. Several different mechanisms may be involved in the formation of spilites from tholeiitic basalts. Perhaps sea water and water logged sediments associated with the volcanic rocks are the sources of Na+ ions and water necessary for albitization and associated alteration. Water streaming upward from eugeosynclinal sediments undergoing compaction is envisaged as percolating up through the cooling submarine lava causing alteration.

Alternatively, autometamorphism or alteration by residual aqueous fluids derived from the original magma might be involved. Little physical or petrographic evidence is available in any area to substantiate or reject such a mode of origin.

Another suggestion (Waters, 1955) is that spilites are the result of low-grade regional metasomatism of a volcanic sequence. According to this scheme the Eocene spilites of Washington were formed from tholeiitic basalts by sodium rich solutions derived from low grade metamorphism of eugeosynclinal deposits at depth.

The spilites of Skagit Bay would appear to be of metasomatic origin. The intense degree of alteration and secondary mineralization indicates the rock is chemically different from its character at the time of formation. The occurrence of secondary albite, generally as water clear grains, especially within veinlets, indicates at least some of the albite is secondary. Secondary chlorite, calcite, sericite and quartz with minor epidote is evidence of breakdown of calcium silicates, especially feldspars and pyroxenes. During alteration silica is also released which may re-precipitate interstitially and in veinlets, either as quartz or jasper. Secondary quartz veinlets are moderately abundant in the spilites examined.

Further evidence is provided by a few feldspar grains which appear to have positive relief indicating a higher than normal calcium content. Probably these represent original grains not albitized. Although the writer feels the evidence proving a metasomatic origin is conclusive, no evidence is available to indicate what sort of metasomatic process is responsible.

AGE

Petrographically the spilites of Skagit Bay are similar to those described by Calkin in the Mesozoic(?) rocks of Lummi Island, by McLellan in the San Juan Islands, and by Park in the Eocene rocks of the Olympic Mountains. However as pointed out earlier, spilites throughout the world have very similar characteristics and associations. Within the Pacific geosyncline spillites are present throughout the stratigraphic column. Unless the volcanic rocks are associated with fossils, or can be "walked out" in outcrop, they can not be equated in time. In the Skagit Bay area no fossils were found, with either the volcanic rocks or associated graywackes.

Because these spilites are found intimately associated with, and presumably interbedded with sediments which are tentatively considered to be Paleozoic, the lavas also are of probable Paleozoic age.

LATE CRETACEOUS-EARLY TERTIARY SEDIMENTS

OCCURRENCE

Plant-bearing, arkosic conglomerates and sandstones crop out at sporadic intervals along the south-edge of the map area and are especially prominent where they form low hills along the North Fork of the Skagit River. A number of small, isolated outcrops occur south of the river and are collectively known as "Delta Rocks". Ika Island, to the west, is composed almost entirely of older Tertiary sediments and is the only island within the map area not formed of pre-Late Cretaceous, plutonic, or volcanic rocks. As explained in the section discussing "Structure", the Tertiary rocks are preserved in a large east-west syncline.

STRATIGRAPHY

Stratigraphically the Tertiary rocks are a conglomeratic sequence with sandstone, siltstone and limy mudstone interbeds. The conglomerate is well indurated and topographically resistant. Fine-grained portions are much less resistant to erosion.

Two units, which appear parallel and concordant, make up the Tertiary of the map area. As will be discussed later, a slightly discordant contact, not visible in the field is thought to be present. Because definite correlation can not be made with described units elsewhere, new formational names are applied to this sequence. The older of the two units will be referred to as the Delta Rocks Formation and is best seen in a 270 foot exposure on the south side of Ika Island. The younger is termed the Ika Formation from the excellent exposures on the west and north sides of Ika Island. As will be brought out in later discussion the author feels these units might be correlatable to the Chuckanut Formation.

Delta Rocks Formation

The Delta Rocks Formation is exposed at Delta Rocks, in two small outcrops southeast of Pleasant Ridge, and on the southeast side of Ika Island. A maximum exposed stratigraphic thickness of 270 feet was measured on Ika Island. The contact between this and overlying Ika Formation is exposed only on the south side of Ika Island, but at no place is a contact between the

Delta Rock Formation and older rocks exposed.

In outcrop this cobble conglomerate appears dark greenish gray while freshly exposed surfaces are a distinctly paler shade of green to gray. Maximum observed cobble size is about 20 cm with the great majority between 3 to 7 cm. Gradation from smallest to largest clastic fragments appears to be the rule.

Fragments larger than 2 cm are generally sub- to well-rounded and those less than 2 cm are largely angular. Pebbles and cobbles are usually of low sphericity and may appear to have been fractured. The matrix is essentially compacted sand and silt though rarely calcite cement is present.

Cobbles and pebbles are composed of many rock types, especially quartzite and chert with lesser amounts of greenstone volcanics, indurated sandstone, and argillite. A pebble of sandstone as seen in thin-section was made up principally of angular quartz with lesser amounts of plagioclase and minor quantities of orthoclase, biotite, pyrite, epidote, hornblende, muscovite and chlorite. The matrix is very minor and seems to be largely composed of very small clastic fragments. Possibly this is a pebble of Cretaceous Soleduc derived from the area of the present Olympic Mountains. More likely these pebbles came from Soleduc-appearing rocks to the southeast in the Sultan-Stillaguamish area (Danner, personal communication).

The conglomerate matrix is largely composed of strained quartz with lesser amounts of plagioclase and microcline. Minor quantities of garnet, biotite and epidote are present. Most of

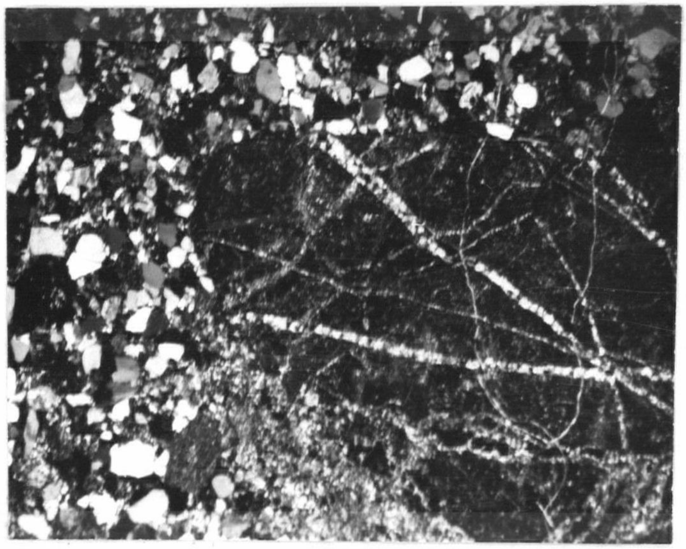


Figure 19. Photomicrograph of conglomerate from Delta Rocks Formation. Rounded quartzite pebble to right. Poor sorting and high angularity of quartz and feldspar grains characteristic. Cross-nicols, x10.

Figure 20. Photomicrograph of conglomerate matrix, Delta Rocks Formation, showing high grain angularity. Cross-nicols, x10.

the grains are angular and broken and have undergone varying intensities of saussuritization. Some silt size fragments are present. An argillaceous matrix or chemical cement is largely lacking.

An interbedded siltstone at Delta Rocks is composed principally of angular strained quartz. Calcic oligoclase, highly corroded and partially replaced by sericite and saussurite is the next most abundant mineral. Hornblende and epidote are present in trace amounts while sericite and chlorite are abundant secondary minerals. A matrix comprises at least 10 per cent of the rock and appears to be largely argillaceous.

A metamorphic source terrain seems indicated by the mineral and pebble assemblage.

No fossils were found in this sequence but in several places small carbonized wood fragments were found associated with the conglomerate. A sample of siltstone was macerated in the search for plant microfossils but with negative results.

Ika Formation

Like the Delta Rocks Formation, the rocks of the Ika Formation are essentially a conglomeratic sequence with interbeds of finer material. The maximum exposed stratigraphic section crops out on Ika Island where 430 feet are exposed. About 80 per cent is conglomerate while the remaining 20 per cent is sandstone and siltstone. Shale appears to be absent. The color of the conglomerate, both on fresh and weathered surfaces, ranges from buff to pale red to dark red, while finer-grain portions may be buff to pale olive gray.

Maximum observed boulder size was 30 cm with a gradation downward to an argillaceous sandy matrix. The larger pebbles and cobbles are sub-rounded to rounded and smaller sizes appear more angular. A low sphericity characterizes the majority of clastic grains.

Pebbles and cobbles are composed of vein quartz, chert and quartzite with a variety of other rocks occurring locally. Sandstone, argillite, slate, dacite, volcanic rocks and undetermined granitic pebbles characterize the latter. Pebbles of "Soleduc-appearing" rocks which are common in the Delta Rocks Formation do not appear to be present in this sequence. The matrix is largely formed of poorly sorted angular quartz and feldspar sand-size grains. Although many of the pebbles and boulders are red, most of them are black to green; the overall red color of the unit is caused by a red matrix.

Carbonaceous material is randomly distributed through the conglomerate usually in the form of wood trash and fragments. Two coalified logs were observed, both about 4 feet in length and a foot in compressed diameter.

Interbedded with the conglomerate are thin lenses and discontinuous beds of sandstone, siltstone and calcareous mudstone. Shale appears to be totally absent.

Sandstone occurs as lenses or cross-bedded units within the conglomerate. These beds may reach 5 to 6 feet in thickness

Figure 21. Typical conglomerate of Ika Formation, in hills near mouth of North Fork of the Skagit River.

Figure 22. Typical conglomerate of Ika Formation, in hills near mouth of North Fork of the Skagit River. Notice poor sorting and subrounded nature of larger constituents.

but can be traced only short distances along the strike. In hand specimen these sands appear remarkably uniform but poorly sorted. Shale or slate fragments up to 5 mm in diameter are common, and randomly distributed through the sand. Color is light gray to buff, grains are angular, and porosity and permeability appear to be very poor. The matrix appears to be largely argillaceous though locally calcite is present.

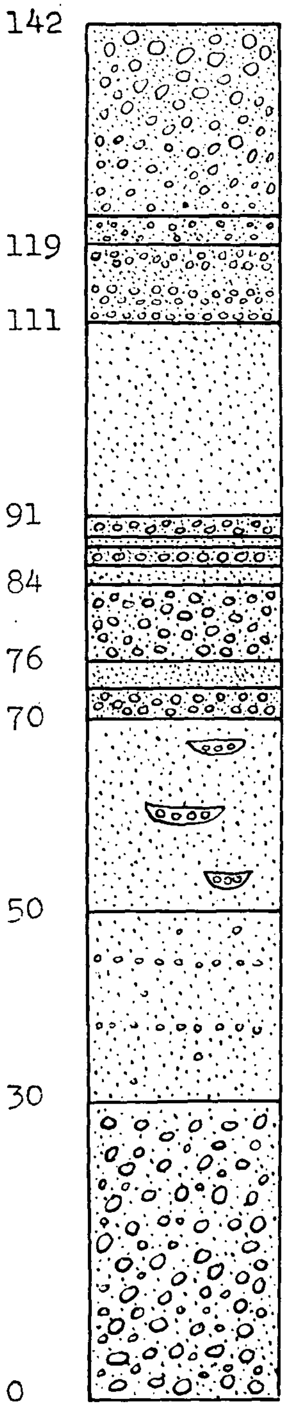
In thin-section the sands are seen to be made up of angular quartz grains, up to 3 mm in size. Undulatory extinction is uncommon. Borders of grains are corroded and grade into the matrix. Chert and plagioclase are present in subordinate amounts. Chert pebbles show the same marginal corrosion as do the quartz grains and appear to be sub-rounded, probably indicating this is at least a second sedimentary cycle. Plagioclase is usually saussuritized and the composition is difficult to determine. On the basis of several unsatisfactory determinations, and because of their apparent positive relief, the writer feels they are probably andesine. Trace amounts of K-feldspar are present. Minor secondary chlorite occurs, largely as an alteration product of matrix or plagioclase. Matrix is minor and argillaceous. Carbonaceous material is randomly disseminated through the rocks as small flecks, and plant microfossils were extracted from this material.

True siltstone is also present, and except for smaller grain size is similar to the sandstone. Carbonaceous material and limonite are common, the latter occurring largely along

MEASURED SECTION
of
portion of the
IKA FORMATION

Below New Bridge across North Fork of Skagit River

1" = 20'



Conglomerate, becomes progressively coarser upward. Boulders to 30 cm in diameter.

Sandstone, pebbly, of chert-quartzite.

Conglomerate, few thin sandy beds, considerable black flint.

Sandstone, medium to coarse grain, fair sorting, abundant carbonaceous material, including coalified tree trunk.

Sandstone and conglomerate interbedded, some shale and slate fragments, rare, small limy nodules, abundant carbonaceous material.

Sandstone, fine to medium grain, fair sorting, local cross-bedding, minor pebble lenses, some platy slate fragments, abundant carbonaceous material.

Sandstone, medium to coarse grain, subgraywacke, contains many pebbles to 3 cm in diameter, occasional interbedded pebble layers.

Conglomerate, massive, boulders to 26 cm in diameter, subrounded to rounded, formed of chert, quartzite, sandstone, rare granitic rocks.

PLATE 3

minor fractures and coating grains near these fractures. Calcite is minor but occurs in microscopic veinlets.

Immediately above the pre-Upper Cretaceous unconformity on Ika Island, where the Delta Rocks Formation is absent, is a series of discontinuous limy beds which might be considered either argillaceous limestone or limy mudstone. Calcite grains in places reach a size of 0.5 mm in diameter, and are surrounded by argillaceous material. This may grade into a very argillaceous rock with abundant disseminated calcite. Coarse quartz sand grains are sparsely and randomly present and limonite is locally present in considerable amounts. Associated with this limy mud are thin zones made up largely of limonite and scattered limonite oolites. Oolites are slightly deformed but show strong concentric development and, locally, radial structure. Plant microfossils were found in thin silty beds associated with the limy mud. The stratigraphic position and general appearance of the sequence suggests local deposition in a fresh water pool.

Sedimentary Structures

Cross-bedding is the most conspicuous primary structure within the sandstone units. Time was not available for a statistical study of their orientation, but they range in thickness from several inches up to 2½ feet. Bedding planes are commonly marked by biotite flakes, and in at least one case by magnetite grains.

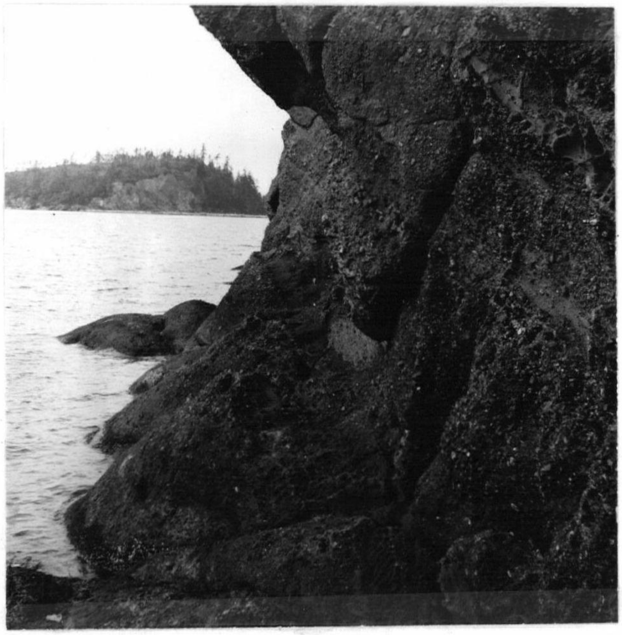


Figure 23. Conglomerate of the Delta Rocks Formation, dipping north (right) South side of Ika Island, Goat Island in background.

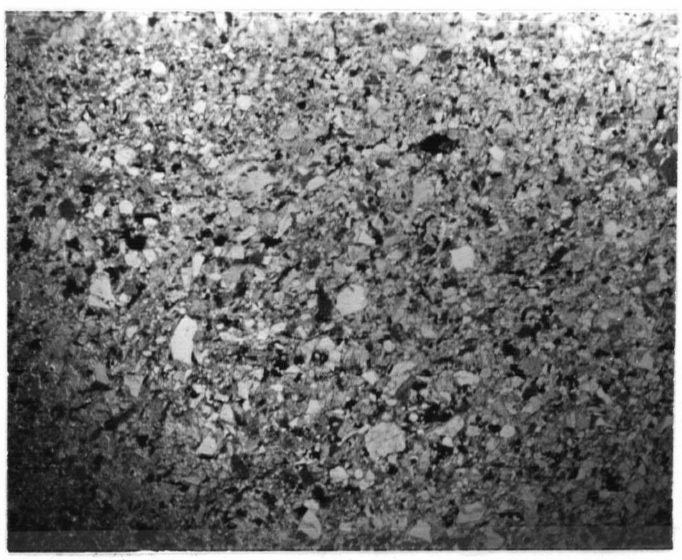


Figure 24. Photomicrograph of sandy siltstone of the Ika Formation. Plant microfossils were extracted from this material. Plane light x 10.

Torrent bedding was observed in one 2 inch thick bed which indicates that at least this thin bit of sequence was formed by deposition in quiet, standing water.

AGE AND CORRELATION

Many lithologic similarities exist between the rocks designated Ika Formation in the Skagit Bay area and those designated Chuckanut Formation by McLellan (1927) and Calkins (1959) on Lummi Island. These include similarities of composition, texture, depositional structures, and presence of abundant carbonaceous material. Unfortunately no fossil criteria are yet available which will definitely establish or disprove correlation of these two units. However, the lithologic similarity and a similarity of ages indicated by their floras suggests that the Ika Formation of Skagit Bay may be an isolated remnant of Chuckanut Formation.

White (1888) first described the Chuckanut Formation in western Whatcom County, and assigned it to the Eocene Puget Group of western Washington. Work was continued by Shedd (1902), Jenkins (1923), McClellan (1927), Glover (1935) and Weaver (1937). The nearest exposures are immediately south of Bellingham where a 10,000 foot section is exposed along the coast.

According to Glover (1935) the Chuckanut is made up of a great thickness of conglomerates, sandstones and shales which unconformably overlie the "schist of the region". Coal is

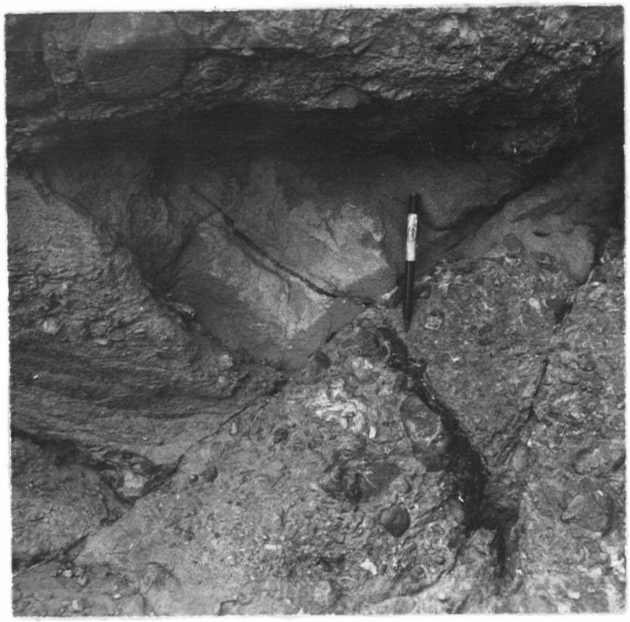


Figure 25. Small fault in Ika Formation on Ika Island. Notice small stringers of coaly material to left and below pencil.

Figure 26. Coalified log in sandstone of the Ika Formation. Log is in plane of bedding. In road cut just north of North Fork of the Skagit River.

distributed throughout the section but reaches its greatest abundance near the top. No limestone is present. A known thickness of 10,000 feet of Chuckanut is present while inferences drawn on drill hole data indicates a possible thickness of 16,000 feet.

Neither invertebrate nor vertebrate remains are known but there is a rich floral assemblage which is currently under study by Miss Marie Pabst at Western Washington College, Bellingham.

At the present time there is considerable question about the exact age of the Chuckanut. McLellan (1927), on the basis of work done by Knowlton, of the U.S.Geological Survey, considered the Chuckanut to be Lower Eocene. Weaver (1935) thought an age of Late Cretaceous to Middle Eocene as most likely. Misch (1952) suggested that the Chuckanut is Paleocene with perhaps deposition commencing in the latest Cretaceous. A possibility exists that what is mapped as Chuckanut in northwestern Washington may be actually two formations, with an as yet undetected unconformity separating them (Danner, personal communication).

Detailed plant microfossil studies have not been made of the Chuckanut so comparisons with those of the Skagit Bay area are not possible. In addition, plant macrofossils were not found in the latter area so comparison is impossible with the rich macrofossil assemblage of the Chuckanut to the north. Faunal remains are absent in both units.

A study was made of spores and pollen extracted from the

Ika Formatiom but a definite age cannot be assigned to the Ika Formation on the basis of microflora so far studied. However, a strong suggestion of a Lower Tertiary (Paleocene-Eocene) age is provided by the following facts:

(1) The presence of Cicatriocosisporites, several species of which flourished in this area during the Late Cretaceous and early Tertiary, but which disappeared during the Middle Eocene:

(2) The presence of Foveasporis, a genus which has been found in Germany to extend only to the Middle Eocene. It was most abundant during the Late Cretaceous, and much less common in the Eocene;

(3) Sabal pollen indicates the presence of Palm trees. These suggest a sub-tropical climate which characterized the Upper Cretaceous and Tertiary of the area. Andrews (1961, p. 204) states: "By Upper Oligocene times the tropical elements in the latitude of Oregon had largely disappeared, for the Bridge Creek flora of the John Day Basin in the eastern part of the State presents a distinctly cooler climatic assemblage". Because warmer climates were migrating southward during the Tertiary, the loss of sub-tropical elements in Oregon must have been contemporaneous with or slightly later than a similar change in Washington. Perhaps the near-sea level position of the map-area allowed a sub-tropical flora to exist slightly longer than in the somewhat easterly position of the Oregon locality. At any rate, the palm pollen indicates a sub-tropical

environment which probably disappeared within the map area by Middle to Late Oligocene.

A further suggestion of early Tertiary age is provided by the doubtful occurrence of Gleichenia. This tropical fern appears to be limited in this region to the Upper Cretaceous (Rouse, Personal communication).

Negative evidence exists to suggest that the Ika Formation is not Upper Cretaceous. Protoeacidites pollen has been found in all the microfloras investigated to date from Upper Cretaceous rocks of the Northwest, but has not been found in Tertiary rocks (Rouse, personal communication). Protoeacidites was not observed in any of the studied samples.

The indications of Lower Tertiary age presented by these floras and the lithologic similarities between the conglomerates of Skagit Bay with those of the Chuckanut Formation on Lummi Island suggests the possibility of equivalency. However as the exact age and exact stratigraphic relations of the Chuckanut are in doubt, and the precise age of the Ika Formation is not known, it appears best to apply new names to the conglomeratic rocks of the Skagit Bay area.

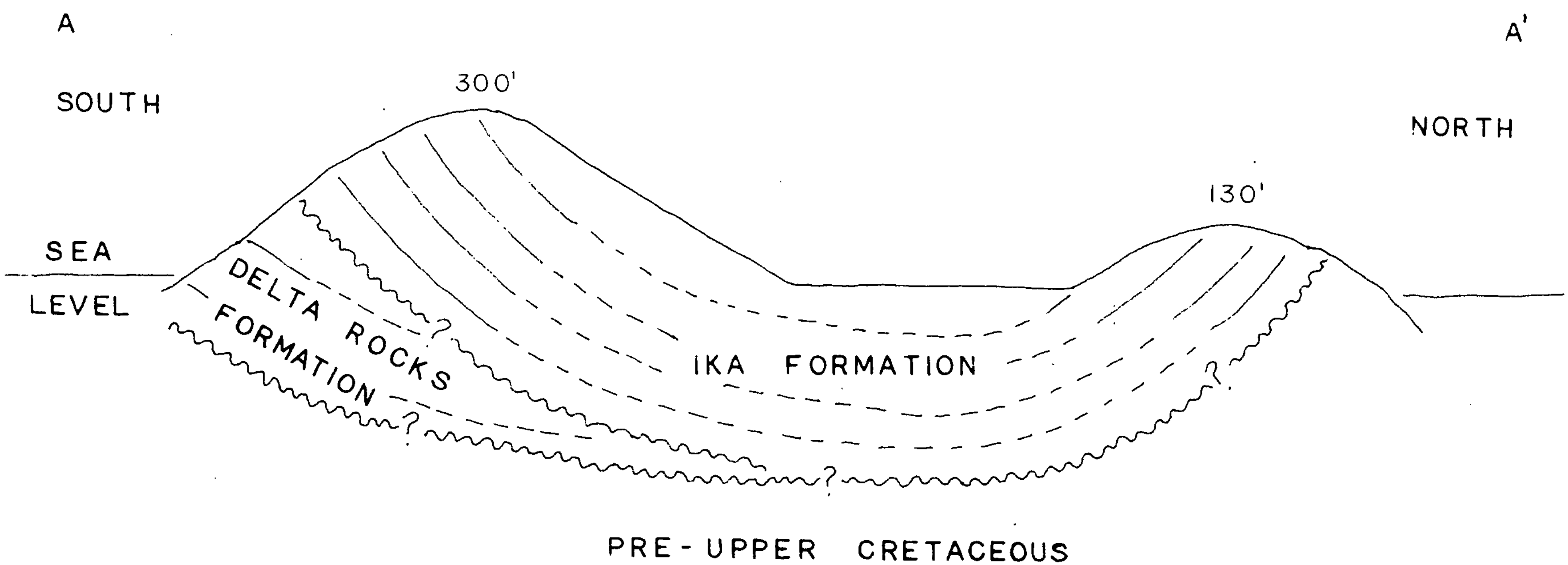
ORIGIN

Delta Rocks Formation

As pointed out by Twenhofel (1947) a conglomerate has less environmental meaning than any other sediment. The competency

NORTH - SOUTH CROSS - SECTION THROUGH IKA ISLAND

SCALE HORIZONTAL 1" = 300'
VERTICAL 1" = 300'



of the transport medium was adequate to bring the constituents to their present location and secondly the source could not be far distant. Other conclusions can be derived only from more detailed study of the specific formations.

On the basis of inadequate exposures the writer has prepared a cross-section of Ika Island to show an erosional cut-off of Delta Rocks Formation. Because of the low angular discordance between the two units and their coarse-grained nature, this angular unconformity is not obviously visible in the field.

On the south side of Ika Island approximately 270 stratigraphic feet of Delta Rocks Formation crop out and dip rather steeply northward. This is overlain by Ika Formation also dipping northward, but presumably at a slightly steeper angle. On north Ika Island the unconformity at the top of the Goat Island Formation intersects the surface but is overlain directly by Ika Formation.

Somewhere in this one-third mile, 270 feet of conglomerate has disappeared. Whether this is a case of non-deposition seems unlikely as it would require tremendous southward thickening which even in a conglomerate seems excessive. Furthermore it would presuppose a source to the north which seems unlikely when consideration is given to the probable source of Ika Formation constituents.

Probably the source lay to the south with thickening of the conglomerate northward. The absence of marine fossils and the presence of occasional woody fragments, the poor sorting, and the occasional cut and fill structure suggest to the writer a continental origin. Contained pebbles of "Soleduc-appearing" rocks suggest the possibility part of the source area lay to the southwest or southeast. In the Late Cretaceous the Olympics were uplifted with consequent erosion. Transport agencies may have carried pebbles to the northeast as far as the Skagit Bay region.

During or immediately after deposition of the Delta Rocks Formation, uplift occurred to the south or southeast, which initiated erosion and removal of much of this unit. However this was soon followed by a flood of clastics, now known as the Ika Formation.

A definite age can not be assigned to the Delta Rocks Formation. It is not highly deformed and like the Ika Formation appears to be affected only by Miocene folding. Consequently it is later than the two periods of deformation which affected still older rocks.

Ika Formation

The Ika Formation of Skagit Bay appears to be continental as suggested by the lack of marine fossils and the abundance of plant remains. The predominant red color is due to earthy hematite in the matrix and hematite staining of constituent grains. This "ocherous hematite is produced by iron bearing minerals in the regolith" (Pettijohn, 1949). Hematite staining is largely restricted to terrestrial rocks, and is caused by oxidation induced by alternate wetting and drying during deposition. Such appears to be the case in this sequence.

Cut and fill structures, especially of conglomerates in sandstone suggest a continental origin. Supporting evidence is given by the abundance of conglomerate and sandstone with an absence of limestone or shale.

The writer envisages these conglomerates as wedge-shaped masses thickening toward the north, possibly representing a lateral equivalent of the Chuckanut exposed to the south of Bellingham. Conceivably they are a coarser, near source equivalent of finer-grained sedimentary rocks lying to the northward.

Available data is not adequate to indicate a source but presumably it lay to the southeast or east. The granitic rocks must have been derived by unroofing of pre-Late Cretaceous acidic intrusions. Dacite boulders appear identical to dacite intrusions occurring in small plugs in the Cascade foothills to the east (Danner, personal communication). Quartzite and chert pebbles, being sub- to well-rounded probably represent at least a second sedimentary cycle.

Piedmont deposition most likely accounts for these deposits. Turbulent, north flowing waters, draining from adjacent highlands and largely unconfined by channels would carry boulders, pebbles and cobbles. These would be indiscriminantly deposited by changes in drainage routes. The large cobbles and boulders would be rapidly rounded, even by short transport. Smaller clastic particles would remain angular to subangular and such is the case in these rocks. Cross-bedded sandstones would form where water courses discharged in ephemeral lakes. That abundant vegetation was carried to the depositional environments is indicated by the now coalified logs and the abundant carbonaceous remains.

Alternate wetting and drying of the sediments is facilitated by the postulated frequent changes in the drainage pattern. This would result in the partial oxidation of iron-rich minerals to hematite, imparting the characteristic red color of the matrix.

PALEOBOTANY

GENERAL

During field mapping of the Tertiary conglomeratic sequences, several thin siltstone and very fine-grained sandstone units were observed. Invariably these contained carbonaceous material, generally as carbonized twigs or small fragments of wood. No leaves or other identifiable macrofossils were observed. It was thought that these fine-grained sediments might contain plant micro-fossils and with this in mind several large specimens were collected. Stratigraphic relations between one locality and another are largely unknown, but because of the limited thickness and nature of the Ika Formation, the specimens are thought to be essentially contemporaneous.

ANALYTICAL PROCEDURE

Six samples of Ika Formation and one sample of Delta Rocks Formation were macerated. All the Ika specimens yielded plant microfossils, but the Delta Rocks specimen contained none.

Treatment of all specimens was identical. Aproximately fifty grams of disaggregated material was covered with hydrochloric acid to remove any carbonate present. After rinsing in clear water, the specimens were immersed in hydrofluoric acid for periods ranging from 24 to 100 hours. After decanting the acid and rinsing in clear water a residue of microfossils, carbonaceous fragments, and insoluble mineral matter remained. This residue was immersed in nitric acid for 3 to 24 hours, which was followed by a final treatment of potassium carbonate to free the microfossils from their carbonaceous coat. Several washings in clear water followed and the residue was concentrated in a centrifuge. Where considerable insoluble mineral matter remained, a heavy liquid separation was made using a zinc chloride solution of specific gravity 2. Safranine dye was added to stain the fossils. Finally the microfossil residue was divided among 5 to 7 slides and immersed in a plastic medium dissolved in benzene.

After preparation, the slides were studied under a Zeiss binocular microscope with adjustable micrometer stage. Photographs were made through the microscope using a Leica 35 mm camera. Adox Dukopan film was used and a green filter inserted in the light source to increase contrast. Final printing was on high contrast Kodak photographic paper. The magnification of prints was 500 diameters. Fossil identification was made with photographs and by direct examination through the microscope.

IDENTIFICATION

On the whole, the spores and pollen for the samples investigated are poorly preserved. They show signs of considerable abrasion and many were broken. Diagnostic features, such as ornamentation and pores, were largely obscured, making identification difficult.

The writer made tentative identifications of some forms using largely the group classification of Krutzsch (1957). More specific generic identifications were made by comparisons with Burrard (Eocene) microfossils (Rouse, manuscript in press). Dr. G.Rouse made positive identification of all spores and pollen which could be determined. The writer gratefully acknowledges the considerable help rendered by Dr. Rouse in this connection.

The following were identified:

Alternoseptites sp.	alga
Phragmothyrites eocaenicus Edwards	fungus
Cicatriocosisporites intersectus Rouse	fern
?Gleichenia sp.	fern
Foveasporis Krutzsch	cf. fern
Pinus sp.	pine
Taxodium hiatipites Wodehouse	bald cypress
Sabal granopollenites Rouse	palm
Juglans sp.	walnut
Carya juxtaporipites (Wodehouse) Rouse	hickory
Platycarya sp.	hickory
Tilia sp.	basswood (linden)
Corylus tripollenites Rouse	hazel
Alnus sp.	alder

Other forms were present in the specimens studied but could not be readily identified. *Gleichenia*, a diagnostic tropical fern, was doubtfully identified. The paucity of specimens combined with the poor state of preservation made absolute identification impossible. *Gleichenia* became extinct this far north in the earliest Tertiary, so a definite identification would have considerable age significance. Many of the forms listed above are characteristic of the Burrard Formation of Eocene age. (Rouse, personal communication).

Brief examination by the writer of microfossils from the Sooke Formation (probably Lower Miocene) indicated little similarity between the Sooke and the Tertiary rocks of the Skagit Bay area. Using the broad classification groups of Krutzsch (1957), plant microfossils indicate a Middle to Late Tertiary age for the Sooke flora.

Two preparations of Chuckanut microfossils were also briefly examined and these showed similarities with those of the Skagit Bay area. Especially important was the presence of _Foveasporis_ Krutzsch, also found in the Ika Formation of the Skagit Bay area, which is restricted to the Middle Eocene in Germany.

ENVIRONMENTAL SIGNIFICANCE

Two of the Lower Tertiary genera, _Taxodium_ and _Sabal_, are warm-temperate to sub-tropical. _Gleichenia_, if truly present is also indicative of a subtropical climate. The remaining forms are indicative of a moist but somewhat cooler environment.

The relative percentage of genera in the original flora or the distances spores and pollen may have travelled to the site of deposition, are not known. Probably the mixture of subtropical forms with those characteristic of cool temperate climates is indicative of mingling of distinct floral zones. Perhaps the palms, cypress and tropical ferns were a characteristic part of a lowland flora. The more temperate forms may have come from hills and mountains to the south or east.

Durham (1950, p. 1244) states: "... the Lower Eocene faunas of the Crescent Formation in the State of Washington (at about 40°N lat.) include reef corals, large foraminifera, brachiopods, and tropical molluscan genera, clearly indicating that this fauna too, lived in a tropical environment". The tropical element in the Skagit Bay flora is compatable with the Eocene environment as known by other evidence.

As pointed out earlier, under the section "Upper Cretaceous--Lower Tertiary Sediments", the thick wedge of conglomerates strongly suggests a high mountain source. These high and cooler areas might easily have supported a temperate vegetation which is represented by spores and pollen in the Skagit Bay rocks.

The writer has observed a modern day equivalent, bordering Lingayen Gulf on the west side of Luzon Island, the largest in the Philippine Island Group. A sea level coastal plain supports a thick tropical flora including ferns, palms, bananas, etc. One-half mile to one mile inland, mountains rise abruptly, culminating in peaks up to 6500 feet in elevation. A steady vertical change in flora occurs with various conifers and other cool temperate forms making an appearance at the higher elevations. It seems conceivable that a mixture of tropical and temperate floral elements could occur in lowland areas of deposition, such as represented by the Skagit Delta.

It is also interesting to note that at the foot of the mountains, on this tropical coastal plain of Luzon, extensive wedges of continental conglomerates are being deposited. During much of the year these are largely exposed to the drying effects of heat and sun, but during the monsoon season, large quantities of coarse conglomeratic material are brought down by turbulent streams. Interbedded shales and silts probably contain tropical to sub-tropical to cool temperate floral remains, as do those of the Skagit Bay Tertiary sediments. The writer envisages the Ika Formation as being deposited under climatic conditions and with a depositional environment similar to those now prevailing along the west coast of Luzon.

MARINE PLEISTOCENE

Fossiliferous marine Pleistocene beds are exposed in a pocket 10 to 15 feet above sea level at the west end of Hope Island. The deposit is small and rests unconformably upon serpentinite. The basal portion of the unit is a polymictic, unsorted conglomerate composed of angular to rounded boulders up to 2 feet in maximum dimension. Upward through the exposed 12 to 14 feet, the average particle size decreases. Present are thin interbeds of pebbly sand enclosed in subrounded cobble conglomerates. The entire deposit is very poorly sorted, with pronounced and abrupt vertical changes in grain size. In overall appearance, the beds resemble a sedimentary unit deposited by rapidly moving, turbulent water which was rapidly agrading and forming new channels.

The unit appears to be dipping east at about 22°, but because there is no evidence elsewhere of post-Pleistocene deformation this is probably a primary dip.

Interbedded with the conglomerates are pebbly sands, exhibiting two types of faunal remains. The first are sandy layers containing an exceptionally high percentage of pelecypod shell fragments, usually less than one-half inch in size. Locally the shell concentration is so high the bed might properly be called a coquina. Another sandy bed near the top of the unit contains relatively undamaged marine invertebrate remains. Lack of any substantial transport or abrasion is indicated by the presence of numerous, fragile, thin-walled mussel shells showing negligible damage. Barnacles are less commonly present and are attached to pebbles in growth position with no evident abrasion.

Faunal forms collected from the Pleistocene are:

Schizothaerus sp. - (horseclam), a large, thick-shelled pelecypod.

Saxidomus sp. - (butter clam), a thick-shelled pelecypod

Pecten sp. - (scallop)

Mytilus sp. - (blue mussle), thin-shelled

Balanus sp. - a small barnacle

Serpula sp. - worm tubes

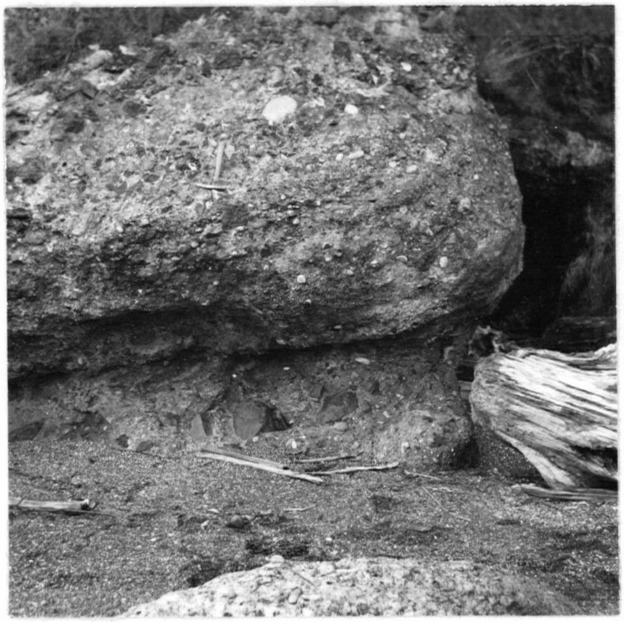


Figure 27. Invertebrate-bearing, marine Pleistocene conglomerate at east end of Hope Island. Hammer resting on "coquina" zone.

Figure 28. Glacial striations and grooving, indicating ice movement toward observer. South side of Kiket Island.

These genera are still found inhabiting parts of Puget Sound, Straits of Georgia and bays of the open coast (Dehnel, personal communication).

The writer believes this unit was deposited in marine waters near the toe of the retreating Vashon ice sheet. Outwash gravels and sand flats were formed immediately to the south of the ice, much of it being laid down under water. Marine organisms such as Balanus and Mytilus established themselves on rocks, while the Schizothaerus, Saxidomus, and worms occupied the finer-grained sediments.

Occasional channel shifting of the high velocity, turbulent streams draining the ice margin resulted in erosion, concentration, and burial of these faunal forms.

The coquina-like beds, which contain a sand or pebbly sand matrix, suggest strandline concentrations. Wave action broke up and concentrated pelecypod shells which are preserved as distinct units.

INTRUSIVE ROCKS

OCCURRENCE

With the exception of the extreme southeast end, the entire mass of Hope Island is composed of ultrabasic intrusive rocks. To the east, across a narrow channel, these same rocks, are exposed both at Hunot and Tosi Points. Other outcrops occur near the village of Snee-oosh Beach and along the main highway immediately east of town.

The south side of Hope Island is delimited by a west-southwest trending fault of unknown displacement which has brought volcanic rocks into contact with serpentinite. The volcanic rocks occupy a very small area at the extreme southeast tip of the island. On both sides of the fault the volcanic rocks and serpentinite are intensely sheared and slickensided.

Another ultrabasic intrusion occurs at the southeast end of Fidalgo Island associated with a vein of strontium minerals and calcite. Although this is also a serpentinite its character and nature of occurrence are somewhat different from the serpentinites of the Hope Island-Tosi Point-Hunot Points area and is discussed in the section on Economic Geology.

McLellan (1927) assigned the name Fidalgo Formation to intrusive masses of serpentinized dunites which occur in the San Juan Islands. He recognized three distinct rock types: (1) masses of very coarse-grained dunite, (2) veins of fine-grained dunite injected into fractures of the coarse variety and (3) stringers of serpentinized pyroxenite. Most of the dunites have been serpentinized.

On the basis of Lithology and association, the ultrabasic rocks of the Skagit Bay area are considered to be part of McLellan's Fidalgo Formation.

Figure 29. Jointed serpentinite on north shore of Hope Island.

Figure 30. View west along south shore of Hope Island. Cliffs formed of serpentinite.

PETROLOGY

General

The term "ultrabasic" is applied to those intrusive rocks high in iron and magnesium. Typically they are made up of varying quantities of olivine and pyroxene with little or no plagioclase, amphibole or biotite. Dunite is defined (Leech, 1953) as a rock containing 95 per cent or more olivine, with or without minor pyroxene. With more than 95 per cent pyroxene the rocks are called "pyroxenites". The intermediate phases are named on the basis of their orthorhombic-monoclinic pyroxene ratio. "Peridotite" is an olivine rich, non-feldspathic rock, which therefore includes dunite and intermediate phases but not pyroxenite. The varieties of peridotite of interest in this area are dunite and harzburgite, the latter being an olivine-orthopyroxene rock. Serpentine is a collective term for a group of hydrous magnesium silicate minerals, and serpentinite is a name applied to a rock composed of serpentine minerals.

The ultrabasics of Skagit Bay are serpentinites composed essentially of serphophite, antigorite; minor chrysotile, talc, chromite and magnetite with rare residuals of olivine and enstatite.

Field Description

In weathered outcrop this rock appears dark gray to dark green though a fresh surface is always a dull dark green. The typical brownish-weathering serpentinite is not abundantly present, probably due to the low iron content. It is a topographically resistant, commonly jointed rock, which is invariably a cliff-former. Fractures and joints are commonly filled with smears of carbonate. When these surfaces are exposed by weathering or erosion the carbonate gives the rock a splotchy, gray-white appearance.

Thin-Section Description

The mineralogy, as seen in thin section is simple, and evidently homogeneous over the entire area. Texturally the serpentinite consists of a mesh of antigorite veinlets enclosing cores of serphophite and more locally relics of olivine. Typically the interstices are zoned, consisting of a marginal zone of fibers growing at right angles to the grain margins and a central zone in which the fibers are at right angles to the first two zones.

Enstatite formerly constituted about 5 per cent of the rock, but where originally present it has commonly been replaced by serphophite and antigorite to form bastite. Chrysotile though rare occurs as small fibers intimately associated with the antigorite. In at least one section incipient steatization was seen with talc having slightly replaced the antigorite.

Very small flecks of chromite are sparingly visible in hand specimen with a hand lens. In thin-section they are seen to be scattered randomly throughout the rock, displaying a variation in size with a maximum up to about 0.2 mm. Chromite is mainly anhedral, though some euhedral forms exist. Magnetite is rare, appearing as dustlike particles distributed mostly in intergranular spaces. The small amount of magnetite strongly suggests the original olivine was iron poor.

During the alternation of olivine to serpentine the replacement appears to have progressed uniformly from grain boundaries, and replacement is complete in several specimens. As mentioned, the enstatite, where present, has been pseudomorphically replaced so an indication of original mineralogical composition is possible. On this basis the original rock is interpreted as a dunite or very olivine rich harzburgite.

ORIGIN

Serpentinite is in contact with only two other lithologic types. The first is the earlier mentioned fault contact with volcanic rocks and the second is an unconformable contact with overlying glacial outwash and till. Neither of these is of material assistance in a genetic interpretation except to suggest that either the volcanics or the serpentines are exposed because of faulting. The following discussion is based principally on ideas of Hess (1933, 1938, 1955), Leech (1953) and Turner and Verhoogen (1960).

The serpentinites of the Skagit Delta area are of the "Alpine type" which typically occur in folded eugeosynclinal sediments and orogenic belts. They most commonly occur as lenticular sheets and tabular bodies frequently concordant with the deformed sediments, however many massive cross-cutting intrusions are known.

Much controversy has arisen, and still continues, over the origin of "Alpine type" ultrabasic rocks. The discussion has finally resolved itself into two alternative explanations:

(1) Intrusion of a peridotite magma, perhaps of serpentine composition as has been most forcefully presented by Hess.

(2) Intrusion by solid flow of ultrabasic rock, perhaps largely formed of crystallized olivine and some pyroxene, the whole lubricated and given mobility by intergranular fluids. Bowen and Tuttle (1949) have placed this concept on a solid chemical foundation.

Hess, in his support of a true hydrous magnesian melt, has agreed that many ultrabasic intrusions were semi-solid at time of intrusion, but does not believe this to be a "general" explanation. He points to low dip, and concordant sills of serpentinite which are comparatively thin; the frequent lack of flow structure; and the lack of evidence for eruption which should result from release of pressure on intergranular fluids. Because shallow intrusions would lose water, serpentinization should increase with depth. The reverse is actually true, Hess maintains, with virtually all shallow ultrabasic intrusions being serpentinized. Because Hess considers serpentinization to

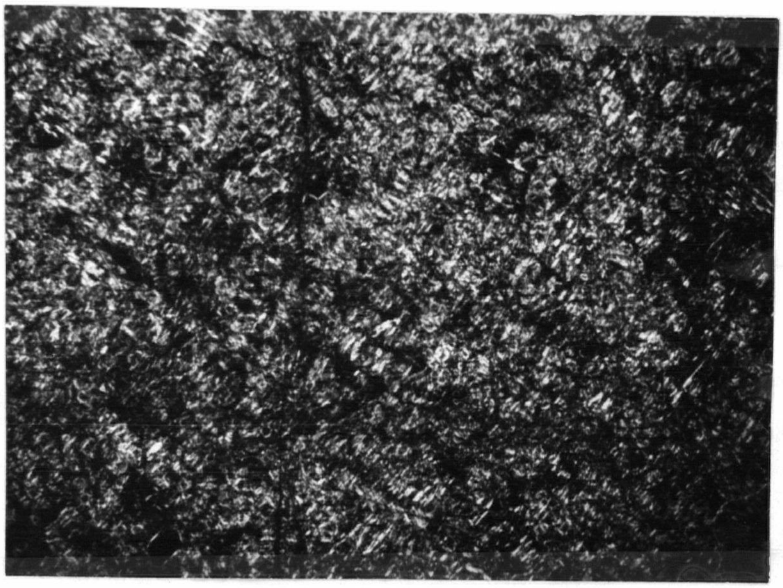


Figure 31. Photomicrograph of serpentinized dunite with characteristic mesh texture. Specimen from Hope Island. Cross-nicols, x10.

be a deuteric process, he suggests the necessary volatiles to be derived from the magma itself, with a lesser amount coming from the country rock.

Bowen and Tuttle (1949), largely on the basis of laboratory experiment, have presented evidence to support the concept of "solid intrusion" or a magma composed essentially of crystalline olivine and pyroxene supported and surrounded by an intergranular magmatic fluid. After considerable experimentation Bowen and Tuttle concluded that there is "no likelihood that any magma can exist that can be called a serpentine magma, and certainly no possibility of its existence below 1000°C." In this connection they emphasize the lack of contact effects on intruded country rock, hence probable low temperature. Furthermore olivine might be expected to flow under stress, perhaps more easily than any other silicate. While passing through sedimentary rocks the magma might pick up volatiles from the water-rich geosynclinal rocks resulting in serpentinization and consequently still easier flowage.

Both the hypotheses of ultrabasic emplacement tentatively accept the concept of original source material in a peridotite substratum.

Recent laboratory and field evidence increasingly suggests the Bowen and Tuttle hypothesis as most acceptable for "Alpine type" ultrabasic intrusions. In this connection Turner and Verhoogen (1960, p.321) summarize:

"We are now able to accept as a satisfactory working hypothesis the dual concept of intrusion of peridotite "magma" in a largely crystalline condition, with simultaneous or subsequent serpentinization of its constituent minerals (olivine and enstatite) through the activity of aqueous solutions or vapors derived for the most part from the surrounding geosynclinal sediments or from intrusive bodies of granitic magmas. But this, like any other hypothesis, is subject to future modification or rejection should it prove incompatable with facts yet to be discovered".

SERPENTINIZATION

There are two principal theories to explain the serpentinization of ultrabasic rocks;

(1) Deuteric alteration with serpentinizing fluids coming from the cooling ultrabasic body and

(2) Hydrothermal alteration brought about by solutions coming from outside the ultrabasic mass, perhaps from younger intrusive rocks.

The first concept, supported principally by Hess, calls for a preliminary crystallization of olivine, then a reaction between the olivine and water to produce serpentine. Support for this theory is offered by large, more or less uniformly serpentinized bodies which show no relation to sediments, structure or other intrusive bodies.

The second theory is favored by Bowen's experimental work. This explanation, like the first, requires addition of tremendous volumes of water which presumably come largely from water charged eugeosynclinal sediments. Olivine is replaced by an equal volume of serpentine with excess MgO and SiO_2 being removed in solution. Although locally silicification and magnesia metasomatism of adjacent rocks does occur, it is not common, hence what happens to the magnesia and silica in these cases? Unfortunately the serpentinites of the map area give little help in making a genetic interpretation.

STEATIZATION

Locally talc is present in very small amounts replacing antigorite. The process of talc formation in an ultrabasic rock is termed "steatization" (Hess, 1933). It is a hydrothermal reaction, generally unrelated to, and later than serpentinization.

A few examples are reported where the only source of active solutions is the ultrabasic body itself. In these cases it would seem that talc formation is an aftermath of serpentinization. The two are related, in that steatization solutions would be similar to, but of a lower temperature than those causing serpentinization.

Talc formation is very minor and very local in the Skagit Bay region which would suggest that it was a late and low temperature alteration brought about by the final cooling of serpentinizing solutions.

AGE

McLellan (1927) describes ultrabasic rocks of the San Juan Islands, intruding the Upper Paleozoic Leech River Group. These ultrabasics were, in one locality, intruded by acidic rocks which he considered Late Triassic or Early Jurassic. He concluded that the Fidalgo Formation is of Triassic age.

As pointed out earlier no field or petrographic relations are present in the map area to give evidence as to age of ultrabasic intrusions. Hess (1955) indicates that "Alpine type" ultrabasics of the orogenic belts are intruded during the earliest phases of deformation. Because the eugeosynclinal rocks of the Skagit Bay area are known to be only of pre-Tertiary age and because several periods of deformation are known, it is only possible to state that the serpentinites are probably pre-Tertiary.

Leech (1953) described similar occurrences of alpine type ultrabasic rocks from the Shulaps Range of southwestern British Columbia. He found that the main ultrabasic mass cuts Upper Triassic rocks and further that chromite, presumably from the ultrabasic intrusions, was found in rocks containing probably Lower Jurassic fossils. Hence these intrusions are probably Upper Triassic.

In the Cascade Mountain foothills, about 33 miles northeast of La Conner, and just southwest of Mt. Baker is a large intrusive dunite. Contained within it are layers and lenses of chromite, some of which has been mined commercially. This ultrabasic rock, called the Twin Sisters dunite, is considered Tertiary in age, but the basis for this age assignment is unpublished and unknown to the writer.

Hess (1955, p.396) presents a map entitled "Serpentine Belts of North America". An arcuate band of ultrabasics, concave westward, and including the ultrabasic intrusions of the map area, are shown to be Late Triassic in age. Other ultrabasic intrusions of central and northern British Columbia are thought to be also Upper Triassic.

Using the postulated ages for similar rocks in adjacent areas the writer tentatively suggests an Upper Triassic age for the serpentinite of the Skagit Delta area.

STRUCTURE

Regional

Although the oldest rocks are highly deformed, the earliest orogenic activity that can be interpreted with any degree of accuracy occurred during the Late Miocene. At that time the whole coast of North America was thought to have undergone varying degrees of uplift, with local areas undergoing more intense deformation.

One such local area was a broad, northwest-southeast trending upwarp that extended from southern Vancouver Island, through the San Juan Islands, through western Skagit County and southeast through the site of the present central Cascade Mountains. The Chuckanut Formation, near Bellingham, lies on the northeast flank of this uplift. The map area is on the crest of this Late Miocene uplift, and in consequence erosion has removed most of the Tertiary cover, exposing the more intensely deformed pre-Tertiary sedimentary rocks.

Again in Late Pliocene and Early Pleistocene times, the whole region was affected by north-south uplifts and downwarps that created the present day Cascade and Olympic Mountains and the Puget Sound Trough. Tertiary rocks of the western Skagit Delta preserve evidence of Late Miocene, northwest-southeast deformation, but do not show signs of the north-south Pliocene uplift. Pliocene-Pleistocene deformation in the Skagit Delta area was probably simple tilting with little compression.

Local

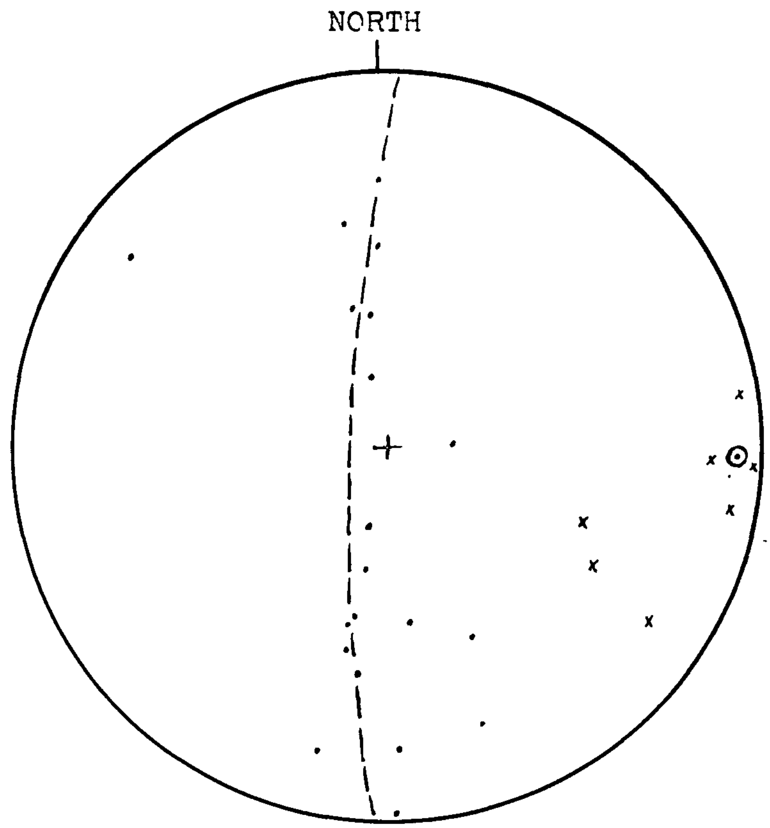
Deformation is very intense in the map area and detailed structural analysis of pre-Tertiary rocks is severely handicapped for the following reasons:

(1) Paucity of outcrops

(2) Highly weathered and decomposed nature of many outcrops.

(3) Lack of any fossil or stratigraphic control.

Within limits set by time and the author's ability, measurements of bedding, cleavage and lineations were made. Because of the almost omnipresent flow and fracture cleavage,



PALEOZOIC(?) GOAT ISLAND FORMATION

from southern Fidalgo Island
and Goat Island.

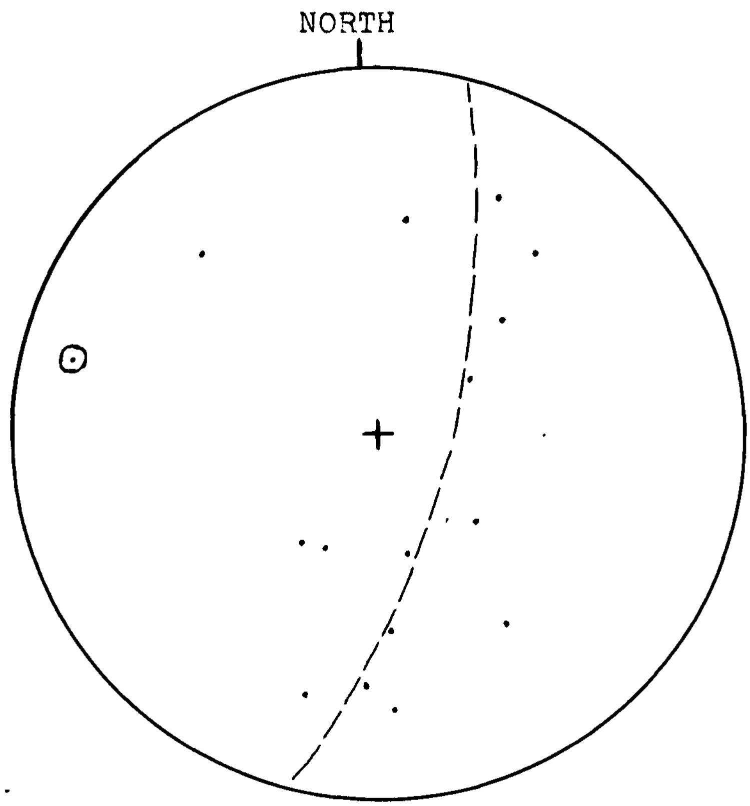
• Poles to cleavage (20 points)

x Lineation (7 points)

⊙ Pole to average great circle through poles to cleavage.

Plotted on lower hemisphere of equal area net.

PLATE 5



DELTA ROCKS AND IKA FORMATIONS

• poles to bedding plotted on lower hemisphere of equal area net.

⊙ Pole to average great circle through poles to bedding.

15 Points

PLATE 6

bedding was seldom observed, especially in Paleozoic rocks. Consequently analysis was made almost entirely on the basis of cleavage and lineation.

At least two stages of pre-Tertiary deformation occurred. An earlier cleavage is marked by elongated pebbles which are oriented with the long axes essentially horizontal and trending east-west. A later deformation intensely folded this cleavage and locally folded the earlier formed elongate pebbles. This latter folding may be responsible for the recumbent isoclinal folds which are incompletely exposed in road cuts on either side of the new La Conner bridge.

Stereographic analysis, utilizing all available data, indicates the pre-Tertiary rocks are folded along an east-west axis with a plunge of 0° to 5° easterly.

Tertiary rocks are sporadically exposed at the south edge of the map area in a broad, generally east-west syncline. The contact between Tertiary and pre-Tertiary rocks is visible only at the northwest end of Ika Island. An angular unconformity is evident in the field, with a flow breccia folded into a roughly east-west trending syncline overlain by uniformly south dipping Tertiary sedimentary rocks.

No cleavage or lineations were observed in the Tertiary sequence and there was considerable scattering on the net of poles to bedding. However a pattern of points is evident and the writer has concluded that the Tertiary deposits were folded into a syncline whose axis plunges 17° to the N 75° W. The anomalous points are most probably explained as readings taken on cross-bedding or channel sands.

Consequently, within the map area, at least three distinct stages of deformation have occurred. The first two were definitely pre-Tertiary, as Tertiary rocks are not affected. The third was post-Eocene, presumably late Miocene, and associated with a broad northwest-southeast upwarp.

The most interesting observation is the striking persistence of east-west structural trends. Pre-Tertiary rocks are deformed essentially along east-west axes. Tertiary folding, although less intense, has also been aligned east-west.

Furthermore as will be pointed out in the section on Economic Geology, all major structural features of the area, including faults, serpentinized ultrabasic intrusions, and a strontium vein, have a general east-west trend.

More detailed structural analyses of this and surrounding areas might shed much light on the structural evolution of the pre-Tertiary rocks of the northern Puget Sound Region.

ECONOMIC GEOLOGY

STRONTIUM

Occurrence

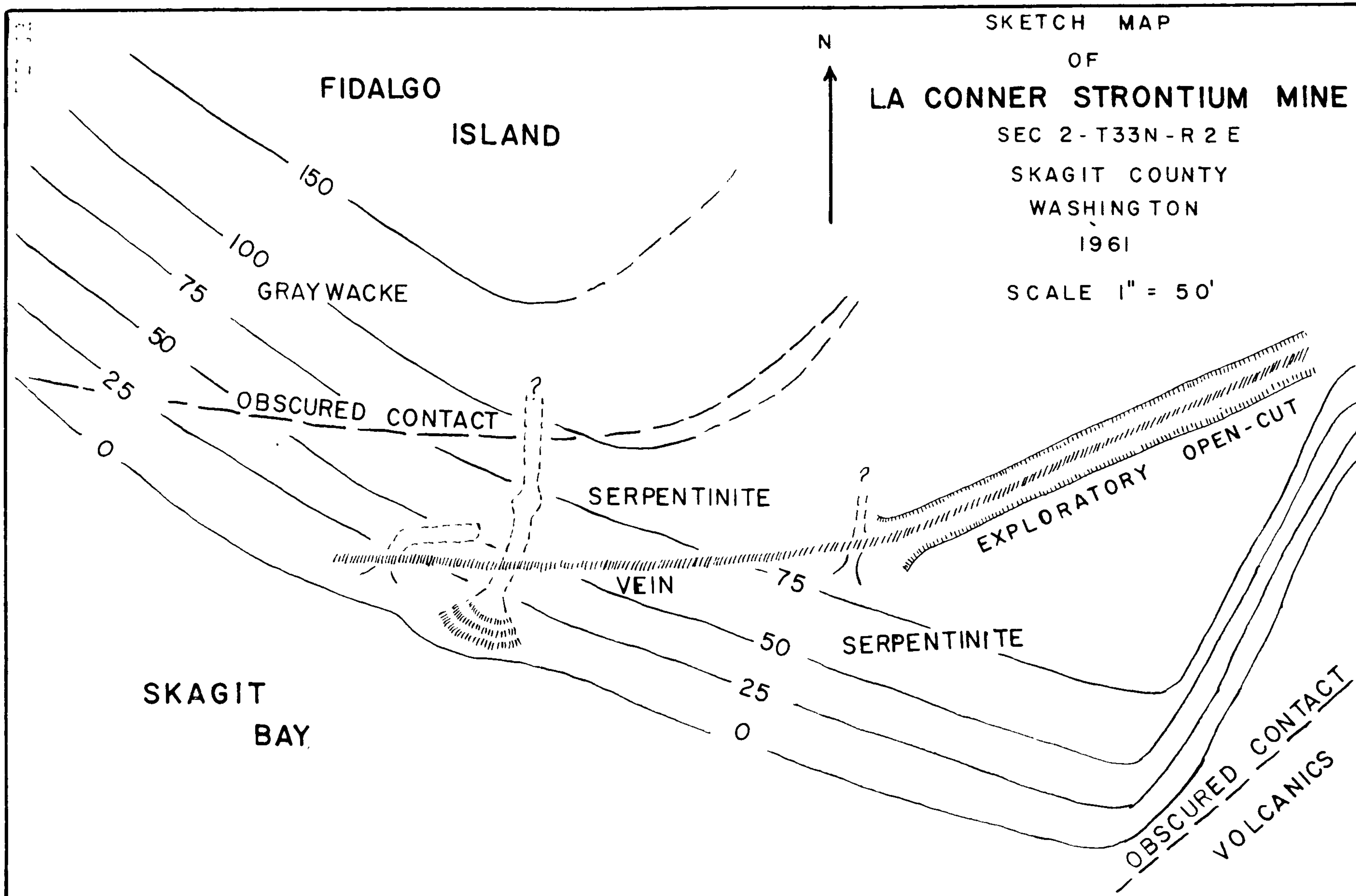
The La Conner celestite-strontianite deposit is located about one mile southwest of the town of La Conner, at the southeast end of Fidalgo Island. Access is easiest by boat from La Conner. To the west, road extends to within three-fourths of a mile from the mine, but access to the mine is limited to times of low tide.

The deposit, discovered sometime prior to the first World War, was mined during both wars but has largely remained idle at other times.

Local Geology

Until 1929 the geology of the deposit had never been investigated in detail though Hill (1915, 1916) made reference to it. Landis (1929) published results of visits to the area in 1921 and 1928. In 1950 Caldwell and Waterman published a brief article, essentially recapitulating the geological findings of Landis. The present writer visited the deposit several times during the fall of 1961, collected specimens, made sections and prepared a sketch map of the area. This report is based largely on the latter work and to a lesser degree on the findings of Landis.

A sea-cliff running west-northwest--east-southeast and about 90 feet high provides fairly good rock exposure. Northeast from the brow of the hill an old surface cut exposes the vein on strike for about 125 feet. Glacial drift and forest vegetation obscure any further outcrop. Three adits penetrate to the vein from the bluff face. Generally unsatisfactory condition of the tunnels, and the abundance of caved material, hinders geologic interpretation.



SKETCH MAP
OF
LA CONNER STRONTIUM MINE
SEC 2-T33N-R2E
SKAGIT COUNTY
WASHINGTON
1961
SCALE 1" = 50'
N
FIDALGO
ISLAND
GRAYWACKE
OBSCURED CONTACT
SERPENTINITE
VEIN
SERPENTINITE
EXPLORATORY OPEN-CUT
SKAGIT
BAY
OBSCURED CONTACT
VOLCANICS
150
100
75
50
25
0
?

The deposit consists of a celestite-strontianite vein striking N60°-70°E and dipping 45° to the northwest. Enclosing the vein is a sheared intrusive mass of almost completely serpentinized dunite, now largely carbonatized. To the east, the serpentinite is in fault contact with highly altered, spilitic volcanics. To the west a fault(?) contact places serpentinite against pre-Tertiary graywacke.

Vein Mineralization

The vein is a series of pod and lens-shaped bodies 6 inches to 30 inches in thickness, all lying along the same horizon. In the field the vein material appears to be about half celestite ($SrSO4$) and half strontianite ($SrCO_3$) with minor amounts of calcite. Detailed analyses of run of mine material indicates celestite makes up 37 per cent, strontianite 50 per cent and calcium carbonate and serpentinite make up the remaining 13 per cent. Specimen pieces of celestite are almost 100 per cent pure and strontianite 95 per cent pure with calcite making up the 5 per cent impurity (Caldwell and Waterman, 1950).

Characteristically the celestite has a bluish to very pale gray tinge. Rarely it is colorless and translucent or even milky white. It is considerably coarser-grained than the strontianite and shows good basal cleavage. Strontianite has commonly replaced celestite along cleavage planes and also coats external cleavage faces.

The strontianite, except where colored by limonite, is a milky white, finely crystalline, powdery substance. On

Figure 32. Two of the three adits driven to celestite-strontianite vein. Southeast Fidalgo Island.

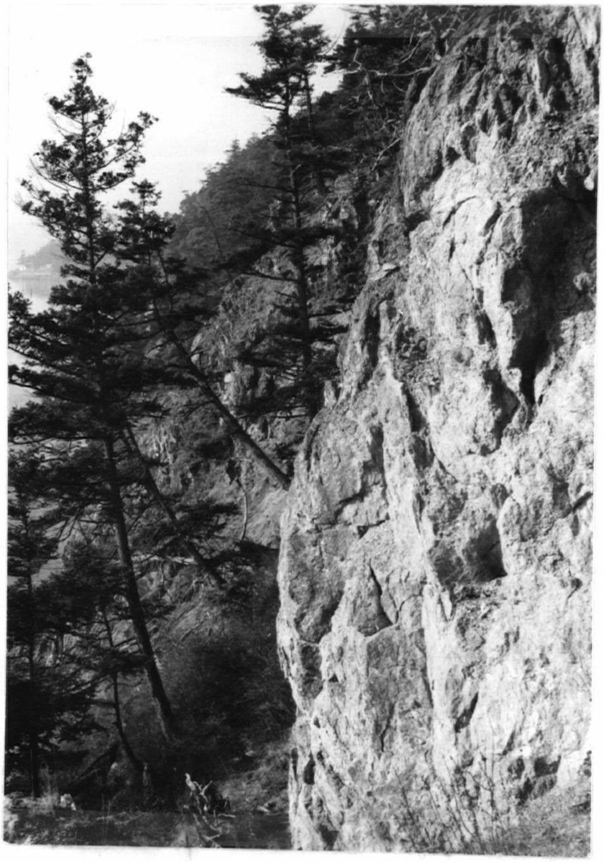


Figure 33. Serpentinite cliffs above adits shown in Figure 32.

surfaces of vugs and outcrops it generally shows a mammilary or botryoidal form, whereas freshly broken surfaces are reticulated with a box-like outline. Evidently a slight reduction of volume took place during replacement as evidenced by vugs and other irregular openings in the strontianite. These are not conspicuous in the primary celestite.

Evidently the strontianite replacement is the result of circulating ground waters above the water table. Hill (1915, 1916) observed that carbonate waters will dissolve strontium sulfate and replace it with water-insoluble strontium carbonate. The strontianite-celestite ratio is said to increase upward in the vein, toward the outcrop (Landis, 1929).

Calcite is colorless, milky to transparent, occurring in small veinlets up to an inch in thickness. These veinlets frequently show comb structure, indicative of open space filling.

Limonite is locally present within the vein, frequently imparting a pale brownish stain to the strontianite.

Not observed by the writer, but reported by Danner (personal communication) are small quantities of orpiment and realgar.

Rare small, subangular to subrounded fragments of carbonatitized serpentinite are found within the vein, especially near the margins. These inclusions may be the result of some differential movement of the vein walls during deposition of the vein minerals.

Serpentinite

The Serpentinite host rock is about 180 feet thick with the strontium vein lying about 60 feet from the top. Contacts of serpentinite with adjacent rocks are nowhere exposed but can be inferred within fairly close limits, and strike about N65°E, dipping about 45° northwest. The suggestion is that, in this restricted outcrop, the serpentinite is a tabular body dipping northwesterly with an included vein of strontium minerals also dipping at about the same attitude.

Of structural significance is the presence of west-southwest--east-northeast structural trend in rocks exposed west of the entrance to Swinomish Channel, especially west of the mine. At least one major and several smaller faults are present in the pre-Tertiary sediments west of the mine, all striking approximately N70°E to East. Much of the rock cleavage shows similar attitudes though dip may be steeply north to south. As mentioned, the lower (eastern) contact of the serpentinite against volcanic rocks is brecciated and gradational through a zone at least 25 feet wide. Fragments of volcanic rocks and argillite, up to 2 inches in diameter are set in a sheared serpentine matrix that grades upward into a sheared serpentinite without clastic fragments.

The upper (western) contact of serpentinite against pre-Tertiary graywacke is of a different sort. Through a zone averaging 10 feet in thickness, quartz layers are conspicuous.

Commonly these layers are 1 to 3 inches in thickness, massive, and vuggy, the vugs containing white to light gray quartz and locally small cubes of pyrite. Other quartz bands of comparable thickness show a well pronounced comb structure and numerous well developed, small, singly terminated, quartz crystals. Locally, near the top of the cliff, the quartz is conspicuously red, as the result of iron staining derived from leached overlying glacial till. Available evidence is strong for open-space filling.

There is no evidence of significant alteration in graywacke adjacent to serpentinite except for minor silicification. However, silicification is no more intense than that seen elsewhere in graywacke not affiliated with intrusions.

Apparently the serpentinite occupies a portion of a fault zone with a number of parallel oriented slices. Key beds are absent and slickensides are at random angles so the direction of movement remains unknown. Displacement along any single plane of movement was probably slight.

A variation in mineralogy is conspicuous, both in hand specimen and thin section from the vein towards either border of the intrusion. Near the vein the serpentinite is highly carbonitized and the amount of serpentine low. Away from the vein the rock is almost entirely serpentine and no residual olivine was observed.

Chalcedony and opal are both extremely common in the vicinity of the vein. The chalcedony is highly fibrous and locally spherulitic. Opal is a dark green, semi-transparent form which, like the chalcedony, has formed in open spaces and minute fractures. Both appear to be late minerals in the paragenetic sequence because of their t endency to surround and dissolve calcite, especially along the calcite margins which are locally strongly corroded.

Calcite is an ubiquitous mineral, present throughout the rock, but in greatest quantity near the vein. Near the vein it forms a mosaic with individual grains up to 2 mm in length, and in the serpentinite it forms a plethora of ramifying and intersecting veinlets.

Of special interest is the occurrance of pictotite (chromium-rich spinel) throughout the serpentinite. A rim of magnetite surrounds most grains of pictotite. Both magnetite and picotite also occur as dusty, irregular aggregates, as small discrete grains and as large euhedral masses up to 0.8 mm in maximum dimension. Consideration of these minerals makes two facts clear:

(1) The presence of a chromium spinel indicates the original rock was an ultrabasic intrusion and not simply a serpentinized volcanic rock.

(2) The magnetite indicates that the original olivine must have been fairly iron rich. This is in distinction to the serpentinite of Hope Island, in the northwestern part of the map area, which has only trace quantities of magnetite, and consequently was formed of iron-poor, magnesia-rich olivine. Perhaps this fact indicates two fundamentally different ultra basic magmas

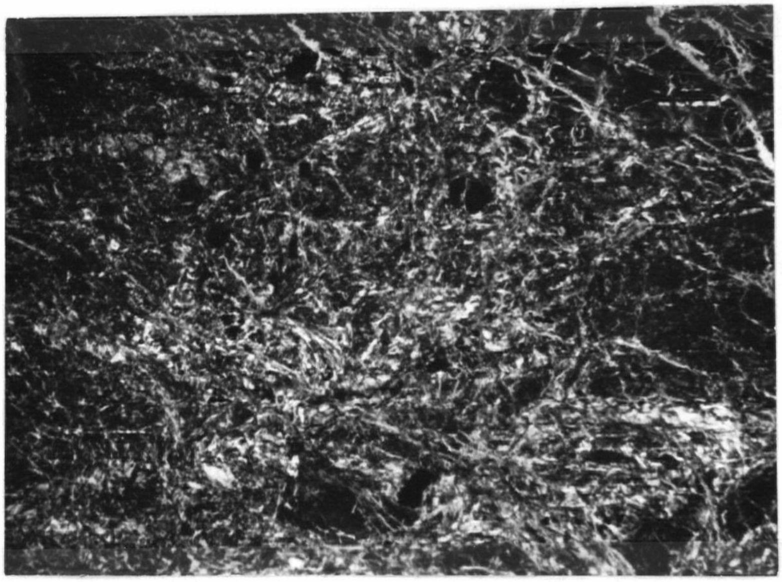


Figure 34. Photomicrograph of serpentinite enclosing celestite-strontianite vein. In addition to antigorite, chromite and magnetite are abundant. The whole is cut by numerous ramifying calcite veinlets. Cross-nicols, x10.

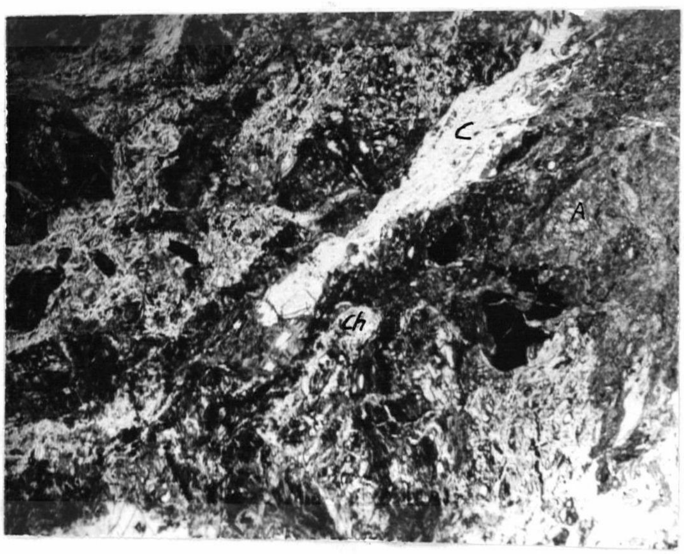


Figure 35. Photomicrograph of serpentinite adjacent to celestite-strontianite vein. Antigorite (A), calcite(C), chalcedony(Ch) and chromite are abundant. Cross-nicols x10.

were operating at different times. Probably time of intrusion was the same but some sort of chemical segregation resulted in two slightly different bodies forming. Evidence is lacking to solve this problem.

Pyrite is sparsely present in the serpentinite, as it is in the quartz veinlets. However where present it is concentrated in distinctive, commonly sinuous stringers. It is undoubtedly associated with silicification.

A similar though much smaller serpentinite mass lies at the extreme southeast tip of Fidalgo Island, at the western entrance to the ship channel. This small outcrop is intensely deformed with the serpentine cleavage highly deformed. Quartz and calcite veinlets are uncommon, nor is there any other sign of mineralization. Whether this is a faulted portion of the serpentinite exposed to the west, or a separate parallel body is not know.

<u>Origin of the Deposit</u>: <u>Serpentinite</u>

A suggestion has been made that the serpentinite lies in a fault zone. Evidence for such an interpretation is summarized below:

(1) Parallel to sub-parallel faults in a west-southwest--east-northeast direction through southeast Fidalgo Island. A similarly oriented fault borders the south side of Hope Island.

(2) Abundant rock cleavage with a general southwest--northeast orientation.

(3) Evidence of brecciation at the base of the serpentinite.

(4) Shearing in the serpentinite in a west-southwest--east-northeast direction.

(5) Celestite-strontianite vein striking west-southwest--east-northeast direction.

(6) Dips of all the above features are generally northwest.

(7) The area lies athwart a large northwest-southeast trending disturbed zone, which is actually near the crest of a Miocene uplift, extending from Vancouver Island southeast through the site of the present central Cascade Mountains.

<u>Origin of Deposit</u>: <u>Strontium Vein</u>

Celestite is commonly considered to be a sedimentary mineral and indeed is usually associated with sedimentary rocks, especially limestone and dolomite. It can occur in sedimentary rocks and become concentrated by the action of ground waters or it has been known to precipitate out as an evaporitic deposit. However in the case of the La Conner deposit it is thought to be hydrothermal for the following reasons:

(1) Occurrence of the Strontium minerals in a vein, consequently it is necessarily epigenetic.

(2) Complete absence of any associated limestone or dolomite.

(3) Occurrence of the vein in an ultrabasic rock.

(4) Presence of pyrite-bearing quartz veins.

On the basis of the above criteria the writer proposes the following sequence of events to explain the genesis of this deposit:

(1) Deep faulting occurred along a disturbed zone at an unknown date (Triassic?). Associated with faulting was intrusion of ultrabasics, probably dunite. As the intrusion moved slowly upward it was gradually serpentinized by water, silica and carbon dioxide streaming up the same fractured zone. Perhaps some or much of the water was derived from the surrounding eugeosynclinal rocks.

(2) After the serpentinite was emplaced, fractures formed allowing the hydrothermal solutions to continue their upward movement. Quartz veinlets and pyrite first formed, principally on the upper margin of the intrusion.

(3) As the hydrothermal solutions continued to cool, celestite and calcite were precipitated in a central lenticular shaped vein. Some movement occurred, perhaps by local faulting, which fractured the vein walls, allowing some mineralization around serpentinite fragments.

(4) At very low temperature chalcedony and opal filled remaining spaces and locally corroded earlier calcite.

(5) In the last step, probably after uplift and erosion to near the present level, ground waters started dissolving $SrSO_4$ and reprecipitating $SrCO_3$.

General

In common with other strontium deposits, the La Conner deposit is small. Recent estimates (Caldwell and Waterman, 1950) suggest reserves of 10,000 tons of ore above sea level which could, if necessary supply the worlds needs for eight months.

Strontium is not a vital metal and consequently its value is low. The United States uses over one-half the world's total annual production of approximately 14,000 short tons. This strontium is imported from England and Mexico at ballast rates, and at lower total cost than strontium minerals could be produced domestically. During war periods when the use of strontium compounds rose sharply, domestic sources became important; the La Conner deposit has been of definite value during both World Wars.

The principal interest in this deposit is its hydrothermal origin and association with ultrabasic rocks.

GRAVEL AND CRUSHED ROCK

Three rock quarries are located in the region. One quarry, southeast of Pleasant Ridge (Figure 36) is opened in conglomerates of the Delta Rocks Formation; a second to the west of Pleasant Ridge is in graywackes of the La Conner Formation; and the third quarry is on northern McGinn Island in Goat Island Formation graywackes. Rocks in all three quarries are tough and

Figure 36. Quarry in conglomerate of the Delta Rocks Formation. Located near southeast end of Pleasant Ridge.

well indurated. All quarries are operated by Skagit County. The rock is used in the crude state principally for rip-rap along the Skagit River and in dikes around La Conner and other parts of the Skagit Delta. A limited amount is used on county roads.

A small gravel pit, in glacial outwash at the south end of Pleasant Ridge is privately owned and is intermittently used as a source of concrete aggregate.

GLACIATION

GLACIATION IN THE PUGET SOUND TROUGH

The original Pleistocene studies in the Puget Sound Lowland were by Willis (1898) and Willis and Smith (1898). The stratigraphic succession presented in these papers has remained essentially unchanged though elaborated on and modified in more recent work. Willis established an older period of glaciation which he termed the Admiralty glaciation, a long post-Admiralty interglacial, called the Puyallup, followed by the extensive and most recent Vashon glaciation.

Bretz (1913) in his classic paper entitled "Glaciation of the Puget Sound Region" continued this classification. Although recognizing the presence of multiple glaciations, Bretz justifiably avoided correlation problems by defining the Admiralty as containing all the pre-Vashon deposits of the lowland. Again in

1920 he employed this classification in a discussion of the "Juan de Fuca Lobe of the Cordilleran Ice Sheet".

Considerably later, in 1949, Hansen and Mackin, by a marriage of geomorphology and palynology established, at least locally, several Pleistocene stages.

Crandell, Mullineaux, and Waldron (1958), working in the southeastern portion of the Puget Sound Lowland were able to subdivide the Admiralty of Willis and Bretz into at least three glacial and two interglacial periods. The Pleistocene terminology which they introduced is as follows:

Vashon Glaciation
   Erosional interval (non-glacial interval)
Salmon Springs glaciation
   Puyallup non-glacial interval
Stuck glaciation
   Alderton non-glacial interval
Orting glaciation (oldest)

Except for the Vashon, which seems to correlate to the Tazwell (maximum Wisconsin stage of the central United States), the ages of the three preceeding glaciations are uncertain. Possibly the Salmon Springs is of pre-Wisconsin age, and the Stuck is Early to Middle Pleistocene. The age of the Orting glaciation is even more problematical but because it is the oldest known Pleistocene deposit, it is considered, but not proven, Early Pleistocene. The climatic conditions of the interglacial periods were not markedly different than those of the present.

Modern day topographic features are almost entirely the result of effects following the Salmon Springs glaciation. Consequently pre-Unnamed interglacial deposits will not be considered.

Following the Salmon Springs glacial interval extensive stream aggradation occurred in the Puget Sound Lowland. Probably a great plain of terrestrial deposits, containing some coal and marine fauna near the base, was deposited at the front of the retreating Salmon Springs Ice. Later uplift, perhaps of 1000 feet, resulted in a long period of atmospheric erosion. Because of the unconsolidated nature of the material the area became deeply incised by trunk valleys and tributary streams, largely arranged in a north-south direction.

Later, while the streams were presumably in a state of submaturity, the Vashon ice moved south from the ice fields of British Columbia. Tremendous quantities of outwash were spread at the southern terminus of the ice, but to the north only a thin mantle of ground moraine and till overlies the interglacial topography. Locally, greater thicknesses of Vashon ground Moraine obscured the interglacial, streamformed topography. Continual ice retreat resulted in a complex and continually changing pattern of lakes in ice-blocked valleys. All these glacial lakes were ultimately drained when the Vashon ice melted back beyond the Strait of Juan de Fuca, permitting drainage to the ocean. At the time of this retreat the region stood at about its present elevation. Shortly thereafter, subsidence occurred as evidenced by marine invertebrate fossils found *in situ*, overlying Vashon till, up to a maximum of 280 feet above present sea level. Because strand lines, where present, above 100 feet are poorly developed this submergence must have been for a very brief period of time. Below 100 feel well developed strand lines are identified which are usually correlatable. Since the retreat of Vashon ice then, and a maximum submergence of -280 feet, there has been a gradual, though not steady rise in the Puget Sound area to the present time. Effects of this land rise in the map area will be discussed in a section covering geomorphology.

GLACIAL EFFECTS IN THE MAP AREA

Subdivision of glacial deposits north of the Puget Sound Lowland is difficult due to the great thickness of Vashon till which mantles and obscures older deposits. All Pleistocene deposits exposed within the map area are believed related to the Vashon glacial stage and the pre-Vashon erosional interval.

Studies in the Cascades, on Vancouver Island and the San Juan Islands indicate that at the maximum extent of the Vashon glaciation the ice would be between 2000 to 3000 feet thick in this area (Bretz, 1920). Consequently even the highest hills within the map area should have at one time been capped by close to one-half mile of southward moving ice.

It would be expected that glacial erosion and deposition within the area would be intense, and such seems to be the case. Except on Pleasant Ridge, compacted till is uncommon. Glacial outwash is present and on Fidalgo Island appears to be very thick. Glacial striations were seen only at one locality. Closed depressions, occurring within Skagit Bay are probably the result of glacial scour, and will be discussed under "Geomorphology".

Glacial outwash mantles the surface of Fidalgo Island, though deposits are very thin at the southeast end. Because of dense forest growth exposures are few except on the west shore of the Island. Here bluffs 25 to 50 feet in height are composed essentially of glacial outwash, probably the result of melt water activity at the front of the retreating Vashon ice. The outwash consists largely of sands and pebbly sands, generally cross-bedded and containing thin lignitic lenses.

Unconsolidated outwash deposits are also present locally on the crest of a small hill along the north shore of the Skagit River where a gravel pit is located. Here the outwash is thinly bedded sands and pebbly sand, containing pebbles up to 50 mm in maximum dimension. Pebbles and grains are subrounded to rounded and are composed of many rock types.

Pleasant Ridge, the only extensive area of glacial till, is an elongated hill, about two miles long, trending north-northwest--south-southeast. Its highest point of about 110 feet elevation, is at the northern end, and the surface slopes gently to sea level at the southern end. Exposures are poor and restricted to the northern and western edges where outcrops are exclusively glacial till. A water well drilled on the west side of the ridge penetrated 50 feet of compacted till underlain by 60 feet of undifferentiated Pleistocene sands and shales (Sceva, 1950). Evidently the rocks composing Pleasant Ridge were deposited during one of the "admiralty" glaciations. Pre-Vashon erosion and canyon cutting left a portion of this material as an interstream residual in the same way as pre-Tertiary rock units were left. During Vashon glaciation a thick layer of till was plastered on the interglacial hill, probably strongly modifying its shape.

Glacial striations were seen only on the south side of Kiket Island on a rounded expanse of polished graywacke, close to sea-level. The principal direction of slickensiding is N58°E though a second, more weakly developed grooving transects and cuts these. The bearing of the secondary slickensides is N18°E. Present also are rockgouged troughs up to 20 feet long, 2 feet across and 4 inches deep. They have a bearing of N52°E so accompany the primary striations. Small triangular chatter marks are locally present in the trough bottoms.

The early grooving is essentially parallel to the long axis of the island and suggests formation at an early stage of glaciation where the topography is yet exercising some local influence on direction of ice movement. The weaker striations are a later phase, formed when the ice was thicker and moving bodily southward over topographic obstructions.

GEOMORPHOLOGY

SKAGIT DELTA

The Skagit Delta is a conspicuous and major physiographic feature of northwestern Washington. It is a low, subtriangular area of approximately 120 square miles. The gradient, sloping westward, is 2 to 4 feet per mile, and is so low that drainage problems are common place. The delta itself fills a former valley cut into unconsolidated Pleistocene sediments that were deposited in a basin underlain by Tertiary or older unconsolidated rocks (Sceva, 1950). The westward flowing Skagit River itself is the principal constructive agent, building the delta westward into Skagit, Padilla and Samish Bays. The modern River drainage is into Skagit Bay where its westward margin is encroaching upon, surrounding and eventually tying to the mainland the islands of Skagit Bay. The Samish River drains hills to the north of the delta and is currently expanding the delta into Samish Bay.

Growth of the delta is rapid because of the high sediment load of the Skagit River and the protection of its margins from sea erosion offered by Fidalgo and Whidby Islands.

A feature of some interest is the incision of the Skagit River. Exact measurements of incision are not available but elevations taken from the U.S.Geological Survey topographic maps show the river surface varying from 0 feet below land level at the mouth of the Skagit River, to perhaps 15 feet north of Mt.

Vernon. This suggests recent uplift, perhaps on the order of 10 to 15 feet. Other evidence bearing on recent uplift will be discussed in the following sections.

SHORE LINES OF MAINLAND AND ISLANDS

The contact between the delta and the waters of Skagit Bay is gradational. A fluctuating, irregular zone of salt water swamps and mudflats separates the dry land from the waters of the bay. The shore line, in places, appears more abrupt due to man-made dikes which have reclaimed parts of the swamp border, and turned them into rich agricultural land.

Where the shore is the result of active erosion rather than aggradation, as it is on the delta margin, the topographic effects are considerably different. Most of the islands show incomplete and narrow rock-cut terraces with accompanying cliffs. Locally they may show notching at the base of the cliff. The widths of wave-cut terraces are variable and nowhere exactly known. It appears, however, to be broader on the south shore of islands, presumably due to increased wave activity, which in turn is caused by the prevailing southwesterly winds.

A similar situation prevails on the west shore of Fidalgo Island as shown within the map area. The only real difference between this shore and that of the islands lies in the character of materials being attacked by wave erosion. Whereas the islands are composed of resistant rocks such as serpentinite and indurated graywacke with a consequent slow rate of erosion, the west coast of Fidalgo Island is formed of relatively unconsolidated till and outwash. The unconsolidated deposits erode rapidly with the formation of a wide wave-cut and wave-built terrace. The bay bottom within several hundred feet of shore is composed of sand and silt with included pebbles, cobbles and boulders derived from glacial till.

Between Snee-oosh Beach and Tosi Point serpentinite crops out at sea level resulting in a reduced rate of erosion and a narrow wave-cut terrace.

On the whole, the water immediately to the north of islands appears to be the site of deposition. This is probably a "leeward effect" with water moving northward under wind and current influence, eddying in the lee of the islands, resulting in deposition of its coarse clastic load.

Physiographic evidence of any but the most recent uplift is non-existant in the islands. The isolated and poorly developed strand lines, found in the northern Puget Sound Lowlands and in the San Juan Islands, lying between 100 and 280 feet above sea level, are missing. Also absent are any evidence of the more highly developed shorelines lying between sea level and 100 feet. Perhaps these are absent only because of later erosion around the margins of islands and the removal of earlier, incipient wave-cut terraces.

Around several of the islands, especially Goat and Hope, and also on the rocky headland of southeast Fidalgo Island, there is a suggestion of an incipient notching at an elevation of about ten feet above mean sea level. This notching is very weak, being usually nothing more than a slightly rounded depression in the cliff face, but they are all consistent in having the same elevation. Obviously, wherever a rock-cut terrace is present at modern sea level, incipient notching probably is not present. Probably this is why notching is not conspicuous or common. While not proof in its own right, this notching offers corroborative evidence that uplift on the order of 10 feet occurred in the recent past.

COVES SEA CLIFFS AND CAVES

Except for the fact they are surrounded by alluvium rather than water, the hills of western Skagit Delta are similar to the islands of Skagit Bay. Pleasant Ridge is composed of till and unconsolidated sediments rather than indurated pre-Pleistocene rocks but topographically it seems to have reacted to erosion in the same way as its older counterparts.

Especially along the Skagit River, but also along McGinn Islands north side, the hills are characterized by rocky promentories enclosing a semi-circular lowland, open away from the hill. These enclosed areas are flat-floored, usually of the same elevation as the surrounding alluvial plain, and bounded by vertical to near vertical cliffs of 2 to 20 feet in height. They are, in general appearance, shaped like a diminutive cirque.

The floors of these coves are always swampy and covered with a thick growth of reeds, horsetails and other swamp vegetation. A very similar cove is now in the process of formation on the west side of Ika Island. It is characterized by a roughly semi-circular shape, by steep walls, a flat floor and a prolific swamp growth which is yet open to the bay and subject to the vagaries of tides. The hollow on Ika Island is quite obviously the result of marine erosion, in this case parallel to the strike of the rocks and along the axis of a syncline. A similar origin is postulated for the hollows now existing in hills of the delta. In other words the genetic sequence was: marine erosion, silting of the cove with alluvium, and later, gradual uplift isolating the cove from the sea.

A feature characteristic of practically all the hills is steep cliffs, especially on the western and southwestern sides. This is the same situation now displayed on the rocky cliffs of the islands. An origin of marine erosion is ascribed to both.

Another feature of interest, though not conspicuous, are sea caves at the base of many cliffs. These are usually shallow and elongated in a horizontal direction. If they could be seen while looking at a hill from a distance they might be described as lens-like, with a long axis parallel to the ground. Caves are restricted to the south side of hills, composed of Tertiary Sedimentary rocks, exposed along the North Fork of the Skagit River. Their elevation is always the same, perhaps 10 to 12 feet above sea level. Their form and shape seems to be largely determined by bedding which in these areas dip toward the sea cliffs, and permitted excavation of entire bedded blocks. A strike parallel to the cliff materially aided the agents of erosion, and indeed, caves are entirely absent on cliff faces where the formation strike is at a large angle to the cliff.

The largest cave occurs in a conglomerate-sandstone sequence on the north side of the North Fork of the Skagit River in the location marked on map "cave". This cave is about 35 feet wide by 5 feet high at the entrance and extends back perhaps 25 feet.

A feature of interest in this cave is the roof coating of amorphous white calcite, sometimes almost mammilary in form. No stalactites are present. The cliff above the cave is about 30 feet high while on top a heavy forest vegetation grows to the cliff edge. The writer ascribes the following origin to this calcite coating: rain water, percolating through the forest soil tends to become slightly acidic. As this acidic water continues downward it dissolves calcium carbonate from the interstices of the conglomerate. When the water percolates out through the cave roof it evaporates with resultant precipitation of calcium carbonate. Evidently stalactites are not formed because the water is not following specific channels, but is percolating almost indiscriminately through the conglomerate and seeping out over the entire cave roof.

Blocks excavated during cave formation are totally absent except for those that have recently fallen. The only possible genetic explanation is that these are sea caves, carved by the waves of Skagit Bay prior to a recent, slight local uplift.

"DEEPS" IN SKAGIT BAY

The term "deeps" is here used to characterize closed depressions on the floor of Skagit Bay. Within the map area two such deeps occur: one southeast of Hope Island and the second west of Seal Rocks.

The first is roughly circular, has a closure in excess of 60 feet and covers an area, below the 60 foot contour, of 130 acres. The second is of linear shape and parallel to the long axis of Skagit Bay. It also has a closure of about 60 feet and covers an area of 270 acres.

Bretz (1913) discusses the drainage surface developed on the uplifted "Admiralty" deposits during the interglacial prior to the readvance of Vashon ice. He concludes that most of the main Puget Sound channels are glacially modified river valleys formed on this Admiralty Plain. Skagit Bay, from Hope Island south, supports this concept. Moving south down Skagit Bay into Saratoga Passage and through Possession Sound to Admiralty Straits the waters become progressively deeper and the bathymetric contours display a form very reminiscent of terrestrial river canyons.

North of Hope Island the bathymetric picture is confused though the overall pattern of a channel is still present. South of Hope Island drainage was obviously south while to the north the situation is not so clear. Did drainage go west from here, through Deception Pass or southward into the main channel? At the present time Deception Pass is entirely too shallow to have served as a channel. However, perhaps Vashon drift or till has partially blocked the channel, or perhaps slide and talus material from the high bordering cliffs has reduced its depth.

However that may be, it appears drainage from the area southeast of Hope Island was north, between Hope and Fidalgo Islands, thence either west through Deception Pass, or around Hope Island and south down the main channel. This latter course admittedly results in a peculiar stream pattern for drainage which is thought to be consequent.

A number of cases of southward drainage swinging west and intersecting northward flowing rivers are recorded on the Admiralty sedimentary plain. This seems to be the case in the Skagit Bay - Saratoga Passage and at the present time defies explanation.

The "deeps" of Skagit Bay lie in these old channels but are not directly related to them. An explanation can be made only by interpretation of bathymetric contours and the known history of the area. Consequently the writer suggests two possible origins:

(1) a damming of the channel by moranic or till material or

(2) glacial goug~~k~~ing by Vashon ice.

Adequate evidence is not available to select between these two alternative explanations.

SUMMARY OF POST VASHON HISTORY AS INDICATED BY PHYSIOGRAPHY

As pointed out earlier, evidence shows that at the time of Vashon glaciation sea level lay slightly higher than it does now. In the immediate area Bretz (1913) says the following:

> "In the bluff overlooking the city of Mt. Vernon, in the same latitude as Cattle Point (San Juan Island), Vashon outwash gravel shows stream bedding to the base of the exposure, altitude 40 feet. Though delta bedding is present, it occurs only in individual horizontal beds in which the gravel is foreset. This section thus indicates that the sea was below 40 feet above tide when the Vashon Ice retreated across the region".

In work on the Qualicum Delta, underlying Northern Bellingham, Bretz goes on to show that sea level lay between 30 and 75 feet above present mean tide during the retreat of Vashon ice. Work in the San Juan Islands and farther south indicates sea level was some 40 feet higher during Vashon retreat than now.

Within the map area the only indicator of sea level is the occurrence of marine invertebrates in glacial outwash on the east end of Hope Island. The lower limit of fossil occurrence is now about 12 feet above sea level indicating only that the water was above this level.

Evidence from other areas as mentioned in the section on glaciology shows that the region sank after retreat of the Vashon ice, and has subsequently risen to an altitude somewhat greater than that possessed during the Vashon de-glaciation. No evidence of this was observed within the map area.

One could point out here that this crustal movement, downward after glaciation, prior to a rise upward, is not in the best harmony with the theory of eustatic rebound. Latest ideas in the Great Lakes area indicate an oscillating up and down movement (Danner, personal communication).

The latest diastrophic movement, a slight uplift of perhaps 20 feet as indicated by uplifted rock-cut terraces and marine molluscan remains, is seen farther south in the Seattle-Bremerton areas. Confirming evidence of recent uplift, though of lesser intensity, within the map area has been cited. These include incision of the Skagit River into the Delta surface; uplifted sea cliffs and accompanying caves; isolated, swampy, marine eroded coves in hills of the delta and incipient notching of certain island cliffs.

BIBLIOGRAPHY

American Geological Institute, 1960, Glossary of geology and related sciences with supplement, 2nd ed.

Andrews, H.N., 1961, Studies in paleobotany: New York, John Wiley and Sons, Inc. 488 p.

Arnold, C.A., 1947, An introduction to paleobotany: New York, McGraw-Hill Book Co., 433 p.

Bailey, E.B., 1930, New Light on sedimentation and tectonics: Geol. Mag., v. 67, p. 77-92.

------- 1936, Sedimentation in relation to tectonics: Geol. Soc. America Bull., v.47, p. 1716-1718.

Bain, G.W., 1936, Serpentinization of Vermont ultrabasics: Geol. Soc. America Bull., v. 47, p. 1961-1980.

Bayley, W.S., 1898, The educational series of rock specimens collected and distributed by the United States Geological Survey: U.S. Geol. Survey Bull. 150, 84 p.

Bowen, N.L. and Tuttle, O.F., 1949, The system MgO-SiO_2-H_2O: Geol. Soc. America Bull., v. 60, p. 439-460.

Bretz, J.H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bull. 8, 224 p.

------- 1920, The Juan de Fuca lobe of the Cordilleran ice sheet: Jour. Geology, v. 28, p. 333-339

Brown, R., 1870, Glacial scratches near Bellingham Bay, Washington: Am. Jour. Sci., v. 50, p. 323

Caldwell, W.E. and Waterman, G., 1950, A Northwest strontium mineral deposit: Sci. Monthly, v. 70, p. 267-270

Calkin, P.E., 1959, The geology of Lummi and Eliza islands, Whatcom County, Washington: Unpublished Masters thesis, University of British Columbia

Cambell, C.D., 1953, Introduction to Washington geology and resources: Washington Division of Mines and Geology, Infor. Circular 22

Carozzi, A.V., 1960, Microscopic sedimentary petrography: New York, John Wiley & Sons, 485 p.

Clapp, C.H., 1912, Southern Vancouver Island: Canada Geol. Survey Mem. 13

Clark, B.L. and Arnold, R., 1918, Marine Oligocene of the West Coast of North America: Geol. Soc. America Bull., v. 29, p. 297-308

Crandell, D.R., Mullineaux, D.R. and Waldron, H.H. 1958, Pleistocene sequence in southeastern part of the Puget Sound lowland, Washington: Am. Jour. Sci., v. 256, p. 384-397

Crickmay, C.H., 1930, The structural connection between the Coast Range of British Columbia and the Cascade Range of Washington: Geol. Mag., v. 67, p. 481-491

Culver, H.E., 1936, The geology of Washington, pt. 1, General features of Washington geology: Washington Division of Geology Bull. 32

Daly, R.A., 1912, Geology of the North American Cordillera at the 49th parallel: Canada Geol. Survey Mem. 38

Danner, W.R., 1955, Geology of Olympic National Park: Seattle, University of Washington Press, 68 p.

------- 1960, An introduction to the stratigraphy of southwestern British Columbia and northwestern Washington: Guidebook for geological field trips in southwestern British Columbia, pub. by Geol. Discussion Club, Vancouver, B.C. for Geol. Soc. America meetings in 1960, p. 1-6.

Daugherty, R.D., 1959, Early man in Washington: Washington Division of Mines and Geology, Infor. Circular 32

Dorf, E., 1955, Plants and the geologic time scale: Geol. Soc. America Special paper 62, Crust of the earth (symposium), p. 575-592

Durham, J.W., 1950, Cenozoic marine climates of the pacific coast: Geol. Soc. America Bull., v. 61, p. 1243-1264

Erdtman, G., 1943, An introduction to pollen analysis: Waltham, Mass, Chronica Botanica Co., 239 p.

Foster, R.J., 1960, Tertiary geology of a portion of the central Cascade Mountains, Washington: Geol. Soc. America Bull., v. 71, p. 99-126

Glover, S.L., 1935, Oil and gas possibilities of western Whatcom County, Washington: Washington Division of Geology, Rept. of Invest. 2

------- 1936b, Preliminary report on petroleum and natural gas in Washington: Washington Division of Geology, Rept. of Invest. 4

------- 1947, Oil and gas exploration in Washington: Washington Division of Mines and Geology, Infor. Circular 15

Hansen, H.P., 1947, Postglacial forest succession, climate, and chronology, in the Pacific Northwest: Am. Philos. Soc. Trans., new series, v. 37, pt. 1, 130 p.

Hansen, H.B., and Mackin, J.H., 1949, A pre-Wisconsin forest succession in the Puget Sound Lowland, Washington: Am. Jour. Sci., v. 247, p. 833-855

Harness, C.L., 1942, Strontium Minerals: U.S. Dept. of the Interior, Bureau of Mines information circular 7200

------- 1949, Strontium minerals: Industrial minerals and rocks, 2nd ed., New York, Am. Inst. Min. Met. Eng., p. 980-988.

Hess, H.H., 1933, The Problem of serpentinization and the origin of certain chrysotile asbestos, talc, and soapstone deposits: Econ. Geol., v. 28, p. 634-657

--------1938, A primary peridotite magma: Am. Jour. Sci., 5th series, v. 35, p. 321-344

--------1955, Serpentines, progeny, and epeirogeny: Geol. Soc. America Special Paper 62, Crust of the earth (symposium), p. 391-408

Hill, J.M., 1915, U.S. Geol. Survey, Mineral Resources, pt. 2, p. 187

------- 1916, U.S. Geol. Survey, Mineral Resources, pt. 2,p.194

Jenkins, O.P., 1923, Geological investigation of the coal fields of western Whatcom County, Washington: Washington Division of Geology Bull. 28

------- 1924, Geological investigations of the coal fields of Skagit County, Washington: Washington Division of Geology Bull. 29

Krutzsch, Von. W., 1957, Sporen- und pollengruppen aus der Oberkreide und dem Tertiar Mitteleuropas und ihre stratigraphische verteilung: Zeitschrift fur Angewandte Geologie, v.3, p. 490-588

Kuyl, O.S., Muller, J. and Waterbolk, H.Th., 1955, The application of palynology to oil geology with reference to western Venzuela: Geologie En Mijnbouw, new series, v. 17, p. 49-76

Ladoo, R.B., and Myers, W.M., 1951, Nonmetallic minerals: New York, McGraw-Hill Book Co., p. 515-521

Landes, H., 1911, The road materials of Washington: Washington Geological Survey Bull.2

Landes, K.K., 1929, The strontium occurrence near La Conner, Washington: Am. Mineralogist, v. 14, p. 408-413

Leech, G.B., 1953, Geology and mineral deposits of the Shulaps Range, southwestern British Columbia: B.C. Dept. Mines Bull. 32

Livingston, V.E.Jr., 1958, Oil and gas exploration in Washington, 1900-1957: Washington Division of Mines and Geology, Infor. Circular 29

McLellan, R.D., 1927, The geology of the San Juan Islands: Univ. Wash. Pubs. geology, v. 2, 181 p.

Misch, P., 1952, Geology of the Northern Cascades of Washington: The Mountaineer, v. 45, p. 4-22

Park, C.F., 1944, The spilite and manganese problem of the Olympic Peninsula, Washington: Am. Jour. Sci., v. 244, p. 305-323

Pettijohn, F.J., 1943, Archean sedimentation: Geol. Soc. America Bull., v. 54, p. 925-972

------- 1949, Sedimentary rocks: New York, Harpers and Brothers, 526 p.

------- 1957, Sedimentary rocks, 2nd ed.: New York, Harpers and Brothers 718 p.

Potonie, Von R., 1951, Pollen- und sporeformen als leitfossilien des Tertiars: Sonderdruck aus "Microskopie", v. 6, p. 272-283

Ross, N.E., 1949, On a Cretaceous pollen and spore bearing clay of Scania-a preliminary report: Geol. Inst. Upsala Bull., v. 34, p. 3-44

Rouse, G.E., 1957, The application of a new nomenclatural approach to Upper Cretaceous plant microfossils from western Canada: Canadian Jour. Botany, v. 35, p. 349-375

------- 1962, Plant microfossils from the Burrard Formation of western British Columbia: in press

Sanderson, L., 1940, Strontium: Canadian Mining Jour., v. 61 p. 726-728

Sceva, J.E., 1950, Preliminary report on the ground water resources of southwest Skagit County, Washington: U.S. Geol. Survey Open File Ground Water Report 1

Shedd, S., 1902, Building and ornamental stones of Washington: Washington Geological Survey Ann. Rept. v. 2, p. 62-65

Stewart, J.E. and Bodhaine, G.L., 1961, Floods in the Skagit River basin, Washington: U.S. Geological Survey Water Supply Paper 1527, 66 p.

Tegland, N.M., 1933, The fauna of the type Blakely Upper Oligocene of Washington: Univ. Calif, Pub. Geol. Sci., v. 23, p. 81-174

Turner, F.J. and Verhoogen, J., 1960, Igneous and Metamorphic petrology 2nd ed.: New York, McGraw-Hill Book Co., 694 p.

Twenhofel, W.H., 1926, Treatise on sedimentation: Baltimore, Williams & Wilkins Co., 661 p.

------- 1939, Principles of sedimentation: New York, McGraw-Hill Book Co., 610 p.

------- 1947, The environmental significance of conglomerates: Jour. Sed. Pet., v. 17, p. 119-128

------- 1950, Principles of sedimentation, 2nd ed.: New York, McGraw-Hill Book Co., 693 p.

U.S. Bureau of Mines, 1959, Minerals yearbook: Washington, D.C. U.S. Govt. Printing Office

U.S. Geological Survey, 1959, Surface water supply of the United States, pt. 12: Water supply paper 1636

Waters, A.C., 1955, Volcanic rocks and the tectonic cycle: Geol. Soc. America Special Paper 62, Crust of the earth (symposium), p. 707-722

Weaver, C.E., 1916, The Tertiary formations of western Washington: Washington Geological Survey Bull. 13

------- 1916, Tertiary faunal horizons of western Washington: Univ. Wash. Pubs. Geology, v. 1, 67 p.

------- 1937, Tertiary stratigraphy of western Washington and northwestern Oregon: Univ. Wash. Pubs. Geology, v.4, 266 p.

------- 1942, Paleontology of the marine Tertiary formations of Oregon and Washington: Univ. Wash. Pubs. Geology v. 5, 803 p.

------- 1945, Geology of Oregon and Washington and its relation to occurrences of oil and gas: Am. Assoc. Petroleum Geol., v. 29, p. 1377-1415

White, C.A., 1888, On the Puget Group of Washington: Am. Jour. Sci., v. 136, p. 443-450

Whitebrook, R.B., 1959, Coastal exploration of Washington: Palo Alto, Calif., Pacific Books, 161 p.

Williams, H., Turner, F.J., and Gilbert, C.M., 1955, Petrography, an introduction to the study of rocks in thin sections: San Francisco, W.H. Freeman and Co., 406 p.

Willis, B., 1898, Drift phenomena of Puget Sound: Geol. Soc. America Bull., v. 9, p. 111-162

Willis, B. and Smith, G.O., 1899, Geologic atlas of the United States: Tacoma folio, n. 54

Willis, C., 1953, The Chiwaukum graben, a major structure of Central Washington: Am. Jour. Sci., v. 251, p. 789-797

Wodehouse, R.P., 1935, Pollen grains, their structure, identification and significance in science and medicine: New York, McGraw-Hill Book Co., 574 p.

Writers program, 1941, Washington - a guide to the evergreen state: Portland, Ore.: Binfords and Mort Publishers