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HENRY LANDES, State Geologist

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Glaciation of the Puget Sound Region

By J. HARLEN BRETZ

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LETTER OF TRANSMITTAL.

Governor Ernest Lister, Chairman, and Members of the Board of Geological Survey:

GENTLEMEN: I have the honor to submit herewith a report entitled "Glaciation of the Puget Sound Region," by J. Harlen Bretz, with the recommendation that it be printed as Bulletin No. 8 of the Survey reports.

The surface deposits about Puget Sound, as shown in the sea-cliffs, excavations for streets, tunnels and elsewhere have always attracted much attention. They are of economic importance, not alone from an agricultural standpoint, but because of the valuable beds of clay, sand and gravel which they contain. Local chapters in the story of the glaciation of Puget Sound have been contributed by different writers at different times, but this bulletin by Mr. Bretz is the first detailed account covering all phases of an interesting portion of the geological history of the region. This report by Mr. Bretz has involved several years of field-work and study, the expenses of which were sustained by him personally, except that a small allowance toward the cost of the field-work was granted him by the Survey during the summer of 1911.

Very respectfully,

HENRY LANDES,
State Geologist.

University Station, Seattle, May 1, 1913.

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INTRODUCTION.

GENERAL PHYSIOGRAPHY OF THE PUGET SOUND REGION.

The basin or depression of Puget Sound in western Washington lies between the Olympic Mountains on the west and the Cascade Mountains on the east. In its northern portion, it opens to the Pacific Ocean through the great valley occupied by the Strait of Juan de Fuca between the Olympic Mountains and Vancouver Island. The basin is enclosed on the south by a low divide between the Sound and the Chehalis River, the latter flowing to the Pacific south of the Olympics.

The name "Puget Sound" was originally given by Vancouver to that portion of these inland arms of the sea which lies south of the "Narrows" near Tacoma. Vancouver distinguished two other main portions of these inlets; Hoods Canal and Admiralty Inlet. His usage was respected by Wilkes of the United States Exploring Expedition a half century later, but today the term "Puget Sound" embraces all three portions and is frequently used to include all marine waters connected with the Strait of Juan de Fuca south of the International boundary line. In this broad sense it is used in the title of this paper.

The depression of Puget Sound is genetically synclinal, belonging to the most western synclinorium of North America. The Gulf of Georgia north of it, and the Willamette valley of Oregon, the Great Valley of California and the Gulf of California south of it are likewise portions of this structural trough. There are interruptions in it, and different parts have doubtless had different histories. The Puget Sound depression itself is partially interrupted by a mountainous spur of the Cascades extending diagonally across toward the northwest, just north of the Strait of Juan de Fuca. The mountain range of Vancouver Island is perhaps a continuation of the spur.

The area studied extends from the International boundary on the north to the divide between the Chehalis and Columbia rivers on the south, a distance of 170 miles, and from the base of the Cascades to that of the Olympics, in an east and west direction, this distance averaging 50 miles. South of the Olympics, the Chehalis Valley has been studied from the low divide between it and the Sound basin to the Pacific Coast. Though beyond the limits of glaciation, outwash from the Puget Sound Glacier was carried through several gaps in the rock hills to the Chehalis River, and thence down the valley of this river to the head of Grays Harbor on the Pacific.

The forests on the western coast of North America, from Puget Sound to Alaska, have been repeatedly described as almost tropical in density. Newberry, Russell, Willis and others who have worked on the geology of Puget Sound, note the remarkable luxuriance of the forests and their almost impenetrable character, except along routes of travel. The presence of this primeval forest over a considerable portion of the country embraced in this study, has offered the greatest difficulty encountered in its prosecution. It has been possible to examine many large areas only along railroad grades, roadways and trails, and in such cases no detailed study was attempted. Burned-over or logged-off lands of Puget Sound, unless taken up for agriculture, are usually quickly reforested, and the second growth is almost as great an obstruction to the student of topography as is the original forest.

Five United States Geological Survey maps have been made thus far in the area embraced in this paper, covering about three tenths of the whole. Absence of such maps for the larger part of the region has been an obstacle to satisfactory interpretation.

Altitudes have been determined chiefly by aneroid, using railroad profiles largely for check stations. A few United States Geological Survey bench marks have been available in some parts of the region. Much of the country along the inlets has been examined with no better check stations than the coast line with its tidal range, varying with season, locality, etc.

PREVIOUS WORK ON THE SUBJECT.

1845 Charles Wilkes. Captain Charles Wilkes of the "United States Exploring Expedition," now known by his name, spent several months in surveying Puget Sound. His narrative, Vol. 4, pp. 313 and 415, refers to the puzzling mounds on the outwash plains south of the Sound.

1873 George Gibbs. This author published an account of a geological reconnaissance of the northwestern boundary of the United States, in the Journal of the American Geographical Society for 1873. He described and figured the mounds of the outwash prairies, gave sections of the drift of Puget Sound, and noted elevated marine terraces on San Juan Island.

1873 and 1874 Joseph LeConte. In a paper entitled "On the Great Lava Flood of the West, and on the Structure and Age of the Cascade Mountains," published in the Proceedings of the California Academy of Sciences in 1873, and in more complete form in the American Journal of Science in 1874, Joseph LeConte discussed the origin of the Puget Sound fiords, and the genesis of the mounds occurring on the plains south of the Sound. He recognized the occurrence of a Glacial, a Champlain and a Terrace epoch in the region.

1884 John Newberry. A paper presented by John Newberry before the New York Academy of Science, entitled "On the Origin of the Fiords of Puget Sound" is printed by title in the "Transactions" of that body for 1884. Kimball, noted below, credits Newberry with the idea that the fiords were glacially eroded by northward flowing ice, and with frankly confessing the mounds to be inexplicable.

1893 G. O. Rogers. The American Geologist, Vol. II, No. 6, contains an article on the ever popular subject of the remarkable mounds of the outwash region of Puget Sound. The paper briefly describes these forms, discusses various hypotheses for their origin, and adds a new one to the list.

1897 James P. Kimball. In the American Geologist, Vol. 19, Nos. 4 and 5, this observer describes the "Physiographic Geology of the Puget Sound Basin." He considers a Pliocene baselevelling to have preceded the Pleistocene, and further excavation to have been accomplished by later glacial erosion.

But one glaciation is alluded to. Post glacial stream erosion produced the valleys now occupied by the Sound. Post glacial crustal movements thus have been (1) an elevation, (2) a subsidence, and (3) from the presence of raised beaches, a slight re-elevation.

1897 Bailey Willis. In a paper published in the Bulletin of the Geological Society of America, Vol. 9, entitled "Drift Phenomena of Puget Sound," Willis presents his generalizations of Puget Sound's glacial history, from work on the Tacoma quadrangle. Following Russell, whose notes on this region were never published, he distinguishes two glaciations and makes inferences as to the character of the interglacial epoch. The contact of Puget Sound ice with Cascade ice is partially drawn, various features of the last glaciation are described, and the origin of the fiord-like valleys and their separating highlands is considered.

1899 Bailey Willis and George Otis Smith. Tacoma Folio, No. 54. U. S. Geological Survey. The Pleistocene history of the Tacoma quadrangle is described in detail.

1904 Warren Upham. American Geologist, Vol. 34, No. 4. The article here noted, on "Glacial and Modified Drift near Seattle, Tacoma and Olympia" was based on too little field work, and much of it is in error.

1905 Albert Reagan. Kansas Academy of Science. A description is given of some Pleistocene and recent features of the region between Bellingham and the International boundary, and interpretations are attempted.

1908 Warren Upham. A brief paper comparing the Puget Sound coast line with that of the Saguenay River. Abstract published in Science.

1910 J. H. Bretz. A preliminary paper on the "Glacial Lakes of Puget Sound." Journal of Geology, Vol. 18, No. 5.

1911 J. H. Bretz. "Terminal Moraine of the Puget Sound Glacier." Journal of Geology, Vol. 19, No. 2.

CHAPTER I.

OUTLINE OF THE PLEISTOCENE HISTORY OF THE REGION.

SYNOPSIS.

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CHARACTER OF THE PLIOCENE.

Most of the formations outcropping in the Puget Sound basin are of Tertiary age, and all of them south of the Strait belong to this division of geological history. Eocene and Miocene sedimentary beds record a shallow sea, with frequently changing depths and shore lines. Beds of terrestrial sediments are interstratified with the marine, many of the Tertiary coal seams of Puget Sound preserving forest floors with tree stumps *in situ*. The Tertiary Sound region was one of constantly shifting land and water areas, and of frequent alternations of fresh and salt water. Contemporary lava flows, both from fissures in the basin and from extrusions which originated in the surrounding areas, are intercalated among the sedimentary beds.

For this region, the Pliocene period was primarily a time of diastrophic movement and erosion. The Eocene and Miocene beds were domed and folded, the whole area was lifted higher than at present, and subaerial erosion developed great relief in the weak Tertiary rocks already deposited. Further lava flows occurred, of the same character as the earlier ones, but apparently no volcanic cones were produced.

PLIOCENE ELEVATIONS YET EXISTING IN THE BASIN.

In the succeeding Pleistocene, great sedimentary deposits of glacial origin buried the Pliocene topography. A drift plain was aggraded which reached from one side of the basin to the other. Above this rose, island-like, a few regions of originally greater uplift. The chief Pliocene elements of the present topography are (1) the diagonal mountain spur from the Cascades across to Vancouver Island, including the San Juan Island group, (2) the Blue Hills between Hoods Canal and Admiralty Inlet, (3) Newcastle Hill and Squak Mountain east of Seattle, and (4) the Black Hills, Bald Hills and other marginal elevated areas on the south.

EPOCHS OF THE PLEISTOCENE KNOWN IN WESTERN WASHINGTON.

Russell first noted the existence of two till sheets and of inter-till sediments in Puget Sound. Willis later named the three recorded epochs, Admiralty (glacial), Puyallup (interglacial) and Vashon (glacial).

ADMIRALTY EPOCH (GLACIAL).

Good exposures of the till of the Admiralty glaciation are rare, there being hardly a score in the many miles of sea-cliffs on Puget Sound. The epoch and its till are named from Admiralty Inlet, along whose shores the till was examined by both Russell and Willis. The base of the till, so far as known by the writer, is exposed in but two or three places in the entire region, and nowhere along Admiralty Inlet. Willis notes the absence of evidence of earlier glaciations, within the limits of his study.

The Admiralty till, in positively identified exposures, is nowhere deeply weathered, though in some places stained by percolating water. Its pebbles are for the most part firm but decay has softened them in some cases. These variations in the amount of weathering appear to have been determined by the thickness of cover over the till of any locality during the interglacial epoch. No estimate can be given of the thickness of the till sheet, and the topography of its surface is unknown. The character of the surface over which the Admiralty ice advanced is also unknown.

A few exposures of deeply weathered glacial drift have been found, in which the decay of all but highly siliceous material far surpasses the alteration of Admiralty till, where the latter is clearly identified. Suspicion has arisen from discovery of these exposures that a drift older than the Admiralty exists in Puget Sound. Admiralty till, however, has not been identified in section above the supposed older drift.

PUYALLUP EPOCH (INTERGLACIAL).

Extensive stream aggradation occurred in the Sound basin after the deposition of Admiralty till, and before the advent of the following glaciation. It is not an exaggeration, probably, to say that nine-tenths of the Pleistocene deposits of Puget Sound exposed above sea level belong to this series. The material is assorted glacial drift and probably was derived largely from the waning Admiralty ice. Its beds, as exposed in the present sea-cliffs, rarely retain the same character for more than a mile; lens structure, abrupt transition, or gradual change in character being the rule. In many places, forest floors and swamp beds are preserved in the series as lignitic seams, and a few clay beds at the base contain marine molluscan and crustacean remains. Stream bedding is common in the gravels, delta bedding is rare. In the southern part of the basin, the structure of the deposit indicates southward flow of the depositing water. A few intercalated till lenses prove that glacier ice was still in the region. No indications are known of extended subaerial exposure of the Admiralty till before deposition of these beds. In brief, a great plain of terrestrial deposits, containing a few marine beds in the lower portion, is conceived to have been aggraded in front of the waning Admiralty glacier, as it withdrew to the north. This conception is essentially similar to that advanced by Tarr and by Blackwelder for the genesis of the Yakutat foreland of Alaska.*

Following this extensive aggradation, uplift of the region, relative to sea level, occurred, and a long period of atmospheric exposure and stream erosion ensued. The gravels and sands became stained and locally cemented with iron oxide, and near the surface were somewhat decomposed. The impervious clays, however, were unaffected by the percolating waters which stained the gravels many feet below the weathered zone. A soil must have been formed during this time of exposure, but it has not yet been found preserved beneath the later till.

Consequent drainage developed on the surface of the plain. The southern portion appears to have drained southward to the Chehalis River and Grays Harbor, while the northern portion sent its waters to the sea by way of the Juan de Fuca Valley. A part of this interglacial drainage system can be reconstructed today with considerable probability.

Stream erosion advanced in the unconsolidated drift to submaturity. The area became deeply incised by broad trunk valleys, and minor tributary valleys were well distributed on the divide slopes. A general north to south orientation of main valleys prevailed throughout, largely determined, presumably, by the original slope of the Admiralty drift plain.

Willis names this interglacial epoch from stratified sands, typical of the sedimentary series, which, with Vashon till unconformably overlying, are exposed near the town of Puyallup. The sands truly are inter-till in position, but only their staining and the erosion of the valley in whose sides they are exposed, are considered as interglacial. According to this interpretation, no interglacial sediments are known in Puget Sound, and the Puyallup interglacial epoch is to be considered chiefly as one of weathering and erosion, so far as this region is con-

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* Tarr, R. S. "The Yakutat Bay Region." Professional Paper No. 64, U. S. Geological Survey.

Blackwelder, Eliot, "The Yakutat Coastal Plain of Alaska," Am. Jour. Sci. Vol. 27, 1909.

cerned. Presentation of the evidence for this and other conclusions briefly stated in this chapter will be given later.

VASHON EPOCH (GLACIAL).

The latest glacier of Puget Sound advanced from the north, as did its predecessor, the Admiralty, the ice being supplied largely from the snow fields of British Columbia. Only a minor part of the ice of the Puget Sound Glacier came from the margining mountains, and that portion south of the Strait of Juan de Fuca cannot be looked upon as a piedmont glacier fed by valley glaciers from the Olympics and Cascades. Evidence will be presented to show that the Puget Sound ice of the Vashon glaciation was actually thrust up into some of these mountain valleys, in the face of their descending glaciers.

At the maximum, the ice of this epoch extended at least as far as that of the Admiralty epoch. Admiralty drift is found beneath one portion of the Vashon terminal moraine, but nowhere beyond it. Elsewhere, the fresh Vashon till of the terminal moraine overlies rock apparently never glaciated previously.

A terminal moraine swings across the southern portion of the depression from the Cascades to the Olympics. As a topographic form, it is insignificant in most places, becoming here and there a mere moraine terrace on the north side of rock hills against which the ice impinged at its maximum, and in other places, especially in valleys, being largely buried by outwash gravel. In its greatest development, its apparent height is due in part to buried rock hills whose strata outcrop on the southern slope. Its course records the existence of two lobes of the glacier front, the re-entrant being caused by the domed uplift known as the Black Hills.

Compared with this minor moraine development, the extent of the outwash from the Vashon Glacier is astonishing. Relatively great areas are covered deeply with coarse, clean gravel, producing broad, sterile plains of low gradient. Two wide pathways existed across the rock hills south of the basin of the Sound, at Gate and about Matlock. Through these chiefly, the gravel flood entered the Chehalis Valley, and a part of it was carried to the head of Grays Harbor. The Black Hills constituted the elevated area standing between these two pathways, and minor gravel trains were also carried across them to the Chehalis. With gravel entering the latter valley at several points along its course, earliest by the Gate Pathway, and later by the more western routes, an imperfectly imbricated series of gravel deposits was constructed which, in its present fragmentary condition through subsequent stream erosion, is difficult satisfactorily to resolve into its component elements.

Recessional moraines and outwash plains for a few miles back of the terminal moraine record a varied history of marginal drainage in the early stages of retreat. Gravel plains adjusted to possible outlets at one position of the ice front were trenched and in some cases largely removed by the opening of new courses as retreat progressed, or were abandoned and left as high-lying gravel plateaus with morainic deposits, and ice-contact slopes on their northern descents.

On many of these outwash plains, especially those closely associated with the terminal moraine, there is a remarkable development of thousands of symmetrical gravel mounds of fairly uniform size, closely spaced, but of asymmetrical distribution, and of heterogeneous structure. Many hypotheses have been advanced to account for them, but no one explanation is satisfactory. The writer has failed to find in physiographic literature any description of natural mounds similar to these, and believes them to be unique, so far as present knowledge goes. The mounds are resolvable into two types. The origin of one type will be explained, but that of the other remains an unsolved problem.

The extensive moraine and outwash deposits laid down during early Vashon retreat appear to have completely obliterated the interglacially eroded valleys lying in the southern part of the Puget Sound basin. They produced an upland plain notably different from the deeply trenched depressions containing Puget

Sound. Farther north, however, the supply of debris was much less per unit area, and in most places a thin mantle of ground moraine alone overlies the interglacial topography developed in the Admiralty drift plain. The Vashon till sheet is thus largely a widespread veneer of fresh material on the slopes and summits of the interglacial hills, and in many places on the floors of the interglacial valleys. Locally, stoss and lee deposits of Vashon till attain a thickness sufficient to obscure the interglacial, stream-formed topography. Locally, also, erosion by the Vashon ice notably deepened these trunk valleys. This deepening, however, is submerged beneath the waters of Puget Sound, and is revealed only by the soundings of the Coast and Geodetic Survey.

After the frontal margin of the Vashon Glacier had withdrawn some distance from the southern region of heavy aggradation, it appears to have been melted back more rapidly than during the first few miles of retreat. Except at the south, the valleys exposed by glacial retreat were little modified by outwash or recessional moraine deposits. The aggraded southern region, however, prevented free drainage from these valleys into the Chehalis. With a mountain range flanking the depression on both the east and west, and with the glacier completely filling it north of the bared portion, these valleys filled with water until overflow occurred across the outwash plain and through the Gate Pathway to the Chehalis Valley. Thus was begun the complicated history of the ice-dammed lakes of Puget Sound.

Further retreat exposed more valleys developed by interglacial streams and modified by the Vashon ice. Such of these valleys as belonged to the river system which discharged through the Gate Pathway during the Puyallup interglacial epoch became a part of the glacial lake behind the divide of Vashon drift, then but newly formed between the Sound and the Chehalis Valley. Where, however, troughs belonging to the two other interglacial river systems of Puget Sound south of the Strait were freed from ice, they filled to the level of the lowest places in their borders, across which they discharged to the master lake of the Sound basin in the Gate Pathway valley system. Later, the retreat of the ice from successively lower passes determined successive levels in these independent lakes. In most cases, open connection with the master lake was eventually made, and all the lakes became one. Though the Vashon Glacier left no definite recessional moraines north of its aggraded plain until after the Strait of Juan de Fuca was opened and the glacial lakes were destroyed, evidence of an oscillatory behavior of the ice edge has been found in the records of the lakes. These records are limited chiefly to deltas and outlet channels, and the general rule is that lake levels become progressively lower throughout the period of their existence. Where, however, a delta shows alternating foreset and topset beds in the same section, we have indisputable evidence of an abrupt rise in static water level. Other data show this rise to be due to re-advance of the glacier, and closure of the lake's outlet.

The large glacial lake of Puget Sound, by increase in length northward as the ice front retreated, and by the addition of the area of former tributary lakes, eventually became more extensive than that portion of Puget Sound which lies south of the latitude of Everett. In an earlier paper* this water body was named *Lake Russell*, though its northward extent was not then definitely known. The northern margin can be drawn now with a fair degree of certainty.

Eventually, the westward-opening Strait of Juan de Fuca was cleared of ice, and Lake Russell was drained to sea level, marine waters replacing it in the valleys whose bottoms were below sea level. A few glacial lakes, entirely unrelated to Lake Russell, and to the drainage into the Chehalis River, were formed as the ice front retreated across the mountainous region which partially interrupts the Sound basin. Succeeding the glacial lakes of Puget Sound there was an epoch of submergence be-

*J. H. Bretz, "Glacial Lakes of Puget Sound," Jour. Geol. Vol. 18, No. 5.

neath sea water. This introduces the subject of crustal movements in the Puget Sound region during the Pleistocene.

DIASTROPHISM OF THE PLEISTOCENE IN THE REGION.

The earlier crustal movements of the Pleistocene in this region can be desciphered only in their broad outlines. The post-Vashon movements, however, can be dealt with quantitatively.

The land was high during the Pliocene, presumably higher than at any subsequent time. If we provisionally correlate the known glacial epochs of Puget Sound with the latest two of the northern hemisphere, a plausible correlation, a great part of the Quaternary period has no record in the sediments of the region. Altitude and movements of the Puget Sound basin for much of the Quaternary therefore are unknown. Further, very little is known of the Admiralty glaciation. At the time of the retreat of the Admiralty ice, however, the region was slightly lower than at present; marine organisms in the Admiralty sediments having been found *in situ* a few feet above present high tide.

Early in the Puyallup interglacial epoch, the region was probably a thousand feet higher than now. This permitted the streams of that time to carve the deep troughs in the Admiralty drift plain which are now occupied by the Sound. At the maximum of Vashon glaciation, outwash gravels were poured westward down the Chehalis as far as the present head of Grays Harbor, where they now lie 35 feet above tide, with stream bedding. From this we may conclude that the land had lowered from its high interglacial position to one near that of the present. After Vashon retreat opened the Strait, and marine water replaced Lake Russell in the Sound south of it, subsequently outwashed gravels were adjusted to the new static water levels. Though the evidence is not as clear as could be wished, the sea appears to have filled the Sound basin and to have stood 50 feet or less above the present level.

Marine littoral shells have been found on the bluffs of Puget Sound, in some places accompanied by wave-cut terraces, everywhere overlying the Vashon till sheet, and in some deposits lying on the Lake Russell deltas, and even back in the valleys of Pleistocene rivers discharging into this lake. In the presence of these shells there is positive evidence of a post-glacial submergence of the Puget Sound basin to a depth of 250-280 feet more than now. Shells are most common at the lower levels where fairly definite strands may be worked out. The higher occurrences of littoral shells are rare and yield no more evidence than that of the verity of the occurrence. Data will be presented in Chapter X to show that these shells occur *in situ*.

When the submergence was 120 feet or more in excess of the present, Grays Harbor and Puget Sound were connected by tide water across the site of Lake Russell's discharge-way, and the Olympic Mountains constituted an island. The topographic effects of this submergence are today almost nil. No definite shore lines higher than 100 feet remain, no river deltas of the time have been found, and were it not for the shells, there would be no evidence whatever, to record positively the higher levels of the sea during this episode. Since strikingly developed river deltas record Lake Russell today, and since elsewhere throughout the region post-Vashon stream erosion has been very slight, it is to be concluded that no shore or stream features of prominence were ever developed during the marine submergence. We conclude therefore that it was very brief.

During the diastrophic movements which have submerged the basin of Puget Sound to at least 250 feet below the present sea level, and which have re-elevated it approximately to its immediately post-glacial position, the levels of Lake Russell have not been appreciably tilted or warped. The evidence for this conclusion will be presented in Chapters VI and X.

CHAPTER II.

THE TERMINAL MORAINE OF PUGET SOUND.

SYNOPSIS.

Contact of Puget Sound and Cascade Mountain Glaciers.
The Moraine and the Northern Hills of the Huckleberry Mountain Group.
The Moraine on the Gate Pathway Plain.
The Black Hills and the Moraine.
The Moraine on the Matlock Pathway.
Contact of Puget Sound and Olympic Mountain Glaciers.
General Considerations.

The eastern and western margins of the Puget Sound Vashon Glacier are indefinitely recorded in the glacial deposits. It appears that coalescence between the ice from the north and the glaciers from the Cascades occurred in the northern part of the region, and that no east and west margin can be said to have existed. Farther south, lines of contact appear between the great central invading mass from British Columbia, and the Cascade and Olympic glaciers which descended to it from either side. A definite margin between the area covered by the Puget Sound Glacier and the driftless surface south of it is usually to be found. The description of this margin is the chief purpose of this chapter.

CONTACT OF PUGET SOUND AND CASCADE MOUNTAIN GLACIERS.

From the work of Willis and Smith on the Tacoma quadrangle, Puget Sound drift is known to overlap the deposits of a Cascade piedmont glacier of the Vashon epoch, which they name the Osceola Glacier. Eskers deposited from the Puget Sound Glacier lie on the western margin of a wide till plain composed of material derived from the east, and much flatter than the region immediately west, which is assuredly the product of the northern glacier. An irregular course is mapped for the contact between the two contemporaneous drift sheets. This is not to be considered as marking the contact of the two ice masses, since the position of such contact shifted and no one line can indicate it for all stages.

The writer has not worked in this region of the Osceola (Cascade) Glacier, and the work of Willis and Smith is accepted for most of the Tacoma quadrangle. Error has been found, however, in their mapping of the contact between Puget Sound and Mount Rainier glacial ice in the southeastern part of the quadrangle. The northern glacier pushed well up against the flanks of Mount Rainier, and its ground moraine completely covers the drift hills of the Puget Sound plain which abuts against the flanks of the foothills. No fragments of Mount Rainier lava have been seen in this ground moraine, while bowlders of various kinds of granite typical of Puget Sound drift are abundant up to the base of the foothills. The character of the till,—its color, texture, degree of firmness and coherence, structure and composition,—agrees with that of till which is undisputably of Puget Sound origin. This is true of the country for a few miles south of South Prairie, about Kapowsin and on the east side of the Ohop glacial drainage channel at Eatonville. The Tacoma folio maps the line of contact as running diagonally to the southwest from the region of Orting, but the contact really lies along a line drawn almost straight south from that place.

Ohop Valley is a long, deeply incised marginal drainage channel which connects the Puyallup Valley from a point two miles south of Orting with the Nisqually River valley a few miles southwest of Eatonville. It was the dischargeway for the glacial waters of the White, Carbon and Puyallup rivers from Mount Rainier while the Puget Sound Glacier blocked the lower drainage courses west and north. It also carried escaping water from the Puget Sound Glacier, much of which gathered in a high-level lake in the Puyallup trough about Orting.

A nearly north to south line from Orting to Eatonville lies from one to two miles west of the probable contact of the

Rainier and Puget Sound ice when the latter was at its maximum. It will also approximately divide the plain on the west from the rock hills which rise toward Mount Rainier on the east. Eatonville is built on early outwash gravels of the Puget Sound Glacier which record escaping glacial water before retreat had begun on the north and northwest sides of Mount Rainier. The Puget Sound Glacier at its maximum, however, pushed up on the rock hill slope overlooking Eatonville on the east, to an altitude of 460 feet above this outwash plain 1260 feet above the sea. A fairly definite moraine ridging back on the hill summit here bears an abundance of Puget Sound drift material, such as various granites, garnetiferous mica schist, gneiss, etc., the presence of which in Rainier glacial drift is unknown and altogether improbable.

East of this terminal moraine deposit at the top of the steep rock slope, there is little evidence of any glaciation. The region bears a magnificent primeval forest and exposures are afforded only by overturned trees and by shallow cuts along an old road between Eatonville and Elbe. In spite of the paucity of data, it is apparent that Rainier glacial ice never altered the region more than to remove a residual soil. Only three erratic fragments were found along about ten miles of road. The Nisqually River emerges from the foothills five miles south of Eatonville and enters the Puget Sound drift plain at its most southeastern portion. Here the Rainier foothills on the east and the Bald Hills and the Huckleberry Mountains on the south form a right angle in the mountain wall overlooking the plain, which lies to the northwest. The Puget Sound Glacier crowded up on these slopes as at Eatonville, and granite erratics have been found as high as 1,200 feet above tide.

Deposits of the Puget Sound Glacier partially obliterated the pre-Vashon Nisqually Valley at this angle, and the postglacial stream, failing to follow its former course, has subsequently cut through 40 feet of outwash containing Puget Sound drift, and 300 feet into andesite lava. The canyon thus formed in the rock is as deep as it is wide where crossed by the cable footbridge at LeGrande. The gravel above the canyon brink is nearly 1,000 feet above tide, the highest altitude known to have been attained by outwash gravels of the Puget Sound Glacier. The river is apparently flowing on the pre-Vashon valley floor at the head of the canyon, two miles above the footbridge at LeGrande. The city of Tacoma has developed the water power resulting from this glacial diversion of the river course, by the excavation of a tunnel through the andesite rock from the head of the canyon to the deepest point at LeGrande and the construction of penstock and turbines at that place.

THE MORAINE AND THE NORTHERN HILLS OF THE HUCKLEBERRY MOUNTAIN GROUP.

The Bald Hills from LeGrande westward for several miles present a bold northern face toward the drift plain. The country is densely forested and little is known of the moraine in that region. The Des Chutes River heads in the unsurveyed region lying south of the Bald Hills, and flows out on the drift plain of Puget Sound west of this hill group. The northern glacier crowded back up this valley somewhat, impinging on both north and west slopes of the Bald Hills. Minor valleys on these slopes have been dammed by the moraine, producing lakes and marshes. One such valley possesses three marshes, descending in order from south to north, each with a perfect moraine ridge damming the valley, and the highest with overlooking rock cliffs rising directly from the marsh. Little Bald Hill Lake is the result of a similar moraine damming of a preexisting stream valley.

Moraine ridges are abundant in the forest here, and very sharply defined, though it is impossible to make out a systematic grouping because of the obscuring forest growth. The ridge damming one marsh rises 140 feet above it, and is so sharp crested that there is barely room for the narrow roadway which follows its summit. West of Bald Hill, the moraine is more bowlder strewn and possesses sharper ridges than at any other place known in its entire extent. Bowlders are so abundant here that they are in many places piled up on each other and the forest appears to be growing on a huge bowlder heap.

A lake marginal to the glacier was apparently formed in the Des Chutes River valley above the moraine. In the vicinity of the falls of the Des Chutes (Pl. X, Fig. 2) the valley floor was aggraded by deposits in this lake, the existence of which has determined the location of a few small farms up among the hills. Pebbles of Puget Sound drift are found as high as 1,200 feet in the Des Chutes valley.

West of the Bald Hills the plain region extends farther south, and the glacier accordingly advanced further in that direction. Its margin from Mount Rainier westward to Tenino was controlled entirely by the rock hills lying south of this portion of the Sound basin, the ice having pushed up on their northern flanks for varying distances.

Clear Lake, on the Bald Hill road, lies entirely among bowldery moraine hills. The numerous lakelets and bogs of the vicinity are likewise the result of the moraine topography. A swampy north to south valley immediately west of Clear Lake connects the Des Chutes River valley with that of the Nisqually River to the north. The col or divide in the old water course is within a fraction of a mile of the Des Chutes and there is a uniform descent thence northward to the Nisqually River. Glacial drainage appears to have been the cause of this abandoned valley, but it is not known how such drainage could have flowed north toward the ice front, as the grade records. Another valley of the same character and with the same puzzle concerning its genesis occurs two miles farther west. The high waters of the spring of 1910 actually discharged from the Des Chutes across the fields in this old drainage channel to the Nisqually.

South of Ruths Prairie, the moraine fails to ascend the rock hills which are crossed by the road to the old Mulqueen ranch on the Skookum Chuck. A bowldery ridge about 50 feet high lies along the base of the hill slope, separated from it by a swamp-floored marginal drainage channel formed at the maximum extent of the ice. Though till and erratic bowlders are found on the south side of the channel they do not occur higher than 50 feet above its floor. The Puget Sound Glacier here appears to have stopped just at the base of the hill region, though both east and west of this place it thrust its debris up on these slopes.

THE MORAINE ON THE GATE PATHWAY PLAIN.

A fairly definite moraine begins north of McIntosh and swings westward past Tenino to Black River near Mima. Its topographic prominence is not due entirely to its own mass as will be shown, nor does it mark the maximum extent of the Puget Sound Glacier throughout its length.

Clear Lake, at McIntosh Station, lies in a pre-Vashon stream valley, which is drift dammed at the eastern end. Almost no drift is contained in the valley. The rock hills which constitute its northern divide bear Puget Sound till only on their northern slopes. Yet the Puget Sound Glacier overrode these hills, filled the Clear Lake valley and crowded up on the hills south of the lake more than 300 feet above it. Scattered erratic pebbles and cobbles of fresh material cover these hill slopes up to 650 feet above tide, occurring more than a mile south of the lake. No till, however, was detected on them.

At Tenino, the same conditions obtain. Rock hills north of the valley in which the town lies are capped with till, and bear heavy till deposits with typical morainic topography on their northern slopes. How much is till and how much is rock cannot be stated, but the chances favor the predominance of till. The valuable Tenino sandstone ~~is~~ was quarried from the southern slopes. But the Puget Sound Glacier crossed the Tenino Valley and left scattered erratics on the south side of the valley at 360 feet above tide, 80 feet above the town. Here also till failed to be deposited on the south side of the valley.

About three miles west of Tenino, Grand Mound Prairie is bordered by the moraine on the north and by unglaciated rock hills on the south. Though no erratics have been found on the northern slopes of these hills, evidence from the outwash gravels of this prairie and of the valley from Tenino to the Skookum

Chuck at Bucoda, indicates that the glacier abutted against these hills at its maximum, and forced drainage to take a circuitous course that it abandoned early in the retreat. The data on this question are more fully discussed in the following chapter.

The only known incisions in the moraine ridge between the Des Chutes River near McIntosh and the Black Hills near Little Rock, occur one and one-half miles east of Tenino and at Mima Prairie. The trans-morainic channel near Tenino never carried a great volume of water across from the north, and the extensive outwash gravels of the two Tenino-Grand Mound routes were thus deposited by drainage directly from the ice when it overtopped the moraine. The Mima Prairie incision is virtually a complete breaking down of the moraine topography, perhaps largely because practically all glacial drainage from Puget Sound, from the early recessional stages of ice retreat to the opening of the Strait at the north and the destruction of Lake Russell, passed across the moraine at this place.

North of Tenino, the moraine rises to 550 feet above tide, 250 feet above its base on either side. An outcrop of shale appears in a road cut across its crest, more than 100 feet above the base of the moraine. The width more than the altitude appears to be a function of drift deposition. It is two miles wide north of Tenino and a few miles farther west it increases to a width of about four miles, being in this portion without the rock outcrops at lower altitude, and broken into a number of separate ridges.

The recent construction of the Chicago, Milwaukee & Puget Sound Railroad through this region has afforded a number of valuable sections in the moraine. The railroad follows a route of escaping glacial drainage along the north side of the moraine from Rocky Prairie to Little Rock, where it uses the Mima Prairie incision to cross to the south of the moraine. Almost every cut shows the fresh Vashon till underlain by decomposed and stained drift of much greater age, and in many places also by rotted Tertiary shales. Considerable commingling of fresh and decomposed material occurs, the fresh drift in such case being discolored by iron oxide from the older material.

Vashon till is exposed in road and railroad cuts between Little Rock and Mima Prairie. On the west side of this prairie it overlies an old reddened and decayed till in a railroad gravel pit close to the eastern base of the driftless Black Hills.

THE BLACK HILLS AND THE MORAINE.

From Mima Prairie, the margin of the Puget Sound glacial drift has an almost direct northward course for nearly ten miles, and in that distance rises gradually higher on the flanks of the Black Hills. Waddells Creek is a southward-flowing stream just within the eastern margin of these hills, emerging from them on Mima Prairie. The hills rose sufficiently high about its headwaters and along its eastern side to bar the ice and drainage from the Puget Sound Glacier for most of the stream's length. But, anomalously, this south-flowing stream was ice dammed at its exit from the hills, and, though the glacier never succeeded in entering the valley, glacial drainage was turned into it from the lower portion, and the valley filled with water until an outlet was found westward to Cedar Creek. Scattered glacial pebbles are found in the residual soil on the slopes of Waddells Creek valley to an altitude of about 650 feet, the altitude of the outlet to Cedar Creek. Above this height, erratic material abruptly ceases. The highest glacial drift found on the east slope of the hills in the vicinity of the former dam is about 350 feet above tide, though the ice must have been as high as 650 feet.

The eastern slope of the Black Hills is densely forested and exceedingly difficult to examine. The present study has been content to locate the upper limit of the drift in a sufficient number of places to indicate the general course and altitude of its margin. Moraine ridges are not known anywhere about the Black Hills.

The residual soil of the Black Hills is in striking contrast with the drift flanking it. It usually constitutes a deep red clay so completely covering the rock in places that the region is described by the woodsmen as one of pebbleless clay hills. Outcropping ledges are not common. The logs which are cut on the hills and dragged down the slopes are uniformly smeared with a coat of the unctuous red clay.

The Puget Sound Glacier crowded up on the north slope of the Black Hills, southeast of Summit Lake, to 1,460 feet above sea level, failing by a few tens of feet to top the divide and move down the valley of Waddells Creek from its head. Two morainic terraces lie against this northern slope, at 800 and 1,400 feet respectively, the upper one being indistinct.

Summit or Crooked Lake is due to a drift-dammed preglacial valley whose former direction of discharge was southward, at least through the portion now occupied by the lake. The lake surface is about 420 feet above sea level.

The margin of the Puget Sound Glacier is next known at the Simpson col, through which the gravels of the Wildcat Valley train passed, and through which a minor glacial lake discharged later. The upper limit of the drift was not found here, granite pebbles being plentiful among the angular basalt fragments on the summit of the higher flanking hill, 450 feet above the col and perhaps 950 feet above tide. It is probable that glacial ice crowded through this col for a little way, though no till has been found south of it.

THE MORAINE ON THE MATLOCK PATHWAY.

From Simpson col, the glacier margin swings in a wide curve, convex westward, across the Matlock Pathway to the southeastern foothills of the Olympics. Its position is recorded by a few till hills rising above the gravel plain which here dominates the topography. A definite course may some day be found in these hills, but the present forested condition and the lack of roads have allowed only a reconnaissance thus far, and the moraine course is mapped only approximately. The till in these hills is similar in almost all details to that on the northern slope of the Bald Hills, and to that of the ground moraine in the region of the Puget Sound troughs. The uniformity of character of the Vashon till of the Puget Sound glacier is remarkable. Almost everywhere, it is light bluish gray in color, arenaceous in texture, filled with rounded fragments of rock which resemble stream pebbles and which are seldom striated or planed. It rarely carries bowlders in its mass, though such are abundant on its surface in some places. From the Black Hills to Matlock, the till commonly shows a large proportion of deep red clayey material, intermingled with fresh pebbles. The gravels of the Wildcat valley train likewise possess a reddish color, the suggestion of age which it gives being belied by the freshness in the interior of the pebbles. It seems probable that incorporation of residual soil from the basaltic country rock is responsible for this coloration.

Lake Nahwatzel lies in the most extensive morainic country known in this region. The general expression of the topography is identical with that about Clear Lake near the Bald Hills. Moraine hills here rise 50 feet above the lake surface on all sides.

The moraine is next found at Lake Cushman, in the Skokomish River valley. Its course between Matlock and Lake Cushman was doubtless controlled by the rock hills along the north side of the Matlock Pathway, and it is thus mapped.

CONTACT OF PUGET SOUND AND OLYMPIC MOUNTAIN GLACIERS.

The genesis of Lake Cushman is intimately related to the Puget Sound Glacier. The lake lies in the course of the Skokomish River at an altitude of 800 feet, hemmed in by mountain walls except to the east, where a broad drift plateau, from 400 to 950 feet above tide, lies between it and Hoods Canal. Puget Sound drift is abundant over this plateau, and the presence of granite from the northern Cascade Mountains within less than a mile of the lake proves that the Puget Sound Glacier pushed up to the very mouth of the Skokomish River's mountain valley. Though the drift has a morainic topography close to the lake, there is no trace of Puget Sound glacial material along the lakeward slope, save where a stream of some length enters from the surface of the drift plateau. On the contrary, the rock types shown on the slope facing the lake are foreign to the drift deposited by the Puget Sound Glacier.

The valley of the Skokomish River is thus seen to be dammed by a great deposit of the Puget Sound Glacier which here crowded up the river valley and held back the local glacier that normally would have deployed in the Puget Sound basin. The deposits of the local glacier in the Skokomish Valley give the lakeward face of the drift dam its different character. A till darker than that of the Puget Sound Glacier, possessing angular rock fragments of kinds entirely different from those of Puget Sound drift, lies back of Lake Cushman on the slopes of Mount Ellinor, about 1,300 feet above tide. It doubtless is a deposit of a local glacier which occupied the Lake Cushman basin of today.

Views of Lake Cushman and vicinity from the trail up Mount Ellinor show the relations described above almost with the clearness of a diagram. From the socalled "Half Way Rock" along the trail, it requires only a slight effort of the imagination to see below one the dammed-back Skokomish Glacier opposed by the mightier Puget Sound ice mass which crowded westward against the mountains.

Lake Cushman in early post-glacial time was much larger than at present. The Skokomish River is rapidly filling it with a delta which now has a greater area than the portion of the lake remaining. Incision of the morainic dam has lowered the lake level probably as much as 100 feet. At its former altitude the lake must have reached considerably farther back up the river valley. Stratified clays of the former higher lake levels are exposed along the stage road near the ferry, and a fine series of river terraces is visible from this road a few miles below the lake.

It has not been practicable to determine closely the form and position of the Puget Sound Glacier on the east face of the Olympic Mountains. Granite pebbles exist at least four miles up the valley of the Dusewallips River, and no granite *in situ*

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has ever been reported from the Olympic Mountains. The Puget Sound drift covers the region west of Dabop Bay for five miles or more back from the water. It also constitutes the surface material on Quimper Peninsula, about Port Discovery, and between Port Discovery and Quilcene, all of which are in the structural valley and a part of the drift plain.

GENERAL CONSIDERATIONS.

Willis found drift of the Puget Sound Glacier on the northern flanks of Mount Rainier, 1,600 feet above sea level. The writer has found an upper limit marked by morainic ridging on the western slope of Rainier's foothill country at 1,260 feet, near Eatonville. On the northern flanks of the Bald Hills, the highest known erratics are at an elevation of 1,220 feet, though the moraine is about 300 feet lower. Near Tenino, the highest erratics are 650 feet above sea level, while the moraine summit does not reach above 550 feet. These scattered erratics in some cases may have been transported by floating ice in marginal lakes, but in other situations, the glacier undoubtedly rested at their altitudes on the hill slopes, though considerable bodies of till failed to be deposited there.

In the plain which leads southward to the Gate Pathway, the moraine reaches its lowest altitude. North of Mima Prairie it lies about 175 feet above sea level, though as has been noted this low altitude is in part due to the erosive action of escaping glacial drainage. Yet since the Vashon till descends below 130 feet in this region, it is possible that the pre-Vashon surface was lower here than at any other place in the entire glacial periphery. Though the surface is still lower to the south, the glacier did not advance beyond Mima Prairie.

The ice margin ascended along the eastern face of the Black Hills from Mima Prairie to the region of Summit Lake, and possessed a maximum gradient of 130 feet to the mile for that distance. The altitude of 1,460 feet, reached by the glacier on the northward angle of the Black Hills, is more than 200 feet higher than at any other point along the entire southern margin where facing driftless country. The moraine in the

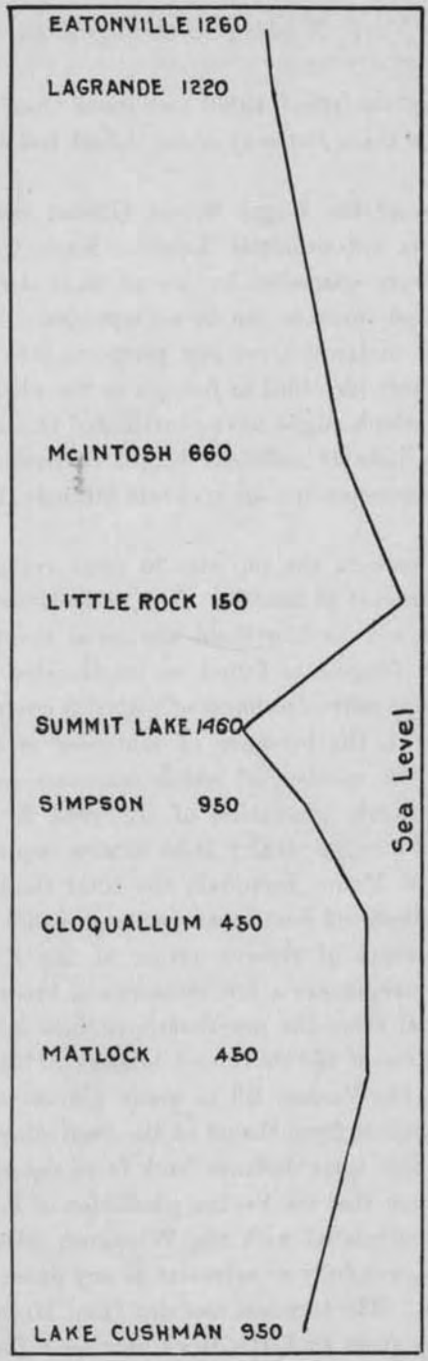


FIG. 1. Profile of the Vashon Terminal Moraine.

Matlock Pathway lies about 1,000 feet lower than this highest point, that in the Gate Pathway about 1,300 feet lower. (See Fig. 1.)

The thickness of the Puget Sound Glacier north of the moraine region is not definitely known. Since the neighboring mountains were glaciated by ice of local derivation, the height of glaciated surfaces can be no criterion. Nor can the height of erratic material serve our purpose, save where such material is positively identified as foreign to the whole adjoining mountain region which might have contributed to former glaciation. Mid-basin hills of sufficient height to have risen above the glacier are necessary for an accurate estimate, and such do not exist.

A hill which answers the purpose to some extent is Mount Issaquah, 15 miles east of Seattle. It is an isolated peak about 3,000 feet above sea level, without the usual mantle of finely comminuted rock fragments found on unglaciated hills of the region. The comparative freshness of material covering the top is in harmony with the presence of scattered erratic pebbles on the summit, the number of which increases on the lower slopes. Both indicate glaciation of the peak by the Puget Sound Glacier. Since Admiralty Inlet attains depths of nearly 1,000 feet west of Mount Issaquah, the total thickness of the glacier in the latitude of Seattle was at least 4,000 feet.

The only evidences of erosive action of the Puget Sound Glacier near its margin are a few instances of incorporation of weathered material from the pre-Vashon surface into the fresh Vashon till. Knobs of old drift and hillocks of decayed shale are seen beneath the Vashon till in many places with no suggestion of deformation from thrust of the overriding ice. This, of course, is not true some distance back from the moraine.

Present data show that the Vashon glaciation of Puget Sound, probably to be correlated with the Wisconsin glaciation east of the Cordilleras, was fully as extensive as any preceding glaciation of the region. The terminal moraine from McIntosh across the Gate Pathway plain to Little Rock overlies a former region of low hills of old drift, some of which is undoubtedly till. No old till has been found south of the moraine limits, and no obviously old and weathered erratics are known in positions indicative of former and more extensive glaciation.

CHAPTER III.

EXTRA-MORAINIC OUTWASH OF THE PUGET SOUND REGION.

SYNOPSIS.

THE PRE-VASHON RED GRAVELS OF THE CHEHALIS VALLEY.
ADMIRALTY GLACIATION AND THE COWLITZ VALLEY.
VASHON GLACIATION AND THE CHEHALIS VALLEY TRAIN.
- SKOOKUM CHUCK GRAVELS.
- STONY POINT VALLEY TRAIN.
- TENINO-GRAND MOUND GLACIAL DRAINAGE ROUTES.
- GATE PATHWAY.
- GATE VALLEY TRAIN.
- OUTWASH WEST OF THE BLACK HILLS.
- MOCK CHEHALIS VALLEY TRAIN
- CLOQUALLUM VALLEY TRAIN.
- SATSOP VALLEY TRAIN.
- ECONOMIC PHASES OF THE CHEHALIS GLACIAL GRAVELS.

VASHON GLACIATION AND THE COWLITZ VALLEY.
- MINERAL LAKE GAP.
- NAPAVINE DIVIDE.
- NEWAUKUM RIVER COL.

In the two known glaciations of the Puget Sound Basin, the invading ice came from the Cordilleran Glacier of British Columbia, and advanced sufficiently far southward between the Cascade and Olympic mountains to close effectually the basin at the north. Water discharging from the Puget Sound region was forced into stream valleys lying south of that basin. There are two river valleys to be considered in this connection: the Cowlitz and the Chehalis. The Cowlitz River heads in the glaciers on the south side of Mount Rainier and flows west to the structural valley of which Puget Sound is a part. Here it turns south to enter the Columbia. There are two low areas across the northern divide of the Cowlitz Valley where glacial drainage could have entered it from Puget Sound. The Chehalis Valley heads in the low coast range south of the Olympics, descends their eastern slope to the same structural valley, which it enters 15 miles north of the entrance of the Cowlitz Valley. Here it has a northward course for 10 miles and then swings about to a westward course south of the Black Hills, whence it continues to the Pacific. The Chehalis Valley lies closer to Puget Sound than the Cowlitz Valley, and between it and Puget Sound there are several gaps in the rock hills, two of considerable width. These gaps afforded ample opportunity for the entrance of glacial waters in the valley.

THE PRE-VASHON RED GRAVELS OF THE CHEHALIS VALLEY.

The maximum extent of the Puget Sound Admiralty Glacier is not known. Old drift, presumably of Admiralty age, underlies the Vashon terminal moraine in the vicinity of Little Rock, but is not known beyond that locality. There is, however, an old gravel deposit in the Chehalis Valley, found at intervals from Gate to the ocean, and thence along the coast, which is very probably Pleistocene in age, and a portion of which may be outwash of the Admiralty glaciation.

The most eastern remnant of the old gravel known at present is at Helsing Junction, on the south side of the Chehalis Valley, opposite Gate, where the Oregon-Washington Railroad and Navigation Company and the Chicago, Milwaukee and Puget Sound Railway unite on their common track down to Grays Harbor. The gravel caps the bluff above the railway grade along the river for two miles. Its maximum thickness is 35 feet, and it overlies the Tertiary shales unconformably, with the contact about 70 feet above the river and about 190 feet above tide. The gravel is deeply stained by iron oxide, possessing a true "ferretto" color almost throughout. Its pebbles are so softened by decay that a blow of the hammer will break them easily. Most of them can be carved with a knife like hardened clay. The bedding is horizontal. No granite, and no metamorphic or sedimentary rocks were found among the pebbles, the deposit being composed almost entirely of fragments of andesitic lava.

A deposit of scattered gravel on the north side of the Chehalis River lies a mile west of Oakville at the summit of a quarry section, perhaps 160 feet above tide. In this gravel, granite is abundant. The pebbles are somewhat softened on the surface, but are firm within. They are less stained than the Helsing Junction gravels, appearing fresher also than the old drift near Little Rock. They are, however, older than Vashon outwash which lies as a broad terrace at the foot of the cliff.

There are several occurrences of the red gravel about Elma. It is found on Wildcat Creek at White's Mill, and here possesses current bedding dipping southward down the present valley in which it lies. It constitutes the larger part of a great terrace which forms the north side of the Chehalis Valley from Elma to Satsop, with a summit level of about 325 feet above tide. It is well exposed a mile and a half west of South Elma, on the joint line of the Oregon-Washington and Chicago, Milwaukee and Puget Sound railways. Here its base is 100 feet above tide and its summit constitutes a considerable plain surface probably to be correlated with the terrace on the north side and visible for several miles from the north side of the valley (Pl. I, Fig. 2). The decay and staining of the gravels in this cut are comparable to that of the Helsing Junction gravels, which they resemble also in composition. More of this early gravel filling remains in the vicinity of Elma and Satsop than at any other place in the Chehalis Valley. This also appears to be the only place where the surface of the filling is still preserved.

A mile west of Satsop village, a prominent table-topped spur projecting from the north side of the valley (Pl. I, Fig. 1) is composed of this red gravel. Its summit is 130 feet above tide and its thickness is about 90 feet. The Satsop River, which enters the Chehalis Valley here, has eroded 15-20 feet below the base of the gravels and has exposed their unconformable contact with the underlying Tertiary sandstone. On the top of the terrace the red gravel has been excavated for road material, and is apparently identical in degree of decomposition, in structure and in composition with the Helsing Junction and the

FIG. 1. The Satsop Red Gravel Terrace.
The high red gravel terrace on the south side of the Chehalis can be faintly seen.

FIG. 2. Surface of Satsop Red Gravel Terrace.

FIG. 3. Section of Red Gravel in Satsop Terrace.
The gravel is decolored above the irregular transverse line, but is as much decayed as below. Current bedding dips with the present valley.

South Elma gravels. Locally its surface parts are completely decolored to a depth of several feet, but its decayed character shows it to be the same deposit as the rest of the terrace, and not material of later age. (See Pl. I, Fig. 3.) Though the height of this terrace does not conform with that of the terraces about Elma, yet the similarity of material and of alteration are convincing evidence that they are portions of the same deposit. The plane of the terrace a mile west of Satsop seems best explained as due to subsequent erosion, and not to original deposition.

At the downstream angle between the Wynooche and Chehalis valleys, a red-stained and decayed gravel is exposed along the highway. The summit of the gravel is about 110 feet above tide, and it bears approximately 50 feet of yellow clay above it. The beds of the gravel are partly horizontally bedded and partly foreset, with dip downstream. It agrees with the previously described deep gravel deposits in its red color, its softened pebbles, and its lack of material which can be unhesitatingly identified as having come from a Cordilleran glacier.

Old gravel, softened and deeply stained, is exposed in many cuts between Montesano and Aberdeen. The structure is either horizontal or foreset; where the latter, the dip is down the present valley. Gravel of the same character is found for several miles along the Wishkah River above its mouth. It also occurs in exposures at Cosmopolis, on the south side of the head of Grays Harbor, but there is a greater variety of rock represented than in most exposures. Granite, however, was not found.

The best exposures of this red gravel in the Chehalis Valley are in the sea cliffs on the north side of Grays Harbor, which is the drowned continuation of the river valley. The maximum thickness here exposed is about 100 feet, with the base above high tide in but one place. The bedding of the gravel is prevailingly horizontal, though foreset beds with westward dip are of common occurrence and locally constitute nearly the whole structure. Beds dipping at the same angle eastward are seen at a few places. In most of the thicker sections, the staining is perceptibly greater near the top, the basal strata being in places almost unstained. The same gradation is shown in the softening by decay. Near the site of the old Grays Harbor City, a median bed of clay lies between two gravel members. Erosion surfaces separate the three. Farther west, one section shows several alternating beds of red clay and red gravel, each stratum averaging four or five feet in thickness. James Island is a picturesque stack of these red gravels, lying off the north shore of the Harbor.

Red stained, partially decomposed and partially cemented gravel of the same character as that of the Chehalis Valley is known along the Pacific Coast north to the Strait of Juan de Fuca. Between Grays Harbor and Moclips at least, it composes a foreland about 12 miles wide.

Wherever the base of this old gravel is seen, it rests unconformably on Tertiary formations. In distribution, it is limited to valleys and the coast line. Distortion of the underlying strata is common but no distortion is known in the gravel itself save at South Elma, where a slide has evidently been the cause. The conclusion seems probable that these red gravels are Pleistocene stream deposits in the Pliocene or early Pleistocene Chehalis Valley, and on a Pliocene or early Pleistocene wave-cut coastal shelf. Their decay and staining are somewhat greater than that of known Admiralty gravels in the Puget Sound basin, and with one exception no granite or other rock has been found in them by which they could be identified with Puget Sound glaciation. The one exception, the Oakville quarry section, itself fails to conform satisfactorily to the other exposures.

For the present, therefore, we must conclude that sufficient evidence is not known to show these old Pleistocene gravels of the Chehalis to be related genetically to the Admiralty glaciation of Puget Sound, or to be glacial at all.

ADMIRALTY GLACIATION AND THE COWLITZ VALLEY.

Since the passes from the Puget Sound to the Cowlitz Valley are higher and farther distant than those of the Chehalis, it seems unlikely that the Cowlitz received outwash of this glaciation if such failed to enter the Chehalis. No old drift of any kind is known at present in the Cowlitz Valley.

VASHON GLACIATION AND THE CHEHALIS VALLEY TRAIN.

SKOOKUM CHUCK GRAVELS. The Skookum Chuck River heads in the unsurveyed Huckleberry Mountains, which lie southwest of Mount Rainier between Puget Sound and the Cowlitz River, and flows westward to join the Chehalis at Centralia. It roughly parallels the Puget Sound terminal moraine for some distance, lying a few miles south of it. Its course, however, is within the Tertiary hill region southeast of the Puget Sound basin. For most of its length, these hills rose sufficiently high to prevent entrance of drainage from the glacier which pushed up on their northern flanks. The stream valley where thus protected, however, possesses a considerable quantity of gravel which appears to have been so rapidly introduced that derangement of drainage followed. An abandoned farm known as Mulqueen's (Fig. 2) lies some miles up the Skookum Chuck Valley on an alluvial flat among the rock hills. Immediately below this the stream enters a gorge with vertical walls, appearing to have been fairly recently superposed on a rock spur into which it has cut. Such an incident could logically follow erosion of a valley train. But a careful search for six miles along this length has failed to bring any Puget Sound drift materials to light, and the flat at Mulqueen's lies 180 feet above the Puget Sound moraine directly north of it. The filling, whatever its source, is not to be referred to the glaciation of Puget Sound.

STONY POINT VALLEY TRAIN. There are three gaps through which Puget Sound outwash did enter the Skookum Chuck Valley, two of them of considerable size. (See Fig. 2.) The most easterly of these will be designated the Stony Point gap. At the maximum of Vashon glaciation, outwash from the entire margin of the glacier lying east of this gap, entered the Skookum Chuck through it. The outwash built a gravel train which contains many granite pebbles and other Puget Sound drift ma-

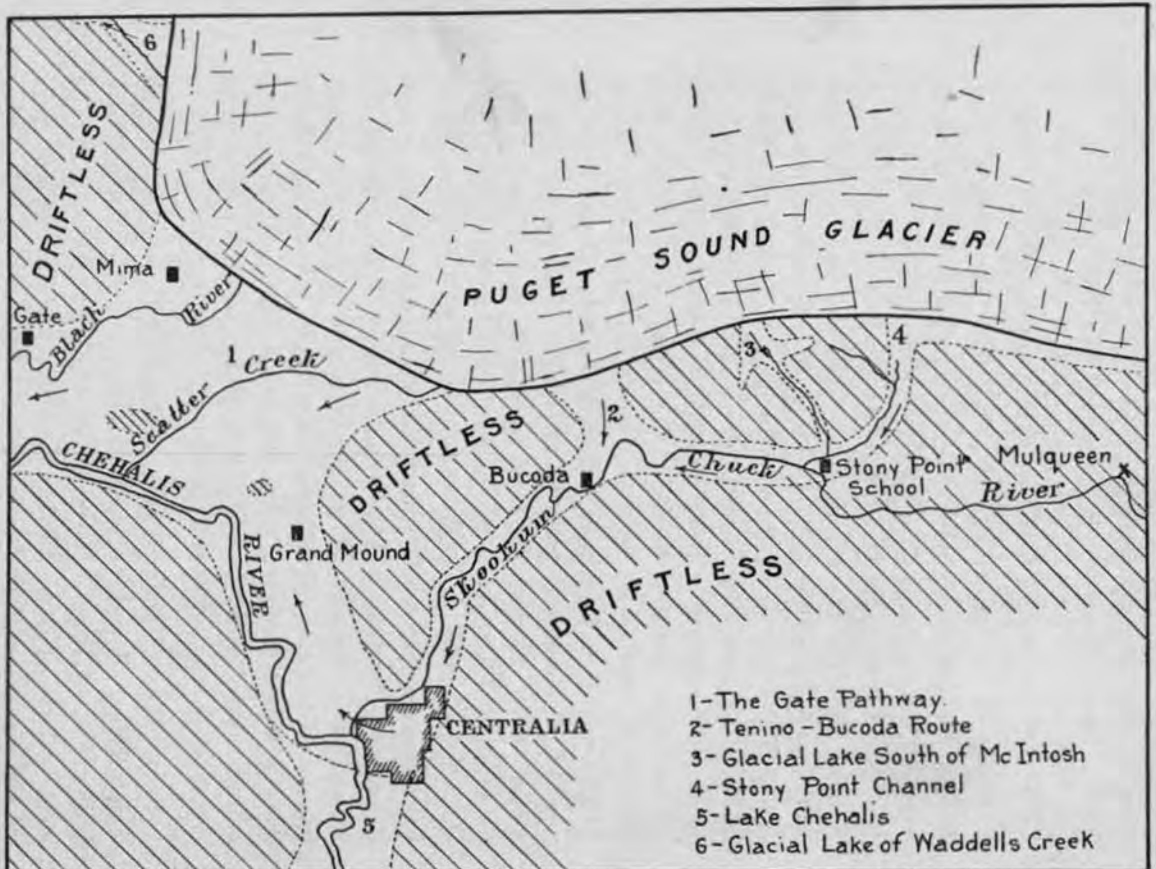


FIG. 2. Glacial Drainage from the Eastern Lobe of Puget Sound Glacier, at its Maximum Extent.

terials. The coarseness of the gravel is probably responsible for its unforested condition. The altitude of the col in the Stony Point gap has not yet been accurately determined, but it lies below 350 feet. Clear Lake at McIntosh station, altitude 346 feet, was never used by marginal drainage, though as the ice withdrew from its maximum stand, the lake's valley lay in so favorable a position and at such an altitude, that the gap was earlier held to have been unavoidably so used, in spite of the absence of glacial gravels. The only explanation for outwash holding to the Stony Point channel until a route on the north side of the hills north of Clear Lake was opened westward, is that the Stony Point channel was lower than the lake. Hence the confidence in the inference regarding the altitude of the gap. From the col to Bucoda along the valley train, the distance is 11 miles, and the descent cannot exceed 100 feet. This is a grade of less than 10 feet to the mile.

A few miles west of the Stony Point gap, the glacier closed a northward descending valley and produced a lake whose discharge was south to the Skookum Chuck. But since this lake caught all outwash gravels, the gap used by the outlet was unimportant in building the Skookum Chuck valley train.

Tenino-Grand Mound Glacial Drainage Routes. The Tenino-Bucoda gap is the largest of the three which led glacial water to the Skookum Chuck. Together with the Skookum Chuck Valley below the point of junction, it constitutes a through valley from Tenino to the Chehalis at Centralia. In this there was probably a preglacial low divide. The greatest constriction occurs just south of Bucoda, and it is possible that the preglacial Skookum Chuck turned northward near that town and flowed to the depression now occupied by Grand Mound Prairie. A triangular driftless area is surrounded by the Tenino-Bucoda-Centralia gravel train on the southeast, Grand Mound Prairie on the north, and the gravel-filled Chehalis Valley on the southwest. (See Fig. 2 and Pl. XXIII.) Outwash from the vicinity of Tenino which took the Bucoda route rounded the southern tip of this area, and returned to Grand Mound, from whence it was carried to Gate and down the Chehalis Valley. The distance from Tenino to Grand Mound by this circuitous route is 16 miles, and the descent of the gravel floor in that distance is 122 feet. Along Grand Mound Prairie on the north side of this area, the distance is nine and one-half miles and the route is straight. Outwash would never have taken the longer route with so low a gradient if the more direct route along Grand Mound Prairie had been open. The only cause which could have operated to close it is advance of glacier ice from the position of the terminal moraine, bordering the prairie on the north, until it impinged on the triangular hill area. Though no erratic material has been found on the northern slopes of these driftless hills, the grades of the gravel outwash make it obvious that the Puget Sound Vashon Glacier at its maximum actually reached this position.

The grade of this Tenino-Centralia-Grand Mound floor is surprisingly variable. Between Tenino and Bucoda it descends six feet to the mile; between Bucoda and Centralia nearly thirteen feet to the mile; and from Centralia to Grand Mound the descent is but five feet to the mile. This last gradient is probably of no value since the vicinity of Grand Mound received gravels from the north after transportation by the Tenino-Centralia route ceased. But the change in gradient near Bucoda in a gravel train which today floors the entire valley, and obviously is practically the same as when abandoned by the glacial river, needs explanation. Two hypotheses are advanced; one that the Stony Point gravel train which entered the through valley at Bucoda was of so much greater volume that it virtually dammed the Tenino-Bucoda length, the other that a pre-Vashon rock divide existed in the somewhat constricted valley just south of Bucoda, and served to back up the gravels to form a low gradient.

Fragments of a higher gravel filling lie 310 to 320 feet above tide on both sides of the valley at Tenino, and scattered glacial pebbles occur up to 360 feet. The 280 foot terrace on which the town is built is continued without break toward Bucoda but ends abruptly with a 30-45 foot descent to Scatter Creek valley, which leads westward along Grand Mound Prairie. A mile or so west of Tenino, only a broad median ridge in the axial part of the prairie remains at the level of Tenino, the lower surface elsewhere recording the later work of glacial drainage along the direct route from Tenino to Grand Mound. The prairie surface is undulating, and no one figure can be given for its gradient. From the broad bottom of Scatter Creek at Tenino, to Grand Mound, however, the descent is not quite ten feet to the mile, and this may be taken as an approximation of the gradient of the gravels along Grand Mound Prairie.

The Gate Pathway. The Gate Pathway from Puget Sound to the Chehalis River is fully eight miles in width. It is interrupted by the isolated hill from which the station and the prairie of Grand Mound are named, and by a plateau-like outlier about a mile in diameter near Rochester. The gravel plain of Vashon outwash completely surrounds each hill. The plain is highest on the eastern side of the pathway, and lowest on the west at Gate, this being because glacial water entered it on the east and northeast, and flowed diagonally across to the west and southwest, and also because as the volume of escaping water waned it became concentrated on the western portion, perhaps lowering this still more. The altitude of the mounded gravel prairie at Gate is about 120 feet above tide, and it is 40 miles distant from the most western occurrence of Vashon gravel in the Chehalis Valley, which lies at 30 feet above tide. Furthermore, gravel terraces which contain Puget Sound Vashon material situated far down the valley lie as high, or nearly as high, as at Gate. It is immediately obvious that no one simple gravel train can embrace these diversely situated gravel terraces, or could extend that distance with as low a gradient as two feet to the mile. The explanation is to be found in the existence of tributary valley trains which head in the outwash plains of the western lobe of the Puget Sound Glacier, and which enter the Chehalis Valley from the north. These brought in great quantities of gravel and each created virtually a new valley train in the Chehalis. In each of these tributary trains the entering gravel was higher than the surface of the outwash gravel which had entered some distance farther up the valley. By relays, as it were, the Vashon gravels succeeded in reaching the head of tide water on the Pacific Coast. (See Plate XXIII for areal distribution of these different gravels.)

Gate Valley Train. The remnants of the Gate train constitute an almost continuous terrace surface from the town of Gate westward to Malone, where it blends with and becomes obscured by the younger Mock Chehalis train. Gate or Baker's Prairie, Oakville Prairie, Cedarville Prairie, and Ford Prairie are portions of the Gate train. Smaller fragments also exist in the valley mouths of Cedar and Porter creeks.

The topography of about half the prairie areas of the Gate train is remarkably mounded. The genesis of these mounds is treated in Chapter V of this paper. Their presence, involving a relief of as much as 30 feet, with many delta-formed terraces and other irregularities of doubtful origin, makes the construction of a satisfactory profile for this train almost impossible. Under the limitations of this study it has not been attempted. In general, however, the gradient of this train is surprisingly, almost unbelievably low. The longest distance between bench marks on this train is from Gate to Porter. Railroad altitudes are here depended upon, and they give a gradient of six and one-third feet to the mile. The gravel, wherever shown, is horizontally bedded or possesses a westward dip, and the material was undoubtedly transported by running water to its present position.

In consideration of the minimum grades a gravel train may possess, the present Chehalis River grade is instructive. This stream descends about four feet to the mile from Helsing Junction to Satsop, at the head of tide water, and is today sweeping the rehandled outwash gravels seaward along this stretch, during flood season at least. The glacial Chehalis, receiving at Gate at least half of the drainage of the Puget Sound basin south of the Strait, was thus presumably capable of carrying the gravels of this valley train even on the low gradient noted.

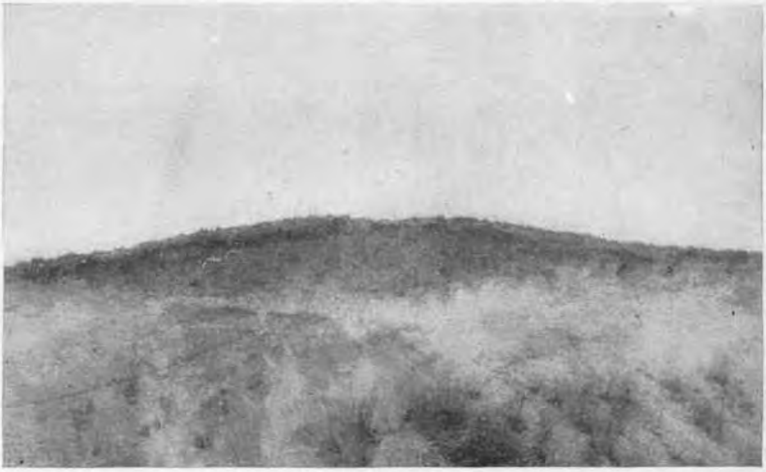


FIG. 1. Mound Section in Northern Pacific Railway Pit, Mima Prairie.
Double convex form of the black silt. Clean stratified gravel below.

FIG. 2. Mound Topography on Mima Prairie.

Terraces occur along Porter Creek for a mile above its junction with the Chehalis. Their material is entirely of local derivation, but they are believed to be contemporaneous with deposition of the Gate train. Here the gravel flood dammed the tributary valley which in consequence was aggraded by stream debris brought down from its unglaciated upper course. Though Porter Creek is the only valley known at present to show this filling, it is to be expected in many tributary valleys of that portion of the Chehalis affected by glacial outwash.

Outwash West of the Black Hills. The function of the Black Hills in the production of the double lobe of the Puget Sound Glacier has been noted. In crowding up on the northern flanks of these hills, the glacier overtopped low divides in two places, and sent slender trains of fresh, light-colored glacial gravel southward along the stream valleys. The gravel of these trains is in remarkable contrast with the black pebbles and deep red residual soil derived from the basaltic hills.

The Mock Chehalis Valley Train. The most eastern of these valley trains is that of the Mock Chehalis, a creek entering the Chehalis at Malone. Two terraces of glacial gravel occur at the mouth of Porter Creek and Cedar Creek, but such are simply remnants of the valley train filling which entered by the Gate Pathway, and these creek valleys above their mouths are entirely without glacial gravel. The Mock Chehalis train begins somewhere in the forested region of Summit Lake. No altitudes are known in its valley, and its grade has not been determined. Its existence has determined the location of a number of farms along the stream, while both Porter and Cedar Creek valleys, lacking the flat bottom, are yet covered by the primeval forest or but party logged off, and have no farms above their mouths.

Most of the Mock Chehalis train still bears the original forest, and no higher terraces have been found except at Sine and again near the head in the vicinity of Summit Lake. Between Sine, on the Mock Chehalis, and McCleary, on Wildcat

Creek, a tributary of the Cloquallum, the rock hills fail, and a broad, fairly level area rises only a few tens of feet above either place. McCleary lies on the outwash plain which poured down Wildcat Creek from the vicinity of Summit (or Hillgrove). The presence of scattered granite pebbles among the sub-angular basalt cobbles which cover the low divide, proves a former connection between the Wildcat and Mock Chehalis trains, and, together with a terrace 30 feet high just east of Sine, and other terraces near Summit Lake, proves the present Mock Chehalis train to have been originally aggraded to a level higher than it now possesses.

Between Malone and Elma it is probable that commingling of gravels from the Gate and Mock Chehalis trains occurred; but the Gate train here lost its individuality, and in two or three miles below Malone the gravels largely lie too high to possibly come into the Gate train profile.

A significant terrace lies two miles east of Elma on the highway along the north side of the river. Its altitude is 80 feet, higher than the large Cloquallum train entering at Elma, and higher than the Mock Chehalis train where it issues at Malone. Inclined strata shown in its sections dip consistently westward. This removes the possibility of the terrace being a portion of a former fan-like spreading of the Cloquallum train which enters the Chehalis just below it. It is confidently referred to outwash through the Mock Chehalis, before the filling of that valley was eroded by later glacial drainage to its present dimensions. It thus corroborates the evidence of the terraces at and above Sine.

The Cloquallum Valley Train. The fourth valley train to enter the Chehalis River valley is that of the Cloquallum, near the mouth of which Elma is situated. This is composed of two distinct uniting trains; one from Summit, or Hillgove, in the valley of Wildcat Creek, the other descending the Cloquallum proper. The Wildcat member, probably the larger, is the second train to the west which was poured across the Black Hills, the gravel floor ascending with a constantly increasing gradient northward to Simpson col, a definite notch at the valley head, where the Puget Sound Vashon Glacier reached its maximum. The Cloquallum member begins in the broad plain which was spread out in front of the western glacial lobe in the Matlock Pathway.

The head of the Wildcat train is a uniform plain, several square miles in extent, broken by a few rock hills which rise like islands above the gravel. No streams have yet incised it in the vicinity of McCleary and Summit. A beautiful valley system is developing on the middle portion, and ravine heads are rapidly advancing into the undrained upper tract. Farther down the valley, both the Cloquallum and the Wildcat have cut through the gravel to the underlying earlier Pleistocene red gravel and Tertiary rock.

From railroad altitudes, including some from a logging railway, the Wildcat train descends more than 40 feet to the mile between Simpson and Elma. These united trains extend out into the Chehalis Valley in a broad, unbroken terrace which reaches down the valley as far as Satsop, the grade decreasing to seven and one-half feet to the mile between Elma and Satsop, though all sections in this length show current bedding dipping westward.

No positive evidence has been found for an earlier, higher surface of the Cloquallum train or either of its members, except the scattered granite pebbles between McCleary and Sine. The significance of this fact will be discussed later.

The Satsop Valley Train. The outwash in the Matlock Pathway is largely covered with forest. It possesses but few prairies, none of them comparable in extent with those on the outwash of the eastern lobe. The altitude of this route is known only approximately from surveys of the logging railways, both Matlock and Cloquallum being given as 400 feet above tide. The width of the plain in the broad gap is probably equal to that at Gate, about eight or nine miles, though the forest and the waste of logging where the heavy growth has been removed, have prevented more than a reconnaissance of the region.

The outwash plain and moraine of the Matlock Pathway are drained by several eastern branches of the Satsop River, and by Cloquallum Creek. The west fork of the Satsop never received outwash from the Puget Sound Glacier.

The valley train heading in this outwash area and extending down the Satsop, and thence down the Chehalis, is the longest of all the extra-morainic trains of the Vashon Glacier of Puget Sound. It also originally lay higher above present valley bottoms than any other, and, further, has been more largely destroyed by post-glacial erosion. Its lowest level constitutes a terrace reaching from a point two miles above the junction of the Satsop with the Chehalis Valley, to Montesano, a distance of seven miles. At Montesano, terraces of fresh glacial gravel with stream bedding dipping westward lie at 40 and 65 feet above tide. In the north part of the city is a terrace 120 feet in altitude, in which wells without exception find fresh gravel beneath a few feet of yellow soil. Though no pits exist in this terrace to show the material, there can be little doubt that its gravel is of Vashon age. There is no higher fresh gravel in the Chehalis Valley below Gate.

Half way between Montesano and Aberdeen, the highway for about two miles traverses a terrace surface well above the valley bottom, one mile of it being 80-85 feet above tide. Its topography practically unbroken by ravines, is indicative of youth. Sections show the material to be typical Vashon glacial outwash, with many fresh granite pebbles. The stream bedding records a westward current at the time of deposition. Some exposures show a peculiar mingling of stained and unstained gravel, strata or masses of stained material alternating with fresh granite-bearing gravel. The staining is irregular and never very dark. It may perhaps be due to local infiltration of the fine reddish alluvium which covers the terrace top, and possibly to the incorporation of older Pleistocene red gravels which underlie this terrace.

The best residence district of the city of Aberdeen is situated on a gravel terrace whose summit is 30-35 feet above sea level.

The gravel is perfectly fresh and unstained in some sections, but near the base of the hill slope against which the terrace lies, its material is red like an old gravel, though the staining is not so deep or uniform. Granite pebbles are not common, but can be found, and are firm and unweathered. The bedding is horizontal with a few strata dipping westward. The pebbles are noticeably smaller than in gravel nearer the moraine.

On the hill slopes above the terrace, considerable street grading has revealed many stream-worn pebbles in the residual earth, and stained by it to its own hue. Slides and creep seem to have interrupted any continuity which may have existed originally, but a considerable bed lies back of the old high school building, east of the ravine back of the St. Rose Academy. It is 90-95 feet above tide. Some pebbles in it are fairly fresh, but most of the material is weathered.

These high gravel terraces along the lower Chehalis, in places actually overlooking tide water, can mean but one thing; namely, that the Satsop valley train, where it enters the Chehalis Valley, has been degraded far below its original level. These terraces must be remnants, indicating the level to which the valley was once filled. They suggest that high terraces, corresponding with these surviving portions of a former deep filling should be found up the Satsop toward the Matlock outwash plain, unless they have been removed by erosion. The Satsop Valley should now be examined.

For the lower portion of the Satsop Valley, there are few glacial gravels above the present flood plain. The lowest terrace surface, which extends down to Montesano, may be followed up the Satsop for two miles. In one place a small terrace rises about 25 feet above it. On the east side of the stream, a slender terrace of fresh gravel lies along the valley slope for a mile and a half. Between the junction of the east and west forks of the Satsop, the road which follows the east fork ascends to Shafer's Prairie, whose altitude is about 130 feet above tide. This is composed of glacial gravel but is not high enough to be correlated with the high terrace at Montesano, or with any terraces west of that place.

The bluff which borders Shafer's Prairie on the west is really a ridge parallel to the edge of the prairie. Beyond its crest there is a small stream valley, beyond which there is still higher land. The ridge appears to be stream-formed, though lying parallel to the adjacent prairie. Its altitude is 90 feet above the prairie, or 220 feet above tide, and it shows fresh glacial gravel on both slopes and crest. Similar gravel occurs also on the ascent to the higher land beyond, but does not reach above 220 feet in altitude.

Though the described ridge parallel to the prairie which lies in the Satsop Valley is somewhat unusual, and not to be considered a terrace, it appears to have been left by the erosion of a former plain, aggraded by glacial gravel to the level of its crest. The presence of the gravel is the vitally important fact. It here lies high enough to allow a descent of 11 feet to the mile to the highest terrace at Montesano, and a continuation of a similar grade down the Chehalis will touch the 80-85 foot terrace between Montesano and Aberdeen and the 30-35 foot terrace at Aberdeen. From the outwash gravel about Matlock, there is a descent of 15 feet per mile to this high gravel overlooking Shafer's Prairie. The outwash plain about Matlock is probably contemporaneous with the lower levels of the Satsop train, and earlier filling about Matlock, correlative with the high gravel above Shafer's Prairie, has probably been destroyed in production of the lower levels. The gradient of 15 feet per mile should therefore be indefinitely increased.

Thus, with one exception, the whole series fall into a consistent stream profile from the moraine region to the sea, the grade becoming more gentle and the material more fine with increasing distance from the moraine. The exception noted is the high gravel at Aberdeen, 90-95 feet above tide. Nothing more than slender hypothesis can be advanced for the occurrence of this gravel, and since its presence is not believed to affect con-

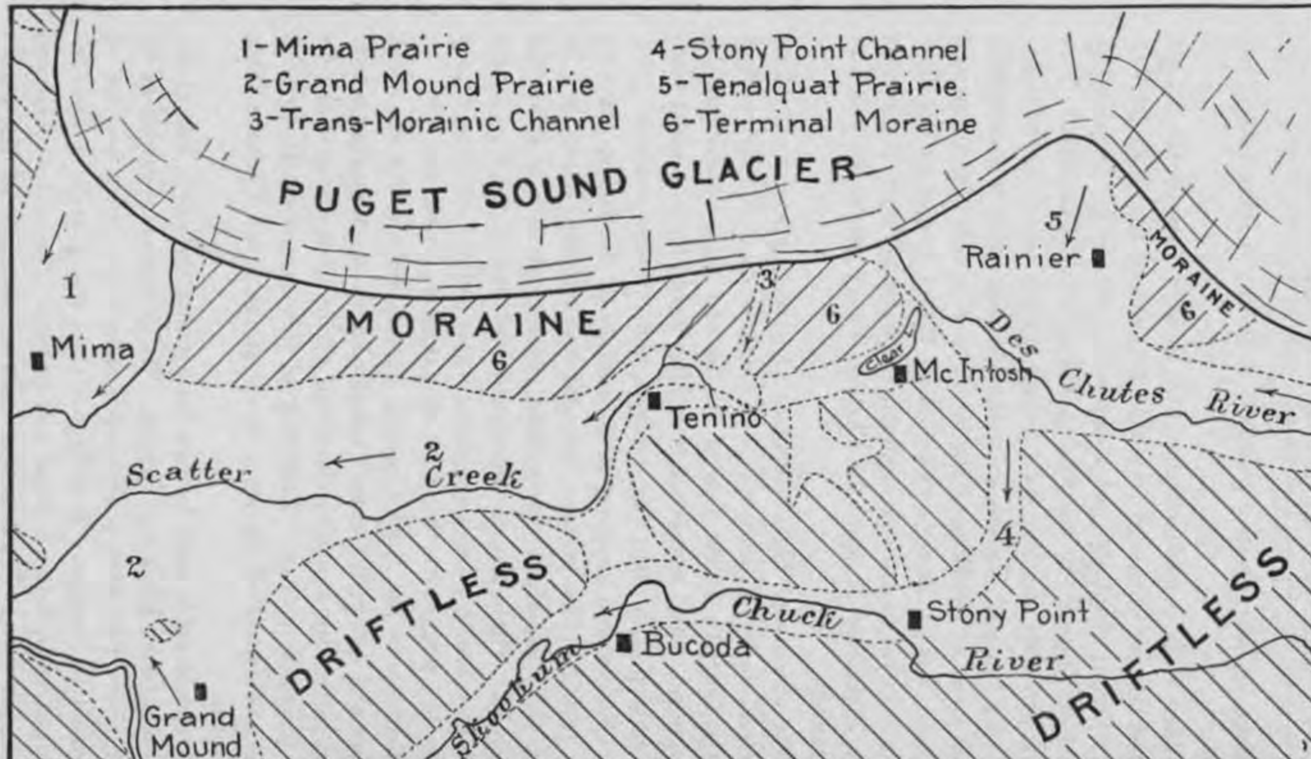


FIG. 3. Glacial Drainage from the Eastern Lobe of Puget Sound Glacier, during building of Mima and Tenalquat prairies. Arrows indicate drainage courses of this stage.

clusions on our present problem, it is not further considered here.

When it is considered that the western lobe of the Puget Sound Glacier advanced to within 15 miles of the Chehalis Valley, where it stood 400 feet above tide, a reason for the original great development of the Satsop Valley train is apparent. This train probably reached the Chehalis Valley before those entering at Elma and Malone, since the Matlock route was doubtless much lower at the close of the interglacial epoch of erosion, and perhaps was a through valley from Puget Sound to the Chehalis. At maximum development, the Satsop Valley train must have effectively dammed the Chehalis Valley above the point of entrance.

The absence of higher terraces of glacial gravel in the Cloquallum Valley is taken to mean that its train did not extend to the Chehalis at the time of the Satsop train's maximum development. Had it done so, trenching would have resulted when the Satsop train dam was removed, and terraces would be present. Subsequent lowering of the surface of the Satsop train by less heavily laden waters, brought the outwash dam down so that the Cloquallum train could extend out to and down the Chehalis. There was no subsequent lowering of the Cloquallum train, presumably because glacial water did not continue to use the valley much after the time of maximum deposition.

Terraces in the Mock Chehalis gravels, both within the creek valley and out in the wider Chehalis Valley are thought to have been caused by a similar damming of the Chehalis at Elma by the Cloquallum train. Lowering of this barrier by the glacial Chehalis permitted the lower levels of the Mock Chehalis train to form.

A considerable sand terrace lies against the north side of the valley between Elma and Satsop. Its altitude is recorded as 90 feet above tide with considerable chance for error because of barometric changes. It is higher than the gravels of the Cloquallum train between Elma and Satsop. Since stratified sand is almost never found in the outwash deposits of the Puget

FIG. 1. Large Intermound Area on Mima Prairie.

FIG. 2. Typical Mounds on Mima Prairie.
Foreground a portion of Plate VIII. Sparing development of intermound pebbles.

Sound Glacier, some special conditions presumably operated to produce this terrace. It is here noted because a possible cause may have been a slackened current, or ponded water, produced by the Satsop train dam in the Chehalis Valley.

The summit of the prominent flat-topped spur of old red gravel in the eastern angle between the Satsop and Chehalis valleys has an elevation of 130 feet above tide, and its surface gradually ascends northward along the Satsop. It is lower than the levels of the red gravel terraces of the vicinity, and 40 feet below the profile of the highest level of the Satsop Valley train at this place. It is therefore to be considered as the product of stream erosion in the destruction of the Satsop train. No fresh pebbles, however, were found on it, as should be expected. More careful search should find them.

Economic Phases of the Chehalis Glacial Gravels. The rock of the Chehalis basin is Tertiary sandstone and shale, and Tertiary or younger basalt. The sandstone is fine grained and does not form a very sandy soil on disintegration. The residual material resulting from the decay of these rocks is sandy loam or clay.

The agricultural development of the country is demanding highways which are passable in the rainy winters. These are never secured from the residual soils, however well graded and drained. The roads must be graveled or surfaced with crushed rock. The latter is too expensive for the more sparsely settled parts of the valley.

Locally, the old red gravels are excavated for road construction. They soon pack and turn water fairly well, but are so soft that they wear rapidly. Indeed, from the very first they fail to give the sharp crunch to hobnailed shoes or iron-tired wheels, which good road gravel gives. The contrast is much the same as that between the noise of traffic on a brick and an asphalt pavement.

Stream gravels have been considerably used for road construction, but their lack of fine material renders them difficult to pack, and hence unsatisfactory.

As a consequence of these factors, the glacial gravels of the Chehalis Valley are of great value. Hundreds of pits have been opened in them, from mere roadside excavations to the ambitious exploitation of the Ford Prairie pit, covering several hundred acres, which is owned jointly by the Oregon-Washington Railroad and Navigation Company and the Chicago, Milwaukee and Puget Sound Railway. The glacial gravels have thus suffered a secondary distribution by man into linear patterns of diverse character. In the cities of Aberdeen and Hoquiam, they have been distributed in rectangular patterns over the residual red clay of the region; on the country roads, they radiate in general from the river; in the Black Hills they have entered Cedar Creek as the ballast of a logging railway, where the glacier just failed of pouring them through as a valley train from the north, and on the railroads they have been disposed in long ribbons across miles of country where they once existed ere post-glacial erosion removed them, and over divides into regions whither they could have been carried only by man.

VASHON GLACIATION AND THE COWLITZ VALLEY.

Mineral Lake Gap. As noted in the opening paragraphs of this chapter, there are two passes into the Cowlitz River Valley from the north through which drainage from Puget Sound may have entered at the time of maximum glaciation. One of these is the valley lying between Mount Rainier and the Huckleberry Mountain group. The Tacoma Eastern Railway uses it to reach the "Big Bottom" country of the Cowlitz, making this agricultural region tributary to a Puget Sound city. The valley north of the pass is occupied by Mineral Creek, tributary to the Nisqually, the valley south of the pass is occupied by Tilton River, tributary to the Cowlitz. The existence of Mineral Lake in the valley suggests glacial occupation, and a plausible hypothesis, in absence of field study, would be that Puget Sound glaciation was responsible for its existence. Examination of the Nisqually Valley between Eatonville and Park Junction shows a definite southern limit to the Puget Sound ice at LeGrande, as stated in the preceding chapter. The Nisqually Valley, for a few miles above that place, possesses very few traces of former glaciation. The same is true of the valley of Mineral Creek as far up as the lake. Mineral Lake lies in a valley tributary to Mineral Creek, dammed by a moraine which crosses the major valley also. Granite is abundant in it but does not exhibit the wide range of character shown by the granitic bowlders of the Puget Sound drift. This moraine with other till deposits farther south, is to be referred to glaciers from Mount Rainier. The col between Mineral Creek and Tilton River is 1660 feet above tide. It is a broad, drift-filled valley, but it was doubtless closed by Mount Rainier ice long before the Puget Sound Glacier crowded up on the north slope of the Bald Hills, in a position where it might conceivably have sent a valley train over to the Cowlitz. Further, the altitude of the col is about 400 feet above the highest Puget Sound drift about LeGrande, so that, even if the Nisqually Valley up to Park Junction and the Mineral Creek-Tilton River valley had been open, it is doubtful if drainage would have flowed across.

Napavine Divide. The lowest place in the divide between the Chehalis and Cowlitz Rivers lies in the axis of the great structural valley of which the Puget Sound region is a portion. The village of Napavine, 444 feet above tide, lies near its lowest point and 11 miles south of Centralia, where the outwash gravels which entered the Skookum Chuck reached the Chehalis. At Centralia, these gravels lie 188 feet above tide and constitute the valley filling on which the city is built. But they hardly reach beyond the city limits, and no trace of Puget Sound gravel has been found south of this place, save where man has obviously transported it. The divide lies about 250 feet higher and, almost without further consideration, might be dismissed as a possible route for glacial outwash from Puget Sound. Railroad cuts across it give positive evidence that only a deep residual soil occupies the divide.

Newaukum River Col. A great outwash filling occupies the Cowlitz River valley below Mossy Rock. In the vicinity of

Ethel it is several miles wide, and wells 150 feet deep fail to penetrate through it. It constitutes an almost flat divide between Lacamas Creek and Newaukum River, and its gravels were carried down the latter toward the Chehalis.

Thus we find that no outwash from Puget Sound glaciation ever crossed to the Cowlitz Valley, but on the contrary, drainage from the south side of Mount Rainier actually invaded the province of the Puget Sound Glacier.

CHAPTER IV.

VASHON RECESSIONAL MORAINES AND ATTENDANT OUTWASH.

SYNOPSIS.

REGION OF FRONTAL MORAINES.

The great relief of much of the Puget Sound basin was unfavorable to the development of distinct moraine ridges. As a consequence, they are well developed only (1) on the upland plains between the Sound and the Chehalis Valley, and about Matlock, and (2) on the lower plains in Whatcom County, near Bellingham. Their complete absence elsewhere seems to indicate that there were no long pauses as the edge of the ice retreated northward. The absence of frontal moraines was noted by Willis in 1897.

RECESSIONAL MORAINES AND OUTWASH OF THE EASTERN LOBE.

Introductory. For the successful delineation of the systematic relations of moraine ridges, a forested country is about the last place to choose. Since much of the Puget Sound region possessing these moraines is densely wooded, the data herewith presented, and the correlations suggested, are to be considered as the result of reconnaissance only.

Except the Bellingham area, the recessional moraines lie so close to the terminal moraine of Puget Sound that they might almost be considered as parts of that moraine belt. But changes of some magnitude in the drainage during the early stages of retreat, and in the outline of the glacier's margin, are thought to justify the use of the term "recessional."

The belt of recessional moraines extends from near Orting and Kapowsin on the east to Little Rock on the west, lying throughout on the Puget Sound drift plain. Its one great feature is an interlobate moraine, the most massive moraine of Puget Sound, which records the resolution of the eastern glacial lobe into two during retreat.

Intra-morainic outwash plains and drainage channels offer the best data with which to work in any attempt to resolve the recessional moraine ridges of Puget Sound into a sequential scheme. They have been relied on entirely in the present chapter.

When the glacier was at its maximum, four different routes carried escaping waters from its eastern lobe to the Chehalis River; the Stony Point channel, the outlet of a small glacial lake just south of McIntosh, the Tenino-Bucoda route, and the Gate Pathway. The Stony Point channel, so named from Stony Point schoolhouse where this valley train enters the Skookum Chuck, received all drainage from the entire glacial margin east of it at maximum advance, and remained in use during the early stages of retreat. The glacial lake outlet and the Tenino-Bucoda route soon ceased to carry glacial water, while the Gate Pathway remained a drainage line as long as the glacier kept the basin closed north of the Olympic Mountains. (See Plate XXIII for areal distribution of moraines and outwash.)

Tenalquat and Rocky Prairie Outwash. Tenalquat Prairie is a gravel plateau, several square miles in extent, lying north of the village of Rainier. Its surface is disposed in great terraces running east and west, the series descending northward. In general, the surface of each terrace has a westward slope. The highest and largest plane surface of the prairie descends

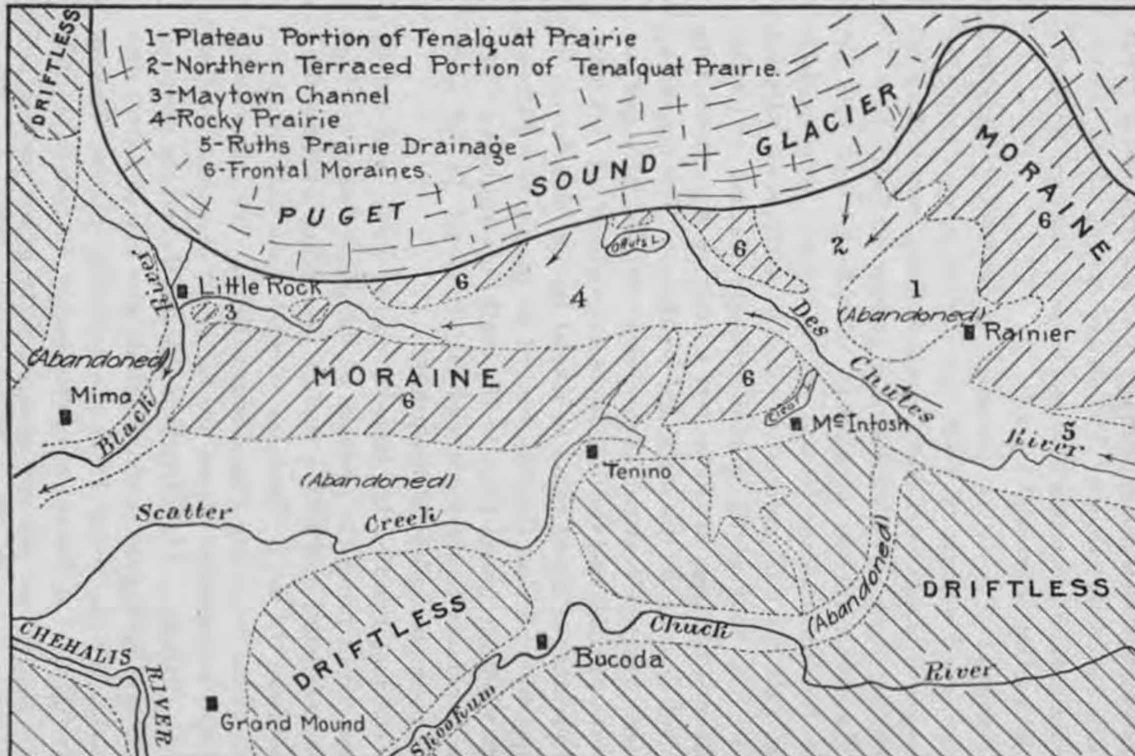


FIG. 4. Glacial Drainage from Eastern Lobe of Puget Sound Glacier, during building of Rocky Prairie. Arrows indicate drainage courses of this stage.

southwestward. The faces of the steep descents between the terraces are in some places clean cut erosion scarps, and in others definite ice contact slopes. The eastern margin of the prairie, like the northern, descends by broad terraces which are separated by ice contact or erosion slopes.

Tenalquat Prairie is composed of horizontally stratified gravel, good sections of which are exposed in cuts along the Chicago, Milwaukee and Puget Sound Railway, west of Rainier, where the depth of such material is at least 50 feet.

The prairie reaches a maximum altitude of about 510 feet near the northeastern portion of its highest plane surface. This wide tract of unforested country overtops all adjacent land. The floor of the glacial drainage channel on which Rainier is built lies at the foot of an abrupt slope descending 70 feet or more to the south and southwest. The descending eastern and northeastern slopes from this high plane are covered with till, and the flora is characteristic of till. Further, the presence of bowlders up to several feet in diameter on the slopes, makes it clear that the front of the glacier rested against them while the gravel plain to the south was aggraded. Morainic surfaces to the north and east lie about 75 feet lower than the highest plane of the prairie.

Tenalquat Prairie, thus bounded on the north and east by slopes which prove the presence of the glacier when the high plain was built, and with a surface descending southwestward away from the ice, is clearly an outwash plain built up at the front of the retreating Puget Sound Glacier. The steep southern and southwestern slopes are the result of erosion by later glacial drainage. The altitude of this prairie and the direction of slope of its highest portion, indicate that glacial waters were escaping by the Stony Point channel when it was formed. (See fig. 3). A descent of approximately 50 feet to the mile exists between the southern margin of the gravel plateau and the present col in the Stony Point channel. The gravel filling probably once continuous across this interval, has been removed by subsequent glacial drainage in the development of

FIG. 1. Mounds on the Northern Portion of Mima Prairie.

FIG. 2. Kettle among Mounds, Mima Prairie.
A few faintly developed mounds lie on slopes and bottom.

the Rainier channel, and by the post-glacial erosion of the Des Chutes River.

That the original gravel filling between Tenalquat Prairie and the Stony Point channel did not possess a gradient of 50 feet to the mile is shown by the slope of the highest level of the prairie, which probably does not exceed 20 feet to the mile. If Stony Point channel received drainage from Tenalquat Prairie, the present low col could not have existed at the time.

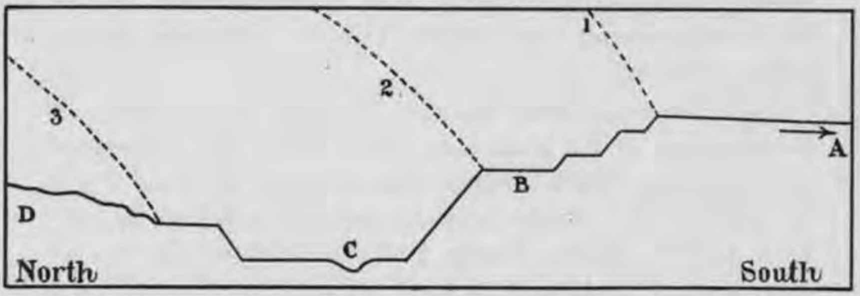


FIG. 5. Diagrammatic Cross-section of Tenalquat Prairie.

A. Plateau portion. Waters flowing southward to Stony Point Channel. Glacier front at 1.

B. Terraces of Northern Slope. Waters flowing westward to Rocky Prairie (toward observer). Glacier front at 2 when individual terrace above B, and ice-contact slope from B to C, were formed.

C. Marginal Drainage Channel for ice at 3, discharge westward to Rocky Prairie.

D. Moraine.

The ice front immediately west of Tenalquat Prairie reached its maximum position a mile south of McIntosh on the rock hills of that region, 650 feet above tide. The valley of Clear Lake at McIntosh was exposed by ice retreat only after the highest levels of Tenalquat Prairie had been aggraded and after the Stony Point channel had been lowered by the erosion of less heavily laden waters. The altitude of the col at the west end of this valley is but little above 350 feet, and the Tenino Valley is a westward continuation of the same axial line. But the abundant outwash gravels about Tenino were not carried through the Clear Lake valley. No evidence is known that glacial waters ever used this valley as a drainage route. Its altitude appears to have been just enough higher than that of the Stony Point channel to keep it free from the invading gravels. Not until the glacier had withdrawn from the northern slope of the moraine which is banked up on rock hills from McIntosh to Tenino, did glacial drainage abandon the Stony Point channel.

The lower route then exposed led westward across Rocky Prairie, and through the Maytown channel to Rutledge and Mima prairies, south of Little Rock, there crossing the moraine and entering the Chehalis Valley a few miles farther south. (See fig. 4.)

Glacial drainage from the east, crossing the southern and lower portion of the plain, soon cut a channel that separated the Tenalquat Prairie gravels from the head of Stony Point channel (fig. 4). To this later drainage course belong the outwash plains of Smiths Prairie, Ruths Prairie and the channel floor on which the town of Rainier stands.

Terraces rise above the eastern end of Rocky Prairie. South of Lake Offut they are 285 feet above tide on the northern flanks of the moraine, 15-20 feet above the adjacent prairie level. Rocky Prairie thus was aggraded to a higher level by early glacial drainage and eroded by later drainage at its head to the depth indicated. Many outwash areas of the Puget Sound Glacier record the same glacial history of early maximum deposition, and subsequent removal of a portion of the deposit. Such has already been noted for the outwash about Tenino and on the Mock Chehalis and Satsop valley trains. It will be seen to be true also of Tenalquat Prairie, Mima Prairie and other outwash areas.

The minor trans-morainic channel a mile and a half east of Tenino (fig. 3) had no part in the history of the Rocky Prairie outwash. It is a narrow valley without gravel terraces, with a swampy floor and with its col 335 feet above sea level. This altitude shows that drainage from Tenalquat Prairie never used this route, which obviously was of but local importance.

By the time that retreat of the ice had opened Rocky Prairie as a drainage route, the front of the glacier had withdrawn from the northern scarp of Tenalquat Prairie plateau, and drainage which issued from its retreating edge built the successive terraces that characterize the northern part of Tenalquat Prairie. Each terrace is genetically a broad valley floor, possessing but the southern wall, the ice having formed its northern side. (See fig. 5.) The series, descending in order toward the north is to be correlated probably with the terraces of Rocky Prairie. There is a slope of nearly 50 feet to the mile between the first terrace on the northern descent from the Tenalquat plateau, and the highest terrace of Rocky Prairie to the west. As on the south side of the plateau, so on the west, the later work of glacial and postglacial drainage has isolated Tenalquat Prairie from the gravels which lie farther down the former courses of drainage.

West from Rocky Prairie, glacial waters converged into an irregular channel among moraine hills, leading to Rutledge and Mima prairies, and constituting the drainage route here described as the Maytown channel. [This is shown on Plate XXIII and fig. 4.] Locally, as at Maytown, small prairies exist on the outwash gravel in the channel, though swamp and forest cover much of this drainage course. The Maytown channel is now drained by Beaver Creek which enters Black River at Little Rock.

The Interlobate Moraine, and Drainage under its Control. Fragments of recessional moraine lie north of Rocky Prairie and Walricks Prairie, and probably indicate positions of the glacial margin while the drainage was following the courses mentioned above. North of Tenalquat Prairie, the morainic surface gradually becomes more pronounced until it reaches a maximum altitude of 200 feet above the plain, in a great spur of morainic hills projecting northward between Lake St. Clair and the Nisqually River. The material of these hills is till. Erratic bowlders of granite are common, and lakelets, bogs, and undrained depressions among short, choppy hills characterize the topography. No outcrops of bed rock are known by residents of the region who are familiar with these hills. This northward projection of the moraine, graphically shown on accompanying maps, (Plates XXII and XXIII and fig. 6) records a considerable indentation in the glacial margin, in which deposition took place from the ice on both sides, forming the interlobate moraine.

As long as the glacier lay against this high moraine deposit, which is the greatest produced by the Puget Sound Vashon Glacier, glacial drainage from the east was forced to pass south of Tenalquat Prairie and across Rocky Prairie to the Maytown channel. When the ice retreated from this spur, a lower pass was opened around its northern end for the water coming from the glacier margin and from local drainage east of this point. The Rainier channel, Walricks Prairie, and the east end of Rocky Prairie were abandoned, and a new gravel plain was built, lying along the eastern flank of the high morainic area. See fig. 6. The portion of this plain which is now treeless, is known as Yelm Prairie. The water flowed toward the northwest, and aggraded a plain whose slope is not more than 15 feet to the mile. The altitude at the northern angle of the interlobate hills is about 270 feet above the sea. The course of the current, after rounding this spur, was southward for a few miles, turning west again near the southern part of the Wm. White donation claim, and continuing thence to the present course of the Des Chutes River.

During the earlier period of this drainage, a gravel plain was built along the route described, to the northern end of Rocky Prairie. The northern end of Rocky Prairie is too high, however, to allow correlation with the 270-foot terrace north of the moraine hills near Lake St. Clair, and must be considered as a deposit of waters directly from the ice.

Later use of this drainage route from Yelm Prairie and Lake St. Clair, developed a definite channel from the prairie land occupied by the Wm. White donation claim, to the course of the Des Chutes. All drainage from the Puget Sound Glacier east of this channel and from Mount Rainier (except the Cowlitz River) flowed in the clean cut old river bed now occupied by Spurgeon Creek. (See fig. 6.)

Another northward projecting morainic area exists west of Rocky Prairie, and in a way similar to that already described, the glacial drainage found its lowest route north of the hills. On the west side of this second moraine spur, the waters spread out a broad, flat gravel plain in the vicinity of South Union. Between this place and Little Rock, the country is level and except where ditched, is covered with swamp. It is doubtless an outwash plain of exceptional flatness, and is probably composed of material finer than the prevailing gravel.

The high morainic hills lying north of Tenalquat Prairie, which controlled the formation of Yelm Prairie and the deposition of outwash south of Lake St. Clair, are interlobate in origin. The ridges which compose them in their northern and most emphatically morainic portion, lie parallel to the two sides of the acute angle which the moraine mass forms. The water which flowed northward along Yelm Prairie directly toward the ice front met some obstacle which does not now exist, namely, the glacier itself, and turned it back to the south for three or four miles to the Spurgeon Creek course, whereas lower surfaces at present lie farther north. Two morainic hills lie on the north side of this southward loop, and doubtless mark the position of the ice front when it had first withdrawn from the interlobate deposit.

There is difficulty in mapping moraine and outwash areas in the northern part of Thurston County. Relief of the morainic tracts is slight in most places, and they may bear but a thin outwash gravel cover and yet be effectually concealed unless excavations reveal their true nature. Kettles cannot be taken as criteria for distinguishing between moraine and outwash because they are common in areas of deep outwash gravels. Both topography and soil may fail to distinguish the two types, and, how-

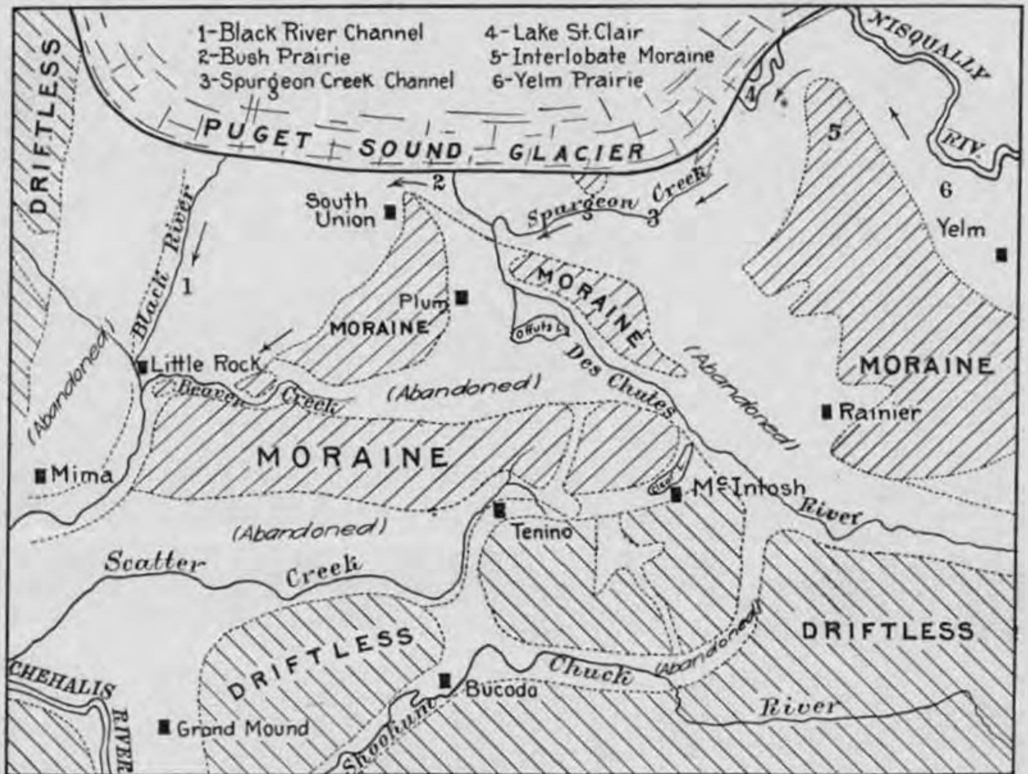


FIG. 6. Glacial Drainage from the Eastern Lobe of the Puget Sound Glacier during the building of Yelm Prairie.
Arrows indicate drainage courses of this stage.

ever the present mapping may delineate the respective areas, it is probable that succeeding students of the region will disagree with it.

Recessional Features in Pierce County. East of the Nisqually River little record has been found of varied and changing conditions during glacial retreat from the terminal moraine. Much of the region is heavily forested, and roads across it are few. On the whole, the region between McKenna, which is 7 miles east of Rainier, and the Ohop Valley may be characterized as ground moraine, and an area south of McKenna and west of the Nisqually River also possesses this character. The Ohop Valley and Yelm Prairie alone give data on which to base conclusions regarding the position of the ice front. These will be considered presently.

Morainic elevations just west of Eatonville rise 150 feet above the outwash on which the town is situated. They are situated with longer diameters east and west, and are probably of recessional moraine character. Their parallelism with the southern drift boundary and entire indifference to the much nearer eastern margin of the Puget Sound drift which lies at a right angle to their course, indicates that the Puget Sound Glacier was not wasting on its eastern margin in a way at all comparable with the retreat of its southern edge. These elevations near Eatonville constitute the only known recessional moraine deposits in this part of the country. From here northward and northwestward the country is apparently a uniform plain of till, here and there incised by minor glacial drainage lines. The region is traversed from north to south in its central part by the Mount Rainier highway. Another good road between McKenna and Eatonville allows examination of the region. To the north, and at a lower altitude, lie the great Steilacoom outwash plains of Pierce County, situated northeast of all outwash thus far described in this paper. Ascent from the Steilacoom plains, most of which are prairie, to the densely forested till plain, is in many places over definite morainic ridges whose orientation parallels the line of contact between gravel and till.

An ascent of 200 feet is made in one mile on the Mount Rainier highway, over morainic country, on the northern margin of the till plain. South of Muck and three miles west of the Mount Rainier highway, sharp, morainic ridges exist, bearing small kame-like hills of gravel on their southern slopes. Again, between Roy and McKenna a series of at least three till ridges lies east of the Chicago, Milwaukee and Puget Sound Railway, trending NNE-SSW. Their trend is out of harmony with evidence from the outwash as to the position of the edge of the ice on this area, as will be shown a little later.

The till plain east of McKenna on the Eatonville road is abundantly strewn with angular granite bowlders. Recent road grading has left them freshly exposed in a region where a heavy growth of lichen and moss ordinarily effectually conceals the character of roadside bowlders. A few cuts in the construction of the road show the characteristic Vashon till of the Puget Sound Glacier.

To understand the correlation here attempted between moraines and outwash of this region, and the same of that portion of Thurston County already described, lying west of the Nisqually River, a bit of glacial lake history must be considered. From Orting northward, the Puyallup River flows in one of the troughs of the interglacially eroded topography which Vashon glaciation failed to obliterate. Being a northward trending valley, it held a marginal lake while the glacier withdrew along its length. This lake, named from the river now flowing in the trough, first had its outlet into the Ohop Valley, which then carried the discharge from the White, Carbon and Puyallup rivers in addition. But most of the western margin of the Puyallup trough is lower than the col in the Ohop Valley south of Lake Kapowsin, and to hold the lake and the rivers named to this course, the ice edge must have lain as far south as Orting. (See fig. 7.)

Now the altitude of the Ohop Valley floor where crossed by the Mount Rainier road near Eatonville, 465 feet, allows a descent of about 10 feet to the mile from this crossing to the

FIG. 1. Rocky Prairie Mounds with Intermound Cobbles.
Vashon terminal moraine in the distance.

FIG. 2. Rocky Prairie Mounds.
Small moundless tract at the left.

lowest terrace of the glacial Nisqually at McKenna. This terrace lies too low to be correlated with the 270-foot terrace on the northern spur of the interlobate moraine, and hence is younger than the Spurgeon Creek channel, itself younger than all other outwash features of Thurston County thus far described.

It thus may be concluded with some degree of confidence that the Puget Sound Glacier hugged the northern flank of Mount Rainier, not retreating north of Orting, until the morainic lake region of Thurston County was exposed by the retreat of the ice. Chambers Prairie, just south of these lakes, is thought to have carried the drainage of this time west to Bush Prairie and the Black River channel.

The correlative of Yelm Prairie is found in Nisqually Prairie on the east side of the Nisqually River. The river valley between these two prairies is younger than the deposition of the gravels and is consequent on the northward slope of a once continuous outwash plain. The erosion of this valley has divided the original plain into two longitudinal portions, constituting Nisqually and Yelm prairies respectively.

From the grade of the outwash gravels on both sides of the interlobate spur west of the river, the ice front is known to have possessed an acute re-entrant angle in this part of the eastern lobe. Persistence of this angle as the front of the glacier retreated is indicated by phenomena of Nisqually Prairie, described in the following paragraph.

Along the northeastern side of this prairie, sharp crested hills of Vashon till rise in three or four groups above the gravel plains. They separate Nisqually Prairie from the broad Steilacoom gravel plains farther northeast. Through the gaps between these groups, outwash gravels appear to have been poured laterally onto Nisqually Prairie whose descent is toward the northwest, at right angles to the direction of this tributary flow. Only with ice well removed from the lake country of Thurston County, could glacial drainage on Nisqually Prairie flow so far toward the northwest; and only with the ice front resting on or directly behind this linear series of moraine hills, could glacial drainage have been poured simultaneously from the gaps among them onto Nisqually Prairie. Unless error has been made in observation, the conclusion is valid that there is here recorded the eastern side of the re-entrant angle which developed early in the retreat of the larger lobe of the Puget Sound Glacier.

In Pierce County, further retreatal stages of the glacier are poorly recorded. The great predominance of outwash gravel on the Steilacoom Plains south of Tacoma, is the striking feature of the topography. Since they are uninterrupted by morainic eminences, it has not been possible in this study to differentiate them in the manner which has been attempted for the outwash of Thurston County. Their northern portion will, however, be discussed in connection with the glacial lake history, in which the area played an important part.

INTRA-MORAINIC OUTWASH OF THE WESTERN LOBE.

The difficulty of examination of the region occupied by this lobe has been noted in the chapter on the terminal moraine. In four traverses between tidewater of Puget Sound and this moraine, covering about all the routes of travel which exist in the region, no recessional moraines have been found.

Outwash plains back of the moraine of the western lobe are identical in almost all details with outwash of the eastern lobe. There is the same clean, well-rounded gravel of perfectly fresh appearance in sections, and the same topographic disposition in terraces, with low gradients of the plane surfaces. These plains, unlike the plains of the eastern lobe, are forested, but the forest is thin. It consists of a scattered stand of fir, with the forest floor entirely free from bushes or young trees in many places. From an agricultural view point, the country is nearly hopeless. There is no inhabitant for 11 miles along the road between Matlock and Shelton, and for 15 miles no stream is crossed by the road.

Basalt hills rise above the ground moraine and outwash about the headwaters of Shelton and Goldsborough creeks, and completely enclose Gosnell-Mill and Little Skookum creeks south and southwest of Shelton. They may be considered as a low northern portion of the Black Hills.

The western lobe of the glacier discharged its drainage into the Satsop and Cloquallum valleys across a summit altitude of approximately 400 feet, while drainage from the eastern lobe crossed the terminal moraine on a floor no higher than 175 feet, at the beginning of retreat. It is therefore to be expected that when the ice of the re-entrant angle about the Black Hills withdrew to an altitude below about 350 feet, the lowest glacial channel known across the Matlock Pathway, diversion of the drainage of the western lobe from the Satsop to the Gate valley train would follow. But the hills above described beneath the ice at this re-entrant angle offered successively exposed barriers, so that not until the interglacial valley of Shelton Creek was ice-free, did the diversion result. And because the open valley of Shelton Creek became an arm of Lake Russell as soon as cleared of ice, all outwash gravel carried southward by the shifted currents came to rest in a great delta whose lakeward face constitutes the northern valley bluff at Shelton. About 15 miles of standing water in Lake Russell intervened between the Shelton delta and Black River channel, by which drainage of the western lobe reached the Chehalis at Gate.

By the time this diversion occurred, the whole history of the eastern lobe reviewed in this chapter had been consummated, and the succeeding history of the glacial lakes was being enacted. The tardy recession of the western lobe of the ice may find explanation in its more northern location and its somewhat higher altitude. It is also to be noted that the region of the western lobe receives at present about 30 inches more rain annually than the region covered by the eastern lobe. If a similar greater precipitation prevailed during the Vashon glaciation and came in the form of snow, it should have effectively retarded retreat of the western lobe.

In adjustment to the new and lower levels, only those intramorainic gravel plains lying between the Skokomish River and

Shelton Creek were altered. A persistent terrace scarp along the road from Scotts Prairie, northwest of Shelton, to the Skokomish River is attributed to such adjustment by glacial drainage from the head of Hoods Canal to Shelton. The scarp possesses features which no ice-contact slope or delta face could have, and lacks characters they should possess. Terrace scarps descending eastward, are crossed between Scotts Prairie and Lake Nahwatzel, and are thought to be attributable to the same cause. The later changes on the gravel plain between the Skokomish River and Shelton belong properly to the history of the glacial lakes, and will be discussed under that subject.

MORAINES NORTH OF THE CASCADE MOUNTAIN SPUR OF THE PUGET SOUND BASIN.

THE WHATCOM COUNTY MORAINES. The plain region of Whatcom County lies west of the Cascades and north of the spur of mountainous hills which were described in the introduction as interrupting the Puget Sound basin. It is included in the Blaine and Sumas quadrangles of the U. S. Geological Survey, and its topography is almost entirely determined by ground moraine and by the post-glacial alluvial deposits of the Nooksak River. A few areas exist where the glacial till has been left in true frontal moraine ridges, among the first to be built in the retreat of the Puget Sound Glacier after those of Pierce and Thurston counties.

A moraine ridge begins southeast of Ferndale and extends northeastward for five miles, passing just south of Laurel. Another moraine ridge lies immediately east of this. Other morainic areas, somewhat scattered, occur along the Bellingham Bay and British Columbia Railroad, near Wahl and Goshen, and also close to Clearbrook and Sumas. Yet other areas of similar character lie between Nooksak and Geary School (Damtown).

The Laurel moraine is the one of most interest. Its orientation affords a clue to the form of the Puget Sound Glacier's front on withdrawal from the mountainous interruption of the basin. The moraine's ground plan describes a curve, with its concavity to the north. The heavy frontal moraine deposits on the eastern face of the large interglacial hill west of Ferndale, together with the Laurel moraine, give a complete outline for this portion of the front of the glacier. It indicates that the ice was moving almost directly from the north when the deposits in question were formed.

Corroborative evidence for this conclusion is secured from glacial groovings on the Chuckanut sandstone in the southern part of the city of Bellingham, the trend of which is magnetic north and south. An element of doubt remains as to exact direction of movement because it could not be determined whether the edges of outcropping strata were responsible for the exact direction taken. In general, however, the ice must have moved approximately south in production of the groovings.

Another item of considerable interest attaching to the Laurel moraine is the fact that marine shells occur in it. An isolated moraine hill two miles west and one mile south of Laurel was opened some years ago under the impression that it was a drift-covered rock outcrop, with the hope of finding coal which exists in the Tertiary sedimentaries of the region. The tunnel which was driven penetrated a stony hardpan so firm that no timbering was required. Clam shells were reported as occurring in large numbers in this till. The writer picked up a few fragments of barnacle shells from the old dump of the tunnel.

Half a mile south of Laurel, a gravel pit has been opened in the same moraine. The section thus made shows about three feet of Vashon till at the top, very like that near the surface in the most southern deposits of the Puget Sound Glacier. Below it is three feet of a stony clay, different from the overlying till. It contains sand and gravel, but has no foliation like the overlying till. Instead, it is cut by roughly vertical, crudely conchoidal joints, along which the clay parts on drying. These surfaces are stained a dull purplish-brown by percolating water, the clay elsewhere being gray. Besides their prevailing verticality, these joints also radiate to a minor degree in all directions from the larger pebbles in the mass. A sharp line of contact exists between the till and this clay. In the clay were found a number of fragile marine shells, some with the valves still attached.

Beneath the shell-bearing clay is stratified sand, and beneath this in turn is the gravel for which the pit was opened. The gravel is undoubtedly of Vashon age. It shows foreset beds which dip toward the south and southwest. The upper surface of these beds was irregularly eroded by running water before deposition of the overlying sand. All these evidences indicate that the moraine was subaerially deposited, and the included marine shells of the peculiar clay apparently must be explained as having been plowed up by the glacier. The shell-bearing clay, therefore, is a till of peculiar facies. Further discussion of this subject will be found in Chapter X, in connection with data on shell-bearing ground moraine of the region.

THE SAN JUAN COUNTY MORAINE. The rocky San Juan Island group, constituting the county of the same name, lies in the line of prolongation of the Cascade Mountain spur which is south of Bellingham. As a rule, the drift deposits of these islands are limited to the valleys. Ground moraine, however, constitutes a large part of Lopez Island, and is present on much of San Juan Island. But the only topographic features of considerable relief which are composed of glacial drift, occur on San Juan Island.

Cattle Point, the most southeastern tip of San Juan Island, is an elongated peninsula trending a little south of east. It bears a triple crested hill of drift near the end, rising nearly 300 feet above the sea at its foot. Between the hill and the main part of the island is a ridge of drift, less than half the height of the hill.

The Cattle Point hill (Pl. XX, Fig. 2) is forested only on the northern slope, and the ridge is completely treeless. The soil where the forest has failed to grow is gravelly, and bears the flora of the outwash prairies south of the Sound. On the northern slope, borings with soil auger by Mr. Geo. B. Rigg of the University of Washington have shown the presence of a clayey gravel or till beneath the forest humus.

A seacliff along the southern foot of the hill shows the surface gravel to attain depths of 20 to 50 feet. Below it is a zone of intimately mingled till and gravel strata, the product of water escaping in the presence of glacial ice. Vashon till of typical facies appears beneath this zone, and in turn, rests on strongly glaciated country rock, with grooves as much as six inches deep. Plucking has interrupted the grooves to some extent.

The gravelly southern face of this great hill of Vashon drift is interpreted as having been originally a steep alluvial fan built on a frontal till ridge at the debouchure of a glacial stream. The gravel in the seacliff shows an imperfect and variable southward dip, which is never as steep as the foreset structure of a delta. It is believed to be the original alluvial fan bedding. The till on the northern slope records the ice wall against which the deposit was banked.

The ridge which connects the trifid hill with the main part of the island constitutes the most perfect frontal moraine in the Puget Sound country. Its southern slope is an outwash apron of more gentle descent than that of the Cattle Point hill. It bears many large bowlders strewn over the surface. The northern slope is steeper and is similarly bowlder-strewn.

This moraine ridge was the site of the American military camp during the years when Great Britain and the United States held joint possession of the islands. Excavation for the earthworks thrown up in 1859 exposed till which has never subsequently become covered with vegetation.

A few miles north of the Cattle Point moraine, and within a mile of the town of Friday Harbor, is South Hill, almost a replica of the Cattle Point hill, except that it has not the trifid crest. Its southern slope is composed of treeless prairie gravel, and its forested northern slope is composed of till. Till intimately associated with the gravel is shown in a seacliff on its southern slope. No moraine ridge is associated with it, as with the Cattle Point hill, and it is considered to record a briefer pause of the retreating edge of the ice.

The absence of forest on the southern slope of these two hills has been explained as due to the strong winds from the broad Straits of Juan de Fuca, to which these slopes are exposed. The trees at the crest are gnarled and wind-twisted, and the wind is certainly of some importance in the ecological problem involved. It is here held, however, that the difference in soil on the two slopes is the chief cause for the distribution of the forest. The moraine ridge of Cattle Point, with a gravelly soil on both slopes, is unforested, and the rock hills of the islands are forested on all slopes alike. The gravelly slopes are treeless for the same reason that the outwash plains south of Puget Sound are prairie.

The San Juan Islands exhibit many fine illustrations of striated rock surfaces. Space cannot be given to a catalogue of them, and such is not necessary, since all known striae and grooves trend between true north and south, and magnetic north and south, a range of 24°. The Cattle Point moraine lies at right angles to this direction, as is to be expected. The great glacier which overrode these islands, overtopping even Mount Constitution, 2,409 feet above tide, had a dominant southward movement toward Puget Sound, a movement recorded alike on the broad top of Mount Constitution, and on the rock shores of the island group.

FIG. 1. Mounds of Rocky Prairie.
Note pioneers of a possibly invading forest.

FIG. 2. Mounds of Rocky Prairie.

CHAPTER V.

THE MOUNDS OF THE VASHON OUTWASH.

SYNOPSIS.

CHARACTER OF THE REGION.

The Vashon drift of Puget Sound may be divided into two different areas, the northern portion being predominantly ground moraine and the southern part being characterized by outwash plains. These plains are largely prairies, because of the coarseness and sterility of the soil. The latitude of Tacoma affords a convenient division line between these two areas.

The outwash from the Vashon Glacier of Puget Sound discharged into the Chehalis River by two main routes, one on either side of the Black Hills. The Black Hills lie on the west side of the axis of the structural valley containing Puget Sound. They bear till on their northern flanks and are entirely surrounded by outwash gravel.

NATURE OF THE MOUNDS.

The remarkable mounds which have often been referred to, cover large areas of these gravelly outwash plains. Their character, distribution and genesis are the subject of this chapter.

TYPES OF MOUNDS.

At the outset two types of these mounds are to be distinguished. They will be termed the Mima type and the Ford type. Though a casual observer might fail to discriminate between them, they are believed to be distinct in origin.

THE MIMA TYPE MOUNDS.

Form and Size. Where best developed, the open prairie bearing mounds of this type appears like a meadow dotted with haycocks. The mounds have a symmetrical, flowing outline, appearing to the eye to be segments of spheres, though their lower slopes blend into the adjacent ground with a surface concave upward. They range in height from those so little as to be just preceptible, to a maximum of seven or eight feet, and in diameter from six to seven feet to sixty feet or more. In any one locality there is a striking uniformity in the size of these mounds. Almost none exceed the dimensions prevalent in that locality, and few fall below. This is the testimony of the eye, though if careful measurements are made a number will be found failing to reach the average dimensions, which by reason of inconspicuousness were not noted in a visual survey. (Illustrations of the Mima type mounds are presented on Plates II to VII.)

They are uniform in shape as well as size. There is commonly an elongation so that one diameter exceeds the other at right angles to it by a small fraction. Two mound crests may be so closely placed that the bases blend with only a saddle between the crests. The elongation, when present, does not conform to any definite orientation.

GROUPING, SPACING. All observers agree that no orderly arrangement of the mounds in ground plan can be detected. Plate VIII is a map of an area on Mima Prairie, 400 by 500 feet, on which the mounds have been carefully located and measured. The lack of orderly grouping is apparent.

In the matter of spacing, the Mima type mounds are usually closely set. There is but rarely an intermound area with a diameter greater than that of the larger mounds of the vicinity. An exception to this statement is found on certain prairies. The surface of Rocky Prairie in particular is affected by long sags and swells with a relief of scarcely more than ten feet. The mounds are almost without exception limited to the higher portions and from these portions, more like platforms than swells, the descent is abrupt to the bottom of the sags.

COMPOSITION OF MOUNDS AND INTERMOUND AREAS. A constant feature of the gravel outwash bearing the mounds is the presence of a black surficial silt. This silt is present in many places where no mounds are developed, but is never lacking in mound-bearing areas. Road and railroad sections on several different prairies show that the mounds are composed of a mixture of loose gravel and black silt. The gravel below the mounds is stratified and free from the black silt. The transition between the mound material and the underlying clean gravel is sharp.

A gravel pit, 40 feet deep, is being worked in Mima Prairie by the Northern Pacific Railroad, in which cross sections of mounds are constantly being made. The black silt here has a thickness of but a few inches between the mounds. In the mound sections, however, the silt is seen to descend lower than in the intermound spaces, giving, with the mound profile, a distinct double convex lens shape to the black silt aggregation, as shown in Plate II, fig. 1.

The lower limit of the silt in the Mima sections in many places has broad, blunt, root-like downward projections, seldom more than a foot in length. These bend abruptly here and there in the plane of the section, or appear as patches of black silt in the gravel just below the mounds, where the section crosses their direction of bend. Roots of the herbaceous plants which grow on the mounds are found practically as abundant at the lower margin of the silt as elsewhere in it, but they terminate abruptly in contact with the clean gravel below, except where seepage lines occur.

Samples of the mingled gravel and silt composing the mounds on Mima Prairie were washed and the fine black material was thus removed. An ordinary gravel and sand like that immediately below the mounds was left. Practically all of the suspended black material settled in twenty-four hours. A sample of it was ignited to determine the organic content. Almost no loss of weight resulted, the material simply losing its dark color and becoming a fine gritty clay. The organic content thus is very small. Black silt, unmingled with gravel or sand, taken from Chamber's Prairie, a moundless outwash area, gave the same evidence of slight organic content. This conclusion fails to harmonize with the general impression of the character of the black silt. It is usually considered as having a high percentage of humus and is so described in the soil surveys of Puget Sound.

In prairies other than Mima, some mound sections show a greater abundance of gravel but where best developed, the composition of Mima Prairie mounds is practically duplicated.

In Rocky Prairie typically, the intermound areas are thickly covered with cobble stones and small bowlders, (Plate V, fig. 1

and Plate VI, figs. 1 and 2). None were seen with a maximum diameter of more than two feet. There is no hint of a closer spacing or piling up of these boulders on the margin of the mounds than elsewhere, such as would occur if they had been distributed evenly at the outset over the whole area and had since gravitated to the intermound spaces. At the west end of the prairie, mounds of pronounced development, with abundant intermound cobbles, lie with a sharp line of separation adjacent to lower mounds on a lower surface, and with no cobbles whatever among them. Among these lower mounds is an area 200 feet long and 20 feet wide, elongated east and west, which has no hint of mounds, but is covered with cobbles, (Pl. VI, fig. 2). It is on this prairie also that the best development of sags and platforms is found. In many cases the cobbles cease as abruptly on the upper edges of the platforms as do the mounds, here and there overlying the brink, but showing no tendency to move down and accumulate at the foot of the slope. Numerous road and railroad sections on this prairie show the mounds themselves to contain no cobbles or bowlders.

Other prairies show this intermound cobble accumulation in varying strength of development. In places the stones are very few, and only large pebbles in size. This is the case over much of Mima prairie and here deep sections show the entire gravel bed to be lacking in cobbles and bowlders, while a well in Rocky Prairie shows the underlying clean gravel to possess many large stones, comparable in size to those in the intermound areas. On Walricks Prairie, railroad sections exhibit the structure of a mound-bearing portion with bowlder-strewn intermound spaces. The bowlders or cobbles here are seen in the sections to continue from one side of a mound in a plane directly beneath it and reappear in the intermound area on the opposite side.

Structure. No stratification or other structure has ever been observed in sections of the Mima type mounds. (See Plate II, fig. 1.) All observers who have published on the subject find this unreservedly true. There is shown in all sections a loose, homogeneous mass of small gravel mixed with black silt.

There does not seem to be a greater proportion of silt near the surface of the mound mass than at the base. In prairies lacking the mounds but having the surficial silt deposit, gravel pebbles do not occur distributed through the silt as they do in the mounds.

THE FORD TYPE MOUNDS.

FORM AND SIZE. Where a beautiful symmetry and uniformity characterize the Mima type mounds, those of the Ford type are unsymmetrical and irregular in form, and variable in size. The largest area of these mounds is on Cedarville Prairie in the Chehalis Valley. The surface of this prairie in some places is almost tumultuously heaped with the gravel piles; in other places it is nearly plane, and in others it is disposed in long gentle slopes. Enclosed hollows are common, drainage by seepage being perfect however. Circular or slightly elliptical mounds are not common. The maximum range in altitude between mound top and adjacent depression is about 20 feet. On Grand Mound Prairie, one Ford type mound stands 25-30 feet above its surroundings. This particular mound (Plate IX, fig. 1) possesses seven peculiar saucer-like depressions on its summit, arranged in a somewhat elongate group transverse to the length of the medial broad ridge of the prairie. With the narrow rims as inter-saucer areas, they cover the entire summit. Their average diameter is ten feet and average depth 12-18 inches. Each bears a small flat mound in the center and thus constitutes only a marginal circular depression, being nearly filled in the center. Cobbles occur in these annular depressions, and also strew the sides of this Ford mound. These saucers, with the mounds in the center, are strikingly similar to those described in the vicinity of Muck. The general character of the form of the Ford type mounds may be best described as essentially kame-like, a statement which cannot be made concerning the Mima type mounds.

GROUPING, SPACING. No trace has been found of any systematic disposition of these mounds or of the hollows among them.

Composition of Mounds and Intermound Areas. Numerous excavations show the Ford type mounds to be wholly of gravel. There is no more black silt on their surfaces than on the intermound spaces, and none enters into the composition of the mass of the mound. No aggregation of cobbles among these mounds has been abserved.

Structure. In Ford Prairie below Cedarville, excavations by the Oregon-Washington Railway and Navigation Company for railroad ballast have afforded sections of the mounds of this type, comparable to the sections of the Mima type mounds in the Mima pit. The material is mainly horizontally bedded but is overlain in one part of the pit by delta bedded gravel dipping westward down the valley, the depth of these beds not exceeding 8 feet. Above the delta beds the structure is confused, current bedding prevailing with no definite foreset or horizontal stratification. This extends to the top of the cut and at the time of the writer's examination included sections of several Ford type mounds. The beds in the mound sections in a few cases showed foreset structure, dipping toward the center. One such foreset stratum had grown from one side of the mound across almost to the opposite side.

TABULATED COMPARISON OF THE CHARACTERS OF FORD AND MIMA TYPE MOUNDS.

The following tabulation gives the points of distinction between the two mound types above described:

MIMA TYPE

Named from the perfection of development on the upper portion of Mima Prairie.

1. Symmetry of form.
2. Uniformity of size in any one area.
3. Structureless.
4. Black prairie soil to base.
5. Maximum relief between mound summits and intermound areas, 7 feet.
6. Usually with intermound cobbles.
7. Closed depressions rare.
8. Uniformity of distribution the rule.

FORD TYPE

Named from Ford Prairie which has given sections that reveal the origin of this type.

1. Asymmetry of form.
2. Lack of uniformity of size.
3. Foreset bedding dipping toward center.
4. No increased thickness of prairie soil.
5. Maximum relief between mound summits and intermound areas 30 feet.
6. Never with intermound cobbles.
7. Closed depressions common.
8. No uniformity of distrbution.

AREAL DISTRIBUTION OF THE MOUNDS.

DISTRIBUTION OF THE MOUNDS WITH RELATION TO PRAIRIES.

There are three classes of prairies in the Puget Sound country, (1) those occurring on rock hill slopes, where the soil does not support a forest growth, (2) those where the soil is too wet for tree growth, and (3) those on the glacial outwash. Our problem deals only with prairies on glacial gravels.

The outwash gravels dealt with in this chapter are of Vashon age, probably to be correlated with the Wisconsin drift. They occur largely as outwash plains, with moraine or ice contact slope along their highest margin. Since all discharging water from Puget Sound was received by the wide Chehalis Valley, the gravels carried farthest take the form of a valley train, which differs in no essential detail from the outwash plains. Fragments of the valley train between Gate and Aberdeen which have escaped postglacial erosion constitute prairies with all the features of those of the gravel plains nearer the glaciated region. In all prairies of the outwash gravel, evidence of flowing water at the time of their formation is to be found (1) in terraces, (2) in the bedding, where exposed, or (3) simply in the general slope.

In the maps accompanying this bulletin, the areas of glacial outwash are shown, and the outer margin of the terminal moraine is indicated. The mound-bearing prairies are indicated on Plate XXIII. In order of development of the Mima type mounds, Mima and Rocky Prairies lead all the others, though each has areas without mounds. Walricks or Eaton Prairie follows in order with numerous but lower mounds. Grand Mound Prairie possesses a strongly accented mound surface near the eastern end, but the mounds gradually become flatter westward until they die out in the vicinity of Grand Mound.

Cedarville Prairie possesses the best development of the Ford type mounds. Gate or Bakers Prairie and Oakville Prairie follow. Ford Prairie, Mima Prairie and Grand Mound Prairie also possess a few mounds of this type.

The prairies above noted are all located on the outwash gravel

FIG. 1. Delta at Corner of Seneca Street and Sixth Avenue, Seattle.
The dark foreset beds are composed of lignite.

FIG. 2. Mounds cut by Highway, Mima Prairie.

of the glacial lobe lying east of the Black Hills re-entrant angle. The escaping water from this lobe converged at Gate into one valley, and produced a valley train which, reinforced by accession of outwash from the western lobe, was originally continuous from Gate to Grays Harbor. Mound-bearing portions do not occur below Malone, at the mouth of the Mock Chehalis, which is the first point of entrance of gravel from the western lobe into the Chehalis Valley.

The largest area of prairie country lies northeast of the Nisqually River, the region being known in general as the Steilacoom Plains. Imperfect Mima type mounds are found here and there on this area, well within the limits of the terminal moraine.

On the outwash from the western lobe, between the Black Hills and the Olympic Mountains, prairies are less common in proportion to the extent of gravel-covered surface than east of the Black Hills. Mounds are known in but one place. This is on Lost Lake Prairie, within the limits of the moraine. The mounds are low and inconspicuous, and do not occur over the whole prairie. There can be little doubt, however, that these mounds are of the same genesis as those so well developed on Mima and Rocky Prairies.

DISTRIBUTION OF MOUNDS WITH RELATION TO MORAINES.

In general distribution, the mound-bearing prairies are associated with deposits of the eastern and lower lobe of the glacier. The Mima type attains its maximum development on Mima Prairie, just outside the terminal moraine, and on Rocky Prairie, between the terminal moraine and a recessional moraine. Grand Mound Prairie, fourth in order of development of Mima type mounds, flanks the terminal moraine on its outer side.

On Mima Prairie the mounds may be traced up on the basal slopes of the low morainic area which lies north of the prairie. In this position they are irregular in size, form and spacing, and are associated with a few shallow kettle holes. One kettle (Pl. IV, Fig. 2) is 20 feet deep and 120 feet in diameter, and bears a few weakly developed mounds on the side and bottom.

On Grand Mound Prairie, in the places examined, they are lacking in proximity to the moraine. On Rocky Prairie they exist within less than 200 feet of the front of the recessional moraine, uniform in size, shape and spacing with those elsewhere on this prairie. At this distance from the moraine slopes, they terminate on the prairie surface, a moundless level zone of the indicated width margining the frontal edge of the moraine.

Walricks or Eaton Prairie lies just east of Rocky Prairie, and, like it, is bounded on the north and south by the terminal and a recessional moraine. Its mounds are low in relief. No relation between the proximity of the till ridge at the north and the character of the mounds was seen.

North of Offut Lake is a thinly forested country with small prairie areas interspersed. The topography is very much broken by kettles, but no morainic knobs occur in the immediate vicinity, the area being apparently a pitted plain. Mima type mounds are common on the level areas between the kettles, but do not occur on the sides or bottom of the depressions.

A drift surface, bearing mound-like forms, which should be noted here, is to be found on the frontal or southern slope of the most northern ridge of the till area south of Muck Post Office. The mounds here are scattered and irregular in form, both Ford and Mima types apparently being present. About a dozen Mima type mounds were seen on the southern slope of the ridge, which is heavily covered with outwash gravel. Till exposed beneath the gravel shows the ridge to be of morainic origin. Each mound lies in a more or less distinct saucer-shaped depression, the rim of which is broken in most cases, and the depth of which was about equal to the height of the mound. These mound-and-saucer arrangements do not occur on the steeper slopes, but lie at the foot. Cobbles and small bowlders lie in the saucer surrounding the mound. The gravel outwash here is 20 feet or more in depth. The forms described are thus of outwash development, and not morainic in nature.

The eastern portion of Grand Mound Prairie bears a median, flat, higher area, elongated east and west in harmony with the longer diameter of the prairie and parallel to the moraine at the north. On it are the few Ford type mounds possessed by this prairie, while Mima type mounds are distributed everywhere except along the present floor of Scatter Creek Valley, and the steeper descents to it.

Mima Prairie is disposed in two levels, the higher being almost plane, and abutting against a moraine. A long spur of this higher portion runs southward across the lower level and bears the Ford type mounds of this prairie. Mima type mounds are common on much of the lower surface.

Both north and south of the terminal moraine, the mounds diminish in degree of development, though they extend farther beyond it than back within the glaciated area. Cedarville Prairie, 12 miles beyond the moraine, has the greatest development of Ford type mounds of the region.

DISTRIBUTION OF MOUNDS WITH RELATION TO ALTITUDE OF PRAIRIES.

An examination of the altitudes of the mound-bearing and moundless prairies of both lobes of the Puget Sound Glacier shows the Mima type of mounds on the highest, Tenalquat Prairie, 500 feet above tide, and on one of the lowest, near Elma, 60 feet above tide. Grand Mound Prairie descends from 270 feet to 160 feet in ten miles, and the Mima type mounds are largest and best developed at the head and lacking at the foot, while on Rocky Prairie these mounds are best developed on the lower extent and absent at the head. Ford type mounds have their highest known occurrence on Grand Mound Prairie, 280 feet above tide, and their lowest on Ford Prairie, 60 feet above tide.

DISTRIBUTION OF MOUNDS WITH RELATION TO DIFFERENT AGES OF THE OUTWASH GRAVEL.

Outwash from the ice at the time of maximum extent formed certain gravelly areas which were abandoned by escaping water as soon as the ice retreated a mile or so from the terminal moraine and exposed lower drainage lines. One of the earliest outwash areas to be abandoned was the Tenino end of Grand Mound Prairie and the valley train which extends south from Tenino to the Skookum Chuck at Bucoda. These gravels just west of Tenino are mound-bearing. Both types are well developed, though the Ford type mounds are few in number. The black silt and intermound cobbles of the Mima type are present. South of Bucoda the mounds disappear, and none have been found on the wide gravel plain about Centralia.

Discharging glacial water ceased to flow through the marginal drainage channel debouching at Tenino at the head of Grand Mound Prairie when the ice retreated to a position north of Rocky Prairie. (See Fig. 4). Deposition of outwash gravel therefore ceased at the head of Grand Mound Prairie and at no subsequent time was renewed. The mounds near Tenino therefore lie on the oldest Vashon outwash.

During the pause at the recessional moraine north of Walricks and Rocky Prairie, the gravels of these prairies were deposited. The escaping water flowed westward along the rear of the terminal moraine to Mima Prairie. Several small prairies exist along the route, one of these, Rutledge Prairie, bearing well developed Mima type mounds. Mima Prairie therefore was an area of aggradation during the two pauses of the ice front, and the mounds of at least its lower portion are no older than those of Walricks and Rocky Prairie, despite the extra morainic position.

Farther back from the terminal moraine of the eastern lobe than the prairies above discussed, there are but four groups of mounds known to the writer, and these are all of the Mima type. They are relatively insignificant, being faint, irregular and scattering.

Lost Lake Prairie, on the area covered by the western lobe, lies a few miles back of the limits attained by the glacier. Its mounds are faintly developed and constitute the only known occurrence of these forms on the outwash from this lobe.

From the above survey, it would appear that only outwash gravels immediately associated with moraine development are mound-bearing, and that only outwash of early deposition bears mounds. This generalization is somewhat weakened, however, by the following data concerning the Chehalis Valley train.

As the eastern lobe of the Vashon Glacier retreated north of the latitude of Olympia, the troughs of Puget Sound became gradually uncovered, and standing water at the ice front resulted. Except on local divides and over the troughless area south of Tacoma, outwash gravel ceased to be deposited. Escaping water from Lake Russell* ponded in front of the ice, flowed close along the eastern foot of the Black Hills to Gate, there entering the Chehalis Valley. This water rehandled the drift over which it flowed, and carried a considerable quantity of gravel into the Chehalis Valley. It eroded its outlet channel at least 40 feet deep at the present col. It appears to have eroded a wide channel on the east side of Mima Prairie. The discharge of Lake Russell continued to flow through this valley, now occupied by Black Lake and Black River, and thence down the Chehalis, until the ice had retreated at least as far north as Foulweather Bluff, between Hoods Canal and Admiralty Inlet. Somewhere north of this headland the ice dam failed, and the level of Lake Russell was lowered to that of the sea. The outwash gravels along the Black-Chehalis drainage line thus may have received their uppermost deposit at a time when the ice front was many miles to the north in its final retreat. An alternative view is that the discharge of Lake Russell eroded a channel in the Chehalis valley train and did not spread over the whole surface. Let us now examine this surface.

Mima Prairie is disposed in two great levels, separated by a more or less abrupt slope descending about 20 feet. Mounds are best developed on the upper level, but occur in typical development on the slope and on the lower level. This lower surface gradually descends eastward to the present floodplain of Black River, and bears mounds so far down the slope that flood water

* J. H. Bretz, "Glacial Lakes of Puget Sound," Jour. Geol., Vol. 18, No. 5, and chapter VI of this bulletin.

of the present river almost reaches them. Their occurrence here possibly may be associated with the operation of the Black Lake outlet of Lake Russell.

At Gate, the prairie is mound-bearing, the mounds belonging to the Ford type. Scattered Ford type mounds occur on the higher areas of the Oakville Prairie. Cedarville Prairie possesses splendid Ford type mounds over most of its surface. Ford Prairie has a few of this type. Three miles above Elma is a low fragment of the valley train whose gravels probably came from the eastern lobe, though below the point of entrance of the Mock Chehalis valley train. It bears faint mounds of the Mima type, the lowest and most western occurrence known. There is thus abundant evidence to suggest that the causes of mound formation operated at a considerable distance from the edge of the ice, and perhaps late in Vashon deglaciation. These mounds of the Chehalis valley train belong to the Ford type, there being but one occurrence of weak Mima type mounds. The alternative view considers that later discharging water through the Black-Chehalis drainage line did not occupy the whole width of the gravel-filled valley, and hence mounds on the higher portions of the valley train may have been formed at an early date. Postglacial erosion has removed so much of the Chehalis valley train that this question can hardly be settled satisfactorily.

DISTRIBUTION OF MOUNDS WITH RELATION TO SLOPE OF PLAIN SURFACE.

Most of the flat gravel plains of the region possess a gentle grade descending in the direction the water flowed at the time of their deposition. Here and there are steeper slopes of the gravels, occurring on the flanks of moraine ridges, on the slopes between terraces, or on the sides of kettles. In one direction the gravel plains may extend from an almost level surface up on low moraine flanks, the mounds here lacking characteristic form and arrangement; in an opposite direction the plains may descend across a terrace scarp, without notable change in the character of the mounds.

In general, mounds on a moraine slope do not possess characteristic form and distribution. They are best developed on a gravel plain with a slope too gentle to be detected by the eye, and they are rarely present on the slopes of kettles.

AREAL INTER-RELATIONS OF THE TWO MOUND TYPES.

Mima and Ford type mounds have not been found associated with each other in maximum areal development. Grand Mound and Mima prairies possess a few Ford type mounds, on the higher portions of the prairie surface, surrounded by thousands of the Mima type mounds. The reverse relation, a few Mima type mounds distributed among many of the larger kind, has not been found. On both the above-named prairies Mima type mounds lie undoubtedly up on the flanks of the Ford type. Nothing has been seen to suggest superposition of the Ford type on mounds of the Mima type.

SUMMARY OF AREAL DISTRIBUTION OF THE MOUNDS.

(1) The mounds occur on outwash gravel from the eastern and lower lobe of the Puget Sound Glacier, only one occurrence of faint Mima type mounds and none of the Ford type being known for the western lobe.

(2) The best Mima type development is found on prairies closely associated with the terminal and earliest recessional moraines, though faintly developed mounds of this type are found on the Chehalis Valley train far from the moraines.

(3) Ford type mounds have been found almost entirely on the Chehalis Valley train and adjoining extra-morainic outwash plains.

(4) No significant relation has been found between the altitude of the gravel plain and the occurrence of mounds of either type.

(5) Mima type mounds are most typically developed on the earlier outwash of Vashon age, though large areas of this are moundless. The Ford type finds its best development on that portion of the Chehalis valley train which entered by the

Gate Pathway. The question regarding its age has been indicated.

(6) Mima type mounds attain their best development on nearly plane gravel surfaces, depressed or steeply sloping areas being commonly moundless. Ford type mounds, where scattered, occur on the higher prairie areas, isolated above the surrounding surface.

HYPOTHESES.

Previous field work on the mounds of Puget Sound glacial drift has been limited to hasty examination of the chief prairies bearing the Mima type. The Ford type mounds have not been previously recognized. The Mima type mounds are so striking in appearance, and so different from topographic forms ordinarily seen, that even the car-window observer is at once interested, and the range of hypotheses for their origin has been considerable. The study herewith presented will be justified if it succeeds in showing the intricate nature of the problem, and in narrowing the range of hypotheses. Distinction of the two mound types must be made, hence each will be treated independently.

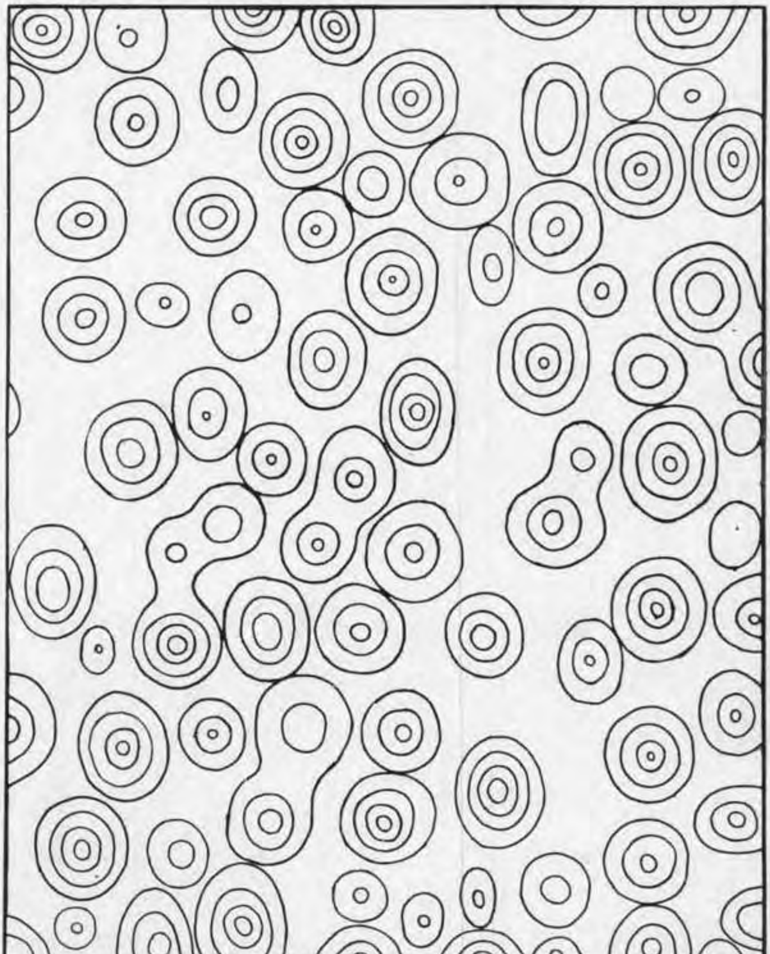
THE MIMA TYPE.

Conditions Controlling the Construction of Acceptable Working Hypotheses. Any working hypothesis for the origin of these mounds to be of value must include recognition of the following general facts:

(1) The mounds have a regularity of form that is remarkable. In the hundreds of acres of the mound prairies, there are but few exceptions to the general form of a spherical segment.

(2) Mounds in any one locality are nearly uniform in size. There are nowhere large mounds scattered in an area of small mounds, though the converse is true in some places. For any one region there is a maximum size, above which almost none go and to which most attain.

(3) There is almost invariably an accumulation of cobbles or pebbles on the surface among the mounds. Where sections



An Area of Typical Mounds on Mima Prairie.

Map constructed on the assumption that the mounds stand on an even horizontal surface. Contour interval, two feet.

are afforded, stones of the size of those in intermound areas in some places continue as a cobble stratum through the mounds themselves. In other places where the intermound areas are cobble-bearing no cobbles are found in the mound sections.

(4) All prairies of the region bear a surficial black silt. In the mounds, the silt has accumulated to a thickness as great as the mound height, and in places greater, so that it forms a lens-shaped accumulation, while between the mounds the silt is thin.

(5) The mounds are best developed on plane surfaces of slight grade. They never occur on surfaces other than those of glacial gravel.

(6) The mounds are structureless.

Hypotheses Previously Advanced. (1) Wilkes. The earliest discussion of the Mima type mounds known to the writer is that of Charles Wilkes in volume four of the "Report of the United States Exploring Expedition during the years 1838-1842." Wilkes twice crossed one of the mound prairies, probably Mima, and on the second trip he had three of the mounds excavated in the endeavor to find relics of human agency which he conceived as responsible for their origin. Nothing was found indicative of the "savage labor" of which he notes that they possess the marks, except a "pavement of round stones at the base." He was certain that they were not places of burial and was inclined to attribute them to the Indian medicine men, though he found no tradition existing among the Indians concerning their origin.

(2) Gibbs (Agassiz). In the Journal of the American Geographical Society for 1873, George Gibbs describes a reconnaissance of the northwestern boundary of the United States in which he examined a number of the mound prairies of Puget Sound. On his return to the eastern states he described the structure and exhibited a sketch of the mounds to Louis Agassiz, who "unhesitatingly" pronounced them to be the nests of a species of sucker. Agassiz stated that this fish

was at that time constructing similar mounds in the ponds about Boston. Gibbs accepts the explanation, noting that it agrees with the occurrence of "lacustrine" terraces which are commonly associated with the prairies.

(3) LeConte. In the same year Joseph LeConte published a hypothesis for the origin of these puzzling features, in the Proceedings of the California Academy of Science. He conceived that the gravel and silt were sediments in the waters of Puget Sound, which he assumed to have once covered the region. Succeeding the withdrawal of the Sound waters, erosion attacked the surface and removed the finer soil in certain areas. Vegetation encroached at the same time and obtained a foothold in the higher regions, holding them while the inter-areas were lowered. Increasing dryness of the climate has caused the disappearance of this vegetation.

(4) Newberry. In 1884 John Newberry presented a paper before the New York Academy of Science on the origin of the fiords of Puget Sound. He frankly confessed the mounds to be inexplicable.

(5) Rogers. The American Geologist for June, 1893, contained an article by G. O. Rogers on "Drift Mounds near Olympia, Washington." This writer reviewed LeConte's description and arguments, and objected to his statements that the intermound areas contain larger pebbles than occur in the mounds, LeConte having presented this as evidence of the erosion of the finer material. Evidently Rogers examined that portion of Mima Prairie which is without cobbles among the mounds, while LeConte may have seen Rocky or Grand Mound Prairie, where cobble distribution is remarkably developed. Rogers's hypothesis is that the gravel plain was covered by a piedmont ice sheet which, on ablation, was traversed by escaping drainage in floods so that the entire surface was covered by washed debris. Such material on coming to rest tended to accumulate in heaps. Insolation caused these heaps to sink in the ice, and sliding of scattered material into the depression further tended to con-

centrate the washed drift. Final melting of the stagnant ice deposited the heaps as the present mounds.

(6) Upham. In 1904, Warren Upham published in the American Geologist some hasty observations from a reconnaissance of a part of the Puget Sound country. He crossed Mima and Gate or Baker prairies and concluded that the mounded surfaces were "correlative with the commonly hilly moraine belts of other drift areas." From personal observation of these two prairies and from verbal descriptions of other prairies of the region having mounds, he mapped the terminal moraine belt of Puget Sound as a broad curve, convex southward, with the most extended portion reaching to Gate.

(7) Other Explanations.* Conceptions of the origin of the mounds, more or less related to those presented above, have emanated from many sources. Most are valueless because based on no careful study of the region. Two leading ideas are those of plant or animal origin. One farmer who has lived on Mima Prairie for a number of years is convinced that the mounds which bear clumps of the stunted oak common to the gravelly soil are increasing in height. He stated that in leveling the mounds for a roadway, the horses plunged knee deep repeatedly in the gravel and silt after the sodded surface of the mounds had been broken, inferring from this that hollows existed where tree roots had decayed.

Weaknesses of the Above Hypotheses. From the preceding description of the structure, form, number, and distribution of the mounds, and from the fact that no relics of human origin have ever been found in or associated with them though hundreds have been opened, the hypothesis of human origin for any purpose whatever must be abandoned. It is not held today by residents of the region, though it is the most seductive of all explanations to the common mind.

* M. R. Campbell discusses "Natural Mounds" in the Journal of Geology, Vol. 14, No. 6. His study was devoted to mounds in the valley of the Arkansas, differing widely in composition, and in character of the subsoil, from those features found in the Puget Sound country. His conclusion of animal origin cannot apply here.

No one who has been in the region and seen the splendid sweep of billowy topography over a thickly mounded prairie surface can give credence to the idea that fish have heaped up the Mima type mounds. It is obviously much farther from the truth than the hypothesis of human origin. The prairies have never been submerged in fresh water, and probably only the lower ones were beneath the postglacial sea water, and that but for a short time. Mima type mounds also occur on the plateau-like summit of Tenalquat Prairie, 500 feet above tide, untouched by any water but direct rainfall since cessation of the glacial outwash.

The impossibility of deposition of the gravels in Puget Sound does not weaken LeConte's idea. The objection which is fatal to his conception is that the porous gravel so effectively absorbs rainfall that hardly a trace of erosion has been detected on any prairie, save that of a few traversing streams whose run-off is largely secured from other areas. Considerable streams flow on to some of these prairies from adjacent and more impervious surfaces after heavy rains, and the water is so greedily absorbed by the gravel that the stream disappears in a fraction of a mile. The pits in Mima Prairie show "open work" gravels for a depth of 30-40 feet below the surface soil. In the face of this evidence, LeConte's comparison with the mounds produced by erosion in eastern Oregon is invalid.

Rogers's conception of the inter-action of glacier ice and escaping water fails to explain the mounds of Grand Mound Prairie about Bucoda, and just above Elma on the Chehalis, all of which lie beyond the terminal moraine and some of which were perhaps formed on the Chehalis valley train during the last stages of glacial retreat from the Puget Sound basin. Further, the many sections in the outwash prairies back of the terminal moraine fail uniformly to record any re-advance of the ice over their surfaces after stream aggradation on them had ceased, and Rogers's hypothesis fails here as well.

In view of this last point, and since the terminal moraine of the Puget Sound Glacier is a definite till ridge, at one place two miles wide and 250 feet high, flanked by these outwash prairies, Upham's hasty conclusion cannot be considered seriously. In order to fit his hypothesis this writer also guessed Lake Kapowsin to lie in a kettle hole, which it does not, and mapped the moraine as traversing the Black Hills from Gate to Elma, all of which stretch is driftless, and some of it 1,500 feet or more above tide. Many other errors in the paper referred to make it almost valueless.

A species of large black ant, *Formica sanguinea*, inhabits the sparse fir forest growing in many places on the gravelly areas of Puget Sound outwash, and constructs hills some five feet high. Such ant hills are built almost entirely of bits of twigs and pine needles. No ant hills could contain the pebbles found in the mounds. Neither ants nor burrowing animals could produce the regularity of form and the uniformity of size in any one locality. The gravel strata below the Mima mounds are undisturbed and no burrows have ever existed beneath them in any way competent to account for the mass of the mounds.

That trees have grown on the Mima mounds where none now exist is suggested by the looseness of the interior, which allowed horses to plunge to the knees in silt and gravel, by the occasional occurrence of sunken areas a foot or so across on these mounds, and by the root-like forms in which the black silt in places penetrates the underlying gravel. The small sunken areas are so recent that the sod has not healed over the marginal cracks. To test this hypothesis more carefully, an area was sought where the oak and other forest trees are growing on the mounds. Such a region was found on a part of Rocky Prairie. But no hint of tree clumps or groups could be made out, the distribution and thriftiness of the trees not being related in any way to the occurrence on mounds or intermound areas.

It is stated that the Indians formerly burned over these prairies annually, and destroyed the trees growing on them. It is certain that today the forest is encroaching. In retracing surveyor's lines run 50 years ago, the limits of forest growth are found to have advanced on the prairies.* The western part of Rocky Prairie bears many scattered small firs. (Pl. VI, Fig. 1.) These were found to possess from eight to ten annual rings at the base, though some were ten feet high and some hardly ten inches. Evidently a wet season a few years ago allowed the seedlings to send their roots deep enough to survive the drought of ordinary summers. The older residents all testify to the former greater extent of the prairies. Many gnarled skeletons of the broad-spreading prairie oaks are found mouldering in a dense growth of young fir which has killed them in the last half century. (See Pl. X, Fig. 1.) Though much prairie land thus is being invaded by the forest, there are large mound-bearing areas where the dry soil probably never can support tree growth and probably never has.

Limitations of a Successful Hypothesis. (1) The mounds were formed at the time of deposition of the gravel outwash. Many facts already cited lead toward this general conclusion. The absence of mounds on the kettle slopes and their presence between the kettles of the pitted plain north of Offut Lake, and the entire lack of topographic change over the prairie surfaces since glaciation, save rare stream incisions, are the most definite facts supporting this conclusion.

(2) The mounds were formed only during the last stages of outwash action over any one area. No trace of their formation during deposition of the stratified gravel on the gradually aggrading plain in front of the ice, now constituting Mima Prairie, is shown in the Northern Pacific Railroad gravel pit. The section which this pit affords is half a mile long and 30 feet in mean depth, and is disposed parallel to the direction of flow of escaping water. The same conclusion is drawn from the Chicago, Milwaukee and Puget Sound Railroad cut of the same prairie, disposed at right angles to the above direction. Were the mounds formed at any earlier horizon, structureless lenses of gravel should appear in the sections.

* Communicated by Henry Landes, State Geologist of Washington.

(3) The mounds are essentially constructive forms. The evidence against postglacial erosion of the gravel plains has been presented above. The form of the mounds is strongly opposed to any conception of partial erosion, by glacial water, of previous deposits. In Plate VIII is shown one of the most definite channel-like areas among the mounds on Mima Prairie. The impossibility of channel origin for that area is at once apparent from the map. The sags of Rocky Prairie might be accounted for by the assumption of erosion by escaping glacial water, but the mounds and intermound cobbles are found on the intervening platforms and are rarely in the sags.

(4) The intermound cobbles were probably not deposited or aggregated by the agency which formed the mounds. It has already been explained that they have not gravitated to the intermound areas from an original equable distribution over the prairie surface, subsequent to formation of the mounds. The Walricks Prairie sections show beyond any doubt that a portion of this prairie surface was uniformly cobble strewn, and that subsequent to this, the Mima type mounds were constructed on this floor, burying the cobbles beneath them, and leaving the portions in the intermound areas still cobble strewn. Cobbles of the intermound type are not known to occur in the gravel and silt of the mounds, but are found in the stratified gravel immediately below them. Where the cobbles are large, the gravel below contains large stones, and where the cobbles are lacking or represented only by large pebbles, the subjacent gravel is deficient in fragments of cobble stone size.

The cobbles on Grand Mound Prairie decrease in size to accompany decrease in dimensions of the mounds westward. But in the town of Tenino, at the head of this outwash area, mounds are not prevalent though the surface cobbles are veritable bowlders, and of great abundance. In order to secure lawns, in the eastern part of the town, the inhabitants dispose of them by constructing stone walls about their property. The explanation of decrease in size of bowlders and cobbles westward from Tenino is, plausibly, that of weakening current of escaping glacial drainage. It does not follow that this proves their distribution to have been contemporaneous with the formation of the mounds, since the mounds may be due (a) to a rehandling of the upper few feet of gravel, assorting the coarser from the finer and heaping the latter into the mounds, (b) to additional deposition to form the mounds after the cobble strewn surface had been produced, as well as (c) to the possible formation at the time when the upper few feet of gravel were first deposited.

(5) The origin of the black silt is not believed to be intimately related to that of the mounds. The black silt seems best explained as being largely the clay and fine sand of the original unsorted drift, not thoroughly removed from the gravel. In the Mima Prairie sections, beds of clay occur interstratified with the gravel and considerable clayey material may be seen on close examination on pebble surfaces and in interstices among the pebbles, though the "open work" effect is found practically throughout. The black color appears to be a color only, the vegetal material imparting it being insignificant in amount in the silt.

This same black silt has been found on small level prairies of the Chehalis valley train as far down as Montesano, and on steeply sloping prairies of glacial outwash as far north as the San Juan Islands, in neither place being accompanied by a suggestion of mound topography. The prairie vegetation and the dryness of the soil are believed to be in some way intimately related to its occurrence. The subject affords an interesting ecological problem.

The mounds are thus to be considered as composed virtually of all the constituents of till, save bowlders, and to be as lacking in structure as till. There is a great difference, however, in the appearance of the loosely aggregated mound material, and the compact till of the adjacent moraine, beside that of color.

The sharp demarkation between black silt and gravel at the base of the mounds is thought to be due to some local factors

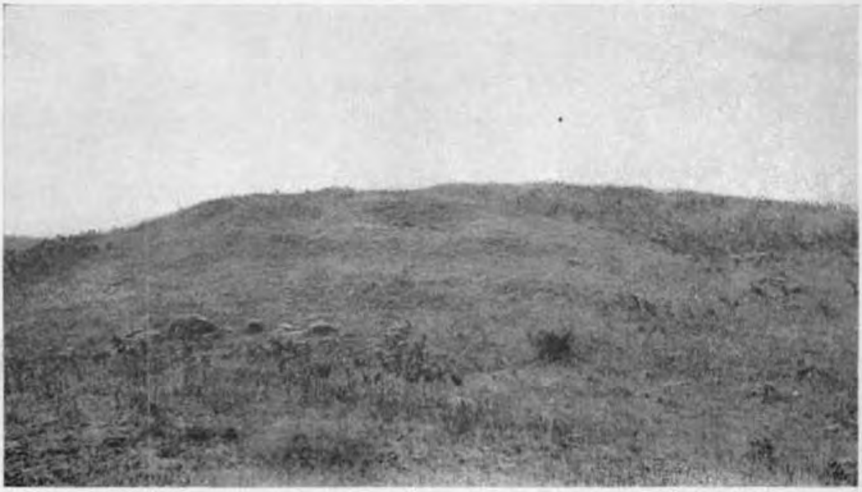


FIG. 1. Ford Type Mound on Grand Mound Prairie.

FIG. 2. Bedding of Mima Prairie Outwash Gravel.

controlling the prairie vegetation. Results of such factors are perhaps expressed (a) in the abundance of small plant roots in the silt and gravel, and (b) their abrupt termination at the upper surface of the clean gravel, and possibly also (c) in the downward extension of black silt beneath some of the mounds, resulting in the double convex lens form of the black soil in mound sections.

(6) Agencies which might have operated under the limitations above enumerated are practically limited to ice and water, either of which may have been standing, or moving, or both. The time of operation was during Vashon glacial retreat and deposition of the outwash. Current bedding and delta bedding in the Mima gravel pit show that water operated in both ways during the aggradation of the gravel plain. If ice was present, it obviously was in fragmentary masses from the adjacent glacier, or had formed on the surface of standing water beyond the ice. If it operated in dynamic phase in construction of the mounds, its motion must have come from the energy of flowing water, or from expansion due to freezing, since no glacial ice thrust could have occurred in many mound localities, nor in most of them where adjacent to the moraine, without having left some indisputable record of its occurrence.

It may be suggested tentatively that if a sheet of ice several feet thick could be formed over the surface of an outwash gravel plain and could subsequently be flooded so that stream-carried debris would be deposited on its surface, it might, on melting, develop pits into which the surficial debris would gravitate. Since water is densest at 39° F., the lower interstices of the gravel in the pits of the postulated sheet of ice would become filled with water at this temperature. Since such water would be 7° warmer than the adjacent ice, it would cause deepening and enlarging of the pits after the earthy accumulation had become so thick that warming of the gravel by the sun ceased to be a direct factor in formation of the pits. Sliding and washing of the surface debris into these pits would expose interpit areas, and the melting of such areas would then proceed more slowly than when rock fragments strewed it, and absorbed the sun's heat.

Some such set of conditions might give rise, on final melting of the ice, to mounds; these being without structure, without assortment, and superposed on current-bedded gravels as are the Mima type mounds. Cobble strewing of the prairie surfaces is known at least locally to have antedated the formation of the mounds, and requires no place in the conception.

The great range in altitude and the widespread distribution of the Mima type mounds constitute a serious objection to this hypothesis. We might conceive of an outwash plain becoming flooded with water and a sheet of ice forming over the whole through some exceptional and local combination of conditions, but it is almost impossible to postulate the repetition of such an occurrence on every mound-bearing surface, especially slopes.

The explanation of the origin of the Mima type mounds of Vashon outwash of Puget Sound glaciation is believed to lie in some combination of water and ice action under the limitations imposed above, such effective combination being unique so far as the writer is aware. Details of this explanation can probably go no farther until observation has detected the formation of similar deposits in the outwash of existing piedmont glaciers or ice sheets.

FORD TYPE.

LIMITATIONS OF A SUCCESSFUL HYPOTHESIS. A satisfactory hypothesis for the genesis of the Ford type mounds must recognize—

(1) Their prevailing extra-morainic position.

(2) Their notable development on that part of the Chehalis valley train which entered the valley at Gate.

(3) Their great variability in size and form.

(4) Their relation to adjacent Mima type mounded surfaces.

(5) Their composition, and

(6) Their structure. The hypothesis need not necessarily

explain each item, but it must contain no incongruous elements in their consideration.

The composition and structure of these mounds, items (5) and (6), form the basis for the explanation to be advanced. Numerous sections show that these mounds are composed entirely of stream gravels. The sections of Ford Prairie have shown the structure of these gravels to be largely foreset, with the beds dipping toward the center of the mound from different sides. This delta structure is confused and imperfect, the layers dipping in diverse directions, some being superposed on others with a different dip. But every bed shows the original flow of the water which deposited the gravel to have been roughly centripetal with reference to the center of the mound.

The only satisfactory explanation of the phenomenon of hummocks or mounds composed largely of centripetally foreset gravel is that the mound sites were originally pools, and that water flowing into these pools, and carrying the gravel which filled them, came from adjacent surfaces higher than the present hummock summits, lying where the depressions and intermound areas are situated now. From this it seems that we must admit the presence of ice blocks stranded on the surface of the delta- and stream-bedded gravels on which the mounds are built, deposition of stream gravel taking place in the spaces among them.

The supposed ice blocks may have been derived from the Puget Sound Glacier or the breaking up of lake or stream ice, and then transported down the glacial Chehalis, or they may have been marine floe ice drifted back up the Chehalis. All the evidence favors glacial, stream, or lake origin for the ice. The practical limitation of Ford type mounds to the Chehalis valley train, item (2), is significant. Limitation to that portion which received its supply through the Gate Pathway may be taken to show that the ice blocks were river-borne glacial bergs, because the greatest volume of escaping glacial water passed through here, and at Little Rock, but a few miles from Gate, the Vashon Glacier front reached its lowest altitude.

The great variations in form and size among the Ford mounds, item (3), with the consequent production of undrained hollows among them, and the lack of any orientation of hummocks or hollows, are facts wholly consonant with the hypothesis advanced; indeed, wholly corroborative of it. An extra-morainc position, item (1), suggests formation at the maximum of Vashon glaciation, though occurrences in intra-morainic situations would not necessarily weaken the hypothesis.

Mima type mounds lie on the flanks of the few Ford type mounds of Mima and Grand Mound prairies. This appears to show the same relation that is believed to obtain between the Mima type mounds and their intermound cobbles; namely, that subsequent superposition has placed the smaller symmetrical mounds on the slopes of the older kame-like pile.

The absence of the black silt throughout the mass of the Ford type mounds and its presence in the Mima type mounds is harmonious with the preceding views. The Ford type mounds are composed of stream gravels, which would contain little or no silt; the Mima type mounds, according to the explanation tentatively held, should possess a considerable proportion of silty material. In both cases, this is the observed fact. If the black silt has had the origin suggested, it should be found throughout the Mima type mounds which have afforded a better soil than the "open work" gravels and not at all in mounds of the Ford type. This also is borne out by observation.

CHAPTER VI.

THE GLACIAL LAKES AND DRAINAGE CHANGES OF THE VASHON GLACIATION.

SYNOPSIS.

INTRODUCTION.

The general topographic relations of the Puget Sound basin —closed on the east and west by mountain ranges, at the south by a low divide, and open to the north whence came the invading Cordilleran ice—favored the accumulation of standing water in the basin while the ice front retreated northward. Because the last glaciation found a topography of strong relief in the Puget Sound basin, and failed to obliterate it by erosion or deposition, the opportunity for a lake history of varied character during the epoch of Vashon glaciation was greatly increased.

The lake history may be subdivided into three periods, determined by the advance, the maximum and the retreat of the Vashon Puget Sound Glacier. Lakes of only the last of these divisions of the Vashon epoch have left records of much importance. Little is known of lakes of the advance of the Vashon Glacier. Those of the maximum glaciation were but small bodies

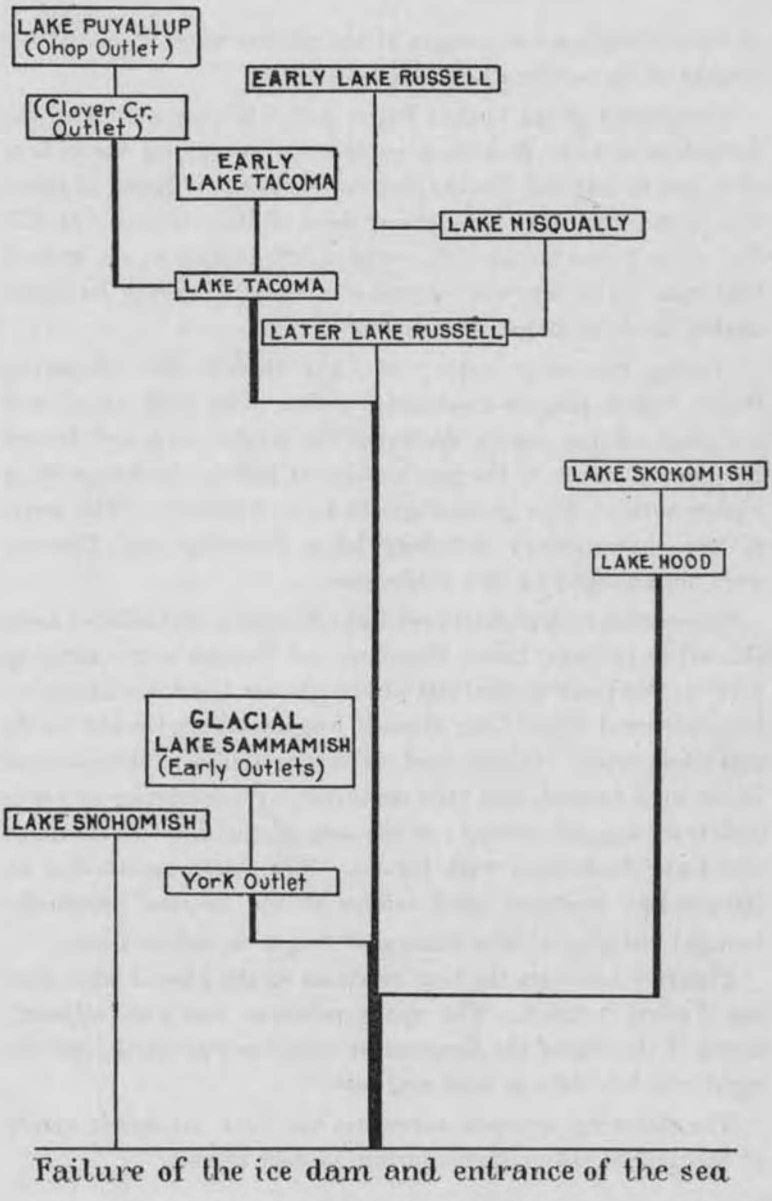


FIG. 7. Time and Space Relations of the Glacial Lakes during Vashon Retreat.

of water fringing the margin of the glacier where it closed the mouths of the earlier stream valleys.

The retreat of the Vashon Puget Sound Glacier permitted the formation of Lake Russell, a water body occupying the valleys of Puget Sound and discharging to the Chehalis River at Gate. The level of the lake throughout most of its existence was 160 feet above present mean tide, perhaps 130 feet above sea level of that time. The lake was lowered 40 feet by erosion of its outlet during the later stages of its history.

During the early history of Lake Russell, the retreating Puget Sound Glacier readvanced a few miles with an altered marginal outline, nearly destroyed the master lake, and forced the ponded water in the pre-Vashon valleys to discharge by a higher outlet. This gave origin to Lake Nisqually. The levels of two contemporary tributary lakes, Puyallup and Tacoma, were not changed by this readvance.

Subsequent retreat destroyed Lake Nisqually and allowed Lake Russell to re-form, Lakes Puyallup and Tacoma early merging with it. No more oscillations of the glacier front are known to have occurred while Lake Russell lengthened northward to its maximum extent. On the west, tributary Lakes Skokomish and Hood were formed, and then destroyed by uncovering of lower outlets during this retreat; on the east, glacial Lake Sammamish and Lake Snohomish were formed. The latter maintained an independent existence until failure of the ice dam eventually brought the glacial lake history of Puget Sound to a close.

Figure 7 indicates the time relations of the glacial lakes during Vashon retreat. The space relations are also approximated if the top of the diagram be considered as south, and the right and left sides as west and east.

The following synopsis correlates the more important events of the glacial lake history during Vashon retreat.

FIG. 1. Prairie Oak, Killed by Invading Fir Forest.

FIG. 2. Upper Falls of the Des Chutes River.

Stages of Master Lake.	*Contemporaneous Deltas of Master Lake.*	*Contemporaneous Tributary Lakes.*
Early Lake Russell. (160 ft. Black Lake outlet.)	Sherlock Delta. Steilacoom and Sequalichew Deltas.	Lake Puyallup. Early Lake Tacoma.
Readvance of Glacier Front and Obliteration of Early Lake Russell.		
Lake Nisqually. (Chambers Prairie outlet?)	Steilacoom and Sequalichew Deltas.	Lake Puyallup. Lake Tacoma.
Retreat of Glacier Front, Re-formation of Lake Russell, Continued Glacial Retreat.		
Later Lake Russell. (160 ft. Percival Creek channel to Black Lake outlet. Lakes Puyallup and Tacoma coalesced with Lake Russell.)	Sherlock Delta. Shelton Delta. Renton Delta. Redmond Delta. Richmond Delta.	Lake Skokomish. Lake Hood. Glacial Lake Sammamish. Lake Snohomish.
(120 ft. Percival Creek channel to Black Lake outlet. Lakes Puyallup, Tacoma, Skokomish, Hood and Sammamish coalesced with Lake Russell.	Brinnon Delta. Redmond Delta. Sherlock Detla.	Lake Snohomish.

GLACIAL LAKES DURING THE ADVANCE OF THE VASHON PUGET SOUND GLACIER.

The low divide between the Sound and the Chehalis River has been shown to be due largely to deposits of the Vashon Glacier. Evidence has been found which argues that the Chehalis-Sound divide was at the Narrows near Tacoma during the interglacial epoch, instead of where it is now. If this conclusion is correct, the streams flowing in the interglacial valleys south of the Narrows were then tributary to the Chehalis.

Less satisfactory evidence suggests that the Hoods Canal interglacial river flowed to the Chehalis through the Matlock Pathway. If the interglacial drainage was disposed as suggested above, the advancing Vashon Glacier could have ponded water in front of it only in the trough of Admiralty Inlet and its tributary valleys. Early drainage of this ponded water should have occurred across the low country about the northern part of Hoods Canal to that trough and thence to the Chehalis. Advance of the ice would early close this, however, and would shift the outlet of the supposed lake to the site of the Narrows.

Here it may be considered to have remained until advance of the glacier to that latitude destroyed the lake.

Little positive data can be expected on such a subject. The hypothetical lake level lay below 250 feet at its highest, and doubtless became lower while it existed, by the down-cutting of the Narrows. Delta deposits should have been formed in such a lake, but they are not likely to have been preserved, since they were immediately overridden by a great glacier.

A delta deposit which may be connected with this hypothetical lake of Vashon advance occurs in the city of Seattle, on the harbor slope of First Hill. Its structure has been well exposed by street grading, especially at the corner of Seneca Street and Sixth Avenue. (Pl. VII, Fig. 1.) Its maximum thickness is about 30 feet, its beds dip southwest, and it rests unconformably on the stratified Admiralty clay, which, beneath the Vashon till, forms the hills of the city. The Vashon till covers the delta beds and has a maximum thickness here of 15 feet.

The striking feature of the delta sections is the presence of fragments of lignite which in some strata constitute half of the material of the foreset beds. The smaller pieces are well rounded, many of them being fragments of wood. A well worn fragment of a mammoth tooth has also been found in these foreset beds.

The line of contact between the foreset beds and the Vashon till is about 200 feet above sea level, a figure which would bring the water level within the limits imposed by theoretical considerations.

These foreset gravel strata are exposed along the slope for nearly five blocks. They have not been seen to run back into the hill, and thus to belong to the Admiralty series. They apparently constitute a deposit on the hill slope, intermediate in time, as in place, between the underlying clays and the overlying till.

The stream which built the delta came from the north, northeast, or east, and must have incised an old swamp bed which was rapidly eroded. A considerable current must have existed to detach and bear along the larger fragments. The destroyed lignite bed lay fairly near the delta, else the weak material would have been disintegrated and reduced to smaller fragments. The lignite bed was soon cut through and the foreset beds lying south of, and therefore younger than, those so heavily charged with lignite, contain little or none of it. This is further evidence of a rapidly eroding stream.

The position of the delta high on the hill slope, and the dip of its beds, makes it difficult to explain the source of the depositing stream. Capitol Hill to the east could never collect sufficient water to form the stream which here left its record, and if the stream came from the direction its foreset beds indicate, it flowed over surfaces which do not now exist, and derived its gravel from them. The swamp which gave origin to the lignite was destroyed, and its deposits consolidated by burial beneath other material long before the stream was formed which tore up the old swamp bed and redeposited its debris in the delta.

The stream which built the Seneca Street Delta is believed to have taken origin from the melting of the advancing Vashon Puget Sound Glacier, and to have crossed a stretch of land somewhere on the northern part of Capitol or First hills, here incising the lignite bed, itself a portion of the Admiralty sedimentary series. Deposit was inferentially in the supposed lake caused by the advance of the Vashon Puget Sound Glacier. Shortly after the delta's formation, the glacier passed over it, and sealed it beneath a cover of Vashon till.

This conclusion explains

(1) the source of the stream,

(2) the volume and strength of the stream,

(3) the rapidity of removal of the lignite bed,

(4) the consolidation of the peat,

(5) the unconformity on the underlying clay, and

(6) the freshness of the gravel, which is not stained in a manner comparable to that of the Admiralty gravels.

The ice overrode this unconsolidated delta material without distorting it sensibly. In one section a cobble was found to have projected for half its diameter above the subjacent gravel surface, and to have been held so rigidly that a furrow at least three feet long was formed in the under side of the till sheet by it. It offers positive evidence that the gravel was solidly frozen when the glacier passed over, and this explains the lack of distortion.

GLACIAL LAKES OF THE TIME OF MAXIMUM VASHON GLACIATION.

In impinging on the northern slopes of the rock hills which lie south of the drift plain, the Vashon Puget Sound Glacier undoubtedly dammed many small valleys, and produced a series of marginal lakelets which have left no record except in a few cases where surviving drift-dammed lakes and swamps attest their former existence. Larger marginal lakes of the maximum stand of the ice as a rule left better records.

MINOR LAKES OF THE BALD HILLS.

The front of the Puget Sound Glacier crossed the Nisqually Valley at LeGrande where the river emerges from the foot-hills of Mount Rainier to the plain. Though an ideal situation for a glacial lake if the valley above were empty, the probable presence of ice from Mount Rainier is thought to have prevented the formation of a lake.

On the northern slope of the Bald Hills, there were small glacial lakes, noted in the chapter on the terminal moraine (Ch. II). These are recorded by marshes and drift-dammed lakes which still exist. There are several bold southern slopes among these hills where the volcanic agglomerate has been weathered so deeply as to leave the larger bowlders of its mass isolated on pedestals, forming anvil- and obelisk-shaped projections. Among these are scattered erratic pebbles. Since these pebbles lie higher than the moraine, and on slopes facing away from the glacier, they are referred to ice floating in marginal water glacially dammed among the hills.

GLACIAL LAKE OF THE DES CHUTES RIVER VALLEY.

The Puget Sound Glacier crossed the Des Chutes River valley where it emerged from the Huckleberry Mountains. The upper part of the Des Chutes Valley was protected by the Huckleberry Mountains against invasion of ice from Mount Rainier, and it was dammed by Puget Sound ice at its debouchure on the plain. This gave rise to a glacial lake. The pebbly clay deposited in this lake probably is responsible for the flat on which is the group of small farms and the Bald Hill School, a mile or two above the moraine crossing.

The lake deposits and the moraine have been responsible for the superposition of the river on a rock spur of its pre-Vashon valley, and the consequent formation of the Des Chutes Falls, a beautiful double cataract with a picturesque canyon below it. (Plate X, Fig. 2).

An interesting problem is afforded by a comparison between the Nisqually and Des Chutes rivers where they enter the Puget Sound drift plain. Both were diverted after the glaciation, and forced to cut through rock for a short distance. Both possess deep post-glacial canyons, but the Des Chutes has a cataract at the head of its canyon while the grade of the Nisqually rises gradually through the canyon until it is at the level of the pre-Vashon valley. The rock is a fairly uniform dense lava in the Nisqually canyon, and a volcanic agglomerate in the Des Chutes canyon. Both are cut by dikes of more resistant rock which project on the canyon slopes. The Des Chutes carries over its fall debris secured by the erosion of the rock in the upper part of its valley while the Nisqually carries outwash gravel from the present Nisqually Glacier on Mount Rainier. The reason why one stream possesses a fall in its postglacial gorge while the other does not may be found in this difference of amount of debris carried, or may lie in other factors.

GLACIAL LAKE SOUTH OF MC INTOSH.

Near McIntosh and Tenino, the glacier at its maximum extent reached a mile or more beyond the southern margin of the terminal moraine. This is recorded in scattered glacial gravel on the hills south of the Clear Lake valley, the moraine lying north of the valley.

The southern slope of the moraine here has numerous rock outcrops and it appears that a line of low rock hills, nearly paralleling the edge of the ice, was here overridden a short distance. These hills appear to have caught the basal debris on their northern flanks and thus to have determined the location of the moraine. The extra-morainic gravel above noted does not represent a deposit from ponded water, because over most of the hill slopes the topography is such that a lake could not have existed, wherever the ice front stood.

There is further evidence that the ice crossed the Clear Lake-Tenino Valley south of the moraine, and rested against the hills on the south side of this valley. This evidence is found in the delta deposits of the two glacial lakes whose existence required an ice dam hard against the hills south of Clear Lake and Tenino.

Back among these forested hills, there is a beautiful valley flat lying a little west of south from McIntosh, and a little south of east from Tenino. It ramifies in several green meadow arms among the hills, and drains northward to Scatter Creek. At the glacial maximum, this northward-draining valley was dammed, and outflow from the resultant lake was across the divide to the Skookum Chuck on the south. (See Figure 2.) Sediments deposited in the lake contributed to the filling of the valley, though subsequent swamp deposits have done much also. A delta deposited in the lake is crossed by a road which enters the valley from Tenino. Its surface is 450 feet above the sea, and its structure, exposed in a roadside gravel pit, is perfectly and uniformly foreset, the beds being 20 feet thick and dipping to the south. The level top of this delta is a noticeable feature of the local topography. Though the outlet channel has not been found, the delta probably records the chief level of the lake.

The valley today has an outlet northward 100 feet or so lower than the delta, and eroded in a drift filling in the lower part of the valley. This drift dam held a lake for some time after the ice withdrew, and the outlet meandered in crossing the glacial accumulation of sand and clay. The stream has subsequently entrenched these meanders, and, with the assistance of encroaching vegetation, has destroyed the lake.

LAKE BUCODA.

A little more than a mile south of Tenino, near Blumauer's Mill, delta beds, dipping southward, are exposed in a terrace of glacial gravel whose surface is 325 feet above sea level. The delta lies just within the Tenino-Bucoda-Centralia through valley, which carried glacial drainage to the Chehalis. The valley is widely open directly north of this delta, and could have been closed there only by advance of the ice front at least 3 miles south of the terminal moraine. (See Fig. 2.) In Chapter III, the outwash gravels which floor this valley, about 45 feet lower than the delta, are shown to prove also that the ice front closed the Tenino-Bucoda-Centralia valley at the north.

The delta gravels are only half explained, however, when the existence of a glacial dam is proved. The valley today is open to the south; but it must have been closed at the time of deposition of the delta gravels near Blumauer's Mill. The same two hypotheses are entertained to explain such damming that were advanced in Chapter III for the low gradient of the gravel between Tenino and Bucoda. (1) Either there was a low preglacial divide in the valley south of Bucoda, cut down by glacial drainage, or (2) the Stony Point valley train, which joins the Tenino-Centralia valley at Bucoda, caused the damming. In either case, glacial gravels of Vashon age should be found near Bucoda at altitudes approaching 325 feet. Investigation has not been exhaustive, but as far as it has gone, it has failed to find Vashon gravels above 270 feet about Bucoda, at which level they occur in a terrace on the west side of the valley south of the village. Nor have gravel terraces higher than the present Stony Point valley train been found along its course. The need of more careful study of the region is evident.

LAKE CHEHALIS.

The gravels which entered the Chehalis River valley at Centralia, coming from the Tenino-Bucoda and Stony Point routes, constitute the most southern occurrence of Vashon outwash of Puget Sound. They entered the larger valley from the northeast and were swung back to a northwest course, at an angle acute to their route to the Chehalis. Their volume was so great as to fill the Chehalis Valley up to an altitude of 188 feet, considerably above the pre-Vashon valley bottom. Excavation at Centralia penetrates these clean, fresh gravels for 75 feet without reaching their base.

The city of Chehalis is about four miles up the river from Centralia, and stands at the same altitude on the same flood plain. But whereas outwash gravels are at least 75 feet deep beneath Centralia, Chehalis is built on a valley filling of river alluvium and lacustrine deposits, and no trace of glacial gravel has been found in the region, save where transported by human agency. The region of the city of Chehalis received no gravel, because the flowing water turned downstream on entering the Chehalis Valley at Centralia and the invading gravels were carried back toward the glacier. Only standing water could have existed at the site of Chehalis when the gravels were deposited, for the valley was dammed by outwash about Centralia and water must have backed up the Newaukum, Chehalis and "Big Swamp" valleys.

Dammed by Vashon outwash, Lake Chehalis (Plate XXIII) came into existence at the time of maximum glaciation. It slowly dwindled as river and swamp deposits filled the depression, never being lowered more than a few feet by incision of the gravel filling. Dammed by a permanent barrier, it probably was longer lived than any other glacial lake of the region. Its position is the most southerly of all water bodies originating in consequence of Vashon glaciation.

FIG. 1. Section in the Steilacoom Delta.

FIG. 2. Section in the Richmond Delta.
Contact between foreset and topset beds is 165 feet above sea level.

Evidences for the existence of Lake Chehalis are largely in the topographic configuration of the region and in the presence of the gravel filling at the north. As the gravel front advanced southward on the outside of the curve in the glacial drainage course at Centralia, a delta structure must have been formed in the lake; but ground water is so close to the surface of the flood plain at Centralia, that excavations are filled to within ten or fifteen feet of the surface and the gravel structure is concealed. The few feet of gravel seen above the water possess stream bedding with southward dip.

Wells about Chehalis have frequently brought buried timber to light, oak tree trunks having been found 50 feet down in clay and sand. No gravel is reported in the well records.

LAKES OF THE CHEHALIS VALLEY TRAIN.

When the flood of glacial gravel was poured down the length of Chehalis Valley, it dammed the mouths of the tributary valleys which bore no contributing gravel trains. In these obstructed valleys lakes arose in the same manner that Lake Chehalis was produced. None of the valleys so dammed were of considerable size and no lakes of consequence were produced. Several linear swamps among the driftless hills about Centralia are referred to damming of preglacial stream valleys by the valley train. A terrace deposit composed entirely of local material exists in the lower course of Porter Creek, which flows from the Black Hills. It reaches a mile back from the Chehalis Valley, and its level probably represents the altitude reached by the gravel filling in the main valley. This deposit affords the soil and the plane surface which have permitted several farms to be developed in the lower valley.

WADDELL CREEK LAKE.

Waddell Creek, which enters Black River from the Black Hills, was dammed by the glacier at the point where it emerged from the hills. Standing water accumulated here to a height of 650 feet, at which altitude a pass westward through the hills to the head of Cedar Creek permitted escape of the rising water.

(See Figure 2.) Floating ice carried glacial drift back in the valley and distributed the pebbles throughout the finer clay which settled in the lake. Much of the clay is fine residual soil which was derived from the surrounding hill slopes. The scattered pebbles are found no higher than 650 feet on the valley sides. A lacustrine flat resulted from this lake, similar to that of the Des Chutes, and in a similar way it is responsible for several farms back in a hilly region which is most unpromising agriculturally.

GLACIAL LAKES DURING THE RETREAT OF THE VASHON PUGET SOUND GLACIER.

The wane of Vashon glaciation afforded ideal conditions for the development of a complicated series of glacial lakes in the Puget Sound basin. In many ways this region resembles the Finger Lakes country of central New York. In both, the trend of the topographic features is north and south, and in both, the major forms were produced before the last glaciation. Ponding in the linear valleys occurred in both regions during glacial retreat, and the general rule in both was that withdrawal of the ice opened successive lower outlets to the north.

But in Puget Sound all water escaping from glacial lakes in the different valleys was forced to pass over the Chehalis-Sound divide into one drainage line. The result of this control of glacial drainage by one pass was to limit subsidence of ponded waters whose valleys had successively lower outlets exposed by ice retreat. Gradually, waters in the troughs and fiords of sufficient depth in the southern part of the area united at a common level; that determined by the present Chehalis-Sound divide east of the Black Hills. The water body whose level was thus controlled has been named Lake Russell*. Its inception was coeval with glacial retreat from Budds Inlet, the most southern arm of Puget Sound. Its maximum was attained just before its final disappearance, the lake then extend-

* J. H. Bretz, "Glacial Lakes of Puget Sound," Jour. Geol., Vol. 18, No. 5.

ing from Olympia nearly to Everett, a distance of at least fifty miles.

EARLY LAKE RUSSELL.

Black Lake Outlet. Glacial retreat across Thurston County developed a low drainage line close to the eastern foot of the Black Hills, the use of which by discharge from Lake Russell was continued after the edge of the ice had withdrawn from the region. There were two, and perhaps more, channels leading out of this lake but converging within a few miles into one which continues as a wide, swampy valley of low grade to the Chehalis. It is now occupied by Black Lake and Black River. Two of these converging channels leave the valley of Budds Inlet, and one may come from the head of Eld Inlet valley. (See Plate XXII.)

The two channels from Budds Inlet are separated by a basaltic hill west of Tumwater. Closely hugging the south side of this hill, a channel floor 150 to 155 feet above sea level passes west from Budds Inlet valley to Black Lake. The altitude of the gravel plain immediately to the south is only 160 feet plus, there being an imperceptible rise southward. It was of course formed by glacial drainage, probably by drainage direct from the ice rather than from the glacial lake. The first appearance of a lake would favor concentration of this drainage and development of a channel.

The channel on the north side of the rock hill has been largely destroyed close to Budds Inlet, by the development of the Percival Creek post-glacial valley. The head of this valley has receded a little more than a mile from the water and here is cut in a broader valley now abandoned. At the head of the creek in the old channel is the divide between drainage for Puget Sound and for the Chehalis River. It is no more than two miles from tidewater in Puget Sound, but more than 50 miles to the same level in Grays Harbor.

The Northern Pacific Railroad uses the valley of Percival Creek to climb from sea level to the col, or divide in the old channel, in a distance of little more than a mile. The col bears

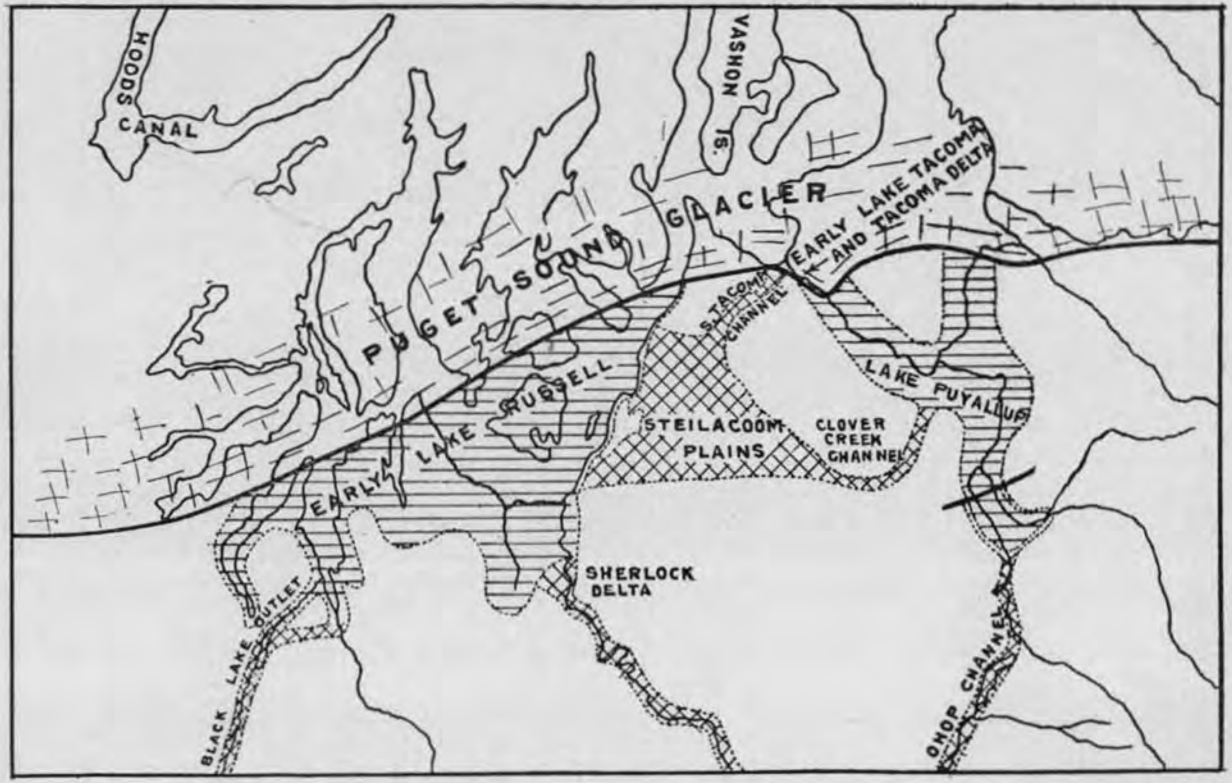


FIG. 8. Lake Puyallup and Early Lake Russell. Channels and Deltas of this stage crosshatched.

a long, narrow swamp which is drained both to Puget Sound and to Grays Harbor. A cleared field at the head of the creek valley (Plate XV, Fig. 2) shows the old channel* here to be less than one fourth of a mile wide, and to be thickly bowlder- and cobble-strewn. Its altitude here is about 120 feet above mean tide. The southern margin is a gravel bluff rising to 150-160 feet, and reaching back at this level for a considerable distance. The northern margin bears a gravel terrace 140 feet above sea level, and a few rods wide, and another at 160 feet, the surface rising from this as a fairly definite bluff to till surfaces at higher altitudes. One can follow the 120-foot floor eastward from the cleared field at the head of Percival Creek ravine, along the north side of the valley, until, standing on the easternmost remnant, the waters of Budds Inlet can be seen. The terrace surface here is covered with bowlders and cobbles.

Black Lake, in the col swamp, is two and a half miles long and half a mile wide. Its longer axis lies with the channel and its surface is nearly 120 feet above tide. From its western side the shore rises abruptly to a 155-160-foot stream floor. Gravel terraces with broad, level surfaces 130, 135 and 155 feet in altitude are crossed by the road in the dense swamp at the northern end of the lake. The 155-foot terrace here lies in the middle of the channel, with lower surfaces on each side.

A third suspected channel is of lesser magnitude than the first described. It skirts the eastern base of an outlier of the Black Hills near the south end of Eld Inlet, perhaps entering the swamp above the head of Black Lake. Its altitude near Eld Inlet is 135 feet. Its definiteness is far less than that of the Percival Creek channel. There is a possibility of a fourth, and yet less definite, watercourse having been in use early in the history of Lake Russell. This doubtful feature lies about half way between Budds and Eld Inlets. The point of weak-

* Warren Upham (American Geol., Vol. 34, No. 4) has noted this channel, which is plainly recognized from the train, and has suggested that it may have carried overflow from a glacial lake in Puget Sound.

ness in both of these suspected channels is that a continuous tracing across the divide has not been made, because of the almost impassable nature of the swamp existing there.

Withdrawal of the edge of the ice from Thurston County left both the Des Chutes and Nisqually rivers free to flow directly northward to the growing body of water in the unobliterated interglacial valleys. The Nisqually carried a large volume of water when it first entered Lake Russell, since the Ohop channel still contributed the drainage of the northern and western slopes of Mount Rainier. It appears to have entered the western side of the interglacial Gate Pathway River valley, and to have contributed considerably toward the obliteration of that valley by deposition of the Sherlock Delta.

THE SHERLOCK DELTA. The front of this ancient river delta rises abruptly 90 feet above the flood plain south of Sherlock. The altitude of its upper margin is 115 feet above tide. Farther west the front is less abrupt, and the altitude of the margin is 120 feet. On both slopes, fine foreset beds of rounded gravel are exposed, dipping northward toward the Sound. The forest covering of the delta is so dense that it was not practicable to examine its topography in detail. The delta was found, however, to possess the 160-foot portion back from the margin and apparently to have a few shallow kettles in its surface.

The Des Chutes is a minor stream and was carrying no glacial drainage when Lake Russell came into existence. It is doubtful whether delta deposits in Lake Russell can be found that may be referred confidently to this stream.

LAKE PUYALLUP.

The comparative study of outwash terraces and channels has given satisfactory evidence that Lake Puyallup, in the Puyallup River trough, did not lengthen north of Orting until the ice had withdrawn somewhere in the vicinity of the group of lakes in northern Thurston County, and had exposed Chambers Prairie and Bush Prairie as drainage routes. Since Lake Russell came into existence soon after retreat of the ice from this region, it is doubtful whether the master lake can claim priority in the glacial lake history.

THE OHOP CHANNEL. The Ohop channel (Pl. XXII and XXIII and Fig. 8), which was the outlet of Lake Puyallup, and the route of the Carbon and Puyallup rivers to the Nisqually, contains Ohop Creek and Ohop Lake south of the present col, and Lake Kapowsin and the Puyallup River north of that point. The col is 595 feet above sea level and Ohop Creek, entering the channel here from the foothills of Mount Rainier, divides on the col, the major portion of the stream turning southward toward the Nisqually, and the smaller branch entering Lake Kapowsin and the Puyallup River. Alluviation by this stream has doubtless formed the divide at this point, and produced Lake Kapowsin in the same way that Bergh Creek has probably produced Ohop Lake in the old channel. The earlier position of the divide was probably between the north end of Lake Kapowsin, and entrance of the Puyallup River into the old channel, and the earlier divide was somewhat lower than the present one.

At the present col, the valley is about 500 feet wide at the bottom, and 340 feet deep. At the crossing of the Mount Rainier road, a few miles from Eatonville, it is 200 feet deep and perhaps 2000 feet wide. Between these two points there is a descent of about 14 feet to the mile from the present divide in the channel. From this point to the lowest terraces of glacial drainage at McKenna, the grade is about 10 feet to the mile.

The narrows of the Puyallup River valley between Kapowsin and Orting are caused by the superposition of the earlier southward-flowing drainage on a rock hill buried in the drift, and the maintenance of this course by the present northward-flowing drainage.

The western side of the Puyallup trough lies at an altitude of about 550 feet from a point nearly two miles south of Orting to a point three miles north of that town. West of this rim is lower land leading to Lake Russell. Whether this altitude sufficed to hold Lake Puyallup to the Ohop channel has not been yet definitely determined. If the Kapowsin col has been raised 50 feet or more by alluviation of Ohop Creek, it is probable that the lake discharge held to the Ohop channel and, with the Carbon, White, and Puyallup rivers, swelled the volume of the Nisqually until the glacier withdrew nearly to the bifurcation of the trough valley near the town of Puyallup.

The Clover Creek Channel. When this region was cleared of ice, Lake Puyallup found a new outlet westward through Clover Creek channel to the Steilacoom Plains south of Tacoma and thence to Early Lake Russell in the vicinity of Steilacoom. (See Figure 8.) The col in the Clover Creek channel on the summit of the bluff south of Puyallup, is a little below 400 feet in altitude. From it a well marked glacial river course leads south, and then northwest, to the broad gravel plains about Spanaway Lake. Salsich Junction, on the Tacoma Eastern Railway, is on the brink of the old valley which the railroad crosses at this place. Lake Puyallup persisted with gradual northward increase of area until the site of the city of Tacoma was cleared of ice. A lower pass was then opened, and because of this and other changes, the history of Lake Puyallup may be considered to end at this time, its area becoming part of Lake Tacoma.

LAKE TACOMA.

A very interesting region in the study of the glacial lakes of Puget Sound lies in the southeastern part of Tacoma. The bluff on which this city is built is a large reentrant angle opening northward toward the tide flats of Puyallup River. The business section of the city lies on the western side of the angle. A residence section occupies the southern side, where the glacial lake history is to be read. (See Fig. 9.)

The Tacoma Delta. A number of gravel pits are located in this part of Tacoma, forming amphitheater-like niches in the face of the bluff. They all agree in exhibiting delta-bedded gravels which dip between north and northwest toward the

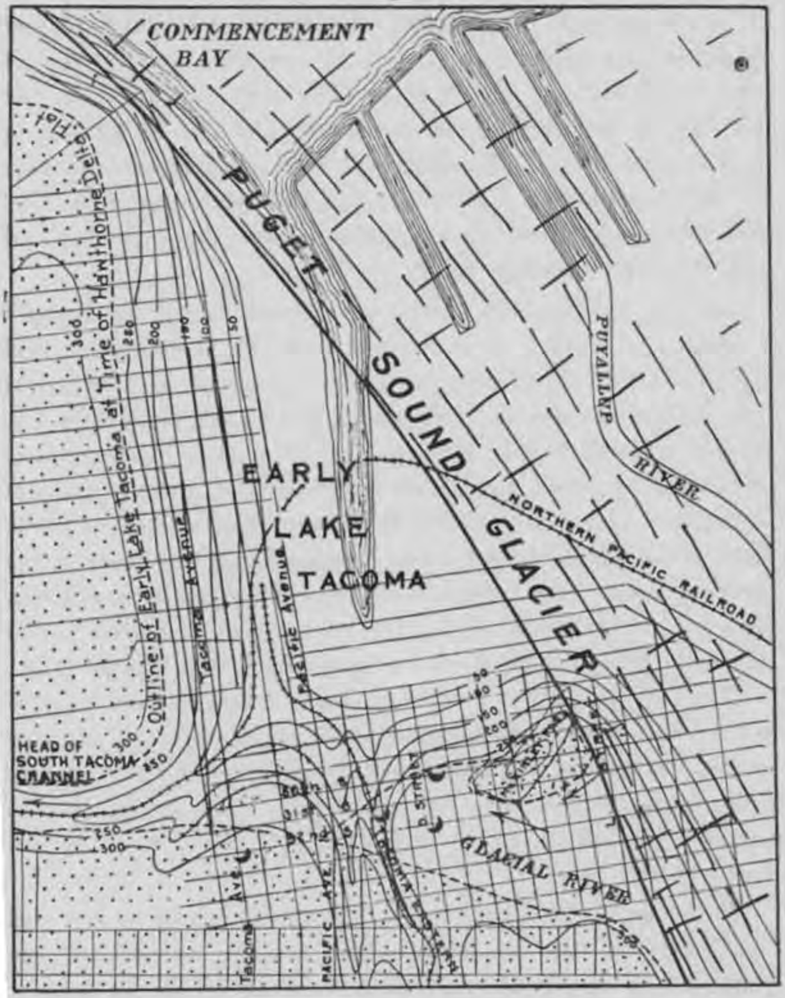


FIG. 9. A portion of the city of Tacoma, showing location of the Tacoma Delta, the various Pits in it, the Head of the South Tacoma Channel, and Position of Ice Front at Time of Delta Formation.

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present Sound. The altitude of contact between topset and foreset beds, however, is not the same in each pit.

In the pit east of the Hawthorn School, at Thirtieth Street South and D Street, topset beds 10 feet thick rest on foreset beds at an altitude of 265 feet. The delta surface above the pit can be traced easily southward with a rise of 10 feet in half a dozen blocks. The delta flat here is a noticeable feature of the topography. To the northeast, McKinley Hill, 330 feet above tide, rises like a buttress between this delta flat and the adjacent Puyallup trough.

Another pit has been opened on the east side of Gallagher's Gulch, a few blocks nearer the apex of the right angle described by the bluffs. The lower portion of the pit is in interglacial gravel, and exposes an intercalated stratum of Admiralty till. A thin layer of Vashon till caps the old, stained gravel, and is succeeded by fresh, unstained, unconsolidated gravel, with an abundance of granite pebbles of various kinds, and none of the soft, pink, purple, or gray lava pebbles found commonly in the lower gravel. This fresh material can be traced without break to a pit in the delta-bedded gravel near by, and definitely places the delta beds as subsequent to deposition of the Vashon till.

The Harrison pit is located at Tacoma Avenue and Thirty-second Street South, in the apex of the right angle. Its foreset strata dip to the northwest, and the altitude of their contact with topset beds is 320 feet above tide. The gravel here is exposed to a depth of 60-70 feet, all but the upper few feet being foreset beds.

If the delta flat south of the Hawthorn School be followed southeastward, the direction from which the stream came, as indicated by the foreset beds and the grade of the surface, it leads to an abrupt descent to the Puyallup Valley, L Street lying along the brink. This slope is somewhat irregular and has no pits like the northward slope just described. Wells penetrate a clayey gravel unlike the material in the Hawthorn and Harrison pits. Till is exposed in shallow cuts, and at the summit of the slope, gravel bedding records a current flowing northward away from the slope and onto the flat.

On the adjoining higher land about these delta gravels, there are no evidences whatever of a stream course which could have supplied them. All evidence collected points to the L Street margin of the Hawthorn School delta flat as the source of the gravel. The bluff here descending to the Puyallup Valley bears many of the marks of an ice contact slope. The conclusion is evident that the river which deposited the Tacoma Delta came directly from the surface of the Puget Sound Glacier when its front lay against the east slope of the delta flat described.

The lack of harmony among the altitudes of the tops of the foreset beds records a water body with changing levels. This is to be expected where a glacial margin is adjacent because changes in its position may change the location and level of the outlet. Such was not, however, the cause of the various altitudes of Lake Tacoma's surface, as will be shown.

THE SOUTH TACOMA CHANNEL. Gallagher's Gulch and DeLynn Street Gulch are two postglacial ravines which enter the Puyallup trough at the apex of the reentrant right angle in the bluffs. Both are utilized by railroads to ascend the bluffs. The Northern Pacific follows the DeLynn Street Gulch to an altitude of 230 feet, where the ravine heads in a flat-floored valley, one-fourth of a mile wide, with no present stream. Terraces of this valley floor, into which the DeLynn Street Gulch has cut, extend toward the Sound on both sides, while westward along the Northern Pacific tracks, the grade, which follows the old valley, at once begins a gentle descent toward the Steilacoom Plains. The old valley at the head of the gulch is 70 feet deep. It here possesses a terrace 250 feet above tide. Farther south, a high, level gravel terrace on the west side of the abandoned valley at about 310 feet above tide ramifies back among the till ridges which bound the valley. Its location is approximately west of South Tacoma, which is built on the channel floor.

Channels and Deltas of this stage are crosshatched.
Outlet of Lake Nisqually approximated.

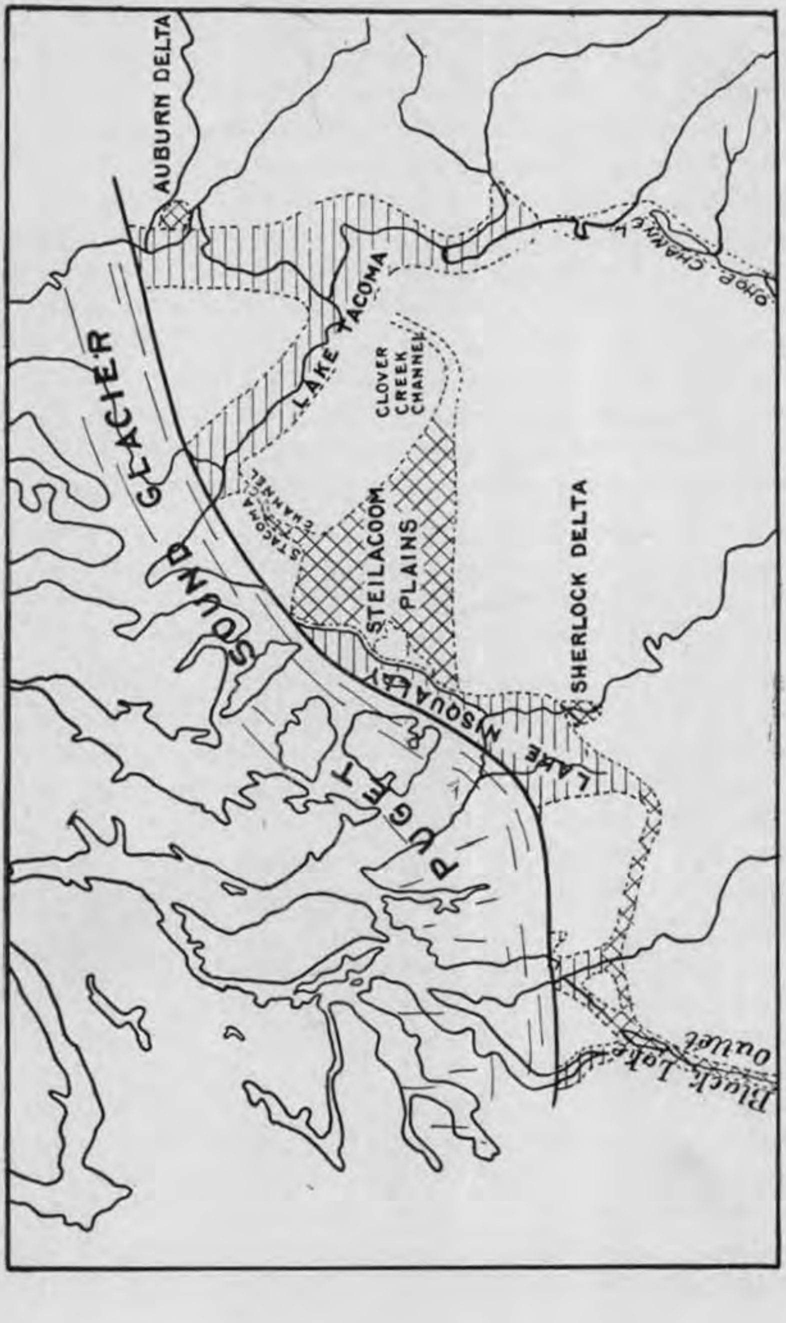

FIG. 10. Lake Tacoma, Lake Nisqually and Early Lake Russell.

Correlation of Tacoma Delta and Channel. Here then is the escapeway of a considerable quantity of water whose course was southward. The channel heads on the rim of the Puyallup trough near the apex described. Water discharging through it deepened it at least 80 feet. Behind it was the water body in which the Tacoma Delta was built, at levels between 265 and 320 feet. There can be no hesitation in correlating outlet and delta levels, even though altitudes are not the same. It is sufficient that the range in altitude of the outlet includes the delta levels. There is no other place for discharge of Lake Tacoma. If the Narrows had been open, the delta levels would have correlated with the Black Lake channel, and the Tacoma Delta would belong to Lake Russell, whose highest altitude was more than 100 feet lower than the lowest level of the Tacoma Delta. The discrepancy in levels of delta and outlet is simply because the channel continued to carry glacial drainage, and was eroded after ice had withdrawn from the head of the Tacoma Delta. (See Fig. 10.)

The most western level of the Tacoma Delta is the highest, and the most eastern is the lowest. In this is recorded the position of the ice front on the site of Tacoma while the outlet channel was lowered 55 feet. Slight recession during this time allowed lower delta surfaces to form successively eastward, their position being determined by the unknown course of the glacial stream, and the local outline of the ice margin, and their altitude by the downcutting of the South Tacoma channel.

Bailey Willis has discussed the Tacoma Delta in two papers.* He concluded that the above described South Tacoma outlet channel was the course of the river which deposited the delta gravels. In regard to this conclusion, it is to be noted

(1) that the direction of dip of the foreset beds is in all cases toward, not away from, the South Tacoma channel, and that the nearest beds (Harrison pit) dip almost directly toward the nearby channel head;

* Tacoma Folio, No. 54, U. S. Geol. Survey 1899.
Bull. Geol. Soc. Amer., Vol. 9, 1897.

(2) that the grade of the Hawthorn School delta flat does not permit the application of his interpretation; and

(3) that the grade of the South Tacoma channel itself absolutely forbids his interpretation, unless tilting has reversed this channel grade in a region where postglacial tilting has not been recognized. Data on the Steilacoom Plains to be presented shortly will throw further light on the subject.

THE AUBURN DELTA. A mile east of the town of Auburn, the Northern Pacific Railroad Company has excavated extensively in the face of the valley bluff for ballast gravel. In the section thus exposed there are splendid foreset delta beds, some of them 50 feet long, dipping west toward the pre-Vashon trough in which Auburn lies. The delta nature of the bluff would hardly be recognized from the topography. The gravel has two summit levels, at 235 and 260 feet above tide, but almost immediately back from the edge of the delta its surface descends in a huge kettle that destroys completely all semblance to a delta surface. White Lake lies in this kettle at an altitude of 105 feet. The south side of the kettle completely breaches the delta front, and presents a resemblance to a river channel, as Willis has interpreted it. The northern rim rises to 160 feet, however, and the presence of many smaller irregular kettles on the delta surface is satisfactory evidence that the Auburn Delta was built on the margin of the waning glacier, blocks of whose ice were buried in the river deposit, to melt out after deposition had ceased.

The Auburn Delta was deposited by Green River in glacially ponded water along the margin of an ice tongue lingering in the White River trough. The correspondence of levels in the Auburn and Tacoma deltas strongly suggests that Lake Tacoma possessed a long marginal arm of water reaching northward to Auburn on the east side of the White River trough, immediately after the Tacoma Delta was abandoned and after the ice had withdrawn from contact against the bluff at L Street, Tacoma. The lowest level of the Auburn Delta corresponds with the col in the South Tacoma channel and completes the record of river deposition to accompany all stages of erosion of the South Tacoma channel. No other outlet exists for the waters in which the Auburn Delta was built except the Narrows, and if they had been open, the Auburn Delta would correlate with the levels of Lake Russell, at least 65 feet lower.

THE KENNYDALE DELTA. On the eastern bluffs of Lake Washington about Kennydale, lies a broken-surfaced deposit of sand and gravel, of considerable extent and depth. Elsewhere the lake bluffs are of till. A level surface exists at the summit of the slope, about a mile back from the lake, 290 feet above the sea. May Creek has cut a canyon into this perhaps 225 feet deep. Fine sand constitutes the surface material, and well stratified gravel is found in shallow excavations.

Followed back from the lake, terrace fragments are replaced by a continuous floor on both sides of the creek. It has a smooth surface, rises gently eastward, and is composed of well washed gravel. Definitely cut bluffs border the southern side of this valley, and the canyon of May Creek shallows rapidly until the stream, three miles from Lake Washington, is flowing in a swampy, wide-bottomed old channel, in places a quarter of a mile wide, with bluffs 50 feet high. This old valley is very distinct along the foot of Squak Mountain (Pl. XV, Fig. 1), where a col in it about 315 feet above sea level divides the head waters of May Creek and Issaquah Creek. Willis* notes the existence of the upper portion of this old valley, and ascribes it to the work of Cedar River sometime during glacial retreat. The strength of development shown by the channel is equal to that exhibited in the present lower Cedar River valley, and suggests a considerable period when the river emptied into the pre-Vashon valley, four miles north of its present junction, and adjusted its channel to a water level about 290 feet above tide.

The Kennydale Delta is too high to be correlated with Lake

* Tacoma Folio, No. 54, U. S. Geol. Survey, 1899. Bailey Willis and G. O. Smith.

Tacoma levels north of the Tacoma Delta. This latter form definitely proves that Lake Tacoma was lowered to an altitude of 265 feet at the time the ice contact slope of L Street was abandoned, and the lake became free to extend northward. The Kennydale Delta is to be interpreted more satisfactorily as a deposit in a local lake between the ice tongue of the Lake Washington valley and the bluff, being tributary either to Lake Tacoma or to Lake Russell, which subsequently replaced the earlier water levels.

CORRELATION OF LAKES PUYALLUP, TACOMA AND RUSSELL.

THE STEILACOOM PLAINS. This large area of outwash gravel possesses a uniform westward descent from the broadening out of Clover Creek channel near Spanaway Lake to the abrupt truncation of the plains by the bluff of Puget Sound on the west. (See Figs. 8 and 10.) The grade commonly is between 10 and 15 feet to the mile. The surface of the plains is disposed in delta-like terraces in many places, and long channels are to be recognized on the western portion, descending westward with the general slope. Some portions are rolling, and suggest morainic topography, but till is rarely exposed in sections. Faint Mima type mounds are found on some of the plains, southeast of Hillhurst for example. The area is largely natural prairie, interrupted by forested portions. The coarse, gravelly soil provides an excessive under drainage and the plains are of little value agriculturally. The region has given the U. S. Bureau of Soils their Spanaway type of gravelly soil.

Lake Puyallup emptied through the Clover Creek channel onto the Steilacoom Plains at their eastern terminus, while the northern side of their area received the discharge from the earliest stage of Lake Tacoma, then a small body of water in the re-entrant angle which contains the Tacoma Delta. Following retreat of the ice from the L Street slope, Lake Puyallup's waters found a lower outlet through the South Tacoma channel and became a part of Lake Tacoma. By the use of both of these dischargeways, the glacial gravels previously deposited on the Steilacoom Plains were rehandled and added to. Though the gradient is low for stream-deposited gravels, it is paralleled in many places in Puget Sound outwash, where other conditions make it certain that such grades were produced only by glacial drainage, and that they are without discernible subsequent deformation.

The westward-facing bluff which terminates the Steilacoom Plains affords further indisputable evidence that they are stream gravels. The town of Steilacoom is built on the western slope of a hill of morainic aspect which rises above gravel plains on the north, east and south, and interrupts the continuity of their bluff line on Puget Sound. (See Pl. XXII and Fig. 10.) Immediately north of Steilacoom the bluff is of fresh gravel for two miles, with an even crest line of 180-200 feet. North of this to Tacoma the bluff exposes till surfaces and edges of truncated Admiralty sediments, rising to 400 feet above tide. The hill on which Steilacoom is built forms the bluff for three miles south of the town and is then succeeded by a bluff of fresh gravel, with even crest line, nowhere more than 200 feet high, this continuing to the mouth of the Nisqually River. These gravel bluffs constitute the western edge of the Steilacoom Plains.

THE STEILACOOM DELTA. Extensive excavations have been made in the face of the bluff north of Steilacoom, by the Pioneer Sand and Gravel Company of Seattle. The gravel is sluiced out by hydraulic methods, carried to the bunkers, and there sorted, all by gravity. The pits are abandoned when their floors are lowered so that running water will not successfully carry the gravel from pit head to bunker. Great amphitheaters are thus formed in the bluff, and the structure of the gravel is splendidly shown. (See Pl. XI, Fig. 1.)

Without exception, the material from bluff top to sea level is fresh, unstained, unconsolidated Vashon gravel, and this gravel is disposed everywhere in foreset and topset beds. It seems evident that the whole wall of Puget Sound here has been advanced on the inlet by delta growth.

The largest pit has sides 100 feet high in which, at the time of examination, great, unbroken foreset beds, certainly more than 100 feet long, were exposed without interruption. These beds descend westward toward the Sound with an average slope of 15°. No faulting or other deformations have affected them.

Above the long, unbroken foreset beds is a stratum of topset beds, about 12 feet thick near the seaward end. Shallower foreset beds overlie this in turn, with a depth of 10 feet, and their truncated edges disappear upward in the surface soil. A broad ridge of gravel, overlying the upper foreset beds, is cut in section by the south side of the pit.

With such evidence, no hesitation can be felt in saying that the Steilacoom Delta was deposited in rising water. The water level stood for a long time at the upper plane of the great foreset strata which largely compose the section. The altitude of this is between 160 and 165 feet. The delta front was extended at this time until it reached much beyond the present bluffs, topset beds being 12 feet thick here. Originally they must have reached out with gradually diminishing thickness to nothing at the delta edge.

A rise of the water level to 180 feet ensued. Foreset beds were now begun back on the submerged delta plain, and were advanced seaward until the second foreset stratum, 10 feet thick at the edge of the bluff, was deposited.

If topset beds ever accumulated on these, they have been removed by subsequent changes. The cross section of the broad ridge overlying the upper foreset beds has a diagonal stratification, which dips landward at about the same angle at which the foreset beds dip seaward. The ridge lies parallel to the edge of the bluff. No explanation for this form has been found, save that of a wave-built bar. The strata are not arranged with seaward dip to record accretion on the exposed face, and the only satisfactory explanation is that the bar was being driven inland across the top of the delta by waves which eroded the seaward face, and threw the gravel over its crest to be deposited in the anomalously dipping beds.*

The surface of the delta was originally thinly forested, but to supply the gravel works with fuel the forest has been sufficiently removed to expose several acres of surface. It is surprising that the configuration of the surface is irregular and unsystematic, giving almost no hint of the nature of the underlying material.

By the aid of the nearby sections, the irregularities are identified, with some reserve, as bars and channels on the top of the delta.

The occurrence of a terrace 200 feet above tide, back a little from the head of this pit, and not cut so as to show structure, possibly indicates that the water level rose 20 feet above the upper foreset beds of the sections. The presence of the supposed bars above the same foreset beds is further evidence of such submergence. This highest water level may be considered as of so short a duration that the delta plain was not completely built up to the new level.

The gravel plain back from the edge of the Steilacoom Delta rises very gradually eastward, and widens out as the Steilacoom Plains. A somewhat lower portion of it gradually narrows northward until it becomes the old outlet channel of Lake Tacoma. The waters of this lake lowered the grade of the South Tacoma channel from about 13 feet to the mile to a little more than five feet to the mile.

The Sequalichew Delta. The gravel bluff between Steilacoom and the mouth of the Nisqually River is being exploited for gravel by the same company which is operating in the Steilacoom Delta. Two pits have been opened half a mile north of Sequalichew Creek, and in one of them the structure of the gravel is clearly revealed. On the south side of the pit, during the summer of 1911, the structure shown was identical with that described for the Steilacoom Delta. The highest level

* Gilbert, in Monograph 1, U. S. Geol. Survey, has described a similar procedure of wave action in Toronto Harbor.

of foreset bedding is here at an altitude of 185 feet, instead of 180 feet, and no bars exist above it. The same history is thus recorded that has been read for the Steilacoom Delta. The surface of the Sequalichew Delta is somewhat irregular and fails to resolve itself into channels or bars. A satisfactory explanation for the irregularities has not been found.

Foreset beds exist in the sea cliffs of the Sequalichew Delta, and back in the valley of Sequalichew Creek. This parallels the occurrence of foreset bedding in the valley of Chambers Creek which similarly incises the Steilacoom Delta. Both creek valleys show the delta gravels on the coast to be the full depth of the bluff height, though they become shallower a mile inland. At the head of the Sequalichew Creek, near DuPont, the gravel is but 50 feet thick. It is here cross bedded in intricate fashion, indicating changing currents during a rising water level. From the head of the ravine, the level prairie surface extends eastward with slowly rising altitude, being one and the same plain which forms the Steilacoom Delta front.

Thus the Steilacoom Plains are proved to be a great flat of stream aggradation, whose materials were rehandled and brought to lower gradients by subsequent work of less heavily laden waters coming from glacial Lakes Puyallup and Tacoma. The abrupt western face is clearly a delta front in the glacially ponded water of Puget Sound. Elsewhere the plains are surrounded by ground and recessional moraine surfaces of higher altitudes.

Willis and Smith* have interpreted the Steilacoom gravel plains as the deposit of a glacial lake whose discharge was northward by the Clover Creek and South Tacoma channels to the Puyallup trough. This conclusion is untenable for the following reasons:

(1) The two channels descend toward, not away from, the plains.

* Bailey Willis and G. O. Smith, Tacoma Folio, No. 54, U. S. Geol. Survey.

(2) The plains continue the slope of the channels westward to the bluffs of the Sound.

(3) The delta bedding of the Steilacoom and Sequalichew deltas indicates westward-flowing water across these plains.

(4) There would have been no outlet for the ponded water in the Puyallup trough between Tacoma and Puyallup if drainage had taken the course they assumed.

(5) Their Lake Steilacoom had no westward retaining wall, it being impossible that the ice could so serve, and their lake still have a northward outlet.

LAKE NISQUALLY AND THE OBLITERATION OF EARLY LAKE RUSSELL.

The lower foreset beds in both the Steilacoom and Sequalichew deltas, at an altitude of 160 feet, are, without question, to be referred to Lake Russell at its highest level. The rise in level to 180 feet, and possibly 200 feet, can only mean a closure of Black Lake outlet while the two deltas were still growing, the lake finding a new outlet at higher levels corresponding to the level of the higher foreset beds.

Differential crustal movements do not enter as a possible cause of this change in outlet, the evidence throughout the Puget Sound country being that there has been no warping nor tilting since the Vashon ice was at its maximum. Closure of the outlet by landslides would be impossible. There was no vulcanism in the region during the Quaternary. All but one of the possible ways of causing this rise in water level are ruled out. This one is the closure of outlet by readvance of the glacier. This conclusion has been reached by a process of elimination, because no corroborative field evidence for such advance has been found.

A readvance of the glacier sufficient to close the Black Lake outlet to drainage from the eastern part of the region necessitated a frontal position in the vicinity of Lacy, and the morainic country enclosing the lakes of Thurston County. (See Fig. 10.) Advance to this position would turn the Nisqually River, and the drainage of the Steilacoom Plains across Chambers and Bush prairies, as before the birth of Lake Russell. It would so shorten the area of ponded water in Budds Inlet that, at the most, only a small lake would have remained about Tumwater.

During this advance, the areas of Lake Puyallup and Lake Tacoma were not seriously encroached on. Both the Clover Creek and South Tacoma channels continued to be used, and drainage across the gravel plains adjusted grades to the 180-foot level. At this time the front of the ice had an approximately northeast-southwest course between Tacoma and Olympia. (See Fig. 10.)

For this body of water, changed in level and in outlet, the name *Lake Nisqually* is proposed. The term *Early Lake Russell* is restricted to the glacial lake occupying the southern portion of Puget Sound before the advance which formed Lake Nisqually. When the ice retreated again, the lake which reoccupied the southern part of the Sound did not differ materially from the first in depth or area. It again discharged across the Black Lake channel at the original 160-foot level. It appears, however, that clearing of the Narrows occurred during this retreat, and that Lake Tacoma was thus lowered, and became a part of Lake Russell. The evidence for this conclusion is the fact that the 180-foot level of the Steilacoom and Sequalichew deltas was not eroded subsequent to the reestablishment of the 160-foot level, discharge through the South Tacoma channel having apparently ceased.

If this conclusion is correct, the Auburn Delta of Lake Tacoma was building at the time Early Lake Russell was obliterated; the Tacoma Delta had been already constructed and abandoned, the ice front having withdrawn from the L Street slope. At best, there are weaknesses in the preceding correlation which can be removed only by further study of the region.

GLACIAL LAKES ON THE NORTHERN SLOPE OF THE BLACK HILLS.

With the retreat which destroyed Lake Nisqually, and gave rise to Later Lake Russell, there was sufficient withdrawal of the ice on the northern slope of the Black Hills eventually to permit drainage from the western lobe of the glacier to enter Lake Russell. During this retreat, two minor glacial lakes were formed, one in the Little Skookum Creek valley, and one in Gosnell-Mill Creek valley. The Little Skookum glacial lake discharged at first over the Simpson col to Wildcat Creek, its escaping water flowing on the gravel train built here during the maximum of Vashon glaciation. It probably early found a lower outlet around to the eastern lobe. The head of Gosnell-Mill Creek valley contained a small glacial lake, discharging across the outwash plain of Lost Prairie to the Satsop valley train. Both of these lakes owed their existence to the rock hills of the region, already referred to as the cause of the tardy diversion of drainage from the western lobe to the Gate Pathway.

LATER LAKE RUSSELL AND THE SHELTON DELTA.

With the clearing of Hammersley Inlet the water of Lake Russell backed up into it and into the two tributary valleys of Shelton Creek and Oakland Bay. As the edge of the glacier withdrew from the vicinity of Shelton, outwash gravels carried southward across the tract between Hoods Canal and Hammersley Inlet were deposited in a large delta on the north side of the Shelton Creek arm of Lake Russell. (Fig. 11.) The front of this delta now forms at least a mile of the northern bluff of the valley.

Seen from Shelton, a few feet above tide, the crest of the delta front is strikingly level. According to the aneroid, it ranges between 160 and 175 feet in altitude for the unforested mile of length which has been examined. Foreset beds were seen in two places on the steep front. The material is gravel, with sand in some portions. Back from the edge of the delta, the surface is the typical outwash prairie of Puget Sound, with a thin forest covering much of it a few miles farther north. The whole outwash plain slopes gently southward toward the delta.

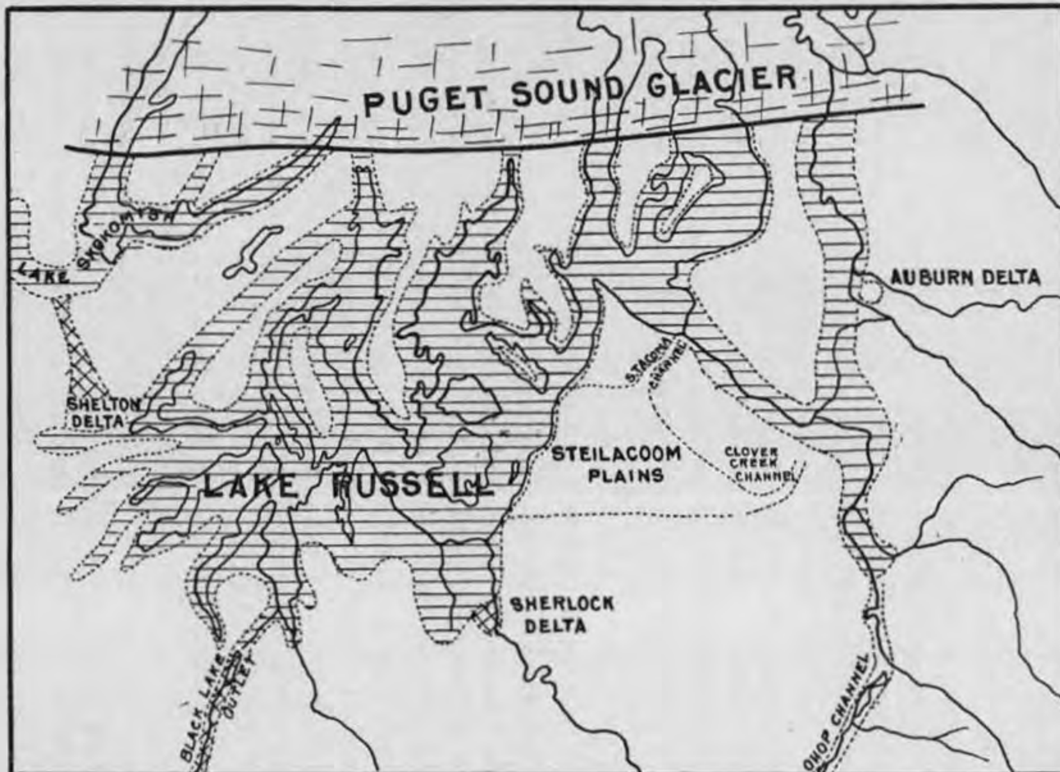

FIG. 11. Lake Skokomish and Lake Russell.
Channels and Outlets of this stage are crosshatched.

There is no gravel on the south side of Shelton Creek valley. The slopes are all of ground moraine, and rise higher than the delta on the north side. From this fact, and from the uniform level of the edge of the delta, it is inferred that the Shelton Delta was never built completely across the creek valley, though advance of the front of the delta considerably constricted the valley a mile above Shelton.

There was outwash across the gravel plain between Shelton and Hoods Canal before the lingering ice tongues in the valleys of the Hammersley Inlet group had been melted sufficiently to allow water of Later Lake Russell to enter them. The evidence on which this conclusion is based is found in a channel from the gravel plain eastward across moraine hills to Oakland Bay. The channel floor across the moraine deposits is about 210 feet in altitude, the highest terrace overlooking the bay being 200 feet above it.

The deposit at the mouth of this spillway is very irregular in frontal outline and in surface. It apparently was deposited against, or on, or in crevasses of, stagnant ice lying in the valley of Oakland Bay. The altitude of the high terrace, 200 feet, proves that locally ponded water, and not the water of Lake Russell, was present.

LAKE SKOKOMISH.

The depression of Hoods Canal is divided into two great arms at its head, each recurving in the form of a hook. The eastern arm contains tidewater today; the western one has been extensively filled with alluvium by the Skokomish River.

The glacial lake first forming in Hoods Canal filled these two valleys, and a part of the main valley as well. Its outlet over the present divide at the south was at an approximate altitude of 350 feet. Two or three abandoned channels are known across the northern part of the gravel plain. They were cut in the higher graded surfaces by waters escaping from the lake and flowing to the Shelton Delta. This stage of glacially ponded water in Hoods Canal may be named *Lake Skokomish* (Fig. 11). It was short-lived, because glacial retreat soon exposed a lower outlet from Clifton, at the head of the northeast arm, across to that part of Lake Russell in Cases Inlet (North Bay).

LAKE HOOD.

The second stage thus inaugurated may be named *Lake Hood.* While the Clifton outlet was used, the waters of Lake Hood gradually extended northward for nearly the entire length of the Canal. As in the case of Lake Puyallup, the only record of this lake is its outlet. Figure 12 indicates the area of Lake Hood at its maximum.

THE CLIFTON CHANNEL. The Clifton outlet channel is a definite feature across the divide on which it lies. It is 60 feet deep at Lake Deborah in the col, 220 feet above tide. This lake now drains both to Cases Inlet and Hoods Canal. Gravel terraces exist along the channel, and one terrace on the east side continues as a small channel directly eastward to Cases Inlet, on whose slopes it opens. The Clifton channel ends in the forest west of Allyn, 160 feet above tide, corresponding with the dominant water plane of Lake Russell.

THE BRINNON DELTA. The only delta of Vashon age known in the valley of Hoods Canal is at the mouth of the Dusewallips River, on the north side of the valley. (See Fig. 13.) At the seaward upper margin, it is 120 feet above the Sound. Its surface is a plane, sloping toward the trough of Hoods Canal. Its altitude makes it obviously a feature produced subsequent to Lake Hood, whose waters were 100 feet higher.

THE POULSBO CHANNEL. The Kitsap County peninsula between Hoods Canal and Admiralty Inlet is sufficiently high to have confined Lake Hood as far north as Breidablik, northwest of Dogfish (Liberty) Bay. A meridional trough of the pre-Vashon topography, styled the Poulsbo Valley in this paper, crosses the peninsula here, Dogfish Bay lying in the southern portion. A swampy col occurs midway of its length at an altitude of 120 feet, and a stream terrace lies on the eastern side of the valley near the col, at an altitude of 150 feet. Other

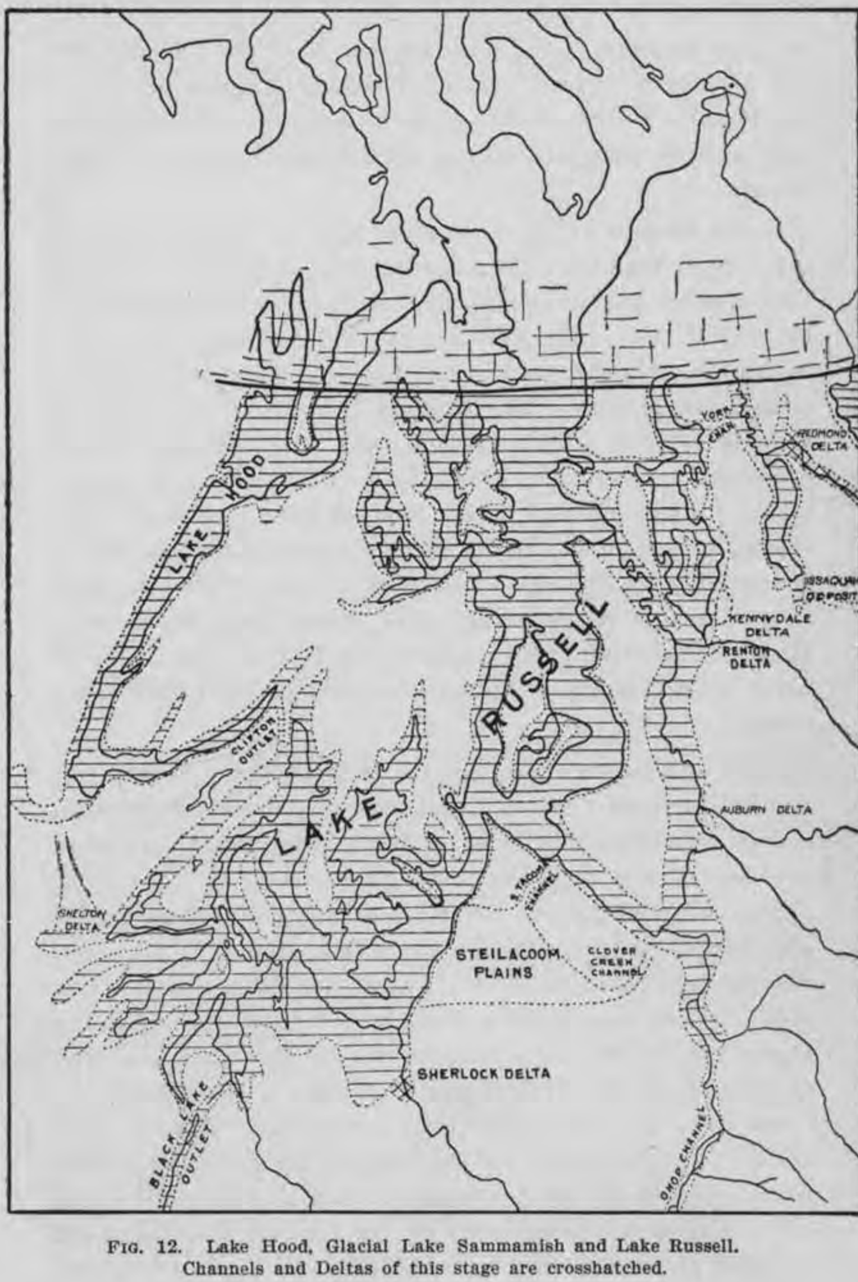

FIG. 12. Lake Hood, Glacial Lake Sammamish and Lake Russell. Channels and Deltas of this stage are crosshatched.

terraces, possibly of the same genesis, occur at 190 and 225 feet. There is evidence here of considerable stream erosion in the Poulsbo Valley which can be consistently correlated with data already presented on the glacial lake history of Puget Sound.

In the Poulsbo Valley, Lake Hood appears to have found an outlet lower than the Clifton channel, and to have entered Lake Russell at the head of Dogfish Bay, north of the latitude of Seattle. (Fig. 16.) The 120-foot col and the 150-foot terrace record the same changes of level that are found along the Percival Creek channel. The Brinnon Delta is to be correlated with the 120-foot level of Lake Russell. The two lakes may be considered as one at this stage, Lake Hood sinking by erosion of the Poulsbo channel to the level of Lake Russell, and becoming an arm of it. If the ice dam causing Lake Russell remained effective during the next few miles of retreat, as there is good reason for believing, Lake Russell levels obtained in Hoods Canal with broad connection across the low northern tip of Kitsap County peninsula, a few miles north of the Poulsbo channel.

Lack of Vashon Deltas of Olympic Rivers. Several vigorous streams enter Hoods Canal from the Olympic Mountains, and are depositing actively in the Sound today; but their valleys have no deltas at the levels of the glacial lakes.

The valley of Quilcene River has a long gravel slope gradually descending from altitudes above Lake Russell to tidewater. Foreset bedding exists in this gravel, and the surface is terraced, but no definite delta levels have been recognized. The Duckabush Valley has a long terrace on the north side, evidently aggraded to levels higher than those of the water in the Canal now, but falling below the level of Lake Russell at its lower end. The valleys of the Hama Hama and Skokomish rivers are densely wooded where Vashon deltas should exist. Though some laborious search on the forested floodplains and adjacent slopes has been made, no deltas of these streams referable to the glacial lakes have been found.

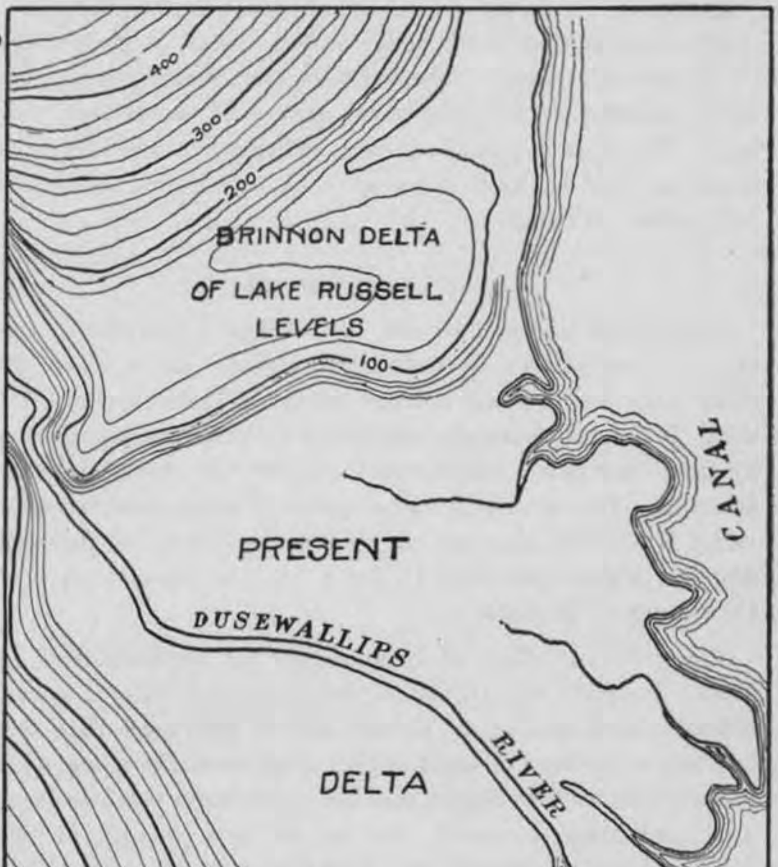

FIG. 13. The Brinnon Delta at the Mouth of the Dusewallips River. A rock ledge occurs at the constriction indicated, and has "defended" the existing portion of the original delta. Drawn from Chart 6450 of the U. S. C. & G. S.

It cannot be considered a serious objection to the interpretations advanced that deltas have not been found at the mouths of all entering rivers. Subsequent stream erosion has apparently regraded the late Pleistocene gravels of two of these valleys. The other two have not been sufficiently studied to make it certain that no such deltas exist, though if this is true, it will not be strange.*

GLACIAL LAKE SAMMAMISH.

The trough occupied by this ancient lake is parallel to and east of that containing Lake Washington. It is about 23 miles long and has an average width of three-fourths of a mile. It deepens gradually southward to its abrupt termination by three rock hills 1,500, 2,000 and 3,000 feet above tide, near Issaquah. The eastern of the two passes leading south from the valley is 315 feet high and the western one is between 350 and 400 feet high. (See Fig. 14 for a graphic representation of the history of this lake.)

First Stage. East of Issaquah, on the northern flank of Mount Issaquah, the highest of the three rock hills, is a considerable level area at an altitude of 425 feet, more than 300 feet above the floor of the trough. Back from the margin the terrace rises 20 feet higher, and has a still more extensive level area continuing eastward. On the southern margin of this high-level gravel deposit are imperfect terraces as high as 465 feet. At the western foot of this plateau, gravel spreads out widely on the valley floor in terraces 215, 195, 175, 160 and 120 feet above tide.

The east fork of Issaquah Creek cuts the gravel plateau to a depth of 300 feet, and sections in the gorge show stream-rolled glacial gravel in beds of variable positions, indicative of shifting currents with considerable variations in velocity. No true delta structure was seen.

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* The remnant of a Vashon delta in the Dusewallips Valley is preserved only by an outcrop of rock at its head in the manner of a "defended" terrace of alluvium. (See Fig. 13.)

The grade of the East Fork of Issaquah Creek ascends rapidly eastward until at High Point the creek is no longer rushing along the bottom of a narrow gorge, but wandering through a wide, flat-bottomed, swampy valley, in which the stream appears incongruously small and ineffective. Two miles east of High Point, this old floor suddenly ends at 540 feet above tide, with the valley at full width. There is a descent here of about 100 feet to Raging River, which comes in from the southeast and turns northward at this point. Represented by terraces, the old valley floor continues up the valley of Raging River for four or five miles where the grade of the latter has risen to the level of the old floor. Fragmentary terraces along Snoqualmie River, between the Falls and the junction with Raging River, and along this river between the junction and Preston, indicate that these streams formerly united at Preston, and that their combined waters built the Issaquah deposit.

At the time of this gravel deposit, the escaping water of these rivers was held back, probably by an ice tongue in the Sammamish Valley which dammed the stream where the deposit now lies. The cols in the two passes among the hills terminnating the Sammamish trough at the south are too low to have caused the ponded water in which the Issaquah gravels were laid down. This, hardly to be considered as a lake deposit, is the oldest record of glacial waters in the Sammamish Valley. The discharge of the Snoqualmie River through the Preston-Issaquah valley was caused by ice blockade of the more northern and lower routes followed later by that stream.

Second Stage. A glacial lake of limited extent must have formed in the southern portion of the Sammamish Valley a little after deposition of the Issaquah gravels. Discharge from this lake was southward through the two rock-walled valleys, both of which are floored with coarse stream gravel, the eastern one carrying the larger amount of water, and for the longer time.

A channel exists across the till ridge between Lakes Washigton and Sammamish at the north base of Newcastle Hill, the lowest of the three rock hills described. Its altitude is some-

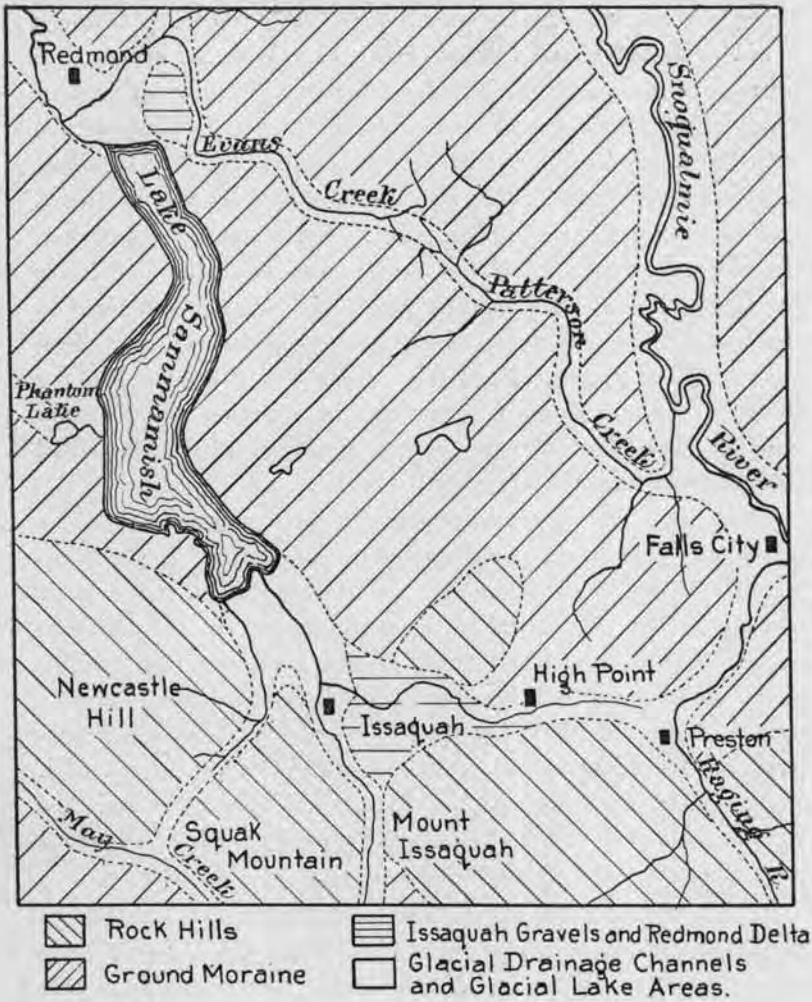

FIG. 14. Map Showing Principal Events in the History of Glacial Lake Sammamish.

FIG. 1. Distorted Admiralty Sediments, McNeil's Island.

FIG. 2. Structure of the Quatsap Point Delta Beds.

what above 300 feet above tide. It is floored with coarse gravel. Another channel at a slightly lower altitude exists a mile farther north, along the line of Phantom and Larsen lakes, both of these lying in a definite channel two and a half miles long across the ridge.

Southward discharge from the Sammamish Valley between the hills did not lower the glacial lake surface below about 315 feet above tide, the altitude of the col in the old Cedar River channel south of Squak Mountain, to which the lower eastern channel was tributary. The two channels just described then must have been in use contemporaneously, or nearly so, with the southward escape. (See Plate XXII.)

These channels show no perceptible descent on crossing the ridge to Lake Washington. The Phantom-Larsen Lake channel ends in a swamp almost on the brow of an abrupt descent of 125 feet, at the base of which lie unmodified kame terraces. These must be younger than the channel, which itself must have discharged to standing water somewhat below 300 feet above tide. These two minor escapeways on the north side of Newcastle Hill probably led to the same water body in which the Kennydale Delta was built. The kame terraces, slightly above 150 feet above tide, show that ice was present in the Lake Washington trough later than the time of Sammamish discharge by the routes described, and therefore must have been in the valley at the time of the lake referred to. Kettles and broken topography on the Kennydale Delta are additional evidence of the immediate presence of ice at the time of its growth.

Third Stage. Redmond Delta. There are terraces in the Issaquah gravel deposit at altitudes between 215 and 120 feet, lower than any outlet channel thus far described for Glacial Lake Sammamish. Their origin will be better understood after consideration of the Redmond Delta.

At the north end of the present lake and on the east side of the valley, there is a deposit of stream gravels which has been given more study than any other feature of the entire region. It will be called the *Redmond Delta*.

East of Redmond, a considerable trough from the north unites with the Sammamish depression. In common with the majority of valleys in the region, it is of pre-Vashon age, not the product of postglacial erosion. Deposition by streams has produced a fairly level floor in this valley, the altitude near the mouth being 50 feet above tide.

Southeast of this alluvial plain a semicircular scarp rises abruptly. It is convex toward the plain, and faces west, north and east. It is a conspicuous feature from the valley floor wherever the view is unobstructed. Its base line is nearly horizontal and about 50 feet above tide. Its summit profile is made up of four levels at 120, 130, 140 and 160 feet respectively.

On examination, the scarp is found to be composed of coarse gravels, everywhere disposed almost as steeply as they will lie. On reaching the top, level terraces of coarse gravel are seen stretching back at the several altitudes noted, covering about a square mile. The 160-foot area is the most extensive and lies in the south and west portion of the deposit. The north and northeast sides are made by the 120- and 130-foot terraces. A considerable portion of the east side is broken and irregular from the presence of two large, roughly linear kettles. The lack of a steep descent along much of the east side is due, probably, to breached kettles along that edge. On the south, the 160-foot terrace abuts against higher till hills. These relations are shown in Fig. 15.

Evans Creek approaches Lake Sammamish from the east, the Redmond Delta lying in the direct continuation of its upper course. The stream makes a detour to the north to pass around the delta, and reach the lake. It rises in a marshy col in a wide valley which extends southeastward for 11 miles, from the Redmond Delta to the present Snoqualmie River valley. The broad floor at the col is 160 feet in altitude, and two splendidly developed river terraces between the col and the delta are 140 and 200 feet above tide. East of the col, fragmentary terraces continue the ascending profile of the old floor eastward

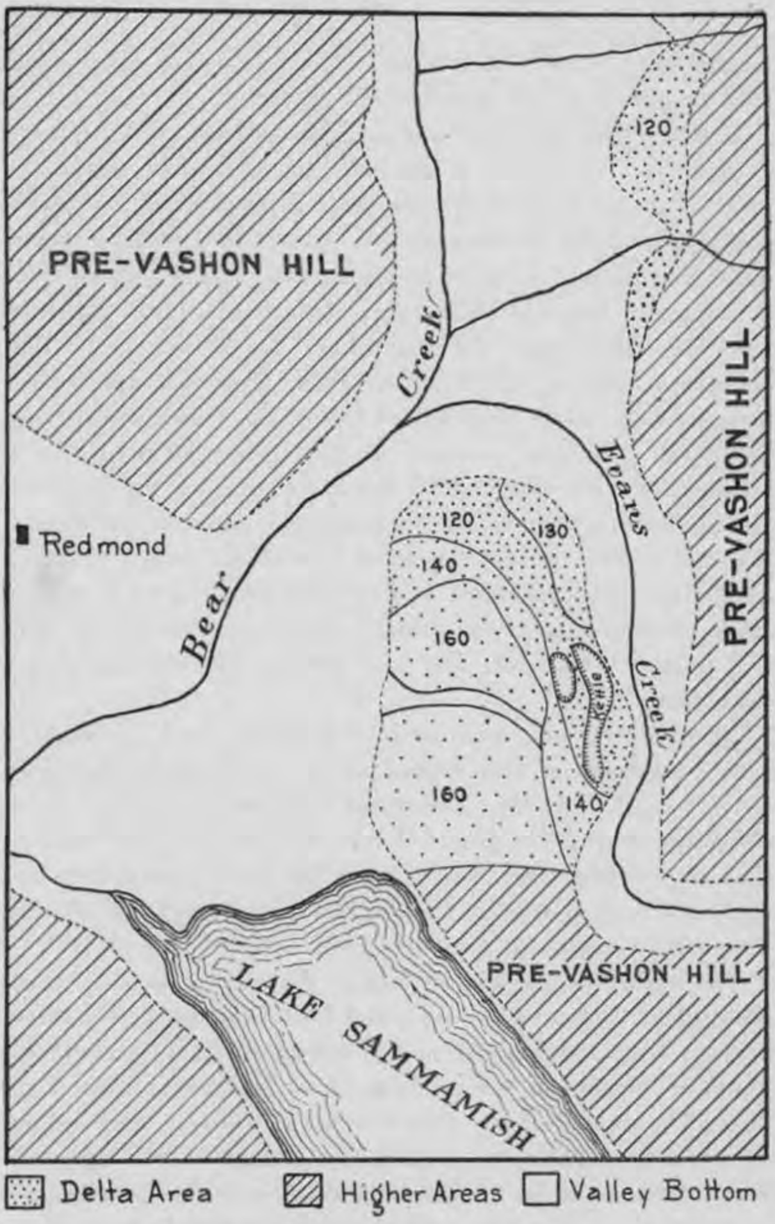

FIG. 15. The Redmond Delta and Environs.

Delta area dotted. Higher areas crosshatched. Valley bottom blank.

toward the Cascade Mountains. The relation of this valley and the gravel deposit is undoubtedly genetic.

It seems clear that the Snoqualmie River took the Patterson-Evans Creek channel to Lake Sammamish as soon as the retreat of the ice had exposed the lower ground which it crosses, that glacial Lake Sammamish had by this time found a lower outlet and its surface stood no higher than 160 feet above tide, and that, in the lake valley near Redmond, ice still lingered when the delta began. (Consult Figs. 14, 15 and 16.) The successive levels of the Redmond Delta show that the higher terraces were being dissected while the lower ones were being developed. The best instance of such dissection occurs in a channel 100 feet wide and 10 feet deep, crossing the 160-foot terrace from east to west, and possessing a miniature but clearly discernible delta on the lakeward face of the larger feature. (Fig. 15.) An excavation at its foot reveals foreset structure in the stratification of the gravel. The occurrence of the 120-foot portion between the 130- and 140-foot terraces also shows dissection.

Three-fourths of a mile north of the delta, there is a considerable fragment of this deposit on the east side of the Bear Creek trough. Its top is level and 120 feet in altitude. It is composed of stratified gravel at least 40 feet in depth. Dissection at a period later than that of the delta growth has destroyed a large portion of the original deposit, and has left this area widely separated from the main body.

The outlet for the glacial lake at the time of deposition of the highest terrace of the Redmond Delta crosses the till ridge between Lakes Sammamish and Washington, in the vicinity of York, or Willows, a few miles north of Redmond. (See Fig. 16.) The summit of the York channel is 160 feet high and no descent is perceptible to the eye in the swampy floor to the west. This argues a similar level of ponded water in the Lake Washington valley. The lake surface today is 130 feet lower than this col. Discharge for the lower stages of the glacial lake recorded in the Redmond Delta, and in the lowest terraces about

Issaquah, passed through the pre-Vashon valley to Bothell, by which the two parallel lakes are connected today at the north.

The 160- and 120-foot terraces of the Redmond Delta, with short, open channels connecting Glacial Lake Sammamish with Lake Washington Valley, indicates that this third stage of the local lake, recorded by the Redmond Delta, is really a portion of Lake Russell's history. Glacial retreat by this time had allowed the northward-extending waters of the master lake to occupy the Lake Washington trough and to control the later static water records in the Sammamish Valley.

LAKE SNOHOMISH.

The old Snoqualmie River channel now occupied by Evans and Patterson creeks, leading to the Redmond Delta, does not continue uninterruptedly up into the Cascade Mountains. It breaks off abruptly on reaching the present Snoqualmie Valley, which is much lower, in the same fashion that the old valley east of High Point breaks off at Preston, except that in the present case, subsequent erosion by Patterson Creek has largely destroyed the eastern portion of the old stream floor, and it is really a projected profile which is abruptly terminated.

Snoqualmie River is flowing in a trough valley of interglacial erosion which lies parallel to, and east of, the Sammamish Valley, and is open to Puget Sound at its northern end. The abrupt descent which takes place at the east end of the projected profile up the valley of Evans and Patterson creeks to the present Snoqualmie River valley thus is not the work of postglacial erosion, as it is at Preston. On the contrary, ponded water must have filled this valley to the height of the truncated profile, in order to flow westward across the divide to the Redmond Delta. This water constituted *Lake Snohomish.* (Figs. 14 and 16.)

Few definite data can be presented concerning this lake. Its altitude was about 250 feet when discharging to the Redmond Delta. Earlier outlet channels to Glacial Lake Sammamish occur parallel to the Evans-Patterson Creek channel, and south

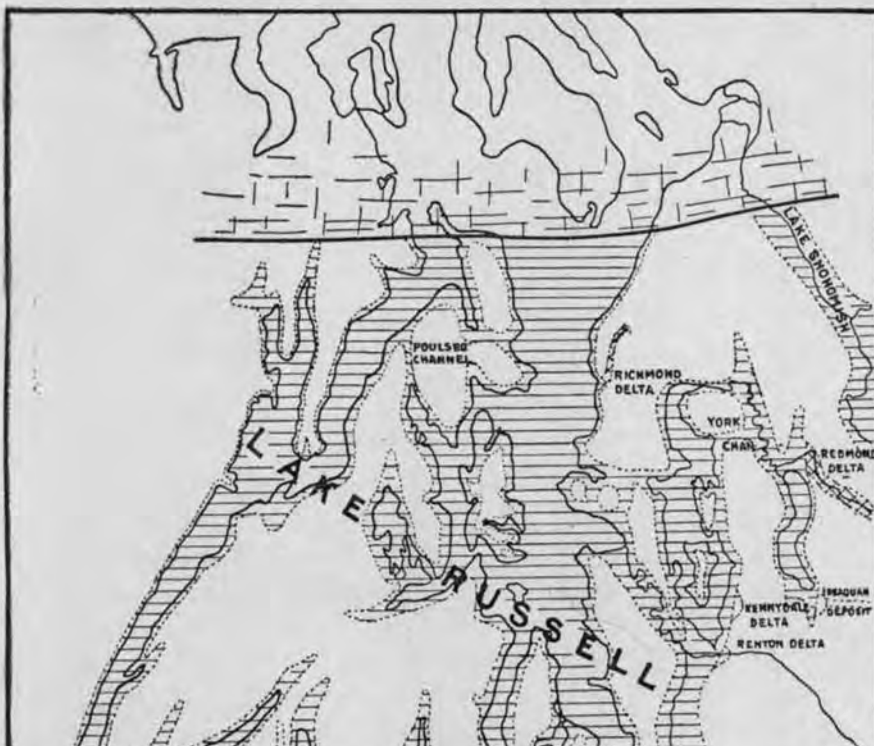

FIG. 16. Lake Snohomish and Lake Russell, at maximum extent of 160-foot stage. Channels and Deltas of this stage are crosshatched.

of it, but their altitudes are unknown. It appears probable that this lake backed up at its higher stages to the foot of Snoqualmie Falls, into which that cataract plunged. The lake extended northward a long distance, perhaps nearly to Everett, but apparently never sank to the level of Lake Russell.

HISTORY OF LATER LAKE RUSSELL.

The retreat which destroyed Lake Nisqually and allowed the re-formation of Lake Russell, early cleared the Narrows and brought about the destruction of Lake Tacoma also. Lake Russell then extended east and south up the Puyallup trough, and north into the White River trough where the Auburn Delta of Lake Tacoma records the earlier presence of standing water.

The Hammersley Inlet arm of the lake originated soon afterward, and the Shelton Delta was then formed. Lake Skokomish quickly passed through its brief history, and Lake Hood began when the Clifton outlet came into existence. Its level persisted while the glacier retreated for a distance of 26 miles. During this time, the channel of the Clifton outlet was cut to a depth of 60 feet, but at the time it was abandoned its grade was still 25-30 feet to the mile. A rapid retreat for the ice for the length of Lake Hood is thus indicated, else the grade of the outlet would have been reduced to a lower slope. The opening of the Poulsbo channel records the presence of the 160-foot level of Lake Russell in Dogfish Bay, and consequently in the great trough of Admiralty Inlet as far north as this latitude.

Presumably the history of Glacial Lake Sammamish and Lake Snohomish was being enacted contemporaneously with that of Lake Hood. Both Glacial Lake Sammamish and Lake Hood became a part of Lake Russell before the Percival Creek channel to Black Lake outlet had lowered the master lake to the 120-foot level.

THE RICHMOND DELTA. For more than a mile south of Richmond the bluffs of Admiralty Inlet are composed largely of fresh Vashon gravel, with Vashon till usually exposed beneath. Foreset structure is to be recognized in the sea cliffs despite the loose character of the material, though the opening of a large pit by the Enamel Brick and Concrete Company offers the best opportunity for study of the gravel. Predominance of foreset structure (Pl. XI, Fig. 2) immediately recalls the pits in the Steilacoom and Sequalichew Deltas. The resemblance is complete, except that there is no second set of foreset beds above the topset. The altitude of the upper plane of these delta strata is 165 feet above the adjacent Sound. At the head of the pit, topset beds are 20 feet thick. Back from the edge of the pit the surface is plane, rising from 185 to 200 feet in half a mile or so, to the slopes of higher hills. A breached kettle in the face of the delta south of the pit, interrupts the continuity of the bluff. The bottom of the kettle bears no gravel, and the ice block must have come to the surface of the delta, or even projected above, when the gravel was deposited, and must have remained until deposition ceased. Another kettle, 60 feet deep and with an irregular form, lies back in the plain, the seaward face of the delta being unaffected by it.

A narrow, elongated deposit such as the Richmond Delta, with the trough of Admiralty Inlet on one side, and ground moraine on the other, higher than the aggraded plain, can find explanation only in the assumption that ice was present in the great trough at the time of delta growth, and formed the retaining wall which has now vanished. (See figure 17.) The presence of the kettles corroborates this hypothesis.

The foreset beds dip westward, however, at a right angle to the length of the delta. The stream which deposited the gravels was confined to a southward course between higher surfaces of ice on the west, and earth on the east. On reaching the beginning of the curve of the ice front in Admiralty Inlet, the stream turned abruptly westward to the trough. As the ice front withdrew along the mile where the delta now exists this procedure of the stream was continued, the delta deposit growing northward as the ice retreated, and the foreset beds dipping westward throughout. The northern portion of the delta therefore is

Cole Point, Anderson Island.

A sea cliff of Admiralty sand.

the youngest, though nearest the channel which gave origin to the deposit.

The stream which made the Richmond Delta entered from the north. Its channel is to be traced with distinctness for a mile northward toward Edmonds, to the point where the enclosing

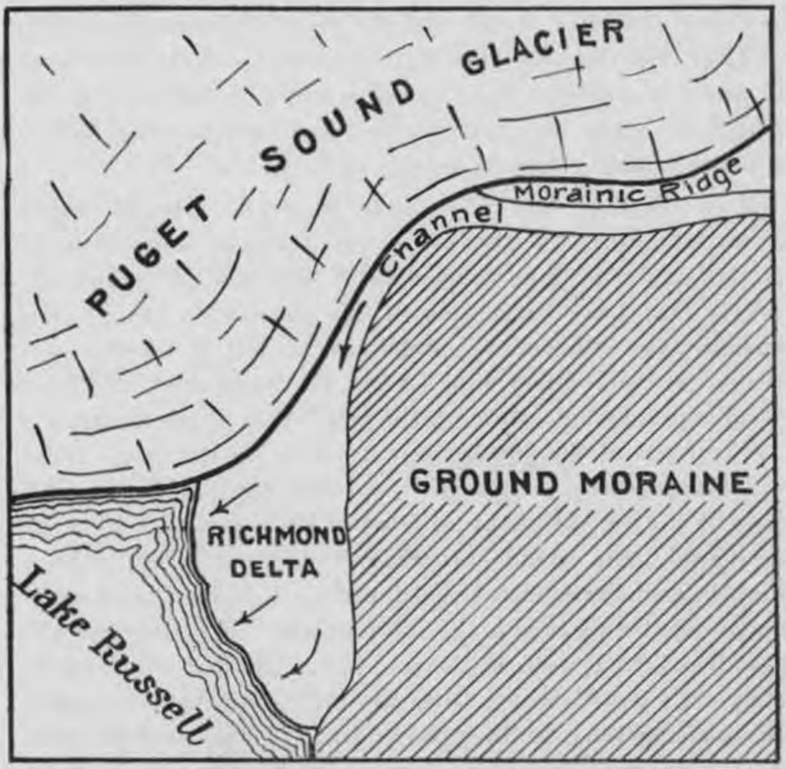

FIG. 17. Relation of the Richmond Delta to Lake Russell and the Puget Sound Glacier.

stream-cut bluffs separate, and the surface becomes broken and morainic. In this distance the channel floor rises gradually from the altitude of the delta plain to 340 feet. Interesting details of the head of the channel in the morainic tract have been worked out, but space cannot be given for their presentation. Suffice it to say, that the stream here originated at the glacier front

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and flowed a mile or so before entering Lake Russell. Its behavior was similar to that of the stream which built the Tacoma Delta.

The edge of the ice over the pre-Vashon ridge which is parallel to Admiralty Inlet on the east, apparently lay but a mile or so north of that in the inlet, though the ridge here is 400 feet above the Sound, and the Point Jefferson Deep (Pl. XXIV), 918 feet below sea level, lies directly off the delta face, It would be expected that this relief would cause the ice in the trough to linger long after the hill had been bared, and thus produce a notably fingered margin to the glacier.

The 120-foot Level of Lake Russell. The Richmond Delta establishes the presence of the 160-foot stage of Lake Russell as far north as the latitude of Richmond (Fig. 16). It proves that Lake Hood sank to this stage when the Poulsbo channel came into use and establishes the fact of a broad connection at the 160-foot level between the Sammamish and Lake Washington troughs through the pre-Vashon valley at Bothell.

The front of the glacier retreated and the Richmond Delta was abandoned by the glacial river before the lake sank to 120 feet. Yet a retreat of the ice front of but a few miles from the Richmond Delta would have allowed open connection between Hoods Canal and Admiralty Inlet, and the Poulsbo channel never would have been eroded to the 120-foot level. It is therefore evident that Lake Russell was lowered to the 120-foot level immediately after the Richmond Delta was made, and that a considerable pause of the retreating glacier front just north of the delta was necessary to hold Lake Hood to the Poulsbo channel, until it likewise had been lowered to 120 feet.

The Brinnon Delta and the lowest portions of the Sherlock Delta and the Redmond Delta are stream deposits in Lake Russell when its surface was 120 feet above sea level.

The Northern Limit of Lake Russell. It is probable that a definite northern limit of Lake Russell will never be determined. Evidences of the lake's existence are scattered, and a continuous record, such as a shore line, is required to establish a definite margin. The limit can be drawn, however, in the form of an east and west zone at the north end of the lake, north of the southern edge of which the ice undoubtedly retreated, and beyond the northern edge of which it never retreated during the lake's existence. The southern edge of such a zone is drawn just north of the Richmond Delta. The northern edge may be drawn through the city of Everett for the following reasons:

(1) The Snohomish trough, which contained Lake Snohomish, and now is used by the Snoqualmie River for most of its length, is open to Admiralty Inlet only at Everett. Its one other opening is the Evans-Patterson Creek channel, the outlet of Lake Snohomish, the use of which built the Redmond Delta. The existence of the 120-foot level in the Redmond Delta proves that the glacier retreated from the 160-foot Richmond Delta, and that the lowest stage of Lake Russell was inaugurated before the Redmond Delta, the product of the outlet of Lake Snohomish, was completed. In other words, Lake Snohomish did not share in the 120-foot level, because the glacier front still lay south of Everett, where open connection exists with the trough of Admiralty Inlet. (See Fig. 16.)

(2) The Pilchuck River, which enters the Snohomish trough at the town of Snohomish (Pl. XXII), carried also the waters of the South Fork of the Stilaguamish River for a time during glacial retreat. Conditions thus were favorable apparently for the formation of a delta in the Snohomish trough, and a channel floor adjusted to its level. Since no trace of either has been found, but in their place is a glacial river valley whose floor is close to present base level, it is evident that no ponded water near Lake Russell levels existed in the Snohomish Valley when the region north of Snohomish and Everett was bared by glacial retreat. Failure of the ice dam which had held up Lake Russell and its tributary lakes, is thus indicated to have occurred while the glacial margin was somewhere between Richmond and Everett.

Lack of Vashon Deltas of the Cascade Rivers. Named in order from south to north, the Puyallup, White, Green, Cedar, and Snoqualmie (outlet of Lake Snohomish) rivers entered Lake Russell from the Cascade Mountains. Only one of these possesses a delta built into that lake.

The Puyallup River has aggraded its trough so largely in the vicinity of Orting that the valley floor now lies above the levels of Lake Russell. Any former delta that may have existed at those levels is of course completely concealed.

White and Green rivers enter the meridional White River trough but two or three miles from each other. Post-glacial deposition has formed a wide plain here about 100 feet above sea level, on which the rivers meander in constantly shifting courses. White River has divided until recently into two distributaries; one, Stuck River, flowing to the Puyallup and thence to Commencement Bay at Tacoma, the other continuing north to Elliott Bay at Seattle.

Though Green River made a delta in Lake Tacoma, no trace of a delta made by either of these streams in Lake Russell has been found. A sufficient reason may exist in the meandering behavior of these rivers which easily could have destroyed such former deposits. The Auburn Delta, or such part of it as remains, has been spared because of its location at the tip of the divide between the two streams.

No delta made by Cedar River in Lake Russell remains, but gravel pits on both sides of the valley at Renton, where it enters the Lake Washington trough, expose foreset beds dipping downstream, and lying against the higher till-covered slopes. Their altitude falls a little below Lake Russell levels, but the upper portion of the delta which would show contact of foreset and topset beds has been removed by erosion. These foreset strata may be interpreted confidently as the remnants of a delta of Cedar River in Lake Russell, the main mass of the deposit having been destroyed by lateral planation of the river during post-Vashon time.

LACK OF SHORE LINES AND SEDIMENTS OF LAKE RUSSELL. The narrow land-locked arms of Lake Russell were not favorable for the development of very effective waves, such as would produce lasting results in a comparatively short time. The bluffs are generally so steep that, were sea cliffs and wave-cut terraces once developed, the chances for escape from destruction by subsequent sliding, or by wave undercutting at the present sea level, which has existed much longer than did Lake Russell, would be small. Under such circumstances, no attempt will be made to correlate the few doubtful old shore records lying high on the Puget Sound bluffs, which might be ascribed to the glacial lakes.

For the reason that Puget Sound at present occupies most of the area covered by Lake Russell, and other portions once occupied by the lakes are now covered by fresh-water lakes or recent alluvium, few occurrences of sediments of this lake can be expected. And because, subsequent to the lake's existence, the basin was even more deeply submerged, this time beneath the sea, unfossiliferous sediments, found overlying Vashon till below the former lake levels cannot be unhesitatingly referred to Lake Russell.

One area only has been found where a clay and sand deposit without much question may be referred to deposition in Lake Russell. This is a few miles northeast of Olympia, nearly north of Lacy. The area is a pitted plain, grading laterally into ground moraine on all sides. The deposit is composed of fine sand and clay, practically free from gravel, and affords an excellent soil. The area now is largely cleared and cultivated, while adjoining surfaces of ground moraine are still in forest or have a few struggling or abandoned farms. It is worthy of note in this connection, that till from the adjacent ground moraine has been used on the roads of this tract with remarkable success, a surfacing ten years old being today in a satisfactory condition even in the rainy winters.

Kame Terraces. Kame terraces form a prominent feature of the modified drift of the Puget Sound country. They were first identified in the region, and have been described in the Tacoma quadrangle by Willis. They have been found by the writer to be abundant on the Seattle quadrangle, immediately north of the former. Since kame terraces are the product of streams, with ice passively cooperating, they should be expected to terminate wherever the depositing stream entered standing water. And if the water of Lake Russell extended northward into all the troughs which were sufficiently low, as the fingers of ice shrank within the valleys, kame terraces should be completely lacking below the levels of that lake.

No kame terraces of the region are known below the 160-foot contour. Several well developed terraces end at about this level, and the topography of the gravel becomes very subdued where the deposit is continued farther down the valley. North Creek, flowing into Lake Washington near Bothell, has a kame terrace six miles long, which, at an altitude of about 200 feet behaves as described above. From Bitter Lake to Green Lake in the northern part of Seattle, is a large kame terrace which disappears beneath the latter body in a peninsula heavily covered with gravel, reappears beyond the lake, and continues down the general trough toward Lake Union. It descends below 160 feet in a short distance south of Green Lake, its character changing at this point to that of a water-laid deposit, and its mass diminishing notably. Other instances of the same character might be cited, but these two illustrate the distribution and behavior of kame terraces sufficiently to show their bearing on the existence of Lake Russell. The presence of standing water in these valleys at the altitude of 160 feet is recorded by the failure of kame terraces to extend below this altitude.

DRAINAGE MODIFICATIONS OF THE STILAGUAMISH RIVER.

The earliest exposed part of the Stilaguamish River valley was the South Fork, which emerges from the Cascade Mountains on the drift plain at Granite Falls. The river now flows eight miles north before joining the North Fork; but when first exposed by glacial retreat, its waters were turned southward into Pilchuck River, a tributary of the Snohomish. At Granite Falls, little more than a mile of low land separates the two streams. (See Plate XXII.)

When retreat of the ice had progressed sufficiently to free the valley of the North Fork, the two streams joined at Arlington, and flowed south through the broad, interglacial Marysville Valley to Port Gardner at the town of Marysville. This valley was filled to an unknown depth with sand and gravel

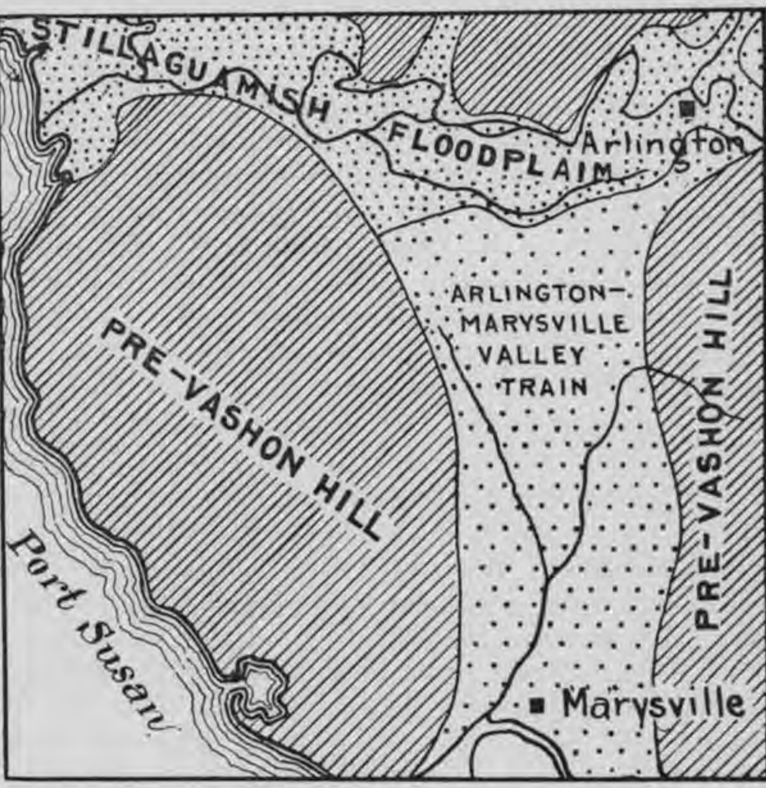

FIG. 18. Vicinity of Arlington and Marysville.

which now constitutes a plain about three miles wide by nine miles long, descending 145 feet from Arlington to Marysville, a grade of 15 feet to the mile. (See Fig. 18.)

The surface in the vicinity of Arlington is strongly terraced, The town is built on two benches, both composed of gravel to their base. The business portion is on the lower bench, 110 feet above tide, and the residence portion is on the higher bench, at an altitude of 160 feet. Numerous pits and street cuts expose the material, which is tumultuously stream-bedded in both. The upper terrace corresponds with one across the river to the north. Both are obviously remnants of a valley train which came down the North Fork Valley from the Cascade Mountains.

The 110-foot terrace at Arlington is too low to belong to drainage which flowed southward from Arlington to Marysville. It was formed by the first drainage which flowed westward along the present course of the Stilaguamish River from Arlington to Stanwood. This later route was blocked by the retreating glacier at the time the Arlington-Marysville valley train was formed, but when opened, proved to be the lower, and has held postglacial drainage to its course.

Erosion in development of the present route west from Arlington has exposed a section of the filling of the Marysville Valley at its northern end. This is composed entirely of sand and gravel to a depth of 50 feet. A road cut in one place exposes a great deal of pumice and volcanic sand or ash in a terrace corresponding to the 110-foot Arlington bench.

The Stilaguamish quadrangle east of the area discussed in the present paper, shows some interesting drainage changes which make it evident that the Sauk, Suiattle, and Skagit Rivers formerly flowed out on the drift plain of Puget Sound at Arlington, and contributed to the formation of the Arlington-Marysville valley train. From the Stilaguamish quadrangle the valley train can be traced up the North Fork valley to Darrington with a grade of about 16 feet to the mile.

Big Lake and McMurray Lake lie in a north and south valley in the diagonal spur of the Cascade Mountains, which juts out into the drift plain north of Arlington. The valley at Big Lake is floored with till. No glacial stream passed through the valley, though the till is disposed on the lower slopes in huge flutings and furrows that resemble the terraces of a gravel train.

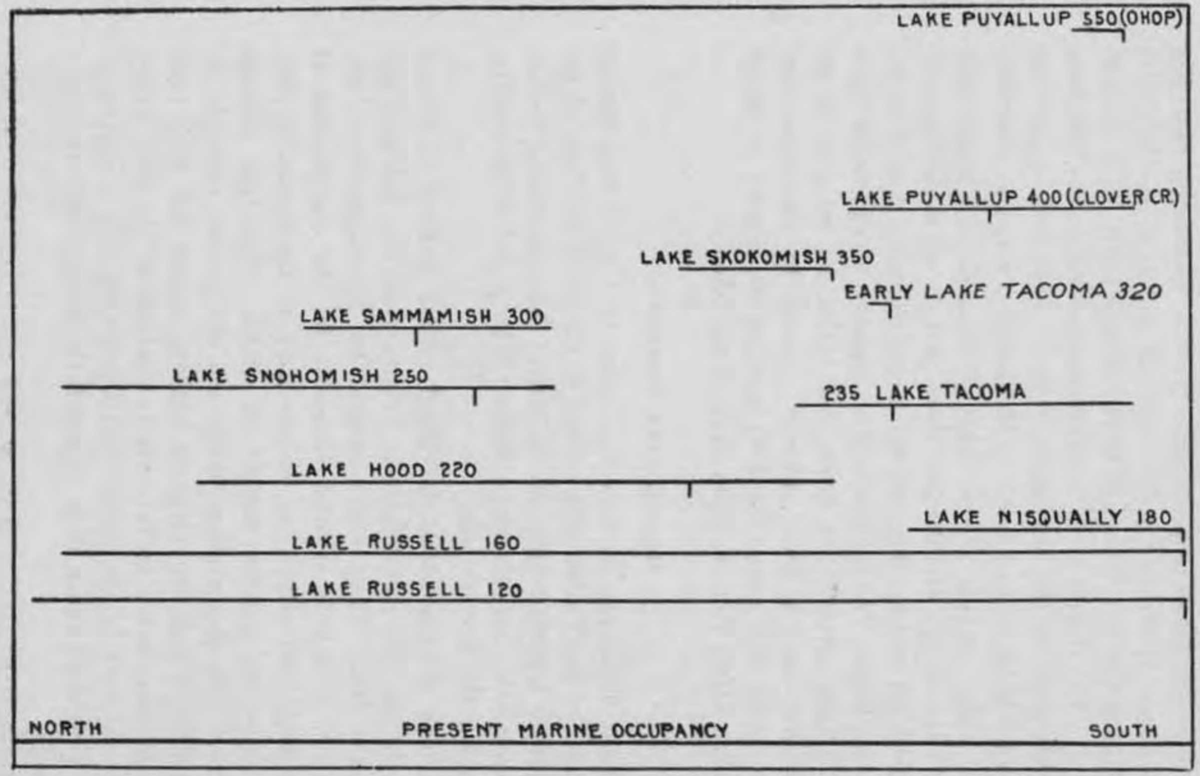

FIG. 19. Profiles of the Glacial Lakes of Puget Sound, projected on a North and South Plane. Position of outlet in the plane shown by the short vertical line attached to each profile. Relative altitudes, lengths, and latitudinal positions shown, the latter corresponding roughly to the sequence of lake formation.

A glacial lake occupied the valley now containing both Big Lake and McMurray Lake, and had its outlet southward to Pilchuck Creek, a tributary of the Stillaguamish below Arlington. This stream is to be distinguished from the Pilchuck which flows to the Snohomish River. The divide in the old channel today is just south of McMurray Lake, and about 250 feet high. A long glacial drainage channel leads south from it to the village of Pilchuck where postglacial erosion has obscured the outlet. The two lakes now drain northward to the Skagit River. The ice dam held up a glacial lake probably eight miles long north of the divide, and turned its drainage to the Stilaguamish. A lower spillway appears to have been used for a brief time across the drift plain to the vicinity of Mount Vernon before final disappearance of the lake.

GLACIAL LAKE WHATCOM.

Lake Whatcom occupies the valley of a northward-flowing stream of pre-Vashon age, eroded in the northern slope of the diagonal mountain spur of the basin. The retreating Vashon glacier left a heavy moraine deposit in the mouth of this valley, causing the present lake.

There are two broad drift-filled valleys opening northward to the low plain of Whatcom County from the northern end of the lake. They are separated by Squalicum Mountain. Either of them is oriented favorably for the continuation of the preglacial valley, but without data on the depths of drift in them, the question cannot be settled. The lake extends farther into the western valley and discharges through it. Whatcom Creek, carrying the outflow, crosses bed rock close to the lake, but is so far over to one side of the filled valley that the rock in the stream bed is probably only a portion of the preglacial valley slope on which the stream has been superposed.

During the retreat of the Vashon ice across this region the glacial front formed a dam too high for northward flow and glacial Lake Whatcom was formed, with discharge from the southeast tip to a tributary of Samish River. The col in the outlet valley lies just north of Mirror Lake at an altitude of 375 feet. A drift filling here has been incised to a depth of 30 feet.

The valley which carried discharge of the glacial lake unites with a larger one at Wickersham. High terraces of glacial gravel occur in this larger valley. At Prairie, three miles south of Wickersham, these terraces are 340 feet in altitude and farther south of here they widen out into a broad plain which leads to the Skagit River.

This train which floors the valley to which Glâcial Lake Whatcom discharged, came down the main valley from the north. Its extent north of Wickersham has not been studied.

After the margin of the ice had withdrawn from Squalicum Mountain, and after Glacial Lake Whatcom had ceased to discharge over the Mirror Lake col, the gravel train was largely eroded by the diverted South Fork of the Nooksak River, which for some time after the disappearance of Glacial Lake Whatcom, was blocked by ice at the north and forced to be tributary to the Skagit. Its course at this time was southwest from Prairie to the present Samish, emerging on the Skagit Delta three miles north of Burlington.

At the inception of standing water at the south end of Lake Whatcom valley, the southwestern arm contained a small independent lake with outlet to Samish River about three miles below Samish Lake. The outlet channel lies on the north side of the drift-filled valley connecting the Whatcom and Samish valleys, with an altitude of about 415 feet.

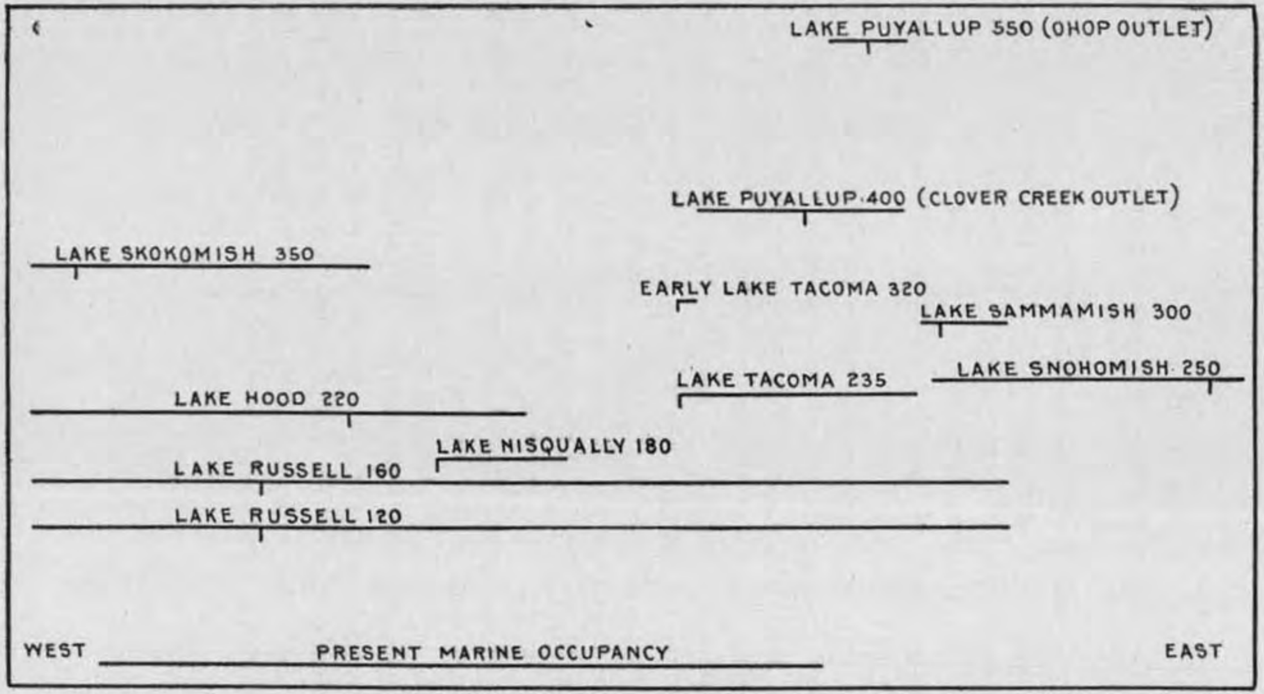

FIG. 20. Profiles of the Glacial Lakes of Puget Sound, projected on an east and west plane looking north. Position of outlet in the plane shown by short vertical line attached to each profile. Relative altitudes and longitudinal position, and greatest east and west extents shown. The grouping shows the eastern or Cascade side of the basin to have had the more varied history.

CHAPTER VII.

THE ADMIRALTY GLACIATION.

SYNOPSIS.

THE ADMIRALTY TILL.

The history of glaciation in Puget Sound preceding the Vashon epoch is very meager in details, and probably always will remain so. The cover of Vashon till and outwash in the Puget Sound basin is almost complete. Drift older than the Vashon is exposed only in excavations, in stream bluffs and in the sea cliffs along the shores of the Sound. In such situations the Vashon till lies almost everywhere on stained and weathered stratified drift of considerable thickness. This stratified material is known in a few places to rest on an older till sheet, named the *Admiralty Till* by Willis.

GREEN POINT.

Admiralty and Vashon till are exposed in the same sea cliff in a few instances, these affording exceptional opportunity for the comparison of the two tills. The cliff at Green Point, between Hales Passage and Carrs Inlet (Henderson Bay), shows both tills, with brown-stained sand between, the sand constituting probably only a part of the stratified drift series. The two tills are very similar in color, composition, degree of consolidation, size, abundance, and rounding of pebbles, absence of bowlders, etc. Both are gray, the Vashon till being somewhat lighter.

HARTSTENE ISLAND.

Both tills, separated by stained sediments, are shown on the eastern side of Hartstene Island. No great difference in the two tills is to be detected, the Admiralty being weathered or stained near its upper surface, and the Vashon being lighter gray throughout. The Admiralty till here may contain a slightly larger proportion of pebbles than the Vashon till, and they are somewhat more angular.

DENNY HILL.

In the Denny Hill regrade of the city of Seattle, a hill composed largely of Admiralty sediments was removed by hydraulic methods from more than twenty city blocks, the maximum cut being 125 feet. (See plates XIV, XV, Fig. 3, and XVI.) Vashon till capped and veneered the hill with an average thickness of 10 feet, and Admiralty till was exposed in the deepest sluiceways, on Bell Street. The only difference between the two tills thus closely juxtaposed was (1) the somewhat weathered condition of the upper portion of the Vashon till, involving a difference in color, and (2) the greater consolidation of the lower till.

POSSESSION HEAD.

Russell, who first recognized the existence of two till sheets in the Puget Sound basin, cites Possession Head, at the south end of Whidby Island, as exhibiting the two tills separated by "medial" sands, gravels and lignite. The writer has found Possession Head to show three distinct till strata, separated by stained sediments. There is little difference among the tills, each being gray in color, and composed apparently of fresh material. The upper surface of each is somewhat stained. The lignite beds reported by Russell lie in the sediments between the upper and middle tills. The lowest, whose base is below high tide, contains many pockets and lenses of gravel, the presence of which may explain why Russell did not recognize it as a till.

The Possession Head section is not closely paralleled in Puget Sound. Its suggestion of three glaciations, the till of the oldest being apparently as fresh as that of the youngest, is not borne out by a study of the sea cliff exposures elsewhere in Puget Sound. The explanation advanced tentatively is that both of the two lower tills are of Admiralty age, a slight retreat and readvance of the Admiralty Glacier accounting for the intercalated sediments. The stained condition of these sediments beneath unstained Admiralty till is thought to be the result of percolation of ground water throughout their mass during the interglacial period, while such would occur through the non-porous overlying till only along seams, leaving the till mass as a whole unstained.

GENERAL CHARACTERS.

In the other exposures of Admiralty till known about Puget Sound, the character is very similar to that of the younger Vashon till. Foliation is shown in many exposures, rounded pebbles are usually abundant, the matrix is arenaceous, and the color is usually an unweathered gray. Granites of various kinds are as common in it as in Vashon till. There are no essential diagnostic differences in the character of the tills themselves, and stratigraphic relations must usually be taken into account in identification.

Willis* has described the Admiralty till as changing to a dense stratified clay in many places, both horizontally and vertically. A similar relation was exposed in the Denny Hill regrade of Seattle, subsequent to Willis's study of the region. Elsewhere in Puget Sound the writer has failed to find this rela-

* Bailey Willis, "Drift Phenomena of Puget Sound," Bul. Geol. Soc. Am., Vol. 9, 1897.

tion, the till being distinctly differentiated from the overlying sediments and rarely containing water-laid deposits.

The base of the Admiralty till was found in digging the Bell Street sluiceway tunnel of the Denny Hill regrade. Dark gray quicksand was reported to underlie it, the thickness of the till being about 20 feet. An exposure of the base of the till is also afforded in the sea cliff at the south end of Bolton peninsula, Hoods Canal. Post-Admiralty crustal movement has locally tilted the beds of the section so that the base of the till lies above sea level. The till is overlain by coarse, dark-stained, decayed gravels, and rests on a weathered and leached stratified clay containing numerous concretionary masses, but with no gravel or sand in it. The clay outcrops along the beach slope below high tide for a quarter of a mile, and possesses throughout a dip of 25°. It is thus remarkably thick for a glacial deposit. It may be interpreted more satisfactorily as Tertiary or early Quaternary, than Admiralty in age.

The Admiralty till is generally unweathered, and is in marked contrast with the overlying gravels, which are deeply stained almost everywhere. There are many cases of direct contact of these unlike materials. The cause for this is probably the same as that for the similar contrast of unstained clay strata interstratified with stained gravels; namely, the impervious nature of the material, and the consequent absence of percolating water. In some exposures, a till which is thought to be Admiralty in age, and which certainly is not of Vashon age, is considerably decayed, so much so that pebbles may be carved with a knife blade like shale, though they were originally of igneous and metamorphic material. This decayed till has been found in cliffs along Port Washington Narrows, in many exposures beneath the Vashon terminal moraine about Little Rock and elsewhere. It is probably of Admiralty age, but because of position near the surface during the interglacial epoch, was weathered, while the more deeply buried till of the same glaciation was unaffected.

A till occurs in Red Bluff, near Ayers Point, Hoods Canal,



Denny Hill Regrade, Seattle.

in which decay has been more profound than is shown elsewhere in Puget Sound. The extent of this decay exceeds that shown by the red gravels of the Chehalis Valley. Excepting the pebbles of quartz, a knife cuts through pebbles and matrix alike without difficulty. The largest fragments, 8 inches in diameter, have no trace of a firmer central part. Decayed granite pebbles retain the appearance of the parent rock, but crush to sand and clay between the fingers. The reddish color of the whole is deeper than is usual for the drift of Puget Sound, and gives the bluff its name. Above and on both sides of this exposure of old drift the bluff is covered with vegetation. The stratigraphic relations of the decayed drift are therefore unknown. It may be very possibly the deposit of a glaciation preceding the Admiralty epoch.

With but two exposures of the base of the Admiralty till, no estimate of its thickness can be made. It is wholly a matter of inference to style it a till sheet. Whether this till overlies older glacial drift, or Pleistocene sediments, or rests on Tertiary rock is unknown. There are no data regarding the character of the topography overridden by the Admiralty ice, and almost none regarding the topography of its deposits.

No glacial drift in the Puget Sound basin is known to lie south of the Vashon terminal moraine and its attendant outwash, and in many places this moraine lies directly on previously unglaciated rock. Considering our present meager knowledge of the Admiralty glaciation, it is perhaps idle to inquire into the causes which allowed the Vashon ice to exceed the limits reached during the Admiralty epoch. A local cause may be found to obtain. It may be suggested that if the Puget Sound basin lay higher, relative to the Strait of Juan de Fuca, during the Admiralty than during the Vashon epoch, a greater proportion of the Cordilleran ice would have passed westward to the Pacific during the Admiralty epoch, than in the succeeding epoch.

THE ADMIRALTY SEDIMENTS.

GENERAL DESCRIPTION.

The stratified beds between the Vashon and Admiralty tills are approximately horizontal in position wherever exposed in the hundreds of sea cliffs of Puget Sound. These beds are truncated abruptly by the bluffs, and by the lower surface of the Vashon till where that overlies slopes in which a sea cliff has been developed. These relations are shown in the accompanying diagrammatic sketch. (Fig. 21.) Fully nine-tenths of the glacial drift exposed in the sea cliffs is composed of these inter-till sediments. From the few exposures of the Admiralty till above sea level, the average altitude of its upper surface may be inferred to be somewhat below that plane, and the total thickness of the stratified beds must be correspondingly greater.

The material of the deposit ranges from clay to fine gravel. Coarse gravel, with pebbles fist-size or larger, is known only along the border of the Olympic Mountains on the lowland. In some places the material is clay for a considerable area and depth. The business portion of Seattle and the residence districts on First, Capitol, Madrona, Renton and Beacon hills are underlain by a finely laminated clay which, in the Jackson Street and Dearborn Street regrades, has been excavated to a depth of at least 75 feet without exposing its base. Other areas show a predominance of sand in the sections. This is notably the case in the sea cliffs of Camano and Gedney (Hat) islands, and some of those of Whidby and Marrowstone islands.

As a rule, there are numerous alternations of material, both vertically and horizontally. Willis has attempted to classify these deposits for the Tacoma quadrangle, distinguishing the Puyallup sands, the Orting gravels, etc. The method can hardly be applied to the entire basin of Puget Sound, since the character of any one deposit seldom persists for more than one or two miles.

Usually the gravels are bedded horizontally, but they possess stream cross-bedding in almost every section. They rarely form extensive or thick deposits, as do the finer materials.

STAINING AND DECAY OF THE ADMIRALTY SEDIMENTS.

The gravel and sand of this series are almost everywhere stained by iron oxid, in some places to a color as deep as that of the red gravels of the Chehalis Valley. The sand is commonly buff colored, the gravel a yellow or orange hue. Rarely, sufficient iron oxid is present to indurate the gravel so that wave erosion sculptures small stacks and caves in it. The stain is uniformly distributed in the thickest beds seen. The clay beds of the series are not stained, though gravel below clay may be notably stained. Though decay has not greatly affected these sediments, none of the gravel is as fresh and firm as that of Vashon age. Usually a test with a knife blade will show a considerable difference in average hardness. Admiralty gravel is not used commercially because of its softness, while the Vashon gravel deposits are opened everywhere for building and road material.

VEGETAL REMAINS.

Deposits of peat or lignite are interbedded with these stratified materials in many places. The lignite is usually composed of swamp deposits, the bulk of it being finely macerated material with seeds, cones, twigs, etc., scattered through it. Rarely, tree and brushwood stumps are found *in situ* at the bottom of such beds. The deposits in some cases are of water-worn driftwood; in other beds, the presence of insect wings, thin-bladed grasses, etc., shows accumulation in stagnant water. A bed of this lignite with a maximum thickness of 10 feet, was discovered in the Denny Hill regrade, its area covering several blocks. Most of it was of finely comminuted organic material, in some places with considerable clay, but large tree trunks, crushed flat by the pressure of overlying beds, were exposed in the excavation. This deposit and one on the south side of Anderson Island have yielded charred logs and sticks and many fragments of charcoal scattered throughout the comminuted material.

A lignite bed on the east bluff of Admiralty Inlet at Des Moines is composed entirely of drift wood in one portion, and pebbles of pumice are plentifully dispersed among the drift wood fragments, the pumice being likewise stream-drift material. Such material could not have come from the glacial drift, and it records the presence of a Cascade river on this central portion of the plain during the deposition of the Admiralty sediments.

In two instances, at least, the lignite beds of the Admiralty sediments have been mistaken for Tertiary coal strata, and prospect tunnels have been driven in them. One of these is at the head of Hoods Canal near Union City. The other is in the valley of Feeny Creek, Colvos (West) Passage. In the latter case, two horizontal tunnels were driven for a number of feet with the hope that the material would get "harder" farther back from the outcrop. The lignite in this place occurs in two beds, three and five feet thick respectively, separated by 10 feet of clay. The upper lignite bed is more resistant than the clay, and has given rise to a pretty little waterfall in the creek.

Lignite has been found from base to summit of the stratified drift between the Admiralty and Vashon till sheets, outcropping below low tide in several places along Admiralty Inlet. Any explanation of the origin of the stratified beds between the Admiralty and Vashon tills must take account of this vertical distribution of the lignite.

ANIMAL REMAINS.

The Admiralty sediments have yielded mammoth teeth and tusks throughout most of the Puget Sound region. No mastodon teeth have been found. A fragment of a tusk five feet long and eight inches in diameter at the butt was found in gravel below the Vashon till in a bluff along Hoods Canal. Mammoth teeth were found in the Denny Hill, Tenth Avenue and Seneca Street regrades in Seattle. Many earlier finds are on record.

Two occurrences of marine shells in the clays of the Admiralty series are known. A stony clay outcrops a few feet above tide at the base of Foulweather Bluff. Marine shells are abundant in it, fragile specimens occurring with valves still attached. The Admiralty till lies directly beneath. Dr. Wm. H. Dall has kindly examined specimens collected from this bed, and has identified the following species:

(1) *Macoma balthica* Lin.
(2) *Macoma calcarea* Gmelin.
(3) *Macoma* (probably young *middendorffii*, Dall).
(4) *Cardium islandicum* Fabr.
(5) *Serripes gronlandicus* Beck.
(6) *Mya truncata* Lin., young.
(7) *Nucula* sp. (like *belloti* Ads.).
(8) *Saxicava arctica* L.
(9) *Leda fossa* Baird.
(10) *Bela* sp. ind.

Dr. Dall states that all species found are living at present in the colder waters of Puget Sound, and thence northward to the Arctic.

Two clay pits at South Seattle, excavated in the base of the western slope of Beacon Hill, have also revealed marine remains. The clay is like that so frequently exposed beneath the business portion of the city of Seattle, in the Jackson, Dearborn, and Tenth Ave. regrades, and elsewhere. Much the same molluscan fauna was found as in the Foulweather Bluff section, and in addition, crustacean claws were discovered. In the southern pit, owned and operated by Mr. Niedergesaess, elk antlers and a whale (?) vertebra have been found a few feet above the horizon at which the molluscan remains occur. Mr. Jerbert, the foreman of the pit, who witnessed the discovery of the antlers, is careful to distinguish slidden material from clay *in situ*, and his statement may be taken without hesitation.

A careful watch was kept for vertebrate remains during the destruction of the Denny Hill lignite bed, but none were found.

The occurrence of marine shells in Foulweather Bluff, close to the base of the Admiralty sediments, affords a problem which will be solved only by the discovery of more marine remains in these sediments. The problem is whether the sea entered by way of the Strait of Juan de Fuca, or extended back from an estuary in the Chehalis Valley. If these sediments are largely outwash from the Admiralty Glacier, it seems impossible that the sea could have entered from the Strait at the north at the time of their deposition.

The occurrence of marine remains only at the base or close to the base of the stratified drift series, so far as observation has gone, is a significant fact which must enter into any explanation of the genesis of the sediments.

INTERCALATED TILL.

Till beds intercalated with the sedimentary strata have been found in a few places. The eastern bluff of Admiralty Inlet two miles south of Des Moines, the south side of Danas Passage, and Tsutsko Point on Toandos Peninsula, exhibit such relation. The section of Possession Head, described in a preceding paragraph, is thought to belong in this category. Deposition of till in this position must have been contemporaneous with accumulation of the sedimentary series, and is explained as the product of an oscillatory re-advance of the ice during the Admiralty retreat.

THE MC NEILS ISLAND SECTION.

A few instances of considerable deformation of these Admiralty sediments are known. The most pronounced case is the bluff of McNeils Island, along the water front of the United States Penitentiary. The deformation here takes the form of folding, in places so pronounced that the anticlinal flexures are sharply apexed and somewhat overturned. (See Plate XII, Fig. 1.) The material affected is unconsolidated sand and gravel, and the folds are probably not more than ten feet across. That this disturbance was not produced by the overriding of the Vashon ice is shown by the existence of horizontal beds of the Admiralty series above the folded strata, the fresh Vashon till overlying both. Sliding or slumping cannot have caused the deformation, since it is persistent in greater or less degree for a mile along shore, and is in coarse material which does not ordinarily slide. There are also no faults such as sliding would produce.

Two other explanations remain; ice thrust during deposition of the series, and crustal movement subsequent to deposition. There is apparently a till layer in the upper part of the bluff at the Penitentiary dock, with stained gravels above it. Inaccessibility of the summit of the bluff prevented positive identification, but the presence of contemporaneous till is practically required, if ice thrust produced the deformation.

Crustal movement seems totally inadequate to produce the sharp crumpling of the gravel beneath nearly horizontal strata of the same age. The surrounding region has not suffered severe diastrophism since the Tertiary. The disturbed gravels of McNeils Island are therefore interpreted as due probably to ice thrust immediately subsequent to their deposition.

SECTIONS OF USELESS BAY, ETC.

An unusual distorted structure of stratified sand and clay is shown in the bluffs (1) on the north side of Useless Bay on Whidbey Island, (2) near Algiers Bay on Camano Island, and (3) along Hoods Canal a few miles south of Foulweather Bluff.

The seacliff of Useless Bay referred to, a mile east of Double Bluff, is nearly 300 feet high. It is composed almost entirely of stratified clay, sand and gravel, a few feet of Vashon till appearing in places at the top of the section. Lignite is present in strata not exceeding two and a half feet in thickness. The thickest lignite stratum is of considerable length, and is uniform in thickness, indicating formation on a flat plain instead of in a channel or kettle hole depression. There is no evidence of the proximity of ice during deposition of the series, and no till is exposed at the base of the section.

A zone about twenty feet wide is exposed in the lower part of the entire bluff, composed of clean gray sand mingled with yellow clay in a most striking fashion. The clay occurs in fantastically irregular masses, ten feet or so in diameter, and distributed horizontally 30 to 50 feet apart. These masses are usually elongated vertically, and possess very irregular arms projecting vertically and horizontally into the sand.

Current-bedded sand lies below, and horizontally bedded sand and clay lie above the deformed strata.

The seacliffs on the east side of Hoods Canal, three miles south of Foulweather Bluff, present a similar structure. In these sections, the yellow clay masses bear a rude resemblance to a sheaf of ribbons, bound at the top, and crumpled and spread at the bottom under its own weight. Smaller masses of the clay resemble spires thrust vertically up into the overlying mass. Horizontally stratified clay lies below these distorted beds, and practically horizontally stratified, clean gray sand lies among the "sheaves."

Distorted clay strata of the same nature are exposed in seacliffs of Camano Island, a little south of Algiers Bay. The distorted stratum is about two feet thick, and in most places is so completely bent and crumpled as to have lost resemblance to a stratum, and to possess the ragged appearance of the clay masses in the sea cliff north of Useless Bay. Some of these clot-like masses are less completely deformed, and the stratum of yellow clay can be traced from either side into them and to the summit, as shown on Plate XVII, the appearance then being more like the sheaf form of the Hoods Canal occurrences. Very little trace of bedding can be seen in the sands which lie between the crumpled masses of clay. The strata of sand immediately overlying the distorted zone are undisturbed.

In the production of the distortion, the clay stratum either has been shortened by lateral compression, thus losing a large fraction of its original length, or has been squeezed thinner by vertical compression which has forced the clay to rise in these fantastic "clots" or "sheaves" to dispose of the displaced material.

There is no evidence in any of these sections that the sediments above or below the deformed zone have been affected. In two cases a slight unconformity exists above the deformed zone, in one of which the tip of an upthrust mass is truncated

FIG. 1. Old River Channel above Kennydale Delta.

FIG. 2. Percival Creek Channel.
Looking north from the 160 foot level. Channel floor at 120 feet A. T.

FIG. 3. "Spite Hill" of Denny Hill Regrade, Seattle.

(Plate XVII). This indicates deposition of the overlying beds after distortion of the clay.

The deformation of these beds certainly occurred during the deposition of the sand immediately overlying the deformed clay strata. Crustal movement or action of glacier ice can hardly have been the cause, either of which would have affected the beds above and below, and the latter of which would have left its own distinctive deposit superposed. Only vertical compression could produce the deformation and leave the underlying strata unaffected.

It is a significant fact that quicksands are exposed at low tide at the foot of the prevailing sand bluffs of Camano and Whidbey Islands. Such beach material is derived without doubt from the erosion of these seacliffs of fine sand. Quicksands are not known to the writer to occur elsewhere on the shores of Puget Sound.

A combination of plastic clay beneath quicksand, especially when the material contains much interstitial water because of the recency of deposition and the lack of complete settling, might possess a mobility which could allow the deformative changes known in the Hoods Canal, Whidbey Island and Camano Island sections. The force producing the deformation must have been directly gravitative. The change produced a greater compactness of the material by expulsion of interstitial water, so that subsequent deposits of quicksand were not affected. The suggested genesis of these distorted masses is somewhat similar to that advanced by Hilgard for the Mississippi Delta mudlumps*, and the cross sections here described possess in some places something of the "onion" structure of the mudlumps.

DELTAS IN THE ADMIRALTY SEDIMENTS.

In the identification of delta bedding in the Admiralty sediments, distinction is to be made between the long foreset strata of a delta mass, and the shorter and commonly interrupted

* E. W. Hilgard, Science, Dec. 28, 1906.

foreset beds of small delta-like deposits built in channel depressions. The latter are common in the horizontally stratified gravel of the Admiralty series, while only four occurrences of foreset delta beds of Admiralty age are known.

(1). A seacliff on Dabop Bay, about a mile north of Pulali Point, exposes horizontally bedded, darkly stained, coarse gravel lying laterally and unconformably against and over finer gravel of the same character but with a dip of 20° N. N. E. South of this gravel with northward dip are other old gravels of the same character, but with the tumultuous bedding produced by swift streams. Pebbles of granite, though rare, exist in each of the three portions of the bluff.

The whole is of Admiralty age. The bedding with 20° dip doubtless originated as the delta deposit of an Olympic river in a lake formed during the Admiralty retreat. Later the lake was drained, the delta partially eroded, and the area then aggraded with the horizontally- and current-bedded coarse gravels. The granite present was probably earlier carried up into the Olympics by Admiralty ice at its maximum, just as was done during the Vashon glaciation.

(2). The peninsula tipped by Quatsap Point forms an exceptional projection into Hoods Canal. Its northern shore is composed of basalt, and its southern bluff presents a splendid section of another delta of Admiralty age. The seacliff for a length of half a mile is composed of brown-stained, stratified gravel, with a northeast dip of about 20°. (See Plate XII, Fig. 2.) Vashon till overlies its eroded upper surface. The gravel contains no pebbles of granite or other holocrystalline rock. At the west end of the section the delta bedding has been truncated by erosion, and a later deposit of buff-stained, horizontally bedded sand overlaps the gravel. Both are of Admiralty age, and overlain by the Vashon till.

The stratified gravel of Quatsap Point cannot be interpreted as tilted strata for two reasons. (a) The thickness, if the strata were horizontal, would far exceed that of any known Admiralty sediments, and would possess the unique feature, among these sediments, of being of one character throughout. (b) There is an oblique truncation of some of the foreset beds by overlying ones which are disposed at a slightly flatter angle, as in figure 22. This could not be formed in strata deposited horizontally, while it is a normal delta structure caused by a slight shifting of the direction of current, just at the debouchure, on the edge of the delta top.

The Quatsap Point Delta was built of Olympic gravel by the Duckabush River at the time of Admiralty retreat, and in a lake ponded in front of the Admiralty Glacier. Like the stream which deposited the Pulali Point Delta, the direction of the flow which constructed the portion now existing was northward, though in each case this portion may be simply the northern part of an originally semi-circular delta.

The base of the Quatsap Point Delta is below sea-level, and its summit plane has been eroded, so that the depth and altitude of the surface of the former lake can not be known. That the two deltas belong to one lake is probable.

The existing remnant of each delta has been protected by an outcrop of rock directly north, guarding it from erosion by the Puget Sound Glacier of the Vashon epoch.

(3). North of Point Lowell, on the west side of Camano Island, foreset-bedded gravel appears in the sections, overlain by Vashon till. It is irregularly stained, but apparently belongs to the Admiralty sediments. The dip is northward, and the thickness exposed is about 25 feet. A lake which received drainage from the south during Admiralty retreat is thus recorded. Like the Admiralty lake of the Quatsap Point and Pulali Point deltas, it was probably ice-dammed.

(4). Willis has described and figured delta-bedded gravels of the Admiralty series in the bluffs above the Northern Pacific dock at Tacoma*. They are not as well developed as are the foreset beds described above. They are to be referred probably to some Cascade River which existed during the retreat of the Admiralty ice. Willis was not fully satisfied that they and

* Willis, Bailey, Bul. Geol. Soc. Am., Vol. 9, 1897.

the Tacoma (Vashon) Delta were distinctly different deposits. Since they are separated by the Vashon till, there is little doubt that they are very different in age.

GENESIS OF THE ADMIRALTY SEDIMENTS.

The stratified material between the Admiralty and Vashon till sheets was deposited during the later stages of glaciation of the basin by the Admiralty ice-sheet. This conclusion is supported by the following evidence.

(1) Rock materials, foreign to the neighboring mountains, are present in the strata. This is especially notable along the Olympic margin of the basin, where splendid exposures by the sea cliffs of Hoods Canal show no dominance, and indeed no considerable proportion, of Olympic waste in the material.

(2) Till is interbedded with the stratified deposits.

(3) The strata in some places are deformed apparently by the thrust of glacier ice.

(4) There is an absence of structures and of gradations in material which would indicate derivation of the detritus from the flanking mountains.

Two conceptions may be advanced for the origin of the Admiralty sediments, both based on the same premises; that they are composed largely of glacially transported material, and have been derived only to a small extent from the drainage basin of the Sound.

I. It may be conceived, first, that tongues of Admiralty ice lay where the troughs or inlets of Puget Sound now are, and that the interspaces became aggraded by water-borne debris from melting of the ice, and by deposits from the ice directly. Final melting would then leave the present hills or ridges separating the depressions which were preserved by the ice during the aggradation. By such method of origin, certain structures would be formed in the deposits, the presence or absence of which in the sea cliffs of Puget Sound should reasonably test this hypothesis.

II. The Admiralty sediments also may be conceived as having been continuous originally over the whole of the drift-covered lowland of Puget Sound, the troughs and ridges being the result of subsequent erosion of this plain. The melting ice, largely responsible for the aggradation, lay to the north, and as its margin retreated, the stream and standing water deposits buried its till. The plain, during aggradation, was traversed by rivers which were continually filling their channels and shifting their courses over the stretches of low, flat land between them. Tracts of quiet, shallow water probably stood over considerable areas at different times. By this method of origin of the Admiralty sediments, certain structures also would be formed, whose presence or absence in the sea cliffs and other sections will be the test of this hypothesis.

The difficulty met at once in consideration of the first hypothesis is the lack of a satisfactory explanation, in harmony with the facts, for the occurrence of glacial tongues on the Puget Sound lowland, oriented in general north and south, and separated by intervals of low but ice-free land. Willis, who has previously advanced this hypothesis, conceived that a pre-Admiralty topography determined the presence of tongues of the Admiralty ice on the sites of the trough valleys of Puget Sound. An examination will be made in the following chapter of the evidence which should be found if this hypothesis is correct.

A glance at the map of Puget Sound will show that if the ridges and hills were formed between tongues of ice, most of them must have been the site of lakes, since the lateral troughs (the casts of ice tongues) generally unite at the south, so that free drainage could not have existed. Deposits laid down under such condition would have the following characters:

(1) Except near shores, lake sediments are clays and fine sand, easily carried out from shore in suspension. Since gravel cannot be so carried, it is deposited about the shores in the foreset and topset strata of deltas, and in beach accumulations, the stratification dipping toward the lake and away from the source of the stream. Only on complete filling or on draining of a lake can streams traverse the area and deposit horizontally bedded gravels over the finer materials. On the other hand,

thick lake clays could never overlie horizontally stratified gravels unless the lake level rose after the ice-bound depression had once been filled.

(2) Swamp deposits of peat and lignite likewise are possible in such a series only after the lake has been shallowed by filling with sediment, or by lowering of outlet. Lake clays above peat or lignite might exceptionally be produced by a rise in lake level.

(3) Marine deposits in the lower beds of such a series would be very improbable.

(4) Ice thrust from the adjacent glacial tongues might be of common occurrence. This would give rise to crumpled sediments and layers of intercalated till.

(5) Since most of the series would accumulate under standing water, erosion uncomformities between strata (caused by shifting stream channels) would be very improbable in the lower beds.

(6) There would be no possibility of correlation of strata in any two such lake deposits.

If the Admiralty sediments were deposited by heavily laden streams which shifted to and fro over an aggrading plain, as the second hypothesis holds, the following characters should be formed in the stratified series:

(1) Deposits from swift streams, sluggish streams and standing water would be superposed above each other in all parts of the region, without regard to what kind of sediments lay beneath. Thus there would be no vertical sequence of sediments, and horizontally stratified gravel would belong as much among the basal beds as among the uppermost.

(2) Since swamps might form at all stages of the aggradation, lignite and peat might occur from base to summit of the series.

(3) Marine organisms would be most likely to occur at the base of the series, before aggradation raised the level of the plain above the sea. Shells of marine molluscs would not occur in the upper beds unless the region sank during aggradation.

(4) The immediate presence of glacier ice is not required by this conception, and crumpling of the sediments by its movement should be rare. Correspondingly, lenses or seams of till, interbedded with the stratified materials, should be uncommon, and associated chiefly with the lower beds.

(5) The lateral shifting of streams over a plain which is being aggraded would erode the surface of beds already deposited, and would produce unconformity in the bedding. This phenomenon should be common from base to summit of the series.

(6) Correlation of strata across the present troughs might be possible in some places, though the repeated horizontal change in character of the sediments would render correlation difficult, if not impossible, in most cases.

To bring the whole problem into concise form, a summary of the features shown in the sea cliffs is herewith presented, and their bearing on the two hypotheses is indicated.

(1) Horizontally bedded gravels and clays are inter-stratified without reference to the vertical sequence demanded by the first hypothesis, but in entire conformity with the second. Delta-bedded gravels are rare in the great mass of sediments, and where present, do not dip from the troughs toward the ridges.

(2) Lignite beds range from the lowest to the highest portions of the sedimentary series. This is very improbable under the first hypothesis, but in perfect accord with the second.

(3) Remains of marine organisms have been found only in the lowest beds above tide, this evidence favoring the second hypothesis.

(4) Crumpling of the sediments by ice-thrust during deposition of the series is rare, and is practically confined to basal beds. It should be fairly common throughout the whole vertical range, according to the first hypothesis. Interbedded till is rare. By the first hypothesis, it should be a fairly common feature in the sections in the periphery of the ridges and hills.

(5) Unconformities of a few feet in vertical range, caused by stream erosion, exist from sea level to the highest sections

throughout the entire series, being especially common in the gravels. This is practically impossible by the first method of origin.

(6) Fairly probable correlations of deposits across troughs have been made, indicating their former extent completely across, and origin of the trough by subsequent erosion.

A summary of this examination finds the first hypothesis—that of aggradation of the ridges between tongues of ice—hopelessly disputed on several points, and without definite support from any. The cumulative value of the evidence cited should establish conclusively that the hills and ridges of Puget Sound are remnants of a once continuous plain of stratified drift.

The hypothesis of accretion, or glacial construction, of the Puget Sound ridges and hills may be applicable in some cases for the Vashon glacial deposits, when tongues of Vashon ice lay in the valleys of interglacial erosion, and outwash accumulated on hilltops, but it fails for the earlier deposits which compose by far the greater bulk of the drift of Puget Sound. The Puget Sound basin then is to be considered as having been floored from rim to rim with a great plain of mingled marine, lacustrine, fluvial and glacial deposits by the close of the Admiralty epoch. Subsequent erosion has produced the troughs in this plain.

Summit levels of the major drift hills and ridges of Puget Sound accord strikingly in the profile of a plane extending from the Olympics to the Cascades. Where the Cascade diagonal mountain spur intersects the basin, fine views are afforded of contrasted drift hill and rock hill profiles. Long and nearly horizontal lines mark the summits of the drift hills, above which the rock hills rise from a few hundreds to a few thousands of feet. This contrast is as strongly marked on the south or lee side of the mountain spur as elsewhere, a feature to be expected in a plain aggraded largely by running water.

In a study of the Olympic margin of the Puget Sound drift plain, alluvial fan and delta structures, current bedding with

FIG. 1. Portion of Denny Hill Regrade, Seattle.

FIG. 2. The Grade of Bell Street, Denny Hill Regrade, Seattle.

eastward dip, prevailingly coarse material, and a high average level of hill summits have not been found to be important features of the Admiralty sediments. Satisfactory evidence is thus at hand that the Olympic Mountains did not supply an important part of the Admiralty sediments.

Exposures are more rare along the base of the Cascade Mountains. Such as have been examined, chiefly the stained gravel of the Cedar River Valley, indicate outflowing water from the Cascades to the Admiralty drift plain. The material is not coarse, however, and in some places contains lignite. That the Admiralty plain reached back into the lower Cascade Mountain valleys is well shown on the Cedar Lake quadrangle of the United States Geological Survey. Its altitude is 800 to 900 feet where abutting on the mountain bases near the entrance of the Cedar and Green rivers on the drift plain. The mid-basin altitude of the dissected Admiralty drift plain, in this latitude, is 400 to 500 feet, at a distance of about 25 miles from the foot of the mountains.

The Cascade Mountains thus appear to have contributed considerably to the building of the Admiralty drift plain, contrasting with the Olympics in a way to be expected, since their area is greater and their rivers are larger. Yet the evidence seems conclusive that, though both bordering mountain ranges contributed, much the larger portion of the Admiralty sediments is outwash from the Cordilleran Glacier and was derived from the mountains of British Columbia north of the Puget Sound basin.

The gravest objection to the hypothesis here advocated for the origin of the Admiralty sediments is their great thickness, and the large amount of fine material and thick beds of lignite in them. The length of time represented by this series is perhaps too great to assign to even a very slow retreat of the Admiralty Glacier along the basin of Puget Sound. When the northward and westward extension of the Admiralty drift plain is studied carefully, more light may be thrown on this question.

The great thickness of the Admiralty sediments in the Puget Sound basin contrasts strikingly with the slight amount of pre-Vashon Pleistocene aggradation in the portions of the structural valley to the north and south. This difference clearly indicates favorable local conditions and the one dominant condition appears to have been the lingering of Cordilleran ice in the basin.

SUMMARY OF THE CHAPTER.

(1) Stratified sediments between the Admiralty and Vashon tills compose at least nine-tenths of the Pleistocene deposits of Puget Sound above sea level.

(2) These sediments were deposited probably largely by water flowing from the melting Admiralty Puget Sound Glacier.

(3) The level of the sea during their deposition was close to present sea level, lignite being found today from below tide to the summit of the series, 400 feet above tide, and marine fossils occurring only in the lower beds, close to the present sea level.

(4) The stratified deposits were laid down as a wide plain in the geosyncline of Puget Sound.

(5) The basal portion of these Admiralty sediments is marine in part. The greater part of the series is terrestrial.

CHAPTER VIII.

ORIGIN OF THE TROUGHS OF PUGET SOUND.

SYNOPSIS.

GENERAL DESCRIPTION.

The most notable feature of the topography of the Puget Sound basin, south of the Cascade Mountain spur, is the meridional parallelism of major forms. The observer with an eye to the origin of this persistent feature is at once impressed with the fact that these meridional valleys and divides, at least above low tide, have been fashioned almost entirely in glacial drift and stratified Pleistocene sediments.

The only part of the basin south of the mountain spur where the troughed and ridged topography fails, is south of Tacoma and Olympia, in the region of greatest deposition during the Vashon epoch.

The greatest trough of Puget Sound occupies the meridional axis of the synclinal valley, and contains Admiralty Inlet. The length of this inlet is 60 miles and its average width is 3 to 4 miles. It maintains a depth between 575 and 900 feet below sea level for a distance of 45 miles. The average height of the bounding bluffs is about 200 feet. The deepest place in the trough is probably off West Point, Seattle, where the water is 800 feet deep, and the bluffs on both sides are 300 feet high.

Like the other smaller but still considerable troughs of Puget Sound, this great valley is a Pleistocene product. The largest trough west of it is Hoods Canal, and the largest on the east is the Marysville-Snohomish-Snoqualmie Valley. The vigorous rivers from the Cascade Mountains have filled the eastern troughs with alluvium, so that the Sound today floods only the middle and western part of the trough system.

THE ORIGIN OF THE TROUGHS.*

Three different modes of origin have been suggested for the Puget Sound trough valleys; stream erosion, glacial erosion and glacial accretion.

Considered from a map alone, the origin of Puget Sound appears a simple problem. Many have referred to it as a drowned river system of preglacial development, confusing it with the river- and glacier-carved fiord coast northward to Alaska. Upham uses it to prove his high continental elevation which brought on the ice age, and when visiting the region, persistently mistook the stratified Admiralty clays for Tertiary shales. Kimball has argued for the postglacial erosion of these valleys.

Newberry probably was the first to bespeak an origin by glacial erosion for these troughs. He thought the glaciers

* References to the literature will be found in the introduction to this paper.

moved northward toward the Strait of Juan de Fuca. Subsequently, others have reversed the direction of glacial movement, but have held to the idea that a piedmont ice mass or broad glacial tongue developed the plexus of trough valleys beneath itself. The seductive feature of this hypothesis of glacial erosion is the rude parallelism of the troughs with the direction of glacial movement.

Russell has advanced, and Willis has supported, the accretion or construction hypothesis for the origin of the Puget Sound valleys. This view is essentially the first hypothesis advanced in our discussion of the origin of Admiralty sediments. Willis removes the difficulty of securing independent ice tongues on the lowland by assuming a pre-existing valley system corresponding to that of the present, on the divides of which the glacial and sedimentary series was deposited.

"By repetitions of this process, [ice occupancy of the troughs, and deposition on the inter-areas,] the antecedent divides were built out to plateau forms, and the axes of the original valleys were maintained as relatively shallow hollows which are thus the casts of glacial tongues."*

In the above statement Willis definitely commits himself to the hypothesis of glacial construction. His statement apparently includes Admiralty as well as Vashon glaciation. The great improbability of such origin has been shown in the preceding chapter, and it may be added further that a study which has included almost every sea cliff of the Puget Sound country has failed uniformly to find any trace of underlying rock masses supposed to exist in the ridges and plateaus of glacial drift. Where rock does appear in a sea cliff, it bears no relation to the hills of drift, and in many places interrupts or constricts the troughs, a relation which would be impossible if they were preglacial valleys.

In the volume on "Glaciers and Glaciation," of the Harriman Alaska Expedition report, G. K. Gilbert suggests that Admiralty Inlet may have been the lower course of the Columbia River

* Bailey Willis, Bul. Geol. Soc. Am., Vol. 9, 1897.

which in pre-glacial time may have flowed northward in the structural valley, from Portland to the Strait of Juan de Fuca. Data presented in previous chapters of this paper make it clear that such a hypothesis finds nothing in the field to support it, and that there are insuperable objections to it. The divide at Napavine probably has never been crossed by a stream, certainly not since the deep decay of the Tertiary rock. The Gate Pathway, interrupted by two rock hills, is too narrow for the passage of a stream like the Columbia. The Pliocene

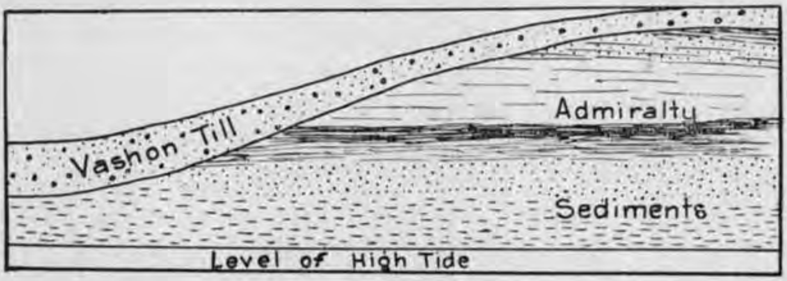

Fig. 21. Relation of Vashon Till to Admiralty Sediments.

Diagram shows truncation of stratified Admiralty sediments by a sea cliff (facing observer) and by a pre-Vashon erosion slope (on the left) bearing Vashon till.

Chehalis Valley is wide open from Gate to the ocean and the Columbia would have taken that course, had it ever crossed the divide at Napavine. And, finally, the troughs of Puget Sound, eroded in Pleistocene deposits, are interglacial, not preglacial, in age.

It is believed that any attempt to explain the origin of the topography of Puget Sound by one process is doomed to failure, that the troughs have had a polygenetic origin, and that study of each trough is necessary to solve the problem of its genesis. Later in this chapter, the various troughs will be considered individually and this conception developed in more detail. Several of the hypotheses advanced earlier have touched upon the truth. Preglacial and interglacial stream erosion have functioned, glacial erosion has operated apparently in certain situations, and glacial deposition has increased the height of some hills relative to the adjacent troughs, during the Vashon glaciation. Of these several processes, that of interglacial stream erosion has been by far the most important.

The evidence for the predominance of this process may be summarized as follows: Most of the troughs show the character and relations of stream valleys, and they post-date the deposition of the Admiralty sediments, and antedate the Vashon glaciation. Data have already been presented (Ch. VII) which bear on the above points, and more will be advanced in the following paragraphs.

THE INTERGLACIAL DRAINAGE SYSTEM SOUTH OF THE STRAIT OF JUAN DE FUCA.

After the Admiralty glaciation, uplift of the region of Puget Sound occurred, accompanied by local deformation of the glacial deposits. This post-Admiralty uplift was probably about 1,000 feet greater than that which has followed the Vashon glaciation and produced present altitudes. A long pause in crustal movement followed, while stream erosion cut deep valleys in the surface of the plain. Since the material was unconsolidated and the stream gradients were high, the work of eroding a drainage system was brief compared to the development of such on a rock terrane.

The stream valleys which were eroded at this time in the Admiralty glacial deposits were masked but little in general by the Vashon glaciation. Locally, they were apparently deepened by erosion of the Vashon Glacier. Valleys lying at right angles to the course of ice movement were obscured more than those with other orientation. In the southern part of the basin, the troughed topography was completely obliterated by the peripheral deposits of the Vashon Puget Sound Glacier.

ITEMS CONTROLLING THE RECONSTRUCTION OF THE DRAINAGE SYSTEM.

Any attempt at reconstruction of the interglacial drainage system must recognize the following items:

(1) The elevations of the Pliocene topography which rose

above the Admiralty drift plain, and controlled the inception of the interglacial drainage pattern:

(2) The original slope of the Admiralty plain:

(3) The possible deformations of this slope.

(4) The orientation of the major troughs of Puget Sound.

(5) The relation of the Vashon till to the interglacial valleys.

(1) Elevations of the Pliocene Topography above the Admiralty Plain. In the consideration of this item, account need be taken of but two areas, besides the hills and mountains margining the structural basin.

The Blue Hills are situated centrally in the basin. They rise a few hundred feet above the ridges and plateaus of drift which separate the troughs of Puget Sound. These hills lie between the two master troughs now flooded; Hoods Canal on the west, and Admiralty Inlet on the east. Though not sufficiently elongated to serve as a divide, the area of the Blue Hills must have been the effective factor in determining the consequent drainage which produced these two great troughs.

The Black Hills constitute a larger and higher remnant of the preglacial topography. They lie north of the Chehalis River, and separate the Gate and Matlock Pathways which are also preglacial topographic features. In the absence of deep borings, nothing is known of the depth of the drift in each broad gap. In this lies the weakest point in the reconstruction of the interglacial drainage system of Puget Sound as will appear shortly. It has not been proved yet that the red gravels of the Chehalis Valley are outwash of Admiralty age carried through the Gate and Matlock Pathways, though the current bedding of the Admiralty gravels in the southermost part of Puget Sound possesses a persistent southward dip toward the Gate Pathway.

(2) Slope of the Admiralty Plain. Since the Admiralty plain was aggraded probably by water flowing toward the south (Ch. VII), the debris and water being supplied largely by the Admiralty Glacier at the north, the original slope must

Crumpled Clay Stratum of Camano Island.

have been southward. The common shallow foreset- or current-bedding of the Admiralty outwash gravels nearly everywhere dip in conformity with this theoretical consideration. This fact makes it probable that the red gravels of the Chehalis Valley are correlatives of the gravels of the Admiralty plain, though granite, the characteristic rock of Puget Sound drift, has not been identified in them.

Though the region of Puget Sound has been elevated and depressed repeatedly since the aggradation of this plain, the seacliff sections record only local and slight deformation of the strata resulting from these movements. The summits of the ridges and plateaus of the former plain become gradually lower

FIG. 22. Oblique Truncation of the Foreset Beds of Quatsap Point Delta.

southward from the latitude of Seattle or Tacoma and this descent may record the original slope of the Admiralty plain.

We have seen that during the retreat of the Vashon Glacier from the Sound, diversion of glacial water from the Chehalis Valley at the south, to the Straits of Juan de Fuca at the north occurred before the front of the ice had receded to the Strait. It is entirely probable that the history was similar during the retreat of the Admiralty Glacier. If so, the Admiralty plain in the northern part of the basin should have had a northward and westward slope, and this slope should be recorded today in a northward and westward dip to the current-bedded sediments and perhaps also in a gradual lowering of summit levels in the same general direction.

The Tacoma, Seattle, and Mt. Vernon quadrangles together cover a meridional distance of about 100 miles in the basin of Puget Sound and must include the latitude at which the Admiralty drainage abandoned the southward course and began to flow to the Strait. Except near the mountains, the summits of the ridges and plateaus of drift for the whole distance are about 550 feet in altitude, and no evidence of the former divide is found in the present topography.

Current bedding in fine sand of Admiralty age, beneath Vashon till, is exposed in the sea cliff on the east side of Marrowstone Island. The dip is almost without exception toward the north. Sand of much the same character across Admiralty Inlet on Whidbey Island possesses current bedding with dip in the same direction. Though this dip does not prevail in the Admiralty sediments of this part of the Sound, it is seldom disputed by southward dip in the cross-bedding, and the conclusion appears sound that water flowed northward or northwestward across this portion of the Admiralty plain during the time of its aggradation.

The deduction from this consideration of the slope of the Admiralty plain is that the interglacial drainage pattern was probably controlled by a mid-basin low divide which crossed from the Cascades to the Olympics south of the latitude of Everett. The Chehalis River received the water from the southern slope, and from rivers debouching on it from the bordering mountains, while the Strait of Juan de Fuca received the direct and contributed runoff of the northern part.

(3) Post-Admiralty Deformation. The strata of the Admiralty drift plain have been elevated twice since their deposition, a downward movement intervening. Since, however, the plain is made of terrestial deposits with the stratification produced by constantly varying conditions of swift, sluggish, and standing water in different localities, no stratigraphic methods for detection of deformation, other than continuous tracing of individual beds, can be used.

Deformations shown in the sea cliffs of Puget Sound are only local, though sharply accented in places, and by far the larger number of exposures give no suggestion of disturbance. Whatever influence these movements may have had in shaping the topography and in determining the consequent drainage, it

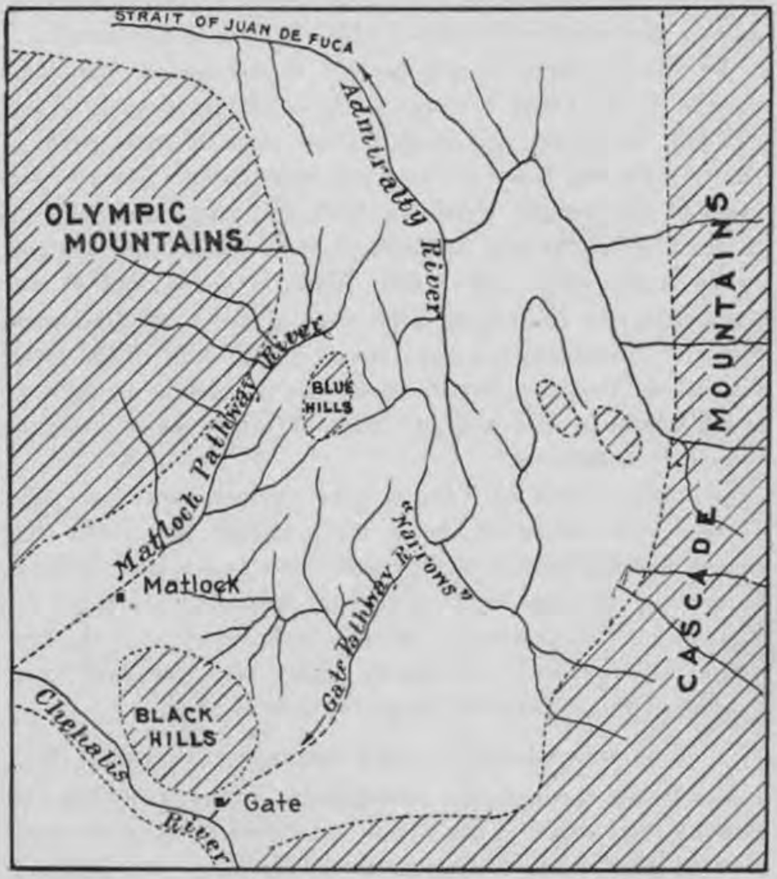

FIG. 23. Interglacial Drainage Pattern of the Admiralty Plain.

probably was not general. The third factor thus apparently is negligible.

(4) ORIENTATION OF THE TROUGHS OF PUGET SOUND. The orientation of the valleys of Puget Sound is obviously the factor of greatest importance in a reconstruction of the inter-

glacial drainage system. It must be conditioned, however, by consideration of (a) relative depth of troughs, (b) relative length, (c) relative width, and (d) the existence of troughs containing fresh water, or with floors above sea level. The fifth and last point must also be considered in this connection; namely, the relation of deposits of Vashon till to the troughs.

By construction of bathymetrical lines from the soundings on the U. S. Coast Survey charts of Puget Sound, (Plate XXIV), the forms and proportionate sizes of those parts of the troughs now below sea level are well shown. For the portions of the troughs above sea level, the proportions are approximated by 20-foot contours on these charts, and are correctly delineated for the Seattle, Tacoma, and Mount Vernon quadrangles on the topographic maps of the U. S. Geological Survey. These maps and charts and a field study of the entire region are the basis for the selection of certain troughs as trunk channels, and the grouping of others as primary or secondary tributaries.

(5) Relations of Vashon till to the troughs. The detailed examination of nearly every trough has shown that the Vashon till mantles their slopes down to sea level at least, truncating the edges of the horizontal Admiralty strata. (See Fig. 21.) This position is entirely in harmony with the first two topics discussed, and clearly shows the troughed topography of Puget Sound to be pre-Vashon in origin.

RECONSTRUCTION OF THE DRAINAGE PATTERN.

Briefly summerized, the interglacial drainage system of Puget Sound south of the Strait is believed to have consisted of three rivers; one flowing north to the valley now occupied by the Strait of Juan de Fuca, and two flowing south to the Chehalis River (Fig. 23). Admiralty Inlet is the trunk valley of the north-flowing river *(Admiralty River)*, and Hoods Canal is the main valley of the western river *(Matlock Pathway River)* discharging to the Chehalis. The main portion of the valley of the second southward-flowing river *(Gate Pathway River)* is thought to be largely obliterated by Vashon moraine and outwash accumulations, but to have lain between Nisqually Reach and the town of Gate, passing through the Gate Pathway to the Chehalis. The lower portion of the Hoods Canal river through the Matlock Pathway is thought to be buried deeply in a similar manner by deposits of Vashon drift. (See sketch map, fig. 23.)

It was noted earlier that the weakest point in the reconstruction here advanced is the absence of data on the depth of the drift in these two pathways. The suggested reconstruction must remain hypothetical until deep borings have been made in one of these pathways. At the same time there is so much evidence corroborative of the view advanced, that this reconstruction has been ventured.

The pattern secured by grouping the troughs of Puget Sound into three different river systems has some incongruous elements, though in general it is harmonious with consequent drainage on the Admiralty drift plain.

THE GATE PATHWAY RIVER. A remnant of the former trunk valley of this river probably exists in the troughed portion of the Nisqually River valley, between the mouth of the river and the head of McAllisters Creek. A broad, pre-Vashon valley extends here about five miles southward from Puget Sound. Early in the history of Lake Russell, the Nisqually River emptied into this valley, building the Sherlock Delta on the southeast margin of the then existing bay of the glacial lake. This delta partially obliterated that portion of the interglacial valley which had previously remained because of its position north of the zone of greatest deposition.

The remaining portion of the trough, lying north of the Sherlock Delta (See Plate XXIII), is amply proportioned for a trunk valley for the region believed to have been tributary to it. Toward it, the Carrs Inlet (Henderson Bay) and Cases Inlet (North Bay) troughs converge, deepening and widening like normal consequent tributaries on a sloping plain, and to them in turn most of the minor troughs and valleys of pre-

Vashon origin also converge, deepen, and widen. A study of the bathymetrical lines on Plate XXIV will show this clearly.

In this southern portion of Puget Sound, which is the original Puget Sound of Vancouver, the average thickness of the Vashon till exposed in the sea cliffs, does not exceed 10 feet. It is locally thicker in stoss end or lee end deposits, as on Hartstene Island (See Pl. XIX, Fig. 1), South Head, and elsewhere, but the evidence is overwhelming that the interglacial topo-

FIG. 24. North Shore of Hales Passage, showing drumlinoid till ridges truncated by sea cliffs. Drawn from a photograph.

graphy of this portion of the Sound basin lies now almost as it did before the Vashon glaciation. There are many minor bays and inlets in this region, of which Wollochet Bay on Hales Passage and Vaughns Bay on Cases Inlet are typical examples of large size. In such valleys, the Vashon till entirely veneers the slopes and descends to sea level with long, smooth slopes. Where in places these even-flowing outlines are cut by sea cliffs, Vashon till is everywhere exposed at the top, with stained Admiralty sediments below constituting the real relief features. It is evident that these minor valleys antedate the Vashon glaciation, from which they have received a veneer of fresh glacial till over the weathered and stained surfaces of the interglacial topography.

Hales Passage is a drowned cross-trough of the old river system, the former divide in it probably being near the west end. Almost at right angles to the direction of glacial movement, it shows an interesting modification of the Vashon till veneer, a modification which constitutes the distinguishing topographic feature of the passage. The north slope bears many elongated, drumlin-like ridges descending toward tide water at right angles to the length of the trough. (See Fig. 24.) A few exist on the south side also. (See Pl. XVIII, Fig. 2.) At sea level these rounded ridges are truncated by sea cliffs, and are shown to be composed entirely of Vashon till. The summit

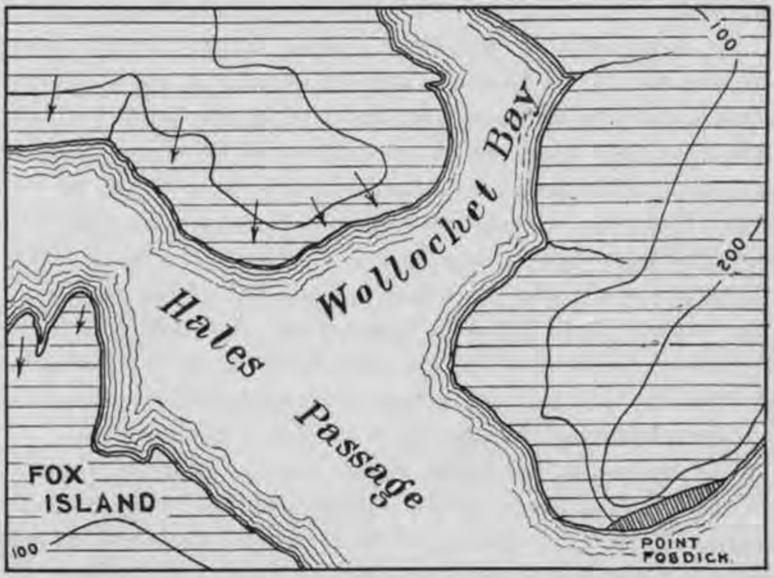

FIG. 25. Course of Radiating Till Ridges about Wollochet Bay. Arrows indicate the ridges.

of the bluff along the north side of Hales Passage thus has a scalloped appearance in section, as shown in figure 24.

In the angle between Hales Passage and Wollochet Bay, twelve distinct, truncated ridges of till are to be seen along the shore. They appear to radiate somewhat from the higher land in this angle, as though in descending the north slope of the passage basal ice was deflected by the valley of Wollochet Bay. (See Fig. 25.)

A few minor valleys opened northward toward the ice which overwhelmed them. Three such valleys lie side by side on the south shore of Carrs Inlet (Henderson Bay). The northern tip of each peninsula between the drowned valleys is a stoss end deposit of Vashon till. The till thins out and its base rises from sea level with approach toward the mainland along the length of the peninsula, until the bluffs expose only pre-Vashon material, severely crumpled by the overriding glacier. South Head is the most conspicuous of these stoss end accumulations of till.

The orientation of Eld Inlet (Mud Bay), Totten Inlet (Oyster Bay), and Skookum and Hammersley Inlets is apparently anomalous for consequent drainage on this portion of the Admiralty drift plain. However, since each is the drowned lower portion of a stream valley descending the north slope of the Black Hills, their orientation does no violence to the hypothesis.

Budds Inlet does not lead back to a valley in the Black Hills. Its course is directly north and appears out of harmony with the restored Gate Pathway trunk river. But low rock hills lie between the head of this inlet and Little Rock, and probably decided the original consequent drainage which produced a northward-flowing tributary to a southward-flowing river.

The course of the trunk stream across Thurston County to the Chehalis River can be outlined within fairly narrow limits. From the vicinity of Sherlock, it probably flowed southwest toward the location of Offuts Lake, thence along the area now bearing Rocky Prairie, passing close to Grand Mound on entering the Chehalis. Practically all other routes are closed because of the known existence of bed rock or Admiralty drift well above the channel level. The crucial region for the future study of this question is the western part of Rocky Prairie, and the terminal moraine from three to five miles west of Tenino. The most constricted portion of the entire valley was here, rock outcrops being known within 2 or $2\frac{1}{2}$ miles of each other, between which the stream must have passed.

Since the system of interglacial valleys that discharged through Gate Pathway is now in open connection with Admiralty Inlet, direct evidence must be presented that a divide exist-

FIG. 1. Vashon Till Sea Cliff at Tip of Cape Horn.

FIG. 2. Drumlinoid Forms of Vashon Till on Fox Island.
Longitudinal axes transverse to the length of Hales Passage, in which they lie.

ed between the Admiralty River and the Gate Pathway River previous to the Vashon glaciation. Should this evidence fail to be satisfactory the entire scheme well may be rejected as too tenuous for serious consideration.

The Narrows, near Tacoma, uniting the troughs of the Gate Pathway River with those of the Admiralty River, crosses the supposed former divide at about its narrowest place. A tidal range, averaging 16 feet for the inlets constituting Vancouver's Puget Sound results in a current of six miles an hour through the Narrows with every change of tide. Undoubtedly this current is widening the passage and perhaps deepening it. All indications are that the Narrows has been widened and deepened by tidal currents since the retreat of the Vashon ice. The passage is a mile wide, and no wind waves of importance can develop on it, yet its walls are as steep as the Admiralty sand and gravel will stand, and much of them is bare cliff face. Only the surging tidal current can be responsible for their notable development in a water body so narrow.

The maximum depths of the Narrows is 30 fathoms. Colvos (West) Passage and Admiralty Inlet, a few miles north, are 65 and 100 fathoms deep respectively. Five miles south of the Narrows, the depth is again 100 fathoms. Though glacial erosion probably has had some part in this deepening both north and south of the Narrows, the Narrows is much too shallow and constricted, even in its present enlarged condition, to be considered a trunk channel connecting troughs to the north and south of it.

The relation of the Vashon till to the Narrows Valley forms the final argument for the existence of a pre-Vashon divide at this place. The sea cliffs of practically all inlets of Puget Sound fail to reach to the top of the valley slopes, a more gentle slope covered with Vashon till lying above the tops of the cliffs. In places the Vashon till descends the sides of the valleys to sea level, and theoretically did so originally for all inlets. Wave work has since steepened the lower portions of the sides of the troughs and removed the veneer of till, leaving it capping the sections and covering the slopes above the cliffs. In the Narrows, the cliffs reach nearly to the height of the surrounding land, and in the Point Defiance section, on the east side of the Narrows, a few feet of Vashon till constitute a flat cover to the summit of the hill. The interglacial hill north of Point Fosdick, which is at the junction of Hales Passage and the Narrows, has a long, gentle slope to Hales Passage on the south, covered with Vashon till, while the side toward the Narrows is abruptly truncated to the top, Vashon till overlying the stratified outwash of Admiralty age. Figure 21 expresses this relation, the observer looking west from the Narrows along the trough of Hales Passage.

From such relations, it appears probable that at the beginning of the Vashon glaciation, there was only a small valley at the site of the Narrows, perhaps tributary to the Gate Pathway River. A low divide at its head was cut across during the Vashon epoch. A considerable part of such incision was produced probably by discharge from the hypothetical lake which existed during the advance of the Vashon Glacier. When Lake Russell levels gave place to the post-Vashon marine submergence, and tidal currents were initiated across this divide, their erosive power is thought to have been sufficient to complete the trough to the present proportions.

The Matlock Pathway River. Evidence for the former existence of a river flowing from the Admiralty drift plain through the Matlock Pathway is less definite than for the Gate Pathway stream. Theoretically, Admiralty outwash should have passed through both broad valleys in the manner of the Vashon outwash of later date. But it does not follow that both valleys would drain the region afterward, the Vashon filling being a case in point, the Matlock Pathway being left 300 feet higher than the Gate Pathway.

The troughs which are connected with Hoods Canal, and which are, with little doubt, stream valleys of the interglacial epoch of erosion, afford the most suggestive evidence in favor of the existence of the hypothetical river of the Matlock Pathway. The valley of the Great Arm of the Canal, which joins the Canal at its southern end, is a continuation of Union River valley, this stream being the successor of the pre-Vashon river which gave origin to the valley. The broad, deep valley of the Tahuyeh River a tributary to this arm, is similarly oriented toward the southwest, a normal position for consequent tributaries on a southward-sloping plain.

Skokomish River valley, the lower portion of which is of interglacial age, is likewise headed toward the Matlock Pathway. The Hoods Canal trough continues south for three miles beyond the head of tidewater, and there stops abruptly, with the outwash and morainic accumulations of Vashon age apparently damming it from further extension in that direction.

Dewatto Creek occupies another tributary valley of interglacial origin, correctly oriented for southward flow of the trunk stream. This arrangement of tributary troughs is found as far north as Quilcene and Dabop Bay.

Hoods Canal trough itself fails to harmonize with its tributary troughs in deepening and widening southward. It deepens gradually from both northern and southern extremities to a maximum depth in the middle. Such cannot be due to original stream erosion. Elsewhere in this paper it will be explained as a result of Vashon glacial erosion. Whether due to this or to crustal movement, which is the only plausible alternative view, does not concern us here.

The seacliff sections in the northern part of Hoods Canal fail signally to indicate an interglacial divide, as at the Narrows. From the tip of Toandos peninsula northward to Port Gamble, the eastern slopes of the Canal are low and bear a cover of Vashon till with characteristic flowing contours. The till here attains a maximum thickness of more than 50 feet, and Admiralty material is seldom exposed. A more favorable stretch for the location of an interglacial divide is between Port Gamble and Hoods Head, where Admiralty sediments are more common in the bluffs, and where few gentle slopes bearing Vashon till exist.

A certain feature of the region of Foulweather Bluff renders the location of an interglacial divide difficult; indeed, makes it problematical whether any such divide ever existed. It is the occurrence of "through valleys," troughs which appear to have crossed the ridges between Hoods Canal and Admiralty Inlet, though not to have been very deep, being more like considerable notches across the hills. Such are (1) the trough containing the Poulsbo channel of Lake Hood, (2) the valley across the peninsula just south of Foulweather Bluff, and (3) the valley west of Hoods Head. If formed by interglacial stream erosion, they apparently must be referred to headward erosion of streams on opposite sides of a divide.

The shallowing of Hoods Canal about Foulweather Bluff accords with the conception of a former divide in this region, but shallowing of the same apparent character exists at the mouth of Admiralty Inlet where, without doubt, a principal drainage way to the Strait formerly existed. The whole region must be treated at present as one too greatly altered during Vashon glaciation to permit the interglacial topography to be deciphered with the degree of success possible farther south in the Sound.

The Admiralty River. This river system suffered most from the Vashon glaciation. (1) Erosive action of the ice in the pre-existing troughs was greater because of its more northern position, and because of the greater capacity of its trunk valley. (2) Vashon till is thicker than in regions farther south, in some places attaining a thickness of 100 feet. The evidence, however, is convincing that the greatest of the interglacial rivers of the Admiralty plain flowed northward through the valley now occupied by Admiralty Inlet.

The Admiralty River system is widely at variance with a consequent stream pattern. Bathymetrical lines and the sea-cliff sections make it appear that the Colvos (West) Passage river flowed south, possibly from Dogfish (Liberty) Bay, and very probably from Blake Island at least, to Tacoma, there joining the Admiralty River and completely reversing its direction of flow, an impossible thing for consequent drainage on an aggraded plain. The Dyes Inlet and Washington Narrows stream also flowed south to Sinclairs Inlet, which was tributary to the Colvos Passage river. Sinclairs Inlet, and Gorst Creek which enters it at its head, lie largely in a preglacial valley excavated in Tertiary rock, which was re-excavated during the interglacial epoch and in some places failed to be located in the old course. Its orientation as a cross-trough is due to control by the underlying rock.

The same incongruity is shown in the orientation of the Lake Washington and White River troughs east of the master valley. Neither of these discharged to the Admiralty River by way of the Elliott Bay valley, through which they now reach Puget Sound. The Duwamish Valley, extending from Seattle Harbor to Renton Junction in the White River trough, is constricted by rock outcrops a few miles south of Seattle, and could not have been more than a minor interglacial valley. The Puyallup trough at Tacoma is, however, sufficiently capacious for the purpose. If the interglacial river in the Lake Washington-White River trough flowed south to the Puyallup Valley before joining the Admiralty River, whose flow was northward, it duplicates the Colvos Passage River in its anomalous relation to the trunk stream.

The depth of Admiralty Inlet suffers a remarkable diminution northward toward the Strait. From an average depth of 100 fathoms, it shallows to 40 fathoms at its entrance into the Strait of Juan de Fuca. The Strait is also shallow in a way that suggests Vashon deposits. In Admiralty Inlet, the shallow portion is indicated on the Coast Survey charts as possessing a rocky bottom. If this is bed rock, and not tideswept drift bowlders, it apparently must indicate a considerable bowing up of the basin floor since the Puyallup interglacial epoch, a movement which has not been found recorded in the adjacent hill summits of the Admiralty drift plain.

From this long recital of objections to consideration of the Admiralty River as normal, the reader may turn with a suspicion that river erosion did not produce the trough. An examination of Bainbridge Island, lying between Admiralty Inlet and Port Orchard Inlet, should do much, however, to bring conviction that interglacial streams have formed the northern troughs of Puget Sound.

According to the hypothesis advocated, Bainbridge Island represents a divide between two parallel stream valleys, and if it has not been too greatly obscured by subsequent glaciation, evidence should be found to prove this contention. The island possesses six minor drowned valleys which are easily made out from any map of the coast line. Of these, the best developed are Blakeley Harbor and Eagle Harbor on the east side, and Greek Georges Bay on the west.

Eagle Harbor is drowned for more than two miles back from Admiralty Inlet and the valley extends nearly a mile farther back into the island. A striking feature of Eagle Harbor valley is the presence of drumlinoid furrows and ridges descending the northern slope of the east and west valley, and, in less perfect form, ascending the southern slope. These broad ridges parallel the direction of movement of the Vashon ice, and are composed of Vashon till, overlying Admiralty sediments. They are comparable in every way, except size, to the till ridges of Hales Passage and Wollochet Bay. Wing Point, at the mouth of the harbor, is an exaggerated ridge of this character.

Greek Georges Bay extends back into the island for more than half a mile, and possesses a broad embayment at its head. Lodge moraine deposits of the retreating Vashon Glacier lie in this embayment and clearly indicate, with the Eagle Harbor drumlinoid ridges, the pre-Vashon origin of these minor valleys, and the failure of the Vashon ice to obscure them.

Sea cliffs of Bainbridge Island show the same relations between the underlying Admiralty sediments and the Vashon till that have been found in the southern part of Puget Sound. Long-continued subaerial exposure has weathered and stained the more porous Admiralty material, and stream erosion has carved the minor valleys which today constitute the indentations in the island coast line.

The 10, 20 and 30 fathom lines off the east shore of the island afford further information on this subject. Blakeley Rock, which lies off the mouth of Blakeley Harbor, is situated at the tip of a submerged divide continuing out from Wing Point. The Eagle Harbor drowned valley continues south from the mouth of the harbor to the Blakeley Harbor valley, within Blakeley Rock and the submerged divide, before entering the major trough of Admiralty Inlet. (See Plate XXIV.) This disposition of the submerged contours harmonizes perfectly with the conception of origin of this topography by stream erosion, and can hardly be explained otherwise. The great increase in gradient, just after union of the two valleys, shown on Plate XXIV, is due to deepening of the main trough subsequent to development of these minor valleys. It will be dealt with presently.

It is evident from the preceding paragraphs that the problem of the interglacial drainage system, at least north of the Narrows, is highly complex and still far from solution. Careful and detailed examination of the troughs by future students should throw more light on the subject.

SUB-MATURITY OF THE INTERGLACIAL EROSION.

By the close of the Puyallup interglacial epoch in Puget Sound, the streams of the region had brought the Admiralty drift plain largely to a condition of slopes. The broader plateau portions of the drift of Puget Sound at present are due usually to deposition of Vashon till and outwash, as Willis has well shown for the Tacoma quadrangle. Few flat-topped divides of the interglacial topography, with a width of more than two miles, exist in the region.

INTERGLACIAL DRAINAGE NORTH OF THE STRAIT OF JUAN DE FUCA.

The extent of the Admiralty drift plain north of the mountainous spur interrupting the basin has not been satisfactorily determined. Contemporary drift deposits were laid down in the Whatcom County lowland, and were eroded during the interglacial epoch by the Nooksak River and other streams. Post-Vashon marine and alluvial deposits in these interglacial valleys have produced the fertile farming land of Whatcom and Skagit Counties.

THE "DEEPS" OF PUGET SOUND.

The soundings on the two Coast Survey charts of Puget Sound show a number of remarkably deep depressions in the bottoms of the major troughs. (See Plate XXIV.) They are elongated with the length of the trough in all cases, and curve with the trough where located at a bend in its axis. Deformation is totally inadequate to explain them, and their situation in stream formed valleys gives no clue to their genesis. They bear a definite relation to the forms of the troughs, however, which throws much light on their origin.

The following list tabulates the important data for each deep.

FIG. 1. Vashon Till Sea Cliff, Brisco Point, South End of Hartstene Island.

FIG. 2. Vashon Till on Marrowstone Island, Admiralty Inlet.

Name of Deep.	*Situation.*	*Form.*	*Max. Depth.*	*Depth Below Rim.*
HOODS CANAL—				
Hoods Canal deep	South of two valleys uniting from the north.	Length indefinite, width half of Canal.	95 fathoms (570 ft.).	
Dabop Bay deep	South of two valleys uniting from north. By side of constriction caused by Pulali Pt. (rock).	Elongated, 8 mi. long	102 fathoms (612 ft.).	30 fathoms (180 ft.).
Browns Point deep	Constriction in trough chiefly above sea level, caused by high bluffs of Admiralty material.		63 fathoms (378 ft.).	
Hoods Head deep	Constriction caused by Hoods Head interglacial hill.		73 fathoms (438 ft.).	13 fathoms (78 ft.).
ADMIRALTY INLET—				
Lagoon Pt. deep	Constriction above sea level by high bluff of Admiralty material on Whidbey Island.	Gentle slopes below sea level, an exception to rule.	104 fathoms (624 ft.).	24 fathoms (144 ft.).
Scatchet (Skagit) Head deep	Constriction below sea level to half the width above. Close to junction of, and in larger of, two valleys uniting from north.		148 fathoms (888 ft.).	38 fathoms (228 ft.).
Pt. Edmund deep	Constriction below sea level	Elongated below sea level without definite rim.	118 fathoms (708 ft.).	
Pt. Jefferson deep	Constriction by submerged salient. Deepest place in Puget Sound.		153 fathoms (918 ft.).	53 fathoms (318 ft.).
West Pt. deep	Constriction below sea level	Very steep slopes, flat bottom, elongate.	138 fathoms (828 ft.).	18 fathoms (108 ft.).
Alki Point-Restoration Pt. deep.	Constriction by rock peninsula on each side.		142 fathoms (852 ft.).	32 fathoms (192 ft.).

Name of Deep.	*Situation.*	*Form.*	*Max. Depth.*	*Depth Below Rim.*
ADMIRALTY INLET—Continued.				
Point Pully-Robinson Point deep	Constriction by two projecting points, one at each end.	Elongate with maximum depth at each end.	Pt. Pully, 127 fa. 762 ft. Pt. Robinson, 123 fa. 738 ft. Mid-length, 111 fa. 666 ft.	27 fathoms (162 ft.). 23 fathoms (138 ft.).
COLVOS PASSAGE—				
Colvos Passage	No constriction or uniting valleys. Deepens to 70 fathoms west of Blake Isl., which forms a constriction.	Very elongate with trough.....	66 fathoms (396 ft.).	36 fathoms (216 ft.).
POSSESSION SOUND—				
Randalls Point deep..........	Constriction by submerged salient.		104 fathoms (624 ft.).	4 fathoms (24 ft.).
Possession Head deep.........	Constriction below sea level....		127 fathoms (702 ft.).	27 fathoms (102 ft.).
Mukilteo deep	Constriction by Point Elliot. Valley narrows.		104 fathoms (624 ft.).	10 fathoms (60 ft.).
SARATOGA PASSAGE—				
Camano Head deep...........	Constriction by Sandy Point....		101 fathoms (606 ft.).	11 fathoms (66 ft.).
Point Lowell deep............	Constriction by two opposite points.		78 fathoms (468 ft.).	18 fathoms (108 ft.).
SOUTH OF THE NARROWS—				
Day Island deep..............	Constriction by pre-Vashon hill.		54 fathoms (324 ft.).	14 fathoms (74 ft.).
Ketron Island deep...........	Constriction by this island, which is an interglacial hill, and by a narrowing of inlet.	Elongate, gradually shallowing northward up Carrs Inlet and southward along Nisqually Reach.	102 fathoms (612 ft.).	60 fathoms (360 ft.).

The above catalogue brings out the close correspondence of deeps to constrictions of the troughs of pre-Vashon origin. The converse relation is also largely true; that no pre-Vashon constriction in a major trough is without an accompanying deep.

Another relation of these deeps to the pre-Vashon topography is their occurrence at the junction of two southward-trending troughs.

These deep places in the Puget Sound troughs are referred to erosion by the Vashon Glacier of the basin. The special condition for their formation was the passage of the basal ice through a constricted portion of a trough which otherwise afforded free onward movement, or what is the same thing in principle, the crowding of basal ice from two troughs into one. Such conditions should favor erosion. It is conceivable that erosion might occur here while on the general surface that was overridden, deposition took place. The survival of the headlands and salients which caused the constrictions indicates that the glacial erosion did not notably widen the troughs.

The idea of glacial erosion may be carried farther, and the great depth of the main troughs may be ascribed largely to Vashon glacial erosion beneath the thicker ice mass which lay over these valleys. An extreme view would be that all of Admiralty Inlet below 40 fathoms or so, the depth of that portion with rocky bottom near Port Townsend, had been produced by glacial erosion. There is a check, however, by which the amount of gracial deepening can be limited. The bathymetric chart (Plate XXIV) shows several submerged salients in Admiralty Inlet and other major troughs whose position is on the inside of a curve in the course of the deeper portion. Those off Jefferson Point and Scatchet (Skagit) Head are characteristic. Whatever their origin, they seem incompatible with the hypothesis of glacial erosion of the larger part of the trough.

MINOR RIDGING OF VASHON ORIGIN.

Note has already been made of rounded till ridges, oriented in the direction of glacial movement, and composed of Vashon till, which occur on the slopes of the interglacial valleys. The best group of such in Puget Sound is on the north slope of Hales Passage. (Fig. 24.) The most striking single ridge of this character is Cape Horn on Hammersley Inlet. (Map on Plate XXIV, photograph on Plate XVIII, Fig. 1.)

Wing Point, on Eagle Harbor, and Salmon Bay Narrows, at the Government lock in Ballard Harbor, are two similar cases, though with less pronounced expression. Till ridges are finely developed in the Dogfish (Liberty) Bay depression.

This ridging of the ground moraine is not limited to cross-valleys, where it seems to find its best development. It also occurs on the summits of the drift hills throughout the entire region. Almost any east and west traverse of Kitsap County or the northern part of Mason County on the Great Peninsula of Puget Sound will describe a consistently ascending and descending profile across long till ridges. In contrast with this, north and south roads may extend for miles without much grade if they hold to the ridges or adjacent furrows. In the southern part of Tacoma, such ridges of the ground moraine have been cut across in street grading. They are composed of Vashon till to the base.

These forms originated apparently by local accretion of ground moraine, the flowing contours being produced by the overriding glacial ice. They differ from drumlins in being more elongated, and in occurring on an earlier topography of greater relief. Where no section exists, they may be taken occasionally for features of the pre-Vashon topography. They are usually much smaller, however, than the ridges of the interglacial topography.

CHAPTER IX.

RELATIONS OF GLACIATION OF THE FLANKING MOUNTAINS TO THAT OF THE PUGET SOUND BASIN.

Very few data are at hand for an intelligent discussion of this subject. Field work bearing on it has been nothing more than reconnaissance, and that only in a limited number of mountain valleys.

THE OLYMPIC MOUNTAIN GLACIATION.

In chapter II the relation of the Vashon Glacier of Puget Sound to the Skokomish Glacier was discussed, and it was shown that the greater ice mass pushed up into the lower end of the Olympic Mountain valley in the face of a descending local glacier.

Theoretically, with the oncoming of glacial climate, glaciers from the Olympic and Cascade Mountains would descend to the Puget Sound plain before the Cordilleran ice sheet entered the basin. The Skokomish Glacier then originally may have extended some distance farther down its valley, and the arrival of the far greater ice mass crowded it back, or overrode and destroyed its lower portion. No superposition of Puget Sound till on Olympic till is known in the Skokomish Valley, but a locality a few miles north on Hoods Canal affords a section that is to the point.

On the east side of this inlet, midway between the mouth of the Lilliwaup Creek and Hama Hama River, a dark-colored till overlying the weathered drift of Admiralty age is exposed in a sea cliff. The till is unlike either Admiralty or Vashon till anywhere in Puget Sound. Its color is far too dark, its pebbles are subangular instead of rounded, and it possesses no granite or other holocrystalline rock. Fine-grained, dark-colored rocks prevail, some being basalt, some metamorphosed sedimentaries. Pebbles with a bright green vein-stuff, and pebbles of bright red jasper are conspicuous in it. The till is very firm. A block

R3W
T23N
Sec 16
mouth
Eagle Cr

several feet in diameter fell from a sea cliff for a distance of 40 feet without disruption, came to rest on the beach between tides, and has since been carved by the waves into a stack 10 feet high.

The characters enumerated stamp this till as Olympic in origin. Its freshness indicates Vashon age, and its position directly above the old weathered Admiralty drift shows that deployment of Olympic glaciers had filled and crossed the pre-Vashon Hoods Canal trough, before the Cordilleran ice entered the field. The position of this till, in failing to lie opposite a valley from the Olympics, is evidence that a piedmont condition of the deployed Olympic ice was attained, to be later destroyed by the Cordilleran Glacier from the north.

Several exposures about the mouth of the Dusewallips River show an Olympic till, possessing the same general characters found in the till above described. It underlies the Brinnon Delta, and appears along the shore for a short distance north of the mouth of the valley, again indicating a deployment of Olympic ice beyond the mountains before the Cordilleran invasion. Though Puget Sound Vashon till has not been found to overlie it, the occurrence of pebbles of granite in the Dusewallips Valley, two miles above its exit from the mountains, proves that Puget Sound ice crowded back that far over the local ice. The lack of a ground moraine of the greater glacier, and the scarcity of Puget Sound drift material in the Dusewallips Valley may mean that the basal portion of the ice in the valley remained Olympic and only the upper ice of the Puget Sound Glacier was pushed up the valley.

Till with pebbles of granite lies on the bottom of the Duckabush River valley, close to its mouth. Here the Puget Sound Glacier evidently displaced the local glacier, in the lower valley at least.

Granitic erratics have been found by Professor Henry Landes, State Geologist, for 25 or 30 miles up the Elwha River valley, on the northern slope of the Olympics. This is further evidence of the dominance of Cordilleran ice on the lowland.

THE CASCADE MOUNTAIN GLACIATION.

Willis and Smith have identified a plane tract of ground moraine in the eastern part of the Tacoma quadrangle as the deposit of a piedmont glacier supplied from the Cascade Mountains to the east. This they name the Osceola Glacier. They also consider that a broad glacial sheet spread out from Mount Rainier, and met the Cordilleran ice on the Puget Sound drift plain. The present study has failed to verify this latter conception, as has been noted. It is true, however, that Vashon outwash in the southern part of the Puget Sound basin in many places bears a large proportion of Mount Rainier lava, even as far west as the Rainier-Walricks Prairie drainage channel, eroded in the earlier-built Tenalquat Prairie (Chap. IV). A terrace of the glacial Nisqually River is traversed for two miles out of McKenna by the road to Eatonville. Its surface is littered with coarse material, largely of Mount Rainier lava, many fragments being four feet in diameter. Granite is not abundant. Ascent from this terrace is to the ground moraine of the Puget Sound Glacier which is strewn with large, angular bowlders of granite, typical of Puget Sound drift, and among which not one bowlder of Mount Rainier lava was found.

The writer's observations in the Cascade Mountains have been limited to the Snoqualmie and Cedar River valleys, in neither of which has a line of contact been found between Puget Sound drift and Cascade Mountain drift. Cedar River valley below Barneston is of post-Vashon origin, and the stream has been superposed on an old drift topography, doubtless of Puyallup interglacial age. The Vashon outwash deposits here are so deep that little has been made out of the glacial history of the region. The Admiralty drift plain is thought to be recognized in the great drift filling which extends back into the mountain valleys.

Cedar River appears to have flowed originally to the Snoqualmie, but by glacial derangement of the drainage to have been turned southwestward through a narrow, mountain-walled valley to enter the Puget Sound drift plain at a more southern point.

The striking features of the Snoqualmie River valley in the mountains are the lower falls, 268 feet in height, and the broad floodplain which stretches back from the falls for seven miles or so up among the mountains. The view of this floodplain from the summit of Mount Si, 3,700 feet almost directly above it, embraces a remarkable assemblage of stream meanders, ox-bow lakes and crescentic swamps, the whole being most strikingly contrasted with the cataract whose abrupt plunge succeeds this aimless loitering course of the river.

The lower part of the floodplain described is bounded by bluffs which rise to the high plateau of drift along the western foot of the Cascade Mountains, the Snoqualmie here having incised it deeply. No exposures of the structure of this plateau of drift are known. The question of its age must be approached from another point of view, one that involves the origin of the falls.

Snoqualmie River plunges over a cliff of lava whose outcrop rises 100 feet or so above the falls on the southern side. On the northern side of the falls is the truncated end of a morainic ridge which crosses the valley in line with the cataract. Excavations for a power plant and a railway grade have afforded instructive sections of this moraine, from which it is evident that the moraine is the cause of the deflection of the river to the south side of the valley. This deflection has caused the stream, in its down-cutting, to become superposed on a spur of the pre-Vashon Snoqualmie Valley, which has given rise to the falls. The presence of this moraine across the valley, and the lack of down-cutting at the falls have caused the broad, aggraded floodplain which is so out of harmony with the cataract below it.

A number of great terrace-like surfaces above present valley floors can be seen in the valleys of Cedar River and the South and Middle Forks of Snoqualmie River from the mountain summits of the region. These terraces appear to lie in a common plane, and have a perceptible descent westward. Grouse Ridge

FIG. 1. Drowned Valley of Chamber's Creek at Low Tide.
Marine shells 110 feet above the sea were found at X.

FIG. 2. Cattle Point Hill, San Juan Island.
Wave-cut benches on southern prairie face. Outwash apron of Cattle Point moraine in foreground.

is one of these flat-topped areas in the South Fork Valley. It lies on the north side of the river and is crossed by the Ellensburg Road. It is composed of drift and apparently is to be correlated with the deposit of drift in which the huge excavations have been made at Ragnar, on the Chicago, Milwaukee and Puget Sound Railway, on the south side of the valley.

These broad tracts in the mountain valleys, several of which are known to be composed of glacial debris, probably can be correlated in a continuous profile of a former drift filling. Such an aggradation of glacial drift in the capacious valleys of the Cascade Mountains further probably can be correlated with the Admiralty drift plain of Puget Sound. Though no stained and weathered sediments have been found in the mountain valleys, this filling has been deeply and broadly excavated where the floodplain of Snoqualmie River above the falls now lies, and in it have been deposited two or three recessional moraines of a Vashon valley glacier, the terminal moraine occurring at the falls beyond the mountain-walled portion.

No evidence has been found to show that the Puget Sound Glacier crowded back into the Cascade Mountains as it did in the Olympics. Such evidence is not to be expected, since the glaciers from the Cascade Mountains were of much greater mass than those from the smaller Olympic Mountains.

CHAPTER X.

PLEISTOCENE AND POST-PLEISTOCENE DIASTROPHISM.

SYNOPSIS.

ALTITUDE DURING THE ADMIRALTY EPOCH.

The known history of Pleistocene crustal movement of Puget Sound begins with the retreat of the Admiralty Glacier. The lower beds of the Admiralty sediments are known to contain marine shells at altitudes of a few feet above present high tide. The altitude of the land was thus slightly lower than at present. Its attitude did not depart much, if at all, from that of the present.

MOVEMENTS AND ALTITUDES DURING THE PUYALLUP EPOCH.

Aggradation of the drift plain was completed while the land lay at this low level. Subsequent to the formation of this terrestrial deposit, regional uplift elevated western Washington at least 1,000 feet above present altitudes. The deeper Puget Sound troughs produced by the interglacial erosion attest a long duration of this high altitude, probably sufficiently long to permit the development of a graded condition in the valleys and the beginning of valley widening.

The duration of this subaerial exposure was sufficiently long to allow weathering to soften the gravel and till exposed at the surface. Limonite, from oxidation of surficial material, was widely distributed by ground water in the deeper Admiralty gravels, and caused the staining, which is a conspicuous feature of the porous Admiralty sediments in the sea cliffs in the Sound. A duration many times the length of post-Vashon time was necessary for the erosion and weathering accomplished during the Puyallup interglacial epoch.

The uplift at the beginning of the interglacial epoch produced local deformation of the Admiralty sediments. Admiralty gravel at the east end of Fox Island is faulted in places and slightly tilted. Deeply stained Admiralty sand in Magnolia Bluff, Seattle Harbor, is somewhat bowed up in the section just south of West Point. The beds of the Quatsap Point Delta are faulted slightly. (See Plate XII, Fig. 2.) Various other sections show comparable deformations of the various sediments composing the complex mass of the Admiralty plain.

The greatest deformation known in the Admiralty sediments is at the south end of Bolton peninsula. The Admiralty till, and its overlying gravels and underlying clay, are tilted to the northward and have a dip of 25°. The movement which produced this deformation was strictly local, for the entire eastern side of Bolton peninsula and the western side of the adjacent Toandos peninsula are exposed by sea cliffs, and no hint of extension of this disturbance into them has been found.

ALTITUDES DURING THE VASHON EPOCH.

At the time of the maximum Vashon glaciation, the region stood at about its present altitude. The time of lowering from the interglacial higher altitudes may have preceded or been contemporaneous with the advance of the Vashon ice epoch; it was attained at least by the time outwash reached Grays Harbor at the mouth of the Chehalis. The shell-bearing till of the

Laurel moraine may indicate that, locally at least, the sea had crept back up the interglacial valleys before the advancing Vashon ice had reached the northern portion of the basin.

THE CHEHALIS VALLEY TRAIN.

The Chehalis Valley was filled by the Puget Sound Vashon outwash to a level much above the rock floor, and the gradients in the valley train, described in Chapter II, were adjusted to a sea level not far from that of the present. The 35-foot terrace of glacial gravel in the city of Aberdeen, at the head of Grays Harbor, possesses stream-bedding from top to bottom, with cross-bedding in places descending westward. It is possible that Vashon outwash built a marine delta in this protected bay, but if so it has been completely destroyed by subsequent changes.

Aside from the western terminus of the Chehalis valley train, no record of the altitude of the region was left until glacial retreat had opened the Strait of Juan de Fuca, and Lake Russell had been drained. Outwash gravels, which, except subglacially, or in deltas, had never been deposited below Lake Russell's levels in Puget Sound, now came to be adjusted to the sea level of the Vashon epoch. The evidence from this is not as conclusive as might be expected but gives a range of about 40 feet, within which the sea level surely lay.

THE CATTLE POINT MORAINE.

The material of the southern slope of Cattle Point Hill of San Juan Island has the stratification of an alluvial fan. There is nothing in the stratification to suggest that it was formed in standing water. As exposed in the sea cliff, the subaerially deposited strata descend to within 25 feet or so of high tide. The sea level was evidently somewhat below this level at time of deposition.

In the bluff overlooking the city of Mt. Vernon, in the same latitude as Cattle Point, 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 this region.

THE SQUALICUM DELTA.

A marginal river formed along the edge of the Puget Sound Glacier as it withdrew northward from Squalicum Mountain, east of Bellingham. Its channel is followed by the Bellingham Bay and British Columbia Railroad between Noon and Bellingham, and descends westward to open out toward the bay in a broad flat of sand and gravel in the northern part of the city of Bellingham. Extensive excavations and railroad cuts in the valley of Squalicum Creek expose the structure of this delta, but the stratification is not in any way comparable to the beautiful structure of some of the Lake Russell deltas.

Strata dipping seaward are common, though of no great length or thickness. Such foreset beds possess no definite upper limit by which the sea level may be determined. Stream-bedding occurs conspicuously at the top, bearing sandy strata with fine cross-bedding dipping seaward. But gravels with rude horizontal stratification occur beneath the foreset beds, at a vertical distance from the sand too great to fall within the tidal range of Bellingham Bay. Beneath the whole is an eroded surface of sand, which is as fresh as the gravel above, and doubtless belongs to the same deposit. In the upper part of the gravel is a persistent clay stratum one to three feet thick.

Obviously, this is the deposit of a heavily loaded stream which flowed through the Squalicum channel. The plain caused by this delta-like deposit has an altitude of 75 feet. From this must be subtracted the variable thickness of the topset beds to obtain the height of the sea at the time of deposition. This was perhaps 50 feet above present sea level. Horizontal and foreset bedding both are to be found within 30 feet of present mean tide.

The sea cliffs of the northern portion of the Squalicum delta plain show 10-20 feet of clay at the top. Since this is at the same level as the sandy and gravelly portions, it must be contemporaneous. It may be explained as part of the delta which during the last stages of growth was not reached by distributary currents, the clay settling in the still water. This conception demands, however, an altitude of 75 feet for the sea level.

The Squalicum Delta plain is bounded on the north by ground moraine which rises 30 feet above it. Sea cliff sections show foreset gravel beneath the till. The till is probably the result of a slight readvance of the Vashon ice while the delta was being built.

The conclusion drawn from the Squalicum Delta regarding sea level during Vashon retreat is that this plane lay somewhere between 30 and 75 feet above present mean tide.

SHELL-BEARING TILL OF WHATCOM COUNTY.

The sea cliffs of the Squalicum Delta and of the shore westward along Bellingham Bay, display two till sheets separated by brown sand, and locally by the overridden portion of the delta. The basal till is gray, the upper one is yellowish. The brown-stained sands are identical in color with the stained Admiralty sediments. Both tills are more argillaceous than is usual for Puget Sound, and both contain marine shells, the lower one the more. A large, thin, entire Pecten valve was found in the lower till.

The topography of this area immediately north of the Squalicum Delta, overlying the shell-bearing stony clay, is hummocky, and possesses numerous kettle holes. It is a typical morainic surface. The intercalated foreset beds, above described, afforded further evidence that the shell-bearing stony clay is a true ground moraine and not a deposit from floating ice near a glacier front. The stained sand is considered as contemporaneous with the delta gravels, the staining being due probably to the almost exclusive use of this porous stratum by ground water.

The shell-bearing stony clay, overlying the Laurel moraine at an altitude of 100 feet, is essentially the same as this till of the Bellingham Bay sections. If the latter is a till sheet of

Vashon age, produced by two successive advances, little hesitancy need be felt in explaining similarly the marine shell-bearing stony clay of the Laurel moraine, five and a half miles north. The shells of the Laurel moraine, 100 feet above tide, therefore do not enter our present problem of the height of the sea level during Vashon retreat.

POST-VASHON CHANGES IN ALTITUDE OF THE REGION.

From the foregoing imperfect data, Lake Russell appears to have been between 110 and 130 feet above sea level at its maximum stage, the plane of which now stands 160 feet above tide. But the history of post-Vashon marine occupancy of Puget Sound is complicated more than is indicated by this evidence of an upward movement of 30-50 feet. It is obvious that a check might be had on the Vashon sea level from marine strands if, since the last glaciation, there had been but this upward movement. But the occurrence of marine shells overlying Vashon till up to nearly 300 feet above mean tide, destroys all chance of using such a check.

Numerous observers have reported marine shell beds on wave-cut terraces of postglacial age as high as 30-40 feet in Puget Sound. The writer has noted earlier the occurrences of marine shells up to 100 feet above tide, inferring from limited data that the Vashon sea level was at that altitude. More study of the region has shown that post-Pleistocene marine strands, recorded by shell beds, lie 130 feet above the levels of the Pleistocene Lake Russell, and perhaps 250 feet above the altitude of the Vashon sea.

HIGH-LEVEL MARINE SHELLS IN SEATTLE.

The best occurrence of marine shells at high level known at present is on the west slope of Queen Anne Hill, in the city of Seattle. The shells are between Tenth and Eleventh Avenues, directly west of the end of McGraw Street. They lie on a sloping terrace, a foot or so beneath sod and loose soil, but above the Vashon till. The shells constitute an almost continuous deposit between 195 and 210 feet above tide. The genera

Mactra (clam), *Paphia* (clam), *Cardium* (cockel), *Natica* (snail), *Thais* (periwinkle), *Mytilus* (mussel) and *Balanus* (barnacle) were found. The amount and the comminuted nature of the material, the distribution, the relation to the terrace and the inedibility of some of the species represented, render origin of the deposit by human or animal agency very improbable. It is a true sea beach with the full tidal range represented.

Directly across the Interbay Valley from this occurrence, on Fort Lawton Hill, a few brittle fragments of *Mytilus* shells were found in plowed ground at an altitude of 208 feet. No terrace exists here. Shells were found also at 180 and 140 feet above tide on the Fort Lawton side of the Interbay Valley.

MARINE SHELLS ON THE RICHMOND DELTA.

A shallow cut along a secondary road which traverses the surface of the Richmond Delta, a quarter of a mile back from the edge of its descent to the Sound, has revealed a bed of shell material, largely comminuted, beneath the forest floor. Shells of *Balanus, Cardium, Mytilus,* a gastropod and several other pelecypods were found in this. The altitude of the bed is 190 feet.

A mile north of the delta, on the sandy floor of the channel which leads to it, fragments of *Balanus, Natica* and *Cardium,* with other unidentified shell fragments, were found at an altitude of 250 feet.

MARINE SHELLS ON THE SEQUALICHEW DELTA.

A few pieces of weathered sea shells were picked up on the surface of the Sequalichew Delta at an altitude of 190 feet. Alone, they signify little, since they may have been carried there. The altitude, however, is the same as that of the bed on the Richmond Delta, which is very probably *in situ.*

MARINE SHELLS AT HIGH LEVELS IN THE SAN JUAN ISLANDS.

These islands are composed so largely of rock that the common beach species with heavy shells, such as the clams and the

FIG. 1. Sea Cliff in South Hill, San Juan Island, with Hook Appended.

FIG. 2. Erratic on Vashon Ground Moraine, near Port Gamble.

large sand-burrowing snail, *Natica*, are rare in the present littoral fauna. For the same reason, they were lacking during the earlier high marine levels. Occurrences of shells on these islands are limited to the marshes and pockets of accumulated finer materials in embayments of the rock hills.

The highest postglacial marine shells yet known in the Puget Sound country occur on Orcas Island. Ditching in a marsh on the old Cap. Olden place, near the quarry of the Cowell Lime Company, disclosed many clam shells in the clay and peat. These were so friable that they crumbled completely on exposure to the air. The altitude of the marsh is 270 feet. A well on the property of Mr. H. F. Pearmain, of Deer Harbor, has yielded fragments of shells at an altitude of 290 feet, this being the highest occurrence yet known. The material in which the shells occur is clay for the depth of the well, 13 feet. It is undoubtedly a marine clay accumulated in a small mud flat near the old sea level.

San Juan and Lopez Islands possess several shell-bearing marshes at altitudes above 100 feet. The Beaverton Valley between Friday Harbor and Roche Harbor is reported to have yielded clam shells in many ditches. Its altitude is about 100 feet. Shells are found occasionally in stratified clay on Lopez Island near Richardson, the highest occurrence being in a well on Mr. W. F. Bolton's farm, one mile north of Richardson, at an altitude of 125 feet.

The most conspicuous record of the former marine submergence of the San Juan Islands is the terracing of Cattle Point Hill and South Hill. Distinct benches are preserved in the sod-bound gravel on the southern face of Cattle Point Hill (Plate XX, Fig. 2), the two highest being 240 and 175 feet above the adjacent sea. South Hill has a similar bench at 265 feet, but none below.

BEACH RIDGES OF WHATCOM COUNTY.

The broad plains of postglacial marine and fluvial aggradation which constitute the fertile farming country of Whatcom County in places bear beach ridges recording the former marine submergence. Such beaches are conspicuous on the plain north and west of Laurel. They are somewhat irregular in crest, and inclined to be duney, and hence are not used for ridge roads. Some are very low and scarcely to be detected. They are composed of clean brown sand with rounded grains. Numerous thin, wavy seams or strata of clay occur in them, but no shell remains were found in them.

The largest ridge observed trends northeast to southwest along the edge of a terrace, the ridge being 20 feet above the plain on the northwest, and 10-12 feet above that on the southeast. This ridge is cut in three places by the road between Ferndale and Laurel, and once by the Pacific Highway north of Laurel. The course of Tenmile Creek is parallel to the ridge.

Beach ridges are numerous between Lynden and Sumas, and are commonly composed of fine gravel. A section afforded by one of these showed strata dipping westward, obviously produced by accretion on the seaward face of the beach.

The highest known occurrence of beach sand on the Whatcom County plain is east of Everson at an altitude of about 100 feet. It does not have the form of a ridge, but from its surficial position and freedom from clay, it is best explained as a shore deposit on the ground moraine. It contains a peaty layer in a position in entire harmony with beach origin but difficult to explain otherwise.

CHAMBERS CREEK AND THE STEILACOOM DELTA.

The above evidence indicates that the region sank after retreat of the Vashon ice, and has risen subsequently to an altitude somewhat greater than that possessed during the Vashon deglaciation. It is not yet established that these movements constitute the whole of post-Vashon diastrophism in Puget Sound. Puzzling relations have been found between Chambers Creek valley and the Steilacoom Delta which possibly may add to the diastrophic history.

Chambers Creek is a postglacial stream which has deeply incised the Steilacoom Delta. Gravel, with foreset bedding, has been recognized on both sides of the mouth of the creek valley, and the delta plain is easily recognizable in the bluff summits on either side. It seems evident that the creek valley must be postglacial.

Yet this valley is drowned for a mile back from the Sound at high tide. (See Plate XX, Fig. 1, and Fig. 26.) In itself, such drowning might be the result of recent sinking, but the following fact needs an entirely different explanation.

On the south side of the valley, fully 1,000 feet back from the mouth, marine shells have been found at an altitude of 110

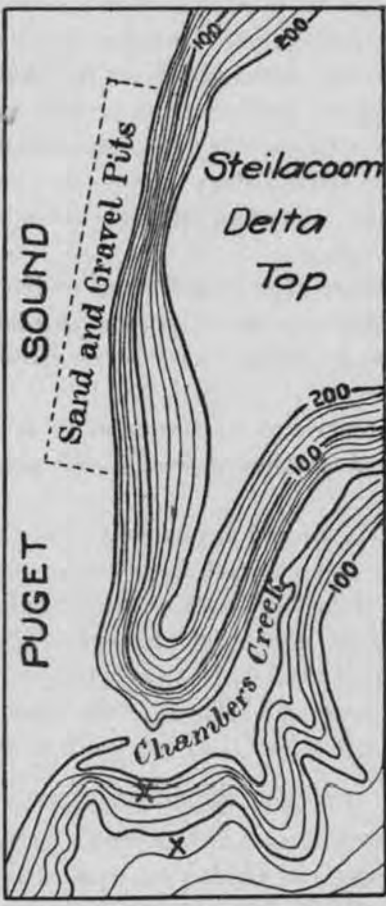

FIG. 26. Lower Valley of Chamber's Creek and Environs. X-Occurrences of Marine Shells.
Drawn from the U. S. C. & G. S. Chart No. 6460.

feet. Below them and somewhat nearer the Sound, though yet within the valley, heavy shell beds up to 30 feet in altitude are conspicuous.

The sequence of events recorded in Chambers Creek valley is apparently as follows:

(a) Deposition of the Steilacoom Delta in Lake Russell and Nisqually.

(b) Erosion of the lower portion of Chambers Creek valley.

(c) Submergence in the postglacial high marine stages.

(d) Emergence to present altitudes, this falling short of the immediately post-Vashon altitudes, leaving the Chambers Creek valley partially drowned. Since the land during Vashon retreat was 30-50 feet lower than at present, and the base level to which Chambers Creek valley has been eroded was lower than that of today, the above history requires the insertion of item

(a^1) An uplift exceeding 50 feet before erosion of the Chambers Creek valley.

Before acceptance of this additional uplift and depression, with a considerable interval of erosion antedating the marine submergence, the hypothesis must be verified from two different points of view:

(1) Other occurrences of marine shells *in situ* in postglacially eroded, and perhaps partially drowned, stream valleys must be found.

(2) It must be proved conclusively that the lower part of Chambers Creek valley is not largely an embayment between lobations of the delta front. Since neither has been established yet, the postglacial diastrophic history of the Puget Sound basin must stand for the present as (a) depression, which succeeded Vashon retreat and submerged the region to at least 290 feet above present sea level, and (b) uplift to present altitudes.

GENERAL CONSIDERATIONS.

It is of interest to note that this crustal movement was downward after the retreat of the ice, not upward as was the case on the Atlantic coast. It does not in this instance bear out the conception of isostatic adjustment, consequent on deglaciation.

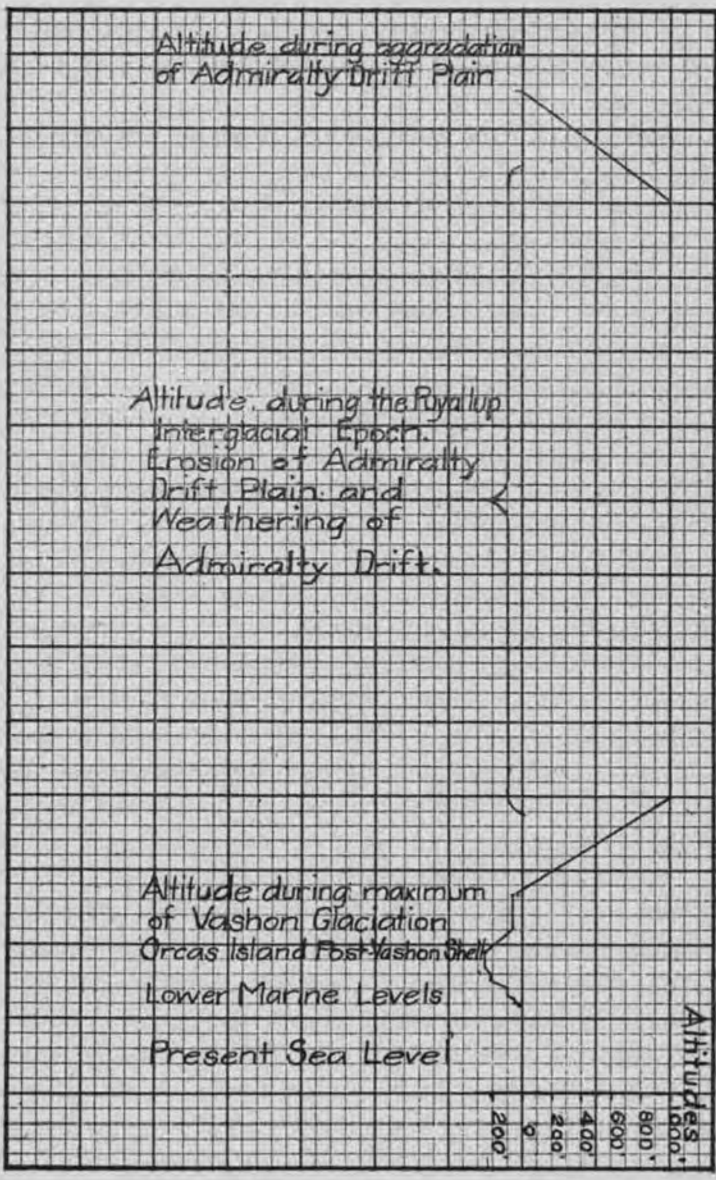

FIG. 27. Diastrophic Movements of the Puget Sound Basin since Admiralty Glaciation. Time relations, indicated by vertical distances, are only approximate.

The glacial mass was, however, of relatively slight amount compared to the continental ice-sheets of Keewatin and Labradorean origin.

Marine shells on the bluffs of Puget Sound are rarely accompanied by wave-cut terraces. The 210-foot shell bed on Queen Anne Hill lies on a fragment of a terrace, and a 105-foot shell bed on Hoods Canal, just north of the Hama Hama River, occurs on a definite bench. But the duration of the higher marine stages appears to have been too brief for the development of many shore lines strong enough to persist to the present. A further evidence of the brevity of the submergence is the lack of stream deltas at the marine levels. During the perhaps equally brief existence of Lake Russell, the streams were heavily laden with glacial outwash, and deltas probably grew far more rapidly than at any subsequent time.

Little warping or tilting of the region has occurred during these post-Vashon movements. The highest level of the Black Lake outlet of Lake Russell is 160 feet. The top of the foreset beds of the Richmond Delta, more than 50 miles north, is 165 feet, and the upper margin of the Redmond Delta, 40 miles northeastward, is 160 feet. These altitudes have been determined with aneroid, and more refined measurements may show slight deformation. For general purposes, however, we may consider the depression and uplift of postglacial times to have been about equal in all parts of the region.

There is a final point regarding the Pleistocene deformation of the region which is intimately concerned with the hypothesis of the Admiralty interglacial river. It is the shallowing of Admiralty Inlet near its junction with the Strait of Juan de Fuca, where the Coast Survey chart indicates a rocky bottom.

If such shallowing is due to Vashon deposition, this gives an unparalleled thickness of Vashon drift of at least 300 feet, the inlet here being shallower than the average depth farther south, by that amount. The thickest sections of Vashon till above sea level are about 100 feet. This supposed deposit lies, further, where erosion, instead of deposition, would be expected. The "rky" of the Coast Survey chart, under this hypothesis, must be considered to indicate a bottom strewn with bowldery drift.

If this shallowing is due to a differential uplift of the region, it should affect also the hills between the troughs. No evidence of such has been found as yet. The time of the differential movement may best be placed in the late Puyallup or early Vashon epoch, when lowering occurred from the high interglacial altitudes.

The depth of the Strait must be considered here also. The depth is 80 fathoms at Port Angeles, gradually increasing toward the ocean, exactly as a stream valley would deepen, possessing a grade of about 9 feet to the mile. Cordilleran ice discharged westward through the Strait, as well as southward into the Puget Sound basin, but has left no hint of its presence in the configuration of the bottom of the Strait Valley. This valley at its present altitude is too high to have served as the outlet of the Admiralty River, though the evidence that it did so serve is convincing. Its present altitude may be due to differential movement of the Strait and Sound regions, or may be ascribed to a drift filling which has left a regular seaward-sloping floor.

The very deep channels among the San Juan Islands, attaining a maximum of 204 fathoms (1,224 feet), are largely the product of preglacial stream erosion, and demand a deep Pliocene Strait Valley, as the Admiralty River demands a deep valley to the ocean during the Puyallup interglacial epoch.

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PLEISTOCENE SURFACE DEPOSITS
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PUGET SOUND BASIN
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Terminal and Recessional Moraines
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SMITH ISLAND
WHIDBY ISLAND
CAMANO ISLAND
SARATOGA INLET
PORT SUSAN
ADMIRALTY INLET
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DABOP BAY
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BELLINGHAM BAY
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CHEHALIS RIVER
Henderson Inlet
Cases Inlet
Budds Inlet
Clover Creek
Nisqually River
Deschutes River
Skookum Chuck Cr.
Newaukum River
Tilton River
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MORAINE AND OUTWASH SOUTH OF PUGET SOUND
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BATHYMETRIC MAP
OF
PUGET SOUND
NOTE: BATHYMETRIC INTERVAL = 20 FATHOMS
SCALE: 1 Inch = 2.56 Miles