

THE GLACIAL GEOLOGY OF THE CITY OF SEATTLE

by

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and

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~~*On file in Department of Geology~~

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THE GLACIAL GEOLOGY OF THE CITY OF SEATTLE

INTRODUCTION

General Setting

Seattle is located in the center of the glaciated portion of the Puget Lowland, which is bounded on the west by the Olympic Mountains, on the east by the Cascade Mountains, and on the south by an arcuate terminal moraine which extends about fifteen miles south of Olympia. Figure 1 shows

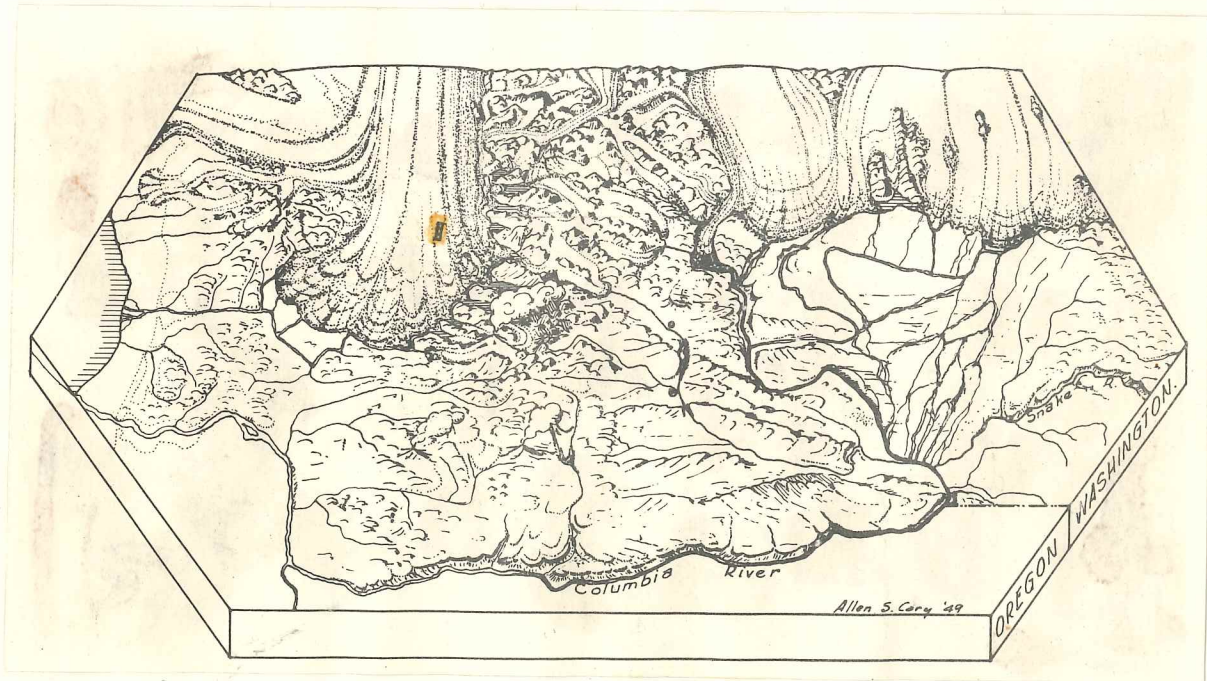


Figure 1. BLOCK DIAGRAM SHOWING MAXIMUM EXTENT OF FINAL GLACIATION OF THE PUGET LOWLAND AND THE POSITION OF SEATTLE (S).

the location of Seattle in relation to the last continental ice sheet that covered this area during the Pleistocene glacial epoch.

Seattle is composed of rounded hills and troughs that have a north-south trend, parallel to the north-south trending Puget Sound lowland; the hills are generally below 500 feet above sea level, while the troughs vary from inter-hill lowlands near sea level to lakes and salt water embayments with their bottoms considerably below sea level.

Bedrock in Seattle is early Tertiary marine and continental beds which have been mapped and described by Weaver (1916), who assigned them to the Blakely formation of Oligocene age. These rocks consist chiefly of marine shales and sandy shales together with minor amounts of sandstones and conglomerates which strike about N70W with a high angle of dip (Fig. 2).

Bedrock is not well exposed in Seattle except in the southeast quarter of the city where the Blakely formation crops out in a belt extending WNW across Beacon Hill from Seward Park to the Duwamish Valley; bedrock appears again along this same WNW trend at Alki Point in West Seattle, where it passes beneath Puget Sound.

Purpose and Scope of Investigation

This thesis stems from the need for complete, systematically recorded data on the glacial geology of the area



Figure 2. BLAKELY FORMATION ON SEWARD PENINSULA SHOWING HIGH ANGLE OF DIP. Beds strike about N70W.



Figure 3. BLAKELY FORMATION AT ALKI POINT, WEST SEATTLE. Beds are fossiliferous shales and sandstones.

included within the city limits of Seattle. The primary aim is to establish a groundwork for the assembling of detailed information needed by engineers on types of materials and the localities where they may be expected to occur at and below the surface within the city.

A secondary aim is to work out a general stratigraphic succession for the Pleistocene Epoch in Seattle which may be used by other workers in regional correlation when the Pleistocene stratigraphy and history is integrated over the entire Puget Lowland.

The field work was done between April 1949 and May 1950. The field procedure consisted of recording on twenty-five foot contour maps every exposure in Seattle which could be relied upon as showing material that had not been moved since its deposition. Sea cliffs and artificial excavations have given the best data. In addition to complete coverage of the area within Seattle, visits were made to exceptionally well exposed neighboring areas; although these sections were not tied to Seattle by detailed mapping they are incorporated in an appendix for the light they shed on problems of age and origin of units within Seattle.

Previous Work

Numerous reports have been published on phases of the Pleistocene geology in the Puget Lowland but few have dealt directly with the Seattle area. Willis (1898) described some

general localities in Seattle from his studies of drift phenomena of Puget Sound. He recognized the fact that at least two continental glaciers had occupied the Puget Lowland in Pleistocene time. Bretz (1911) in the course of his investigation of glaciation of the Puget Sound, stated that the thickness of the last ice sheet that covered the Seattle area was probably in excess of 4,000 feet; later (1913) he described several localities in Seattle, especially those exposed by the regrade projects in operation during his field investigation. Hansen and Mackin (1940) discussed the significance of the plant succession represented by pollens in the peat bearing silts and clays in the Marine Hospital section of Beacon Hill. Mackin (1948) described the varved clay sequence of Beacon Hill, has conducted extensive investigations into various phases of the Pleistocene geology of the Puget Lowland, and has recognized at least three continental glacial stages in this area.

Acknowledgments

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TYPES OF PLEISTOCENE SEDIMENTS

General Statement

The Pleistocene sediments underlying the city of Seattle are composed of unconsolidated clay, silt, sand, and gravel, or combinations of these types of material. The characteristics of each type of sediment are described in this section without regard to position or age, to provide a basis for the stratigraphic discussion to follow.

Clay and Silt

The clays and silts of the Seattle area are composed chiefly of rock flour produced by mechanical abrasion by glaciers, and only to a very minor extent of clay minerals formed by chemical decomposition of rock. The overall fine texture of this class of deposits is a result of deposition in lakes that existed from time to time during the Pleistocene, and variation in grain size is due to variation in conditions of sedimentation in the lakes.

Clay (particle size up to $1/256$ mm) is frequently interbedded with silt (particle size between $1/256$ and $1/16$ mm), and the full size range of the clays and silts may be

present in a single layer. It is, nevertheless, possible to separate deposits consisting predominantly of clay from those consisting predominantly of silt. Deposits consisting chiefly of clay can be further subdivided, on the basis of prominence of bedding, into massive clays, laminated clays, and varved clays.

Massive clay is a homogeneous deposit, showing little or no variation in color and particle size, and containing almost no visible bedding. Some silt is usually present in the clay, but it is dispersed uniformly throughout the deposit and is not seen as separate layers in the clay. The color is usually bluish-gray, varying from light to dark with varying content of water. Most massive clay is hard and cohesive, and smooth to the touch.

Massive clay is almost impermeable. Due to the fineness of the particles, the close-packing of the sediment, and the cohesion of particles, water may move only very slowly into and through massive clay. Ground water commonly seeps out of hills at the top of massive clay layers where these are overlain by more permeable strata.

Massive clay indicates little variation in rate of deposition of different sized clay and silt particles suspended in the water and available for deposition. Rapid deposition of clay and silt in a massive form is favored by salt water because of flocculation of even the finest particles in suspension. Rapid deposition of fine particles is

less favored by fresh water and, as a result, more layers, differentiated according to grain size, can occur. Furthermore, rapid deposition of suspended clay particles is less favored in cold fresh water than in warm fresh water. Thus massive clay and silt are more commonly deposited in salt water than in fresh water, and more commonly in warm water than in cold water.

Weathering proceeds very slowly in massive clay, mainly due to its low permeability. Most beds are not weathered as a whole, but only by the development of soil at the surface. Development of soil destroys the cohesiveness and loosens the clay near the surface, making it more readily removed than unweathered clay.

Impermeability, cohesion, and hardness of massive clay beds make them very resistant to normal erosion. Where massive clay is overlain by weaker sediments, a bench is often formed approximately on the surface of the clay beds. Where massive clay is underlain by weaker sediments, a steep slope is often developed with the clay at the top.

No massive clay is entirely without bedding or laminations. All gradations exist between clay called massive, containing few visible bedding planes or laminations, and clay in which the bedding and lamination are the most striking features.

Laminated clay has thin layers of stratification, generally caused by variations in particle size. Variation

results in thin layers, each composed of particles of a particular size. The color varies from light to dark gray, depending on water content, which is usually controlled in turn by grain size, so that laminated clay often appears as a series of thin light and dark layers. Laminated clay is smooth to the touch and cohesive in individual layers, but cohesion between different laminae is low so that the sediment can be easily broken along bedding planes.

Laminated clays are relatively impermeable, but water moves more easily through silty layers that may be present than through massive clays. Ground water enters laminated clays only very slowly, and tends to seep out of hills at the upper surface of the clay.

Deposition of laminated clay takes place in deep, quiet water, similar in general to the environment of deposition of massive clays. Changes in conditions of deposition, such as rate of settling of suspended sediments and competency of currents that bring the clays into the lake, cause the laminations. Laminated clays are commonly deposited in fresh water lakes, which are often subjected to such changing conditions. Cold water, as previously mentioned, aids in holding fine sediment in suspension, and is a favorable condition for lamination.

Weathering in laminated clay advances slowly, moving preferentially along bedding planes and coarser laminae. As in massive clay, weathering usually advances by the forma-

tion of a soil profile on the surface of the clay. Where laminated clay is being eroded on hill sides, small tabular fragments of clay are often found in the soil below the outcrop.

Laminated clay is similar to massive clay in resistance to erosion, although weaker along bedding planes and coarser laminae. Benches and steep slopes are often developed on layers of laminated clay in the same manner as those developed on layers of massive clay.

Thickness and regularity of laminae are highly variable. The term "laminated" is sometimes reserved for sediment in which the layers are less than one centimeter thick, and those with thicker layers are called stratified or bedded. Such deposits grade into massive clay and are not separately discussed here.

Varved clay (Fig. 4) is made up of a series of similar pairs of laminations. Each individual varve is composed of two members, one thick and one thin. The thick layer is composed mostly of silt, with some clay and fine sand, but the thin layer is composed almost entirely of clay. Each coarse layer grades slowly upward into the overlying fine layer, but the transition from that fine layer upward to the next overlying coarse layer is abrupt.

Varved clays are usually gray, and the fine member is usually darker than the coarse. The layers of fine material are smooth, but the coarse layers are often gritty. Indivi-



Figure 4. VARVED CLAY IN MARINE HOSPITAL SECTION, BEACON HILL. Dark horizontal stripes are winter layers, light horizontal stripes are summer layers.



Figure 5. RIPPLE MARKS IN SILT.

dual layers are hard and cohesive, but the deposit is easily broken along bedding planes.

Varved clays are the most permeable of the three types of clays discussed. Water moves more rapidly through coarser layers of the varves than through laminated or massive clay. However, as in the case of the other clay deposits, water can only move slowly into the varved clays, and tends to drain out of the hill at the top of the varves.

Each varve (Swedish varv--a periodic repetition or revolution) represents one year's deposition in a glacial lake. Varves are usually formed in quiet, cold water lakes, fed by glacial meltwaters carrying rock flour. During the summer season when maximum melting occurs, an abundance of the rock flour is carried into the lake. The coarser silt fraction is deposited soon after being carried into the lake, but the finer clay particles are held in suspension in the cold, fresh water. As colder winter temperatures decrease the volume of meltwater, less coarse material is carried out into the lake, and finally only the fine particles from suspension are being deposited. The thick coarse layer is called the summer layer, and grades up into the fine thin layer, called the winter layer. Increase of melting and floods of rock flour in the spring cause an abrupt change at the base of the next summer layer.

Weathering in varved clay proceeds in a similar manner to weathering in other clays, although it penetrates into

varved clay more easily, due to the presence of the summer layer.

The thickness of individual varves is highly variable, depending on the amount of material carried by the glacial meltwaters in any one year. Individual varves may be less than an inch or more than a foot thick. Varved clays at their base or top usually change into massive or laminated silts or clays.

Silt is common in Seattle as a gradational deposit between clay and sand. Gradation may be by uniform change of particle size, or by an increase of sand or clay throughout until a greater percentage of sand or clay than silt is present. In general, permeability varies directly with variation in grain size. Silt deposits may be massive, bedded, or laminated, but characteristics of all the silt deposits are similar, and they are described together. Ripple marking is common in thin-bedded silts and gives a scalloped appearance in a near-vertical exposure (Fig. 5). Lamination is less common in silt than in clay.

The color of silt varies from light to dark gray, but is usually lighter in color than associated clay, due to smaller water content of the silt. Silt is gritty to the touch, in contrast to the smooth feel of finer clay, and is neither as hard nor as cohesive as clay.

Silt is usually deposited in relatively quiet, shallow water. It is commonly found above clay, with the verti-

cal change representing shoaling of the water. Silt is also typically deposited on river floodplains.

Weathering proceeds uniformly as a front into non-bedded silt, and along bedding planes in bedded silt. Movement of ground water into and through silt may cause oxidation through the entire bed, rather than just the surface. Development of soil on the surface loosens silt, but probably does not increase its susceptibility to erosion.

Beds of silt are less resistant to erosion than most other Pleistocene sediments in the city. In steep banks and sea cliffs, they are usually the weakest member present. Slumping is common and, in general, silt is the most troublesome of the Pleistocene units in the consideration of landsliding in Seattle.

Sand

Sand (particle size between 1/16 mm and 2 mm) is divided into fine (1/16 mm to 1/4 mm), medium (1/4 mm to 1/2 mm), and coarse (1/2 mm to 2 mm) sand. The sand grains are composed of minerals derived from pre-existing rock with some quantity of small particles of rock and other material. Sand is usually made up of rounded to sub-rounded particles, but in this area much of the sand is glacial outwash material and the grains tend to be subangular. Probably no sand deposit in the city is composed entirely of grains of sand size, or of one grade of sand.

Sand deposits may be essentially massive, or may show well-developed horizontal bedding and cross bedding. Cross bedding is stratification with a layering developed at an angle to the horizontal, usually within a given horizontal bed (Fig. 6). Bedding in sand is often shown by variation in general grain size, or by scattered coarser material along a bedding plane. A few pebbles along a bedding surface is a common occurrence in cross bedded sands, and variation through all the range of sand, and even silt and gravel, is common in successive layers of bedded sand.

The color of sands depends in part upon the type of material from which it was derived, but more on the size of the grains and the extent of oxidation and staining. Fine sands and silty sands often have a gray-blue color very similar to clays, particularly when wet. Coarser sands are typically light brown to light gray. If staining has been slight the sands are yellowish to light brown, but if staining has been extreme the sands will be reddish brown to dark brown. In general the extent of oxidation varies directly with permeability, which is in turn a function of grain size.

Deposits of sand in Seattle are of both fluvial and lacustrine origin. The greater portion of sands are probably fluvial, deposited by aggrading streams in shifting channels, usually as cross bedded deposits. The cross bedding is caused by current action and is typical of sand deposited in



Figure 6. CROSS BEDDING IN SAND PHASE OF THE LAWTON UNIT.



Figure 7. PEAT BED AT SEA LEVEL SOUTH OF ALKI POINT, WEST SEATTLE. Clay beds above and below the peat are less resistant and have been eroded away by wave action. Photograph taken on beach at low tide.

river channels. Lacustrine sands, deposited in shallow water bodies where current action is slight, are typically horizontally bedded and have more uniform and continuous bedding than the fluvial sands.

Sand beds in general are weak and easily eroded. Sand with finer material acting as a binder is considerably stronger than loose sand with little or no binder. Rapid erosion in sand beds often produces benches or terraces on underlying stronger beds. Movement of ground water out of sand layers just above more impermeable layers increases slumping and sliding, which are common in sand units throughout the city.

Gravel

Gravel (particle size more than 2 mm) in Seattle is actually gravelly sand, containing enough pebbles and cobbles to cause the coarse material to appear dominant upon casual inspection. The size of the gravel ranges from the upper limit of sand to a few boulders a foot or more in diameter. The gravel is dominantly composed of rounded or sub-rounded fragments of pre-existing rocks, but may also contain boulders of clay and till.

Bedding in gravelly deposits is similar to bedding in sand deposits, with horizontal bedding and cross bedding common. The color of the gravel deposits as a whole is usually light brown to light gray.

Gravel is deposited under conditions very similar to the conditions under which sand is deposited, with fluvial deposits by far the most important. The major difference between the conditions for deposition of sand and gravel is that the water depositing the gravel must be able to carry the larger material along with the sand.

Weathering is generally rapid in gravelly layers, due to the movement of ground water, but there is little effect on the strength of the unit. Development of a soil profile is slow unless considerable finer material is present. Although not as strong as some clay and till, gravel layers stand up well in bluffs and sea cliffs in Seattle.

Peat

Peat is composed of all types of partially decayed vegetable matter, from pollen size to limbs and trunks of trees. It may be composed entirely of organic material or contain considerable amounts of silt and even small pebbles, varying from dark brown to light brown in color as the amount of silt increases.

Most of the peat in this area is very hard, due mainly to compression. Peat layers are usually so hard and compact that they are virtually impermeable.

Peat deposits are developed in swampy areas near sea level, on floodplains, and in the shallow waters of lakes

being filled. A peat deposit may be formed wherever there is an abundance of vegetation and stagnant water in which the plant material may be laid down and covered. It may be partially but not completely decomposed by bacterial action before final burial. Continued accumulation forms a thick deposit of woody material, and subsequent compression gives the peat the hard and compact character common in the peats in the Pleistocene sediments of Seattle.

Hard silty peat beds, containing small pebbles, often have an appearance very similar to silty till. The hardness, compactness, and virtual impermeability of the peaty layers make them very resistant to erosion. Peat layers interbedded with other Pleistocene sediments often form projecting ledges due to differential erosion (Fig. 7).

Glacial Till

Till is an unstratified and unsorted aggregate of clay, silt, sand, and gravel resulting from direct deposition by ice. No sorting or bedding is present. Fresh glacial till is usually some shade of gray in color.

Till has a sandy, silty, or clayey matrix containing scattered pebbles, cobbles and boulders, and where these stones are broken out of the till, a hard cast is left in the matrix (Fig. 8). Most till is hard and cohesive due to the presence of particles of all sizes tightly compressed together.



Figure 8. TEXTURE OF GLACIAL TILL.



Figure 9. SHEETING IN GLACIAL TILL. Apparent bedding in photograph is structure due to ice movement.

Although till is not bedded, an apparent stratification is often present, called sheeting (Fig. 9). Sheeting is structure probably developed in the till during its deposition by the thrust of the overlying ice. Another structure present in till, also due to the movement and pressure of overlying ice, is called kneading, and gives the till a massive, compact, somewhat swirled appearance.

Till is deposited at the base of a glacier as it moves over the ground, and represents, primarily, rearrangement of the original material in a particular location with introduction of varying amounts of foreign pebbles and boulders. As the glacier advances, till is plastered over all the surface over which it rides, leaving a mantle on the pre-existing topography.

Permeability of till varies with the properties of constituent materials; clayey till is least permeable, sandy till more permeable, and gravelly or rocky till most permeable. Weathering proceeds relatively slowly through a clayey till, but more rapidly through a sandy till. Development of a soil cover on the surface destroys the strength and compactness of the till, making it more susceptible to erosion. Where weathering has been extreme, till becomes a loose, brownish aggregate of sand and gravel.

Hardness, compactness and lack of permeability make glacial till one of the strongest sediments in the Pleistocene series. Over much of the hills, capping till is

present, and acts as a strong impervious protective layer over other sediments. Strong till at the surface often aids in the formation of steep slopes by protecting the top of an exposure while lower weaker sediments are eroded away. Where till is eroded from steep slopes it usually breaks off in chunks and blocks. Till is very difficult to excavate, particularly when fresh, and for this reason is commonly referred to as "hardpan."

GENERAL PLEISTOCENE STRATIGRAPHY

General Statement

If the several types of material described in the preceding section had been deposited in an orderly succession, during a single period of glaciation, the internal structure of a typical Seattle hill would be simple. But the Pleistocene sediments of the Seattle area were actually deposited during at least three different episodes of glaciation, separated by long intervals of erosion when the topography of the area was different from that of the present time.

Figure 10 indicates the complexity that results, and makes clear the need for naming each of the major sedimentary units. This section describes the general stratigraphic sequence in the city as a whole, as a basis for discussion of the relations of the individual sedimentary units, by districts, in the sections to follow.

Beacon Till

The oldest Pleistocene deposit in Seattle is a thick glacial till, referred to here as the Beacon till. The type

locality of this unit is in the southern of two brick pits immediately south of Spokane Street on the west side of Beacon Hill; this is the only locality where the Beacon till has been identified in Seattle. The till is at least seventy-five feet thick with the base not exposed. The elevation at the top is variable at about one hundred feet above sea level. The composition is primarily clay and silt with an admixture of rounded pebbles and cobbles. The till is gray in color, showing neither weathering nor any evidence of soil development on the upper surface. These relations indicate that the till was covered almost immediately by sediments laid down during the waning of the ice sheet by which the till was formed.

Duwamish Formation

Sediments that rest on the Beacon till are referred to here as the Duwamish formation. No single type locality can be designated because of considerable lateral variation in the Duwamish sediments, but the nature of the formation can be seen in several excellent exposures along both sides of the Duwamish River Valley from the north end of Beacon Hill south to the city limits.

The maximum exposed thickness of the Duwamish formation is about 225 feet. The base varies from about one hundred feet above sea level to an unknown depth below sea level and the top varies from 230 feet elevation to below sea

level. The Duwamish formation can be divided into a lower part which was deposited during ice retreat and an upper part deposited during interglacial time.

The lower part of the Duwamish formation in the Klinker Sand and Gravel Company yard above West Marginal Way at West Morgan Street is mainly massive blue clay between twenty-five and two hundred feet above sea level, with little or no interbedding of coarser material. The upper part of the formation, between two hundred and 225 feet, is silt and fine sand with a bed of silty peat, in places twelve feet thick. The succession of fine clay to silt and sand with peat suggests filling of a lake followed by swamp development on a floodplain.

A contrasted phase of the Duwamish formation at the north end of Beacon Hill and south end of Capitol Hill is a varved clay sequence in the lower part, between elevations of sixty and two hundred feet, described by Mackin (1948). The bottom varves are sandy, thick, and indistinct. Between elevations of one hundred and two hundred feet, the varves are distinct, and about 470 pairs have been measured with regular, cyclic variations in thickness. A total of about five hundred varves have been counted in one combined section. At the top of the sequence, three or four large indistinct silty varves mark a change from the lower to the upper part of the formation. The upper part is bedded silt between two hundred and 230 feet. A few feet of channel gravel are

present at the top of the silt and these are overlain by five to six feet of hard peat. The succession of varved clay to silt to gravel and peat suggests again a lake filling during waning ice followed by streams and swamps on the floor of the filled lake. This interpretation, based on the sedimentary succession, is confirmed by detailed studies of pollen grains in the peat, by Hansen and Mackin (1940). In these studies they showed that successively higher horizons in the peat bearing zone bear an increasing number of different plant pollens and that the species of plants represented indicate a change from cooler (glacial) to warmer (interglacial) climate.

Klinker Till

Till deposited during the glaciation following deposition of the Duwamish formation is known as Klinker till. The type locality of this unit is in the Klinker Sand and Gravel Company gravel pit below 12th Avenue Southwest and West Morgan Street in West Seattle. The till is twelve to fifteen feet thick, with its base resting on an erosion surface on the Duwamish formation at 225 feet elevation. The composition is very clayey, with considerable rounded pebbles and cobbles throughout. A great deal of kneading is common and included blocks of bedded sand are present. The till is fresh and gray with no weathered zone in the upper part, indicating either that it was immediately covered by recessional

outwash sediments or that any weathering was later eroded off during interglacial time. Because the till is overlain by fine sand and silt without a recognizable erosion break, the conclusion is drawn that the freshness is due to lack of weathering prior to covering with outwash during the ice retreat.

Klinker till varies considerably in thickness in Seattle, ranging from fifteen feet in the type section to eighty feet in the Abrahamson Company brick pit at West Brandon Street and West Marginal Way.

Lawton Formation

Sediments that were deposited after retreat of the ice that deposited the Klinker till but prior to the advance of the last glacier comprise the Lawton formation. The type section is in the sea cliff just south of West Point in the Magnolia District.

The thickness of the Lawton formation in the type section is at least 250 feet. The base is below sea level and the uppermost exposure is at the top of the sea cliff.

The lower portion of the formation is mainly clay with interbeds of silt and sand, especially between sea level and sixty-five feet, overlain by laminated and massive clay up to 150 feet. This lower portion has been designated the clay phase of the Lawton formation because of the predominance of clay.

The upper portion of the formation is mainly medium sand with some lenses of gravel, above a ten foot transition zone of silt and fine sand. The elevation of the base of the sand phase is approximately 160 feet. Above this elevation almost no clay or silt occurs interbedded with the stratified sand.

The base of the formation is not seen at the type locality but it is well exposed in other sections where it is seen overlying the Klinker till or the Duwamish formation. In one locality the base of the Lawton formation is composed of twenty feet of coarse sand and gravel that lies on an unconformity that bevels across the Klinker till and the Duwamish formation.

Variation in the Lawton formation is much less marked than in the Duwamish formation; there is some variation, but the clay phase underlying the sand phase is a consistent relationship, with a gradational contact between the clay and sand varying from 125 to 275 feet above sea level.

Vashon Advance Gravel

Gravel deposited in channels cut into the Lawton formation and earlier units during advance of the Vashon ice are known as Vashon advance gravels. The type locality in Seattle for this unit is in the upper part of the same Klinker Company section in West Seattle previously mentioned as the type locality of Klinker till.

The thickness of the channel deposit at the Klinker pit varies between sixty and eighty feet. The elevation of the base is about 260 feet and top is as high as 340 feet above sea level. The Vashon advance gravel is composed of rounded pebbles, cobbles and boulders with a considerable fraction of finer sand and silt. The gravel also contains some till boulders, clay blocks and other fragments of the earlier Pleistocene sediments into which the channel was cut.

Vashon Till

Till deposited by the last continental glacier to occupy the Puget Lowland is referred to as Vashon till. Willis (1898) gave the name Vashon to extensive capping till on Vashon Island, and there is no doubt that the capping till on the island and the till that veneers the Seattle hills are the same.

The Vashon till varies in thickness in Seattle from a few feet up to 125 feet or more and the base and top of the till sheet both vary from below sea level to above five hundred feet. The till is composed of sand, clay and an assemblage of coarser, rounded stones. The sandy nature helps to distinguish it from the earlier tills which are much more clayey, and darker gray.

STRATIGRAPHY BY DISTRICTS

General Statement

All of the stratigraphic units described in the last section vary markedly in elevation above sea level, some are discontinuous, and even the more continuous units show gradational differences from hill to hill within the city. This section takes these variations into account by describing the stratigraphic relations in the Pleistocene succession by districts.

Seattle has been divided into districts using wherever possible natural boundaries such as waterways and the bases of hills in making the divisions. The districts are indicated on the index map (Fig. 11). Each district represented on the index map has been enlarged and cross sections have been drawn on these individual district maps which help in following the stratigraphic discussion. The cross sections were taken from the contours on the geologic map with a reduction in the horizontal scale to one-third. Vertical exaggeration of approximately five times was considered necessary in order to differentiate the thinner stratigraphic units.

West Seattle District

The West Seattle district includes all of the area west of the Duwamish Valley, from the south city limits north to Elliott Bay (Fig. 12).

Stratigraphically the lowest unit in West Seattle is bedrock of Oligocene age exposed for about five hundred yards along the shoreline and in the old land-tied island at the end of Alki Point. It cannot be ascertained how much of the core of West Seattle is made up of bedrock but the limited exposure around the base indicates that it is a relatively minor part of the hill above sea level.

Above the bedrock the oldest Pleistocene sediments exposed belong to the Duwamish formation. They occur along the eastern margin of the district from the south city limits north nearly to Spokane Street up to 225 feet above sea level, along the western shore from Lincoln Park north to West Genesee Street up to fifty feet above sea level, and in a small area at the northern end in the Fairmount Street gully up to fifty feet above sea level.

The lower part occurs only on the eastern side of the district where it was described as the typical occurrence of the massive clay phase of the Duwamish formation in the previous section. There is little variation in the character and lithology of the lower part of the formation from twenty-five feet to two hundred feet above sea level, this strip

being the only area of exposure of the lower Duwamish formation.

The upper part of the formation, consisting chiefly of peat bearing silts, occurs in each general locality where the Duwamish formation is recognized in the West Seattle district. There is a very marked variation in the Duwamish formation in the West Seattle district from the type locality, particularly in the elevation of the top of the formation. On the east side in the Klinker pits, the peat and silt are about 225 feet above sea level; on the west side along the beach from West Hudson Street to West Genessee Street, the peat and clay member is at sea level; and on the north side at Fairmount Street the peat and silt are about fifty feet above sea level. This suggests warping or tilting after deposition of the Duwamish formation. Tilting of about one degree would account for the elevation differences in the three localities.

In addition to elevation differences, there is some lithologic variation. The Fairmount Street exposure includes a thick bed of peat, silt and some sand and gravel exactly like the type locality at the Klinker pits, but the western beach exposures show relatively pure organic peat and very dense, bleached clay. This suggests the western locality was in the center of a swamp where peat formed in place with little deposition by moving water while the north and east parts were on the periphery of the swamp where peat formed

by accumulation of organic material and silt.

The next higher unit in West Seattle is the Klinker till. It is exposed at several points along the west side of the Duwamish Valley from West Genesee Street south to the city limits, as shown on the geologic map. The only other occurrence of Klinker till identified in West Seattle is in the sea cliff at Lincoln Park. There is little variation in the composition and character of the Klinker till, but the elevation and thickness vary considerably from one exposure to the next. The type locality has a fifteen foot thickness of the till with the base at 225 feet. The thickness in the Abrahamson clay pit to the north is seventy-five feet with the base about 150 feet above sea level while in Lincoln Park the thickness of the till is about twenty-five feet and the base about fifty feet above sea level. The variation in elevation and thickness of Klinker till in West Seattle means little except that some relief was present when the ice depositing that till sheet moved over the district. It is, in other words, not certain whether the tilting mentioned above occurred between the time of deposition of the Duwamish formation and the Klinker till, or after deposition of the Klinker till.

The Lawton formation is the most widespread unit in West Seattle, making up most of the hill, especially in the northern and western parts. Marked variation in the elevation of the base and top of the formation appears to be due

primarily to the fact that the base was deposited on an erosion surface of considerable relief and the top was truncated by another erosion surface of high relief. For engineering purposes, the gradational contact between the lower clay phase and the upper sand phase of the Lawton formation is one of the most important geologic elements in Seattle because it is usually a seep line on steep hill slopes subject to landsliding. This contact varies in West Seattle from 160 feet at the northern end to more than two hundred feet at the southern end. It is not certain whether this variation is due to a change in depositional environment to the south or to later tilting.

The composition of the sand and clay phases of the Lawton formation in West Seattle district is the same as the type section except for an increase in gravel in the upper part of the sand phase. Only 275 feet of sediment are present in the type section of the Lawton formation while at least five hundred feet are found in West Seattle district. The difference is probably due to removal by erosion of the uppermost part of the Lawton formation in the type section.

The next younger unit in West Seattle is Vashon advance gravel, sixty to eighty feet thick, deposited in a channel cut into the sand phase of the Lawton formation (Fig. 13). This gravelly layer, containing material varying in size from large boulders to fine sands, is best exposed in the Klinker pits at elevations from 260 to 340 feet. The



Figure 13. VASHON ADVANCE GRAVEL IN A CHANNEL CUT IN THE LAWTON FORMATION. Line indicates channel boundary. A block of till (T) and a block of clay (C) can be seen in the gravel.

gravel can be traced southward from the city gravel pits at West Findlay Street through the Klinker pits to West Myrtle Street. It is this occurrence that was previously described as the type locality in Seattle of Vashon advance gravel.

The highest unit stratigraphically, and the one generally mantling the upland surfaces is Vashon till. The till sheet is thin and in many cases difficult to recognize in West Seattle, being represented only by somewhat rearranged sand or sandy till already weathered beyond recognition. In many other instances, however, this unit is readily recognized as a strong till sheet.

Beacon Hill District

The Beacon Hill district is bounded on the west by the Duwamish Valley and on the northeast by Rainier Valley. The northern end tapers to a point at the Marine Hospital where it was formerly separated from Capitol Hill by a shallow divide between the two valleys just mentioned. This shallow depression was deepened considerably by the Jackson and Dearborn Street regrades, giving Beacon and Capitol Hills a better defined separation than they had originally. To the south, Beacon Hill is ill-defined on its eastern and southern borders, following approximately Empire Way where it departs from Rainier Valley at the junction with Rainier Avenue (Fig. 14).

Stratigraphically the lowest unit exposed in Beacon

Hill is the bedrock of Oligocene age. It is best exposed along the west edge of the hill in scarps cut by the Duwamish River, where it is present along the valley side for a little more than two miles. The bedrock extends east from these exposures, crossing the hill in a belt running approximately east and west, and crops out again on the shore of Lake Washington, where it is well exposed on the Seward Park peninsula. The bedrock exposures in Beacon Hill constitute nearly the entire exposure of this earlier unit in Seattle.

The next young unit in Beacon Hill is the Beacon till, between fifteen and eighty feet above sea level. The occurrence of this till along the west margin of Beacon Hill south of Spokane Street described in the preceding section is the only known occurrence of Beacon till in Seattle, and represents the oldest Pleistocene deposit in the city.

The unit deposited after the Beacon till was the Duwamish formation, which is widespread over northern and western Beacon Hill district from the bedrock outcrops north to the Marine Hospital. Differences in the characteristics of the Duwamish sediments between the brick pits south of Spokane Street and the Marine Hospital raise an important problem in correlation. At the Marine Hospital, varved clay is present between sixty and two hundred feet elevation overlain by silt and peat, while at the brick pits stratified clay and silt are present up to two hundred feet elevation overlain by a few varves and no silt or peat.

Two possible explanations can account for this rise in the base of the varves to the south: (1) Warping may have taken place after deposition of the varves in horizontal layers. Up-warping of less than a degree to the south would cause the base of the varves to rise from sixty feet elevation to more than two hundred feet elevation between these two sections. (2) Deposition may have taken place under such conditions that massive clay and varved clay were being deposited at the same time in different parts of the same glacial lake. These conditions might be provided by a shallow connecting channel between a body of salt water and the southern end of the lake, so that occasional flooding with salt water would cause immediate flocculation of the clayey particles at the southern end while deposition of varves took place at the northern end. As the lake filled with sediment the conditions of varve deposition would have to have spread to the south in order to correspond to the points along the base of the varves now exposed.

In view of demonstrable warping in the Duwamish formation in other localities the first view is the one favored here; however, sufficient evidence is not available to prove either hypothesis. Figure 15 illustrates diagrammatically the two possibilities.

Any Klinker till that may have been present in the section was eroded away prior to deposition of the Lawton formation, which makes up most of the eastern and southern

sides of Beacon Hill and is present also over the pre-Klinker sediments on the northern and western sides.

Some marked variation from the type section is present in the Lawton formation, especially south of the bedrock on the west side of Beacon Hill. In exposures along the Duwamish Valley side the sand phase can be seen as low as fifty feet above sea level. This sand may represent (1) a lens in the clay phase, or (2) a much later deposit, laid down in a channel cut in clay. Exposures are not adequate to determine which is the correct interpretation, but variation from sand to clay is common elsewhere in the city where it can be clearly seen that these variations are due to differences in conditions of sedimentation.

The highest stratigraphic unit is the Vashon till which almost completely covers Beacon Hill, being generally absent only along the Duwamish Valley side, the northern end, and over part of the bedrock outcrops. Where this till overlies the bedrock, it is markedly different from Vashon till elsewhere in the city, containing large quantities of angular fragments of the bedrock. The till becomes reddish brown in color, reflecting the color of the underlying rocks. Wherever the Vashon till contains a considerable percentage of Tertiary bedrock, it is softer and less cohesive than till containing more clay and silt binding material. It seems likely that such a friable till would permit more meteoric water to pass into the hill than would the more common clayey tills.

Capitol Hill District

The area from the Lake Union-Lake Washington waterway south to Beacon Hill and west from Lake Washington to a north-south line through the center of Lake Union is included in the Capitol Hill district (Fig. 14).

The lowest stratigraphic unit in Capitol Hill is the Duwamish formation which is present as a northward continuation of the varved clay sequence exposed in Beacon Hill. The varves extend from sixty to two hundred feet elevation and are underlain by massive clay in exactly the same manner as they are in Beacon Hill. The Duwamish formation is known to be present only as far north as Fourth and Cherry in the downtown district, and it is probably present at least this far north in the Capitol Hill district. Interpretations based on Bretz' description of the regrade projects (1913) suggests that the Duwamish formation may be continuous under most of the downtown district, and eastward under Capitol Hill. The upper part of the Duwamish formation may be present above the varves, but exposure is lacking due to recent landsliding.

Variations from the type section of the Lawton formation are common in Capitol Hill. The elevation of the contact of the sand phase and the clay phase is again one of the strongest differences; on the east side of Capitol Hill clay is present as high as 275 feet above sea level.

There are two possible explanations for the height of this clay in the Lawton formation: (1) the clay may be a thick lens in a predominance of Lawton sands, or (2) it may be a general rise in the clay phase of the Lawton formation to the east, due to difference in conditions of sedimentation at the time of deposition. The latter possibility, a general rise in the level of the clay phase of the Lawton formation, is assumed to be the truth here because little sand is seen below the clay down to lake level while on the Lake Union side, bedded sands are found at a much lower elevation. This same eastern rise of the clay is seen again in the North Seattle district.

The next younger stratigraphic unit, above the Lawton formation, is Vashon till which is thin on the northern upland of Capitol Hill, but thickens toward the south. It also thickens along the upper eastern and western flanks of the hill and along the base on the west. The trough north of Capitol Hill, which transects at nearly right angles the trend of ice movement, is covered in part by till at least thirty feet thick and perhaps much more, since the thickness only a third of a mile north on the University campus is known to be at least sixty-five feet.

The youngest stratigraphic unit in the Capitol Hill district is alluvium deposited on top of Vashon till. This sediment is present on the Madison Park lowland in the northeastern part of the district. The deposit is generally a few

feet of fine silt and sand which probably washed down in small runoff streams from higher on the main part of Capitol Hill.

Magnolia and Queen Anne Districts

Magnolia and Queen Anne districts can be described together because they are composed of identical stratigraphic units (Figs. 16 & 17).

Stratigraphically the lowest unit in these districts is the Lawton formation, which extends from sea level to about four hundred feet elevation. There is little variation from the type section in either the lithology or the elevation of the sand phase-clay phase contact which is usually close to 160 feet above sea level. However, sands creeping down over the surface give an apparent contact as much as fifty feet too low, especially on the east side of Magnolia district. A few reliable exposures prove that the contact remains at about 160 feet.

The next younger unit in Magnolia and Queen Anne districts is Vashon till, which mantles the uplands and descends down both the north and south flanks, especially in Magnolia district. At the southern end just west of the Navy base the till thickens to about one hundred feet. The till varies from thin unrecognizable deposits to these thick bluffs of solid till.

The youngest unit in both Queen Anne district and

Magnolia district are thin deposits of post-glacial alluvium deposited over Vashon till. The alluvium is for the most part bedded silt and sand which varies up to thirty feet in thickness, particularly low on the northern and eastern slope of Magnolia Hill and the northern slope of Queen Anne Hill.

North Seattle District

The area north of Lake Union and the ship canal from Puget Sound to Lake Washington is included in the North Seattle district (Fig. 18).

The lowest stratigraphic unit seen in North Seattle district is the Lawton formation, which is widely exposed from sea level to 350 feet elevation. On the west side of North Seattle district, there is little variation from the type section of the Lawton formation. The ^{base} elevation of the sand-clay contact is about 150 feet, but on the east side the sand phase-clay phase contact rises as high as 275 feet above sea level in the same manner as it does in the Capitol Hill District.

The upper part of the sand phase along the crest of Phinney Ridge about 350 feet above sea level has a considerable amount of gravel, especially near the contact with the overlying till. Similar increase in gravel in the upper part of the sand phase occurs in the West Seattle district and the Magnolia district at similar elevations, but not as conspicuously as in the North Seattle district.

The next younger unit in the North Seattle district is Vashon advance gravel. In the Sand Point Naval Air Station, gravel pits have been opened up which show a thick sequence of gravels in a channel cut in the Lawton formation. The base of these gravels ranges from lake level or lower to a maximum of thirty-five feet in elevation, and in all cases where its base is exposed, it is underlain by clay. The gravels themselves range from fifty to more than one hundred feet in thickness. They can be seen in spotty exposures for slightly over two miles along the lake shore between Sand Point and Webster Point. So far as it can be determined the gravel is only present along the east margin of the hill, being represented by clay at a comparable elevation only a short distance to the west.

The gravel is very little different from the section of Vashon advance gravel in West Seattle. However, the elevation of the base of the West Seattle gravel is about 250 feet above sea level. The difference indicates that the ice-marginal streams that deposited the gravels were flowing at different elevations, and were probably held at these levels by ice contact with the hill at these elevations.

Vashon till deposition followed immediately after deposition of the advance outwash gravel. The till in North Seattle district varies from a few feet of nearly unrecognizable till to till as thick as 125 feet. North Seattle is more completely mantled with thick till than any other part

of the city, especially down the gradual southern slope in
Ballard to the ship canal.

ORIGIN OF PRESENT LANDSCAPE FEATURES

General Statement

The hills and lowlands of Seattle, like those in all of the Puget Lowland north of Olympia, owe their overall shape to modelling effects of the Vashon ice as it advanced southward from its source area in the mountains of Canada. The most important condition affecting the shape of the present surface was the topography immediately prior to the advance of the last glacier. A fact that is strikingly illustrated in this area is that continental glaciers, as they move over a hill and valley topography, do not bevel off the high spots and fill the lowlands with debris. Usually these huge ice masses do just the opposite, plastering till on the upland surfaces while they are deepening the valleys.

As the Vashon glacier advanced down the lowlands between the Cascade and Olympic Mountains it was able to modify to the greatest extent the stream valleys and hills that were nearest to being in sympathy with this overall southerly direction of movement. This explains why the rounded hills and lowlands are mainly parallel to the trend of the Puget Lowland. In many gullies, narrow steep sided valleys do not

agree with the general north-south trend, but these have been cut since the last ice left the area.

Shape of Hills

The term drumloid has been used repeatedly in discussing the Seattle hills, signifying that the hill has an elongate streamlined form due to ice modelling. Unlike drumlins, which are composed entirely of glacial till, drumloids have cores of other material. In Seattle the cores are primarily pre-Vashon Pleistocene sediments, except in the southern part of the city, where cores of Tertiary bedrock are encountered.

After the retreat of the ice, the east-west cross-sectional outline of the hills was nearly a symmetrical curve, but wave cutting and river corrasion have sharpened up the eastern and western flanks of some of these hills and destroyed the smoothness of the curve. Hills adjacent to Puget Sound and the Duwamish River show such steepening; Phinney Ridge in North Seattle is an excellent example of an unmodified hill. In north-south cross-sectional outline, the drumloids were asymmetric curves with steep north-facing slopes and gentler south facing slopes after glaciation, and in general retain their original shape.

The Seattle hills also show a general similarity in variations in thickness of the Vashon till. Figure 19, by exaggerating the thickness of the till in relation to the

height of the hills shows the normal locations of thickest and thinnest till deposition. Upland surfaces and especially the gradual southern slopes are generally covered by the thickest till deposits. Eastern and western flanks have little or no till, especially along the steeper portions of the slopes. Similarly, the steep northern slopes, which faced the advancing ice, carry little or no till. In some cases the lack of till on the steeper hillsides is the result of removal by later landsliding and stream gullying.

The strongest erosion agent active on the hills in Seattle is wave cutting. The sea cliff along Admiralty Inlet is an example of steepening as a result of wave action, and the steepened lower portion of slopes facing Lake Washington are doubtless formed in the same way. On these slopes the till may have been present after ice retreat, but was removed by wave cutting and associated landsliding.

The drumloidal hills are modified in outline by both pre-Vashon and post-Vashon stream gullies. Pre-Vashon stream channels that have not again been occupied by streams are gently rounded, elongate depressions in the hills, usually showing a north-south alignment. Post-Vashon stream channels are sharply incised features, showing little or no relationship between their location and the trend of the drumloidal hills, except where they occur in the bottoms of the ice-modified pre-Vashon channels.

Examples of both pre-Vashon and post-Vashon stream

channels are common in Seattle. The broad, round-bottomed groove in West Seattle district that separates the district into two hills at the northern end is a good example of a north-south trending, pre-Vashon stream channel that is at present occupied by a later stream. This post-glacial stream has cut a sharp gully through glacial till as it follows the course of the ancient valley. The Ravenna gully in the North Seattle district is a good example of a post glacial stream that shows little parallelism to the trend of the hills. The stream that cut the gully formerly drained Green Lake before artificial drainage was substituted.

Special Features

Green Lake

Green Lake, located in the central portion of the North Seattle district, is in a shallow depression underlain around all the margin and presumably floored by Vashon till. Water collected in an ice erosion depression, filling it until a drainage outlet was found to Lake Washington. The relatively impervious till provided an original water-tight lake bottom.

Terraces

Between one hundred and 150 feet elevation, a well formed terrace is present in many parts of Seattle, especially on the steeper hill slopes. A conspicuous example of

the terrace is seen along the edge of West Seattle from half a mile southeast of Duwamish Head around the end of the point at the northern end of the hill and extending with only minor interruptions as far as Schmitz Park east of Alki Point. This terrace (and others) have formerly been described as old shore-line features, representing elevations of sea level higher than at present (Bretz (1913), Diller (1915), Fennemann (1931)). No evidence was found in the course of this study to support this view.

The best explanation for these terraces which can be offered is that they were formed because of the difference in resistance of the sand and clay of the Lawton formation to erosion. Usually, the surface of the terrace is not a smooth surface cut in the Pleistocene material, but is, instead, a series of small, jumbled slide blocks of sand, as shown in Figure 20. The sand represents a part of the Lawton sand from higher up on the hill which has crept, washed, and slid to its present location on the terrace. The terrace does not disappear with the retreat of the bluff, but remains in existence even after the face of the sea cliff has retreated a distance greater than the width of the terrace. The terrace is due primarily to the fact that the clay phase of the Lawton unit is more resistant to erosion than the overlying sand phase. The development is mainly due to the movement of ground water through the sands and out of the hill at the zone of change from clay to sand. The elevation

of the terrace is less than the elevation of the top of the clay phase, due to some erosion of the top of the clay phase by the sand and water moving down over its surface.

Raised Beaches

Raised beaches are present in at least three localities in Seattle along Admiralty Inlet. These localities include Alki Point, Brace Point and West Point. Of these, Alki Point is the best example.

Alki Point is a conspicuous feature because Oligocene rocks form an ancient land-tied island at the end of the point. This bedrock mass was connected to the mainland by a sand bar (tombolo) on the south side sometime after the Vashon retreat, but relative lowering of sea level since that time has left the Oligocene rocks as a prominence at the end of a low point which is made up of a surficial covering of beach sand over older material. There is on the north side, as a less conspicuous feature, a double tombolo, with black soil of old lagoonal muds between the two segments.

These raised beaches do not necessarily mean that a general lowering of sea level has occurred. It is Mackin's view that very gentle warping down to the south has occurred with the Seattle area only a short distance north of the axis. The evidence is the increasing elevation of raised beaches north of Seattle and increasing extent of drowning in valleys south of Seattle along the east side of Puget

Sound.*

Duwamish River Valley

The Duwamish River flows northward in a wide valley between West Seattle and Beacon Hill, emptying into Puget Sound in the southern part of Elliott Bay.

Vashon till is present low on the valley sides, and on three small knobs on the west side of the valley in South Park, indicating that a lowland was present in the position of the Duwamish Valley at the time of the advance of the Vashon ice.

The Vashon glacier undoubtedly smoothed out the sides of the valley and generally remodelled it as the ice moved southward, leaving a typical round-bottomed, smooth-sided lowland after retreat.

The depth of the lowland that was left after retreat of the Vashon ice is not definitely known, but old well records show that a deep fill is present in the valley. Most of the fill is probably due to the outbuilding of a delta into Puget Sound by the Duwamish, but the upper part of the fill is composed of floodplain silts.

The Duwamish River is in a mature stage of development, swinging back and forth on the valley floor without deepening its channel. When the river swings along the side of the valley it undercuts the banks with a resultant steep-

*Personal communication by Dr. J. Hoover Mackin.

ening of the valley sides. Where the river has cut against the Oligocene bedrock the valley sides are steep, but where the river has cut against the unconsolidated Pleistocene deposits, valley sides are not steep, due to subsequent landslides and erosion by small streams. This action has resulted in deposition of alluvial fans out into the main valley.

SUMMARY OF PLEISTOCENE HISTORY

The following is a point summary of the part of the Pleistocene history for which there is evidence in Seattle.

1. Continental glaciation, indicated by deposition of the Beacon till.

2. (a) Glacial retreat, deposition of the lower part of the Duwamish formation in glacial lakes. Lakes finally filled or drained and covered by floodplain material.

(b) Deposition of the upper part of the Duwamish formation during an interglacial period on a nearly level plane. Widespread peat formation in swamps between streams.

3. Warping (?), and development of erosional relief in the Duwamish formation and earlier units.

4. Continental glaciation, indicated by deposition of the Klinker till.

5. Glacial retreat, minor deposition of clay over the Klinker till.

6. Erosional removal of much of the Klinker till and associated clay.

7. Deposition of Lawton formation, probably during a period of glaciation, but with no direct evidence of ice in Seattle area.

(a) Deposition of lower part of clay phase under alternating conditions of quiet and running water.

(b) Deposition of upper part of clay phase under stable, quiet water conditions.

(c) Deposition of sand phase. Filling or draining of lakes, aggradation by streams on widespread plain.

8. Warping (?), erosion, development of at least five hundred feet of relief in Lawton formation and older units.

9. Advance of the Vashon glacier, with deposition of bedded gravel and sand in channels cut into the Lawton formation.

10. Modelling of Seattle hill and valley topography under Vashon ice, and deposition of Vashon till.

11. Glacial retreat, very little deposition of retreatal sediments in the Seattle area.

12. Moderate post-glacial erosion. Slight regional tilting forming raised beaches.

APPENDIX I - DESCRIPTION OF CRITICAL SECTIONS

Locations of the Seattle sections are indicated on the index map (Fig. 11).

Section at Klinker Sand and Gravel Company, West Seattle

The following section was taken from the Klinker Sand and Gravel Company yard above West Marginal Way at West Morgan Street in West Seattle. The section clearly shows the relationship of Klinker till to the underlying and overlying units and is taken as the type section of Klinker till (Fig. 21).

	<u>Thickness</u>	<u>Description</u>
Vashon till	15 - 20'	Light brown, sandy till. Weathered, weak.
Vashon advance gravel	70'	Light gray to light brown sand and gravel. Horizontally bedded and cross bedded. Contains clay and till boulders.
Klinker till	12 - 15'	Light gray clayey till. Kneaded, hard and resistant.
Duwamish formation	12'	Light to dark brown, fibrous and silty peat. Hard, highly compressed.
	10'	Light gray silt and fine sand. Vague bedding. Crumpled and deformed.

	<u>Thickness</u>	<u>Description</u>
Duwamish formation	175'	Bluish gray clay. Massive or thick bedded. Hard and cohesive. Contains some concretions.

The lowest elevation at which good exposures can be seen in this section is about twenty-five feet above sea level in Duwamish clay. At various horizons in the first fifty feet of Duwamish clay, concretions occur along obscure bedding planes, varying in size from half an inch up to several inches in length.

At the contact between the fine sand and the Klinker till there is evidence of crumpling and thrusting by the ice as it rode over the Duwamish formation.

The twelve foot peat bed lies fifty yards north of the main line of this section but appears to be in nearly the same stratigraphic position as the fine sand directly beneath the Klinker till. At its base, this peat is very woody, being composed mostly of carbonized branches and twigs that have been flattened due to overlying pressure. Above this completely organic, one-foot layer, there are eleven feet of highly organic, waterlaid silts, with some medium sized rounded pebbles scattered sparsely throughout.

The Vashon advance gravels are deposited in channels cut into the sand phase of the Lawton formation. The edge of the channel is not visible in the main line of section but can be seen about four hundred yards to the north in similar gravel pits.

Marine Hospital Section, North End of Beacon Hill

The following section, measured in the slide area at the north end of Beacon Hill above Dearborn Street, is in the best exposures of varved clay in Seattle (Fig. 22).

	<u>Thickness</u>	<u>Description</u>
Vashon till	5 - 10'	Gray to brown till. Sandy, weathered, spotty occurrence.
Lawton formation	50 - 60'	Light brown sand. Horizontally bedded and cross bedded. Contains a little gravel.
Duwamish formation	5'	Gray clay and brownish silt. Thin bedded.
	5 - 6'	Light to dark brown peat. Fibrous and woody. Some silt in middle and upper parts. Hard and resistant.
	5 - 6'	Reddish brown sandy gravel. Bedding poor or absent. Compressed and till-like.
	30'	Light gray silt. Thin bedded, ripple marked. Contains a few layers of coarser material.
Duwamish formation	110'	Light and dark gray varved clay. Irregular thickness of varves. Contains some sand in summer layers.

The lowest elevation exposed in the Marine Hospital section is ninety feet above sea level. However, at sixty feet above sea level clays have been reported to underlie wide, indefinite sandy varves which are the base of the varve sequence.

The varves between ninety and two hundred feet vary

in thickness between one inch and several inches. The thickness variation follows a rough cyclic trend with sets of seven to fifteen thin varves overlain by sets of seven to fifteen varves as much as three times as thick. There is, however, an overall thinning of the varves from the base to the top of the section. At the top of the sequence the last few varves change without gradation to silty varves as much as three feet thick.

The upper part of the fine sediments overlying the varves display good oscillation ripple marks, indicating deposition in shallow water.

The layer of peat above the fine sediments is much harder than the material above or below it so that as it weathers out of the hill it forms a ridge before breaking off in large chunks.

Above the peat a few feet of clay and fine sand are present which probably were laid down in the same sedimentary cycle in which the peat accumulated. The varved clays, silts, gravel, peat and overlying clay are all tentatively assigned to the Duwamish formation.

An unconformity has been inferred to be present above the Duwamish formation, but exposure is lacking, preventing substantiation of the inference. Above the covered portion of the section sands and some gravel of Lawton age are present, overlain by spotty occurrences of sandy Vashon till.

Section at Clay Pit South of Spokane Street, Beacon Hill

The following section, measured in the clay pit one-fourth mile south of Spokane Street, on the west side of Beacon Hill includes the only known exposure of Beacon till in the city, and is the type section of Beacon till (Fig. 23).

	<u>Thickness</u>	<u>Description</u>
Vashon till	10 - 15'	Light brown to light gray sandy till. Moderately weathered.
Lawton formation	20 - 25'	Light brown sand. Horizontally bedded and cross bedded. Contains some pea gravel.
Duwamish formation	10'	Light and dark gray silty varved clay. Indistinct, irregular varves, 4 - 5 inches thick.
	30'	Dark gray clay. Massive and thick bedded.
	10 - 15'	Gray to brown gravelly sand. Very permeable.
	40'	Dark gray clay. Massive and thick bedded. Includes some laminated clay.
Duwamish formation	60'	Light gray to dark gray stratified clay and silt.
Beacon till	60 - 80'	Light gray clayey till. Contains very few pebbles and cobbles. Compact and strong.

Beacon till is present from the base of the exposure to an elevation of approximately eighty feet. The top of the till is a slightly irregular, undulating surface.

The stratification of the overlying silts and clays

show variation in thickness over the irregular till surface, but become constant within a vertical range of five to ten feet.

The Duwamish formation is composed of stratified clay and silt to an elevation of a little more than two hundred feet. Included are massive clay, bedded clay and silt, and a minor amount of varved clay at the top of the formation. An interfingering lens of sand and gravel is present at the southern edge of the exposure at an elevation of about 170 feet.

The Lawton sand is separated from the Duwamish formation by an undulating erosion surface developed on the Duwamish clay.

Weathered Vashon till caps the exposure, varying from five to fifteen feet in thickness.

Section at Fort Lawton, Magnolia District

The following section, measured in the sea cliff south of West Point, is the best exposure of the Lawton unit in the city, and is taken as the type section (Fig. 24).

<u>Top of Bluff</u>	<u>Feet</u>	<u>Description</u>
Sand phase	90'	Yellowish to brownish, sand. Horizontally bedded and cross bedded. Contains minor layers of fine silt, and a little gravel.
Transition	10 - 20'	Light gray, fine silt. Thin-bedded, current ripple marked. Gradation between sand and clay.
Clay phase	40'	Light to dark gray clay, massive to thick bedded.
	35 - 40'	Light and dark gray clay. Thin, laminated bedding. Irregular thickness of laminations.
	10'	Light and dark gray clay. Alternate layers of thick beds (one foot) and thin beds (2 - 3 inches).
	8'	Interbedded layers of gray clay and light gray to light brown sand. Clay makes stringers from 3 - 10 inches thick in sand.
	8'	Light gray to light brown, silty sand. Hard and resistant.
	3'	Light gray, silty clay. Has an undulating, scoured top surface.
	10'	Light brown, medium grained sand, containing a few pebbles. Horizontally bedded and cross bedded.
	4'	Light gray to light brown, silty clay. Hard and resistant.

<u>Feet</u>	<u>Description</u>
12'	Light brown to reddish brown fine and coarse sand, containing a few pebbles. Loose and friable.
12 - 20'	Gray clay and light brown silts, interbedded. Silt is in fine stringers, from one to several inches thick.

Sand layers in the lower sixty-five feet of the section are reddish brown due to oxidation by movement of ground water. The clay interbeds are gray, although they are red-stained in some exposures by wash from the sandy beds.

Many contacts between the interbedded clay and sand in this lower sixty-five feet give evidence of scouring of the clay at the time the sand was deposited. However, the continuity of the clay members suggests that there was not much erosion on the top of the clays.

The clay between seventy-five feet and 115 feet above sea level is laminated, and from a distance the laminations might be mistaken for varves. But close inspection indicates that they represent only irregular variations in grain size, without the clearly marked silt-clay couples that would identify yearly cycles.

The transitional silt between the clay phase and the sand phase of the Lawton formation makes up a very weak portion of the sea cliff that undergoes continual slumping.

The beds below sixty-five feet are horizontal in the northern end of the exposure, but have a dip to the south of

three to four degrees along the southern part of the cliff face. The change in attitude is abrupt, from flat-lying to three or four degrees of dip within a horizontal distance of twenty-five feet (Fig. 25).



Figure 25. LOCAL DIP IN CLAY PHASE OF LAWTON FORMATION IN TYPE SECTION AT FORT LAWTON. Photograph taken looking north.

Section at Possession Point, Whidby Island

The description of the Possession Point section was taken from Mackin (1949) with slight modification (Fig. 26).

	<u>Thickness</u>	<u>Description</u>
Vashon till	30 - 40'	Light brown to gray till.
Lawton formation	90 - 100'	Brown sand and silt, gray clay, interbedded.
"Mid-cliff" (Klinker) till	50 - 60'	Gray clayey till. Hard and resistant.
Duwamish formation	5'	Dark brown peat. Massive and compact.
	15'	Gray, somewhat greenish sandy clay. Contains sand and gravel in lower part.
	1 - 2'	Dark gray to dark brown peat. Hard and compact.
	5 - 10'	Gray silt and clay, bedded.
	1 - 2'	Dark gray to dark brown peat. Hard and compact.
	5 - 10'	Gray silt and clay, bedded.
	1 - 2'	Dark gray to dark brown peat. Hard and compact.
	30'	Light gray silts, brown sand and gravel, interbedded. Horizontally bedded and cross bedded sand.
	4"	Dark gray to dark brown, silty, clayey peat.
Duwamish formation	50'	Gray silt, brown sand and gravel. Stratified, cross bedded.
"Sealevel" (Beacon) till	0 - 10'	Light gray till. Dense and hard.

This section is included because three tills are seen in one continuous section and their relationship to the peat bearing strata is clear. The three tills at Possession Point have been tentatively correlated to the three tills found in Seattle, and the peat bearing formation between the two older tills has been tentatively correlated to the peat bearing Duwamish formation in Seattle.

The till sheet at sea level is overlain by poorly sorted sand and gravel with ice-shove and slump structures. These outwash materials grade upward into dark gray and brown peat-bearing silty clays with lenses of stained gravels.

Some bleached clays are related to each peat deposit indicating reaction with organic acids at the time of deposition of the clay in peaty swamps.

The peat bearing strata are overlain by the "Mid-cliff" till which lies on an undulating, ice-scoured contact.

Section in Sea Cliff Between Des Moines and
Saltwater State Park

This section is in the sea cliff between the town of Des Moines and Saltwater State Park, about fifteen miles south of Seattle. It is included because it shows clearly the relation of Klinker till to the underlying, peat-bearing Duwamish formation and the overlying Lawton formation (Fig. 27).

A sandy, silty, strongly compacted layer with a peculiar bluish-green color when freshly broken is at the base of the Des Moines section. It is overlain by about twenty feet of clay with several interbedded layers of peat. The clay is blue-gray except where, immediately beneath peat, it shows effect of bleaching to a near-white by action of organic acids. The woody peat is so hard and compressed that it is nearly lignitic in character, and stands out as ledges where erosion has removed the weaker underlying and overlying material.

Overlying the top peat bed are thirty to forty feet of interbedded fine sand and clay. Each layer is at least five feet in thickness, but there is considerable variation in each of these beds. These sediments and all the underlying sediments down to the base of the exposure are included in the Duwamish formation.

The Duwamish formation is overlain by a lens of clayey Klinker till at least twenty feet thick. The till is overlain

in turn by a few feet of bedded clay deposited directly on the till during retreat with no intervening coarser material.

The Duwamish formation, Klinker till, and overlying clay are beveled by an erosion surface marked by a fifteen to twenty foot layer of gravelly sand. This gravelly sand is assumed to be the base of the Lawton formation. Approximately one hundred feet of sand, with some beds of silt and clay, above the gravels, make up the rest of the Lawton formation.

In some places, Vashon till up to twenty feet thick makes up the lip of the bluff.

All the sedimentary beds, including those of the Lawton unit, show a southerly component of dip of about one degree.

APPENDIX II - TENTATIVE REGIONAL CORRELATION

The four Seattle sections described in Appendix I, when combined into a composite section, suggest a probable correlation to the Possession Point section to the north and the Des Moines section to the south. Figure 28 illustrates the tentative correlation.

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