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LATE PLEISTOCENE DEGLACIATION HISTORY
AT POINT PARTRDIGE, CENTRAL WHIDBEY ISLAND, WASHINGTON

by Cynthia A. Carlstad

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

[redacted]

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LATE PLEISTOCENE DEGLACIATION HISTORY AT POINT PARTRIDGE, CENTRAL WHIDBEY ISLAND, WASHINGTON

A Thesis
Presented to the Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

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by
Cynthia A. Carlstad
June 1992

ABSTRACT

The study area contains a record of deglaciation events that has not been recognized elsewhere in the Puget Lowland. This record includes both subaerial outwash and glaciomarine deposition. The geologic history of the study area during recession of the Vashon ice sheet is marked by the following events:

(1) deposition of a kame delta complex from grounded ice probably located in Penn Cove and west of Point Partridge. This delta complex was built into marine water with a sea-level at approximately 55 meters. Eventually, ice drained by the outwash streams stagnated in the Point Partridge kettle region.

(2) Isostatic rebound of the depressed land surface caused relative sea-level to drop as the ice continued to become thinner.

(3) Deposition of sand and gravel from outwash streams ceased as the ice continued to thin and eventually floated, depositing glaciomarine drift below approximately 37 meters. Narrow marine terraces were carved into Vashon till and Partridge outwash around the perimeter of Penn Cove.

In addition to these events, the relationship between the Partridge outwash and Everson glaciomarine drift is described. Partridge outwash is an Everson Interstade unit, deposited by meltwater streams in a marine environment.

ACKNOWLEDGMENTS

First and foremost, I want to thank Don Easterbrook, chair of my advisory committee. Through the years that I have known Don, his friendship, wisdom and encouragement have greatly impacted the choices I have made in my life. Chris Suczek and Derek Booth, my other advisors, also deserve special thanks for their valuable guidance and suggestions regarding this project. Chris's encouragement and general positive attitude have helped keep me moving. Derek agreed to join my advisory committee after the project was underway, and his enthusiasm and perspective shaped this thesis in many ways. One of the greatest side-benefits for me in writing this thesis was becoming better acquainted with all of you.

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My employer, ENSR Consulting and Engineering, has been supportive of me in this academic endeavor. Many thanks also to my colleagues at ENSR who have individually offered encouragement and worked around my school schedule during the last several months.

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Last but not least, my gratitude goes out to my husband Bret, who, over the course of this project, has truly demonstrated the power of a life-partner.

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1.0 INTRODUCTION

The Cordilleran Ice Sheet, originating in British Columbia, expanded into the Puget Lowland at least six times between about 2 million and 11,000 years ago. The geologic history of the study region (Fig. 1-1) is a significant chapter in the story of deglaciation from the most recent glacial episode, the Vashon Stade of the Fraser Glaciation.

1.1 Pleistocene History of the Puget Lowland

Investigation of the ice-age landscape of the Puget Lowland was initiated by Willis (1898). Willis recognized two glaciations in the Puget Lowland, which he named the Vashon and Admiralty, separated by the Puyallup Interglaciation. Bretz (1913) assigned additional pre-Vashon glacial sediments to the Admiralty Glaciation. Hansen and Mackin (1949) were the first to document more than one pre-Vashon glaciation. They identified two tills, separated by interglacial sediments, beneath the Vashon till north of Seattle. Evidence for four glaciations in the southern Puget Lowland was documented by Crandell and others (1958), and recognition of some of the stratigraphic units was extended throughout the southern and central Puget Lowland. This framework was later redefined and expanded by Armstrong and others (1965) and Easterbrook and others (1967) and served as the basis for interpretation of Pleistocene stratigraphy and chronology in the Puget Lowland until 1981.

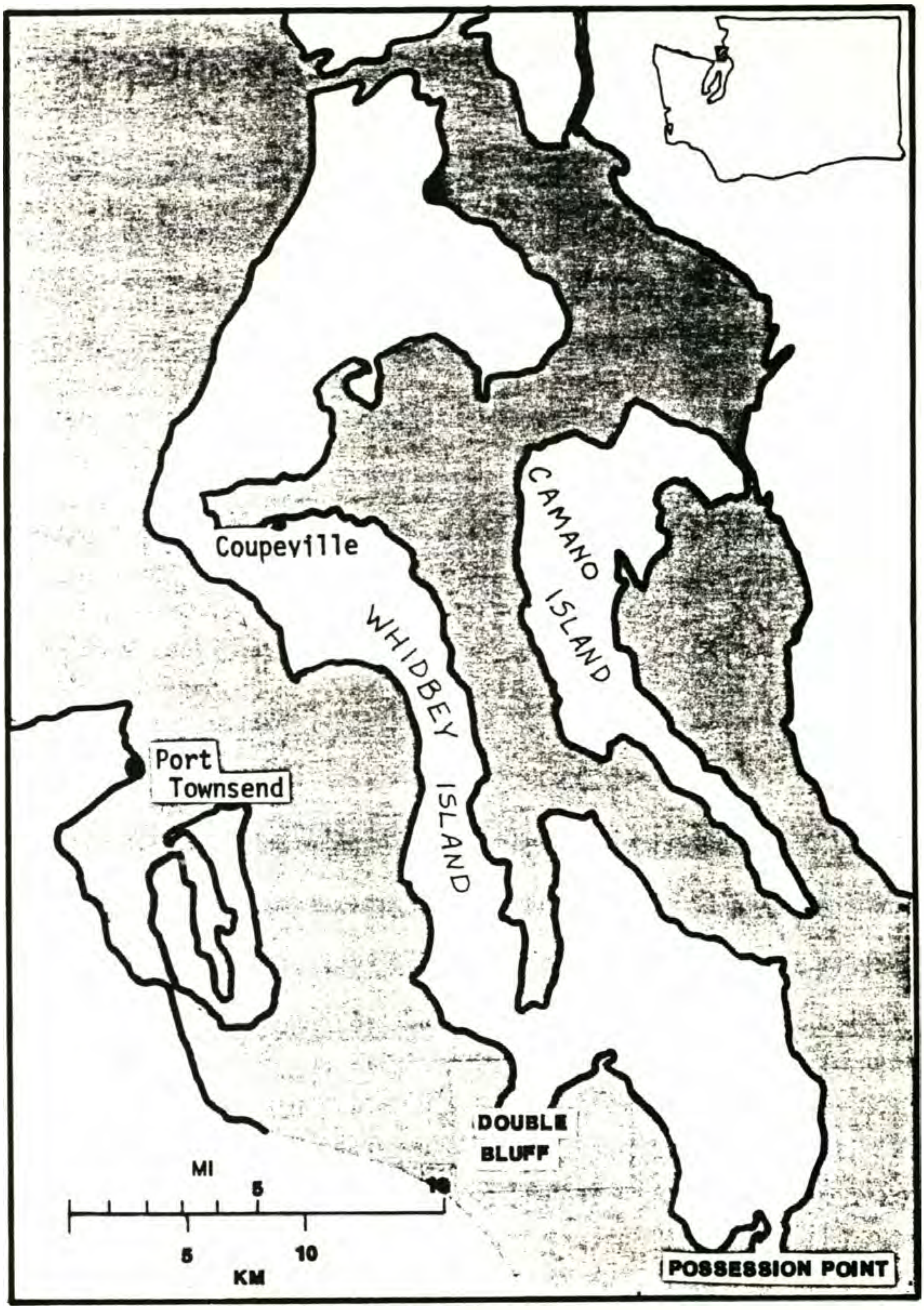

FIGURE 1-1 LOCATION MAP FOR STUDY AREA

Prior to 1981, units beyond the range of radiocarbon dating were correlated throughout the region on the basis of relative stratigraphic position and comparison with known units. A radiocarbon date of 71,500 years b.p. from the type locality of the Salmon Springs Drift in the southern Puget Lowland (Stuiver and others, 1978) supported correlations with second-from-the-top glacial units throughout the Puget Lowland. In 1981 the bottom dropped out of the Pleistocene chronology in the Puget Lowland when Easterbrook and others (1981), with supporting evidence from Othberg (1973), Easterbrook and Othberg (1976), and Easterbrook and Briggs (1979), demonstrated that the Salmon Springs Drift was actually older than 850,000 years. The revision of the Pleistocene chronology necessitated by the older age of Salmon Springs Drift calls for at least six glaciations in the Puget Lowland. Table 1-1 shows the Pleistocene chronology as it is known today.

Correlation and chronology of pre-Vashon/post-Salmon Springs units in the central Puget Lowland have been further quantified by Easterbrook (1986), Easterbrook and others (1988; in press), and by Blunt and others (1987). Thermoluminescence dates on Double Bluff Drift and sediments immediately below have yielded dates between 176 ± 38 ka and 280 ± 81 ka (Easterbrook and others, 1988). Thermoluminescence dates of 96 ± 37 to 150 ± 44 ka were measured for Whidbey Formation sediments (Easterbrook and others, 1988). Previous age estimates, based on amino acid racemization and radiocarbon dating, have been determined for the Double Bluff Drift (approximately 100 to 250,000 years b.p.), Whidbey Formation (approximately 90 to 100,000 years b.p.), and Possession Drift (approximately 70 to 90,000 years b.p. for an early phase and 35 to 50,000 years b.p. for a late phase) (Blunt and others, 1987).

TABLE 1-1

Pleistocene Chronology of the Puget Lowland (after Blunt and others, 1987)

Southern Puget Lowland	Central and Northern Puget Lowland	Years B.P.
Fraser Drift	Fraser Drift	
Vashon Drift	Sumas Drift	10,000
Vashon Recessional Deposits	Everson Glaciomarine Drift	11,000
Vashon Till	Vashon Drift	13,600
Esperance Sand	Vashon Till	
Lawton Clay	Esperance Sand	
	Lawton Clay	
Sediments of Olympia Nonglacial Interval	Sediments of Nonglacial Olympia Interval	20,000
	Possession Drift	28,000 35,000
	Whidbey Formation (Interglacial)	70-90,000 100-150,000
	Double Bluff Drift	175,000
		250,000
Salmon Springs Drift	Not recognized, may be below sea level	850,000
Upper Salmon Springs gravel and till		
Silt, peat, and ash		1,000,000
Lower Salmon Springs gravel and till		
Puyallup Formation (Interglacial)		
Stuck Drift		
Alderton Formation (Interglacial)		1,600,000 2,000,000(?)
Orting Drift		

Since 1981, Roland (1984), Easterbrook (1986), Easterbrook and others (1988; in press) have confirmed that sediments below the Salmon Springs Drift are at least one million years old. Recent argon laser dates on these units in the southern Puget Lowland suggest ages of 1.6 m.y. on the late Alderton Interglaciation. This revised chronology has left a gap in the Pleistocene record between about 250,000 and 1 m.y.

The last of the glacial episodes in the Puget Lowland is known as the Fraser Glaciation. It has been subdivided into four stades during which the following units were deposited (Armstrong and others, 1965): (1) Evans Creek Drift, deposited during an early alpine phase, and Coquitlam Drift in southern British Columbia, deposited from the Cordilleran Ice Sheet; (2) Vashon Drift, deposited during the advance and retreat of the Cordilleran Ice Sheet; (3) Everson glaciomarine drift, deposited from floating ice during deglaciation of the lowland; and (4) Sumas Drift, deposited during a short readvance of the ice before complete deglaciation.

Vashon Drift, deposited during the Vashon Stade of the Fraser Glaciation, is divided into the following three members: (1) the Esperance Sand Member in the Puget Lowland and Quadra Sand in southern British Columbia, both deposited by meltwater streams from the advancing Cordilleran Ice Sheet (Newcomb, 1952; Armstrong and others, 1965; Mullineaux and others, 1965; Clague, 1976, 1977; Easterbrook, 1969); (2) Vashon till (Willis, 1898; Bretz, 1913; Crandell and others, 1958; Sceva, 1957; Armstrong and others, 1965), which overlies the Esperance and Quadra units; and (3) recessional outwash sand and gravel and ice-contact deposits (Newcomb, 1952; Sceva, 1957; Crandell and others, 1958; Crandell, 1963; Armstrong and others, 1965).

The chronology of Vashon sediments in the Puget Lowland is well established with many radiocarbon dates. The Cordilleran Ice Sheet advanced southward across the international boundary shortly after 18,000 years ago and split into two lobes. One lobe flowed westward out the Strait of Juan de Fuca (the Juan de Fuca lobe) and the other lobe flowed southward into the Puget Lowland (the Puget lobe). The Juan de Fuca lobe retreated from the western part of the strait before 14,500 years ago (Heusser, 1973a), and the Puget lobe retreated from its terminus near Olympia to the vicinity of Seattle by about 14,000 years ago (Rigg and Gould, 1957; Porter and Carson, 1971; Easterbrook and others, 1988; in press).

The early recession of the Puget lobe of the Cordilleran Ice Sheet was dominated by proglacial outwash and lacustrine processes. During the time that ice occupied the Puget Lowland and Strait of Juan de Fuca, marine water was blocked from entering Puget Sound. As the ice sheet began to recede from its maximum near Olympia, freshwater lakes were impounded in front of the receding ice sheet in the southern and central Puget Lowland (Bretz, 1913). Thorson (1980) presented the following regional chronology of these lakes. Initially, drainage for the Puget Lowland was south through the Black Lake spillway and out to the Pacific Ocean through the present-day Chehalis River drainage. Configuration of the proglacial lakes changed several times as melting of the ice sheet exposed new controlling outlets. Eventually an outlet to the north opened up through the Leland Creek spillway between Quilcine Bay and Discovery Bay and lake drainage flowed north to the Strait of Juan de Fuca.

The Cordilleran Ice Sheet backwasted and thinned until a time when the ice was thin enough to allow marine water to enter the Puget Lowland through the Strait of Juan de Fuca (Blunt and others, 1987). At that point, the ice apparently floated on sea water, marking the beginning of the Everson Interstade. The dominant deposit associated with this stage of deglaciation is Everson glaciomarine drift, a diamicton that resembles the till laid down by the Vashon glacier except that it often contains in-situ shells and dropstones, is less compact, and has a random fabric (Easterbrook, 1963). Everson glaciomarine drift has been identified over an area of approximately 18,000 square kilometers in the northern and central Puget Lowland (Blunt and others, 1987; Armstrong and Brown, 1954).

Armstrong and Brown (1954) and Easterbrook (1963, 1969) put forth the theory that the glaciomarine drift was deposited primarily from berg ice almost simultaneously over its geographical extent. Pessl and others (1981) and Domack (1983) proposed the contrasting view that the glaciomarine drift was deposited in front of a calving, northward-retreating terminus and is therefore time-transgressive. More than 80 radiocarbon dates have been obtained from shells and wood in the glaciomarine drift throughout the central and northern Puget Lowland. Ages range from 11,500 to 13,600 years b.p. and show no trend toward younger dates in the north than in the south (Blunt and others, 1987; Easterbrook and others, in press). These data suggest that this unit is not time transgressive, but rather that it was deposited almost simultaneously over a large region of northwestern Washington and southwestern British Columbia (Blunt and others, 1987; Easterbrook, 1991; Easterbrook and others, in press).

Fluctuations in relative sea-level dominated the remainder of the recession of the Fraser ice sheet. Three factors simultaneously affected relative sea-level while the Cordilleran Ice Sheet ablated northward. Melting of ice sheets worldwide transferred a great volume of water to oceans, causing a eustatic rise in sea-level. Eustatic sea-level lay approximately 60 to 70 meters below present sea-level 13,000 years ago (Macintyre and others, 1978). Isostatic rebound, which occurred after the weight of the ice sheet was removed from the depressed land surface, caused relative sea-level in the Puget Lowland to drop. Isostatic rebound brought relative sea-level down to below its present level by about 8,000 years ago in most of the Fraser Lowland (Mathews and others, 1970). These two opposing factors would potentially have been superimposed on any tectonic fluctuations in the northern Puget Lowland (Easterbrook, 1963; Easterbrook and others, in press). Holocene tectonism is currently the topic of much research (Gower and others, 1985; Atwater, 1987; Heaton and Hartzell, 1987), and researchers such as Thorson (1989) have suggested that tectonic movements have complicated the late Pleistocene/early Holocene sea-level record to a significant degree.

1.2 Statement of Problem

The study area on central Whidbey Island (Fig. 1-2 and 1-3) contains an extremely important and probably unique record of events that occurred in the Puget Lowland in the realm of ice-recessional history. North of this region, glaciomarine drift is commonly found overlying Vashon till (indicating that region was below sea-level in late Fraser times). South of this area, glacial till of the Vashon ice sheet is often covered with meltwater deposits (outwash, lacustrine, and deltaic deposits). The study area is the only

Figure 1-2 Location map of study area showing localities identified in text

Figure 1-3 Site map, at 1:62,500 scale, showi
landforms described in text.

place in the Puget Lowland that appears to preserve continental deposits (outwash sand and gravel) sandwiched between Vashon till and Everson glaciomarine drift. The implication of this relationship is that this is an area which experienced the following sequence: (1) ice sheet glaciation; (2) subaerial meltwater deposition; (3) submergence by marine water (while ice was still in the area depositing Everson glaciomarine drift); and finally (4) total emergence following ice sheet recession. The focus for this investigation is unraveling the history of the geologic processes surrounding deposition of these units (Partridge outwash and Everson glaciomarine drift).

Two prominent terraces occur at the 60-meter level (high terraces) southeast of Point Partridge on the west coast of Whidbey Island and in the region labeled "Smith Prairie" on Figure 1-2. A lower terraced surface at the 30-meter level (low terrace) separates the higher surfaces in the vicinity of Ebey's Prairie and around the perimeter of Penn Cove (Figure 1-2 and 1-3). Hummocky topography, developed in a unit known as the Partridge gravel (Easterbrook, 1966; 1968), immediately west of Penn Cove and adjacent to the western 60-meter terrace has been interpreted by Easterbrook (1966) to be kettles in late Pleistocene outwash, shed off a lobe of ice occupying Penn Cove.

The objectives for this investigation were the following: (1) interpretation of the late Pleistocene geologic history of the study area, including the origin of the three terraces south of Coupeville; (2) determine the age of the three terraces; and (3) relate findings to deglaciation, fluctuating sea-level, isostatic rebound, and tectonic movements in the late Pleistocene.

The Washington State Department of Natural Resources is currently updating the northwest quadrant of the Washington State geologic map. This thesis is partially funded by the Washington State Department of Natural Resources and will be incorporated into their Washington State Geologic Map.

2.0 METHODOLOGY AND APPROACH

2.1 Methods

2.1.1 Map and Air-Photo Interpretation

Much information in this project was obtained from the study of maps and air photographs of the region. Map and air-photo interpretation was used to identify subtle surficial morphology that is not apparent on the ground. Air photographs were particularly useful in aiding identification of relict channels on the 60-meter (high) terraces, strandlines marking previous sea-level elevations, and other surficial features that do not stand out on published topographic maps. Air-photos were also a valuable tool for planning and implementing an effective field program.

2.1.2 Geologic Mapping

Geologic mapping of surficial deposits at a scale of 1:24,000 was the primary investigative tool used. Stratigraphic relationships, areal extent of certain units, and sedimentary structures provided evidence pertaining to the origin, age, and events surrounding formation of the terraces.

Prior to this project, the geologic history in this region of the Puget Lowland had been determined primarily from studying stratigraphy in beach exposures. Very little attention had been given to tracing contacts across the interior of Whidbey Island. Because of the complexity and interfingered nature of Pleistocene geologic units, projecting the geology inland from beach exposures is not easy (or accurate).

Beach cliffs and gravel pits provide most of the exposure in the study area. Except for the gravel pits, exposure in the interior of the study area is poor. The land is about half forested and half pasture/cropland. Mapping of the inland portion of the study area was accomplished by excavating road cuts where available and studying existing geotechnical reports, well logs, and soil maps.

2.1.2.1 Well Logs

Water-well logs can be a useful tool in subsurface interpretation, particularly in areas where associated geologic units possess distinguishing characteristics that are evident in the drilling process. Geologic characteristics that are identifiable during drilling include contrasting color (light versus dark units) and gravel versus fine-grained (clayey) sediments, which are often described as "hardpan" in water-well logs. Water-well logs are not a reliable source of information in areas where the adjacent geologic units are similar in terms of the physical characteristics described above.

Another uncertainty associated with water-well logs is the exact depth at which a certain unit occurs; a time lag often occurs between when a unit is encountered by the drill bit and when the driller at land surface sees evidence of the change in lithology.

For this investigation, well logs were analyzed for information about the lower contacts of Partridge outwash and Everson glaciomarine drift. Partridge outwash typically overlies Vashon till or the Whidbey Formation; both are fine-grained sediments that are typically cliff-formers in outcrop and could be expected to be harder to drill through than Partridge outwash. Also, drillers are typically able to recognize when they are drilling through gravel, particularly when the gravel contains cobbles and boulders.

Everson glaciomarine drift overlies Partridge outwash in some areas, and Vashon till or Whidbey Formation in other areas. Where Everson glaciomarine drift, typically a diamicton with a fine-grained matrix (clay/silt content usually higher than Vashon till), overlies Partridge outwash, a change in lithology is usually recorded by well drillers. In contrast, a geologic sequence of Everson glaciomarine drift overlying Vashon till or the Whidbey Formation can not be identified reliably in water-well logs.

2.2 Approach

2.2.1 Dating and Correlation

At the onset of this investigation, the state of knowledge about the Partridge outwash did not allow this unit to be classified as equivalent to Vashon glacial deposits or Everson Interstade deposits. One of the goals for this investigation was to obtain a numerical date on the Partridge outwash and a limiting date on the lower and upper terrace surfaces.

Partridge outwash contains tephra and marine shells and was believed to contain charcoal. Such materials could provide information useful in tying down the age of deposition of the Partridge outwash, but attempts to obtain dates from these materials were unsuccessful.

Determination of an upper (younger) age limit for both upper and lower terrace levels would define a minimum age for the cessation of the processes responsible for these landforms. Because the high terraces were determined to be constructional in origin, the age of the surfaces is the same as the date of deposition of the sediments composing the terraces. This scenario is also true for the lower terrace surface (Ebey's Prairie). Erosional marine terraces that occur around the perimeter of Penn Cove (discussed later) are mantled with Everson glaciomarine drift and can therefore be dated by the age of the glaciomarine drift.

2.2.2 Reconnaissance Mapping in Related Regions

Pessl and others (1989) mapped recessional outwash gravel similar to Partridge outwash in several other locations in the region. Reconnaissance mapping was carried out in those locations during the course of this investigation to determine the likelihood of a relationship between the outwash deposits. A reconnaissance investigation was also conducted for gravel deposits on northern Whidbey Island identified by Easterbrook (1991, oral communication) and in the Sequim area (Dethier and others, in review) and to nearby locations that exhibit similar-appearing terrace landforms identified on topographic maps. Terraces at similar elevations to the those of the study area were investigated on Whidbey Island immediately north of the study area and on the west side of Camano Island.

2.2.3 Comparison of Study Results to Existing Knowledge about Final Deglaciation in the Puget Lowland

Because so much study has focused on the deglaciation history of the Puget Lowland, any detailed investigation should relate results to the regional framework of deglaciation in the Puget Lowland. Most of the research on deglaciation in the Puget Lowland to date has fallen into one of two topics. (1) Research in the southern Puget Lowland has centered around recessional outwash deposits and the succession of proglacial lakes that occupied the Puget Sound troughs prior to reentry of sea water into Puget Sound (Bretz, 1913; Crandell, 1963; Sceva, 1957; Thorson, 1980; 1981; 1989; Booth, 1986; Curran, 1965; Anderson 1965); or (2) Research in the northern Puget Lowland has centered around the glaciomarine deposition that was so ubiquitous in that region during deglaciation and depositional models that would explain deposition of such a deposit synchronously over such a large area (Armstrong and Brown, 1954; Armstrong and others, 1965; Easterbrook, 1963; 1969; 1991; Easterbrook and others, in press; Domack, 1983). The current research bridges the gap between these two different ice-recessional environments, because both of the above-described types of deposition occurred in the study area. The study area may have been an isolated occurrence of this depositional setting in the Puget Lowland, or this area may have been the transitional location in the Puget Lowland where the dominant ice-recessional process of the southern Puget

Lowland, continental outwash deposited from grounded ice, changed in the northern Puget Lowland to deposition of glaciomarine drift.

3.0 GENERAL SETTING

3.1 Physical and Climatological Setting

Whidbey Island is about 65 km long and varies in width from about 2 to 16 km. Land area totals approximately 425 km^2. Most of the land surface consists of rolling uplands ranging from 30 to 90 meters above sea-level. In a few places, the uplands are 150 meters above sea-level. Good geologic exposures are found on the west side of the island where wave erosion is vigorous. Poorer exposures occur on the east side of island where vegetation mantles much of the slopes.

Precipitation ranges from 46 cm (18 inches) per year at Coupeville to 107 cm (42 inches) per year at Lake Goss (Anderson, 1968). Precipitation generally occurs as gentle showers or in the form of fog or mist. Variation in the amount of precipitation from place to place on Whidbey Island is influenced principally by two factors: the rain shadow cast by the Olympic Mountains, about 80 km southwest of Whidbey Island, and the land-surface altitude. The effect of the rain shadow can be seen in the central and northern part of Whidbey island, where the precipitation is noticeably less than in the southern part of the island or on neighboring Camano island.

Whidbey Island has little stream runoff, as demonstrated by a poorly developed stream network. Also, the dense evergreen vegetation which covers much of the area aids in holding back surface drainage, which in turn provides greater opportunity for infiltration of water into the soil. Another indication of poor surface drainage is the large number of swamps and marshes found not only in lowland areas but also scattered across upland areas, some as much as 150 meters above sea-level.

3.2 General Geologic Framework

Whidbey Island lies within the Puget Lowland, a topographic and structural depression between the Cascade Range and the Olympic Mountains. Except for the very northern end of Whidbey Island, all of the island consists of Pleistocene deposits. Most of the surface of Whidbey Island consists of till, gravel, and sand deposited during the Vashon Stade of the Fraser Glaciation and glaciomarine drift deposited during the Everson Interstade following the Vashon Stade. Older glacial and nonglacial deposits are exposed in sea cliffs around the island.

The glacial sediments were deposited by repeated advances and retreats of the Cordilleran Ice Sheet that originated in the Coast Range and adjacent areas in southwest British Columbia. The ice was more than 1600 meters thick near Bellingham (Easterbrook, 1963). At Whidbey Island the ice was estimated to be about 1200 meters thick (Easterbrook, 1979).

Deposits from at least three glaciations can be recognized on Whidbey Island. These drifts were first recognized by Bretz (1913) at Possession Point on the south shore of Whidbey Island, but he tentatively concluded that the two lower tills belonged to the same glaciation. Hansen and Mackin (1949) studied the sequence at Possession Point in detail and showed that the three drifts represented three separate glaciations. Evidence of at least three glaciations separated by interglacial intervals on Whidbey and Camano Islands and adjacent areas in the central Puget Lowland was found by Easterbrook (1966; 1968) and Easterbrook and others (1967). The two pre-Vashon drifts were named the Double Bluff (oldest) and Possession. They are separated by the interglacial Whidbey Formation.

All of the late Pleistocene (Double Bluff Drift and younger) units, except Sumas Drift, are known to occur on Whidbey Island. Older glacial units may be present below sea-level but have not been identified.

4.0 PREVIOUS WORK

Easterbrook (1966) was the first to publish interpretations about the origin of the geology of the study area. Later, Easterbrook (1968; 1969) mapped stratigraphy in sea cliff exposures in Island County but did little work in the interior of Whidbey Island. Reconnaissance mapping of beach outcrops between Point Partridge and Ebey's Landing suggested that the western high terrace was composed of Partridge outwash (Easterbrook, 1968). Shell fragments reported by Easterbrook (1968) imply marine involvement in the origin of Partridge outwash, but the lateral extent and age of the unit was not determined.

The age and stratigraphic relationships of Partridge gravel were discussed by Easterbrook (1966). At West Beach, at the north end of the kettled topography, a layer of Everson glaciomarine drift, radiocarbon dated at 12,535 ± 300 years (Easterbrook, 1966), can be seen to overlie the kettled Partridge outwash. Based on this stratigraphic relationship and the morphology preserved within the Partridge outwash, Easterbrook (1966) inferred the relative age of the Partridge outwash at West Beach to be older than the overlying Everson glaciomarine drift and younger than advance of the Vashon ice sheet because the kettle morphology could not have survived overriding ice.

Everson glaciomarine drift has been discussed in the study area by Easterbrook (1966; 1968) and Domack (1982, 1983). Easterbrook (1966) suggested that deposition of Everson glaciomarine drift seemed to have been restricted to elevations below approximately 30-meters in this region of the Puget Lowland. Domack (1982, 1983) conducted a detailed study of facies within the Everson glaciomarine drift on Whidbey Island with special attention to the area around Penn Cove. He concluded that the characteristics of Everson glaciomarine drift, at least in the Penn Cove region, are equivalent to modern deposits accumulating in front of a grounded, backwasting glacier front.

Thorsen (1983) informally identified the West Beach silt just north of the study area. He interpreted the silt to be a loess, based on the presence of characteristics similar to other known loess deposits. Wood near the base of a unit classified by Thorsen as West Beach silt at Protection Island has been dated at 33,490 ± 550 and 31,500 ± 890 years (Thorsen, 1983).

To date, the most detailed geologic map available for this area is the Port Townsend 1:100,000 quadrangle (Pessl and others, 1989).

5.0 STRATIGRAPHY, SEDIMENTOLOGY, AND MORPHOLOGY

This section describes the geologic units and associated landforms present in the study area. Table 5-1 summarizes them.

5.1 Double Bluff Drift

5.1.1 Description

The oldest glacial deposit recognized in the study area is Double Bluff Drift. The type section of the drift is a sea-cliff exposure at Double Bluff on southern Whidbey Island (Easterbrook and others, 1967) where it consists of till, glaciomarine drift, sand, and gravel.

At its type section, the lower part of the Double Bluff Drift consists of about 9 meters of crossbedded sand overlain by 6 meters of pebble-cobble gravel; about 3-4 meters of sand, silt, and clay; and about 12 meters of compact gray till and poorly sorted, crudely stratified glaciomarine drift (Easterbrook, 1968). The lower gravel unit was interpreted by Easterbrook and others (1967), on the basis of lithology and texture, to be proglacial outwash that was overridden by ice. In other places on Whidbey Island, Easterbrook and others (1967) reported that the drift consists of clayey till-like layers interbedded with silt and pebbly silt. The stratification and presence of small shell fragments led Easterbrook

TABLE 5-1

Major Geologic Units and Landforms Represented in the Study Area

Geologic Unit or Landform	Geologic Climate Interval	Approximate Time (years b.p.)
Dune Sand	Holocene	0-10,000
Everson Glaciomarine Drift Low Terraces Partridge gravel Kettle Topography High Terraces	Everson Interstade	11,500 - 13,000
Vashon till 55 meter knob Esperance Sand	Vashon Glaciation	13-18,000
Possession Drift	Possession Glaciation	28-90,000
Whidbey Formation	Whidbey Interglacial	100-150,00
Double Bluff Drift	Double Bluff Glaciation	175-275,000

and others (1967) to believe that these portions of the drift were either deposited subaqueously in marine water or by mudflows into ponded water.

5.1.2 Distribution and Stratigraphic Relationships

The contact between the Double Bluff Drift and the overlying Whidbey Formation was described by Easterbrook and others (1967) in the sea cliffs at Double Bluff and about a quarter of a mile east of the southernmost point at Double Bluff. At the latter location, Double Bluff pebbly silt and oxidized sand and gravel is overlain by sand and peat-bearing silt of the Whidbey Formation. The contact dips eastward and disappears below sea-level. Elsewhere on Whidbey Island, Double Bluff Drift is only rarely exposed above sea-level (Easterbrook and others, 1967). It occurs at Possession Point where it corresponds to the lowest drift recognized by Bretz (1913) and Hansen and Mackin (1949). Bretz included it in his Admiralty Glaciation and Hansen and Mackin informally referred to it as the "sea-level till".

Double Bluff Drift is exposed only at one location in the study area, in the sea-cliff exposure between Ebey's Landing and Fort Casey on the west coast of Whidbey Island where compact till, composed of pebbles, cobbles, sand, silt and clay is overlain by pebbly silt, glaciomarine drift (Easterbrook, 1969; Easterbrook and others, in press). It is overlain by the Whidbey Formation. Figure 5-1 shows Double Bluff Drift south of Ebey's Landing.

Figure 5-1 Double Bluff Drift south of Ebey's Landing

5.1.3 Age

The most recent estimate of age for Double Bluff Drift has been provided by Easterbrook and others (in press). Thermoluminescence analysis has yielded a date of 176,000 ± 38,000 from clay in glaciomarine drift at Double Bluff, and dates ranging from 251,000 ± 81,000 to 280,000 ± 81,000 on sediments beneath tills correlated with the Double Bluff in nearby locations. Previous amino acid analyses have suggested an age in the 111 to 250,000 year range for Double Bluff Drift. The remanent magnetism of Double Bluff glaciomarine drift is normal (Easterbrook, 1976; 1983), providing additional evidence that the Double Bluff Drift cannot be correlative with Salmon Springs Drift in the southern Puget Lowland.

5.2 Whidbey Formation

5.2.1 Description

The type locality of the Whidbey Formation is in sea cliffs on Whidbey Island between Double Bluff and Useless Bay (Easterbrook and others, 1967), where more than 60 meters of the unit are exposed.

The Whidbey Formation, defined by Easterbrook and others (1967), consists of buff to gray sand, silt, and clay interbedded with peat and lenses of gravel. Most of the silt and clay portions of the unit are horizontally stratified. Cross-stratification is common in the moderately well sorted sand. Peat beds are also common, varying in thickness from a few centimeters to a few meters.

Easterbrook and others (1967) interpreted the sediments of the Whidbey Formation to be almost entirely floodplain deposits similar to those described by Hansen and Mackin (1949) at Everett and Possession Point. Hansen and Mackin (1949) interpreted deposits at those locations to be the result of "aggradation by meandering streams flanked by floodplain lakes and swamps". Lenses of gravel and coarse sand were thought to represent channel deposits (Hansen and Mackin, 1949).

5.2.2 Distribution and Stratigraphic Relationships

Exposures of the Whidbey Formation are numerous in the sea cliffs of Whidbey and Camano Islands and in places along adjacent mainland coastlines, but the contact with the underlying Double Bluff Drift is exposed at only a few localities (Easterbrook and others, 1967). Inland the Whidbey Formation is covered by younger sediments and is rarely exposed.

Easterbrook and others (1967) reported that an unconformity is almost always present at the top of the Whidbey Formation, so the original stratigraphic thickness of the unit is not known. At the type locality east of Double Bluff, at Scatchet Head, and on the east side of Useless Bay, the Whidbey Formation is more than 60 meters thick. Elsewhere on Whidbey Island thicknesses vary from a few meters to about 30 meters.

Possession Drift overlies the Whidbey Formation at several localities, but in most places the Esperance Sand Member of the Vashon Drift (Mullineaux and others, 1965) lies unconformably on the Whidbey Formation (Easterbrook and others, 1967). Possession

Drift and the overlying sediments of the Olympia interglacial are not discussed here because they are not recognized in the study area.

Easterbrook (1968) described the upper Whidbey Formation contact where it is directly overlain by Esperance sand. In exposures where the Whidbey Formation consists of sand, distinguishing between Whidbey Formation and Esperance sand is sometimes difficult. Easterbrook (1968, p. 14) provides the following observations regarding these two units: "The Esperance is usually somewhat coarser than the typical Whidbey, consisting mostly of pebbly crossbedded sand with scattered lenses of gravel. The Whidbey is characterized by generally finer sediments, horizontally stratified, with peat layers commonly interbedded. Silt, fine sand, and peat in the Whidbey Formation often stand in near vertical cliffs, whereas the looser sands of the Esperance tend to have slopes of a lower angle. The difference in character of the two units often results in a sharp, well-defined contact. However, in a single isolated exposure, sand of the Whidbey Formation may be indistinguishable from that of the Esperance sand. No peat beds have been observed in the Esperance whereas peat is quite common in the Whidbey."
Analyses of pollen from peat in the Whidbey Formation suggest that the sediments were deposited during an interglacial period characterized by a warm climate, but with cooler intervals at its beginning and end (Hansen, 1947; Hansen and Mackin, 1949; Hansen and Easterbrook, 1974; Heusser and Heusser, 1981; Easterbrook and others, 1967; Easterbrook, 1968).

The Whidbey Formation is fairly common in the study area. It overlies Double Bluff Drift south of Ebey's Landing (Fig. 5-2) and makes up the base of the sea cliff at several

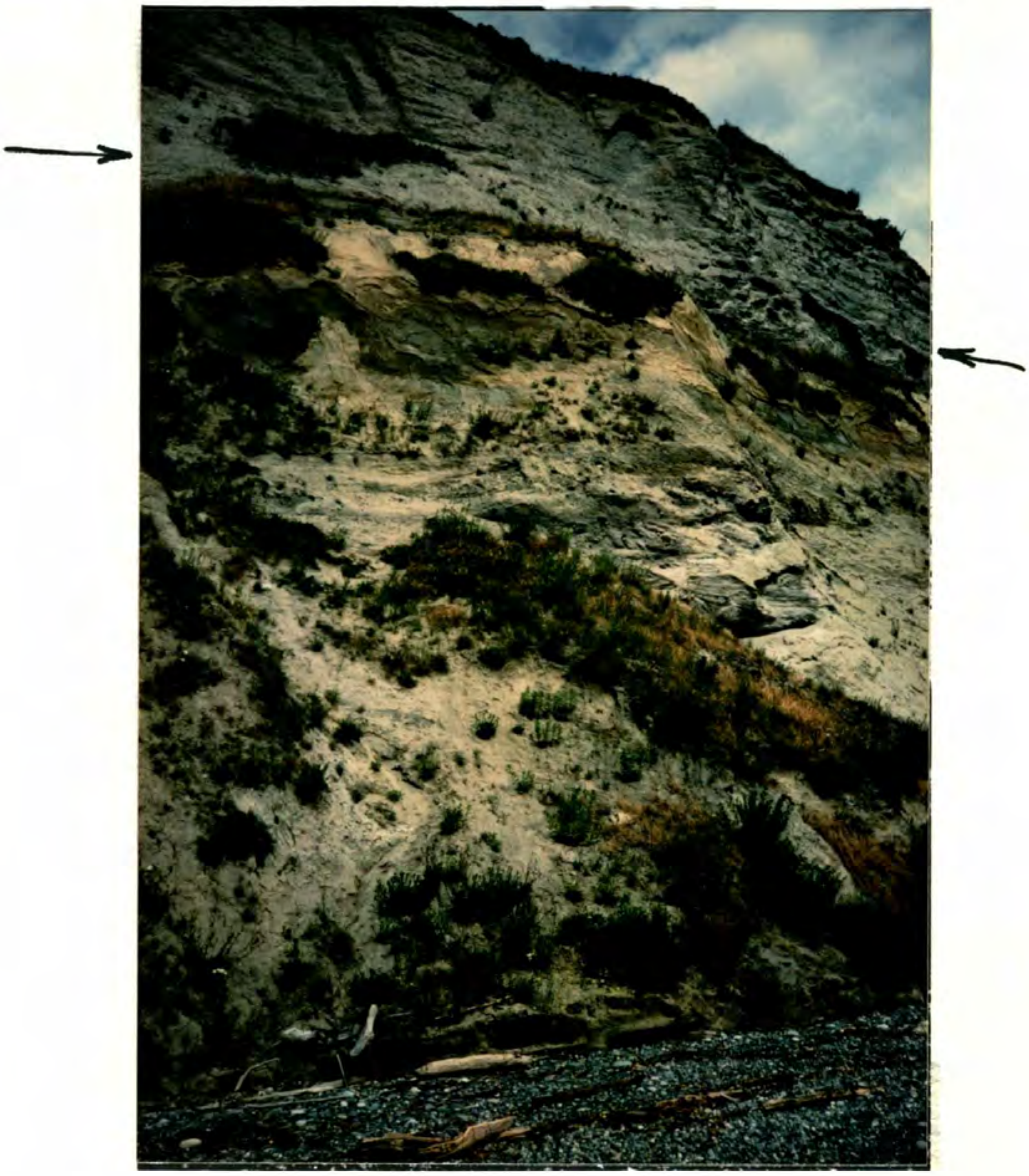

Figure 5-2 **Sea-cliff section 1 km south of Ebey's Landing. Vashon till overlies the Whidbey Formation in this exposure (arrows point to contact).**

locations in the eastern half of Penn Cove, where it is overlain by Vashon till and Everson glaciomarine drift (Fig. 5-3, 5-4).

5.2.3 Age and Correlation

At least 20 attempts to obtain radiocarbon dates on wood and peat from the Whidbey Formation have yielded ages beyond the limits of radiocarbon dating. To date, the most definitive age for the Whidbey Formation has been reported by Easterbrook and others (1988). Four thermoluminescence dates yielded dates between 96,00 ± 37,000 and 150,000 ± 44,000. Previous amino acid analyses of wood and shells in the Whidbey Formation suggested an age of approximately 100,000 ± 20,000 years (Blunt and others, 1987). Measurements of remanent magnetism in Whidbey sediments by Easterbrook (1976) show normal polarity, meaning that the unit must be younger than 800,000 years.

5.3 Vashon Drift

Vashon Drift, deposited during the Vashon Stade of the Fraser Glaciation, includes all sediments laid down between the advance and retreat of the last Cordilleran Ice Sheet that occupied the Puget Sound lowland during the Pleistocene (Armstrong and others, 1965). Two stratigraphic units belonging to the Vashon Drift have been recognized in the study area. The oldest of these is the Esperance Sand Member, which probably represents proglacial outwash later overridden by Vashon ice. It is usually covered with Vashon till. Partridge outwash and Everson glaciomarine drift represent phases of deglaciation and, because of their marine affiliation, are classified in the Everson Interstade.

Figure 5-3 The Whidbey Formation at beach level, south shore of Penn Cove west of Coupeville.

Figure 5-4 The Whidbey Formation overlain by Everson glaciomarine drift along the south shore of Penn Cove east of Coupeville. Shells occur in the glaciomarine drift at this exposure.

5.3.1 Esperance sand

5.3.1.1 Description

The Esperance Sand Member consists mostly of moderately well-sorted fluvial sand and pebbly sand with occasional lenses of gravel. Most of the unit is extensively crossbedded with southward-dipping laminae, suggesting deposition from south-flowing streams (Easterbrook, 1968). Scour and fill structures are common; organic material is seldom present.

On the west side of Whidbey Island south of Swantown, more than 60 meters of the unit are exposed and about 55 meters are exposed 2 km south of Lake Hancock. Elsewhere thicknesses range from zero to about 40 meters (Easterbrook, 1968).

5.3.1.2 Distribution and Stratigraphic Relationships

The Esperance sand is overlain by Vashon till and associated drift in most places, although, at a few localities, Everson glaciomarine drift overlies it. The Whidbey Formation underlies the Esperance in most sea cliff exposures, but, at a few sea cliffs, Possession Drift separates the Esperance sand from the underlying Whidbey. Because of the coarse material in it and the extensive crossbedding, the Esperance is interpreted to have been deposited by outwash streams (Easterbrook, 1968).

Esperance sand was identified at only two localities in the study area, the sea-cliffs south of Ebey's Landing and north of West Beach (Fig. 5-5). Esperance sand overlies the Whidbey Formation in both sections and is covered by Vashon till.

5.3.1.3 Age and Correlation

Interpretation of the sand as Esperance implies correlation with stratigraphic units of early Vashon outwash elsewhere in the Puget Lowland. Newcomb (1952) mapped a unit in Snohomish County which he named the "Esperance sand member of the Vashon drift". He recognized two major units within the Esperance.

> "The earlier phase of the sand member appears to be a coarser continuation of the horizontal Admiralty clay, whereas the later outwash phase is undoubtedly the advance outwash of the Vashon glacier (p. 20)."

In the Seattle area, Mullineaux and others (1965) recognized two early Vashon deposits overlying Olympia nonglacial deposits (sediments from the nonglacial period that immediately preceded the Fraser Glaciation). The lower part of the early Vashon sediments at Fort Lawton in Seattle consists of lacustrine clay defined as the Lawton Clay Member of Vashon Drift. The overlying sand unit was defined as the "Esperance Sand Member of Vashon Drift" but was used in a restricted sense to include only the "later outwash phase" of Newcomb. The Lawton Clay Member was thought to have been deposited in a proglacial lake created by damming of north-flowing streams by the Vashon glacier. The Esperance Sand Member as restricted was thought to represent chiefly proglacial fluvial and lacustrine sediments deposited after the lake was mostly filled with sediment.

Figure 5-5 Esperance sand north of West Beach

Mullineaux and others (1965) dated wood from beneath the Lawton Clay Member in Seattle at 15,000 ± 400 and 15,100 ± 300 years old. No equivalent of the Lawton clay has been recognized on Whidbey Island. The deposits of this interval on Whidbey Island lithologically resemble the Esperance Sand Member.

5.3.2 Vashon Till and Associated Drift

5.3.2.1 Description and Origin

Vashon till, which has been mapped extensively throughout the Puget Lowland, typically consists of a single sheet of poorly sorted boulders, pebbles, sand, silt, and clay with thickness up to 53 meters (Easterbrook, 1968). Thicknesses of 5 to 10 meters are more typical. The till is usually fairly compact and tends to stand in nearly vertical bluffs in sea cliffs. Gravelly phases of Vashon till are commonly crudely stratified. Boulders, cobbles, and pebbles in both the till and gravel phases are occasionally faceted, striated, and polished but the majority of them are rounded, rather than angular, apparently as a result of stream transportation prior to incorporation in the till (Easterbrook, 1968).

The compact till phases of the drift were deposited as lodgment till beneath the glacier, whereas the less compact till and gravelly drift phases probably represent largely subglacial and proglacial meltwater deposits, ablation till, and perhaps flow till (Easterbrook, 1968).

Vashon till is widespread on Whidbey Island. It commonly occurs near the top of sea-cliff exposures and mantles much of the surface inland at elevations higher than Partridge outwash or Everson glaciomarine drift (Easterbrook, 1968).

In the study area, Vashon till mantles the surface of the knob north of Fort Casey. It is also present at sea-level on the east shore of Whidbey Island north of Race Lagoon (Fig. 5-6) where it is overlain by Partridge outwash and at a few places along the south shore of Penn Cove where it overlies the Whidbey Formation and is covered by Everson glaciomarine drift (Fig. 5-7). In this latter area, Vashon till was apparently spread over a rolling land surface composed primarily of the Whidbey Formation.

5.3.2.2 Stratigraphic Relationships

Vashon till rests unconformably on a wide variety of older deposits. In many places Vashon till lies on the Esperance sand with a nearly horizontal contact, but the till cuts across the sand locally, especially on the north and south ends of sea-cliff exposures. In places, Vashon till cuts down across Esperance sand and the Whidbey Formation, descending below sea-level (Easterbrook, 1968).

5.3.2.3 Age and Correlation

No carbon-bearing material contemporaneous with deposition of Vashon till has been found on Whidbey Island or elsewhere in the Puget Lowland. However, sufficient radiocarbon dates have been obtained from sediments above and below Vashon till to

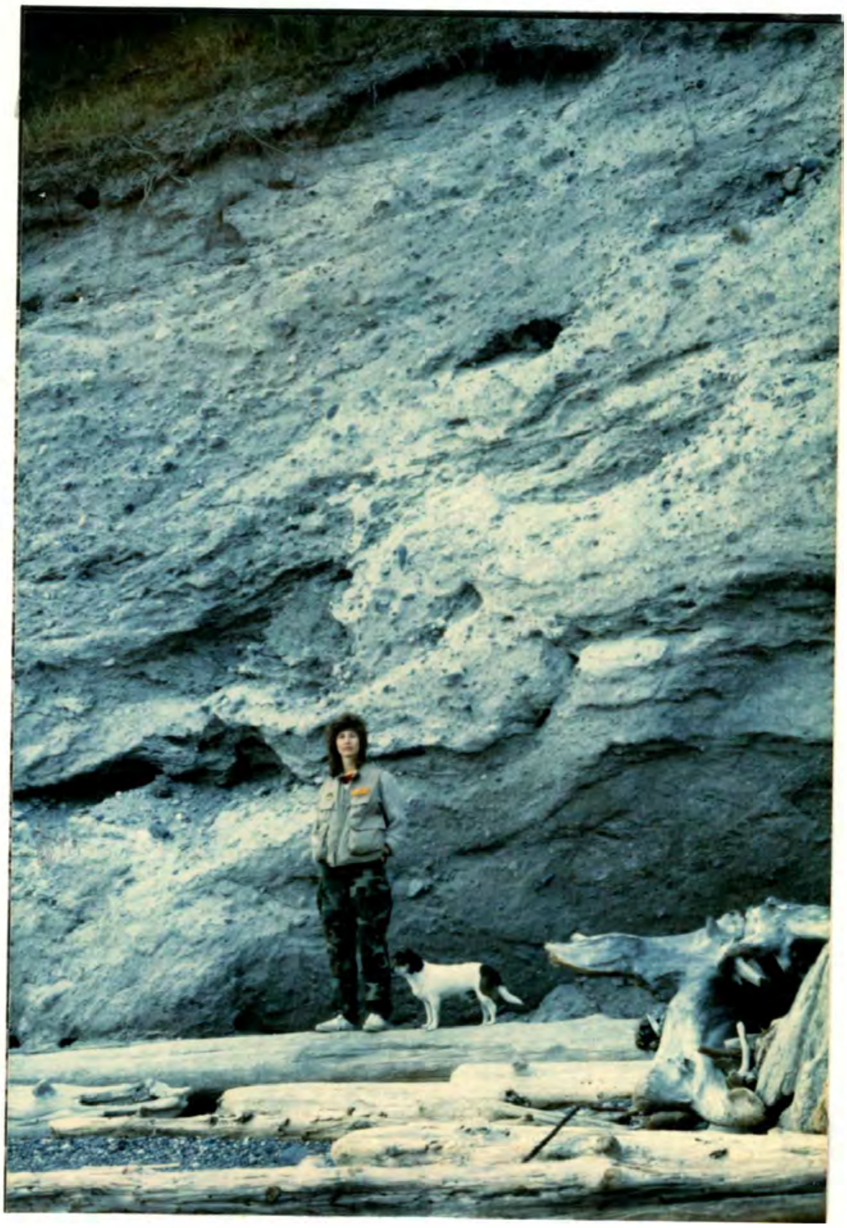

Figure 5-6 Vashon till at beach level, north of Race Lagoon, at the base of the eastern high terrace.

Figure 5-7 Vashon till overlain by Everson glaciomarine drift at the southwest corner of Penn Cove. Arrows beside photo show location of contact.

bracket the time within fairly narrow limits. On Whidbey Island, radiocarbon dates from the overlying Everson glaciomarine drift indicate that the deposition of Vashon till ceased about 12,500 to 13,650 years ago (Easterbrook, 1968; Pessl and others, 1989; Blunt and others, 1987). The only established lower limit for the Vashon Stade on Whidbey Island is the 26,850 ± 1700 age obtained from pre-Vashon peat (Easterbrook, 1968).

5.4 Everson Interstade Deposits

5.4.1 The "Everson Problem"

Researchers in the northern Puget Lowland (Easterbrook, 1963; Armstrong and Brown, 1954; Armstrong and others, 1965; Clague and others, 1982; Mathews and others, 1970) have reported a sequence of, from oldest to youngest, Vashon till, glaciomarine drift (in some places two glaciomarine phases separated by a continental unit (Easterbrook, 1963)) capped by a glacial till of a late Fraser glacial readvance, the Sumas stade. Armstrong and others (1965) defined the beginning of the Everson Interstade as the re-introduction of marine water into the Puget Lowland following the Vashon maximum. Consistent with this definition, post-Vashon-till, late Pleistocene marine sediments in the northern Puget Lowland have historically been assigned to the Everson Interstade. Glaciomarine drift is the most commonly reported type of deposit assigned to the Everson Interstade, but Armstrong and others (1965) also described deltaic sand and gravel deposits within deposits of the Everson Interstade in the Fraser Lowland.

Everson glaciomarine drift has not been recognized south of Seattle, where late Fraser Drift consists of outwash and deltaic deposits. Pessl and others 1989) did not follow long-established, formally defined nomenclature and informally combined Partridge outwash and Everson glaciomarine drift under Vashon recessional deposits for mapping purposes. However, that usage is not followed here because it would violate the stratigraphic code and introduce unnecessary confusion into the stratigraphic nomenclature of the Puget Lowland.

The results of this investigation show that Partridge outwash and Everson glaciomarine drift are two facies of one geologic-climate unit. These two units were deposited in proximity to the recessional Cordilleran Ice Sheet in a marine environment. Partridge outwash was deposited by meltwater streams in a marine kame-delta complex; Everson glaciomarine drift was deposited primarily from material melting out of berg ice. Although Everson glaciomarine drift can be seen to overlie Partridge outwash in places, superposition can be attributed to a change in depositional process. During the time of Partridge outwash deposition, Everson glaciomarine drift was probably deposited in areas where Partridge outwash was not being deposited. For the purpose of this thesis, the two Everson Interstade deposits, Partridge outwash and Everson glaciomarine drift, are described as separate rock stratigraphic units based on their sedimentology and morphology. Both are considered part of the suite of Everson glaciomarine sediments. This classification is consistent with the definition of Everson Interstade and conforms with usage by Armstrong and others (1965).

5.4.2 Partridge Outwash

Easterbrook (1968) designated the type locality of Partridge gravel as the sea-cliff exposures between Point Partridge and West Beach on the west side of Whidbey Island, where approximately 45 meters of sandy gravel are exposed beneath glaciomarine drift of Everson age. The term Partridge outwash is used in this document to avoid conveying the idea that this unit is always composed of gravel.

5.4.2.1 Description

The bulk of the unit is made up of pebble to cobble gravel, with southeast-dipping foreset bedding (Fig. 5-8, 5-9, 5-10), cross-stratification, and collapse structures, particularly in the northern and western exposures between West Beach and Ebey's Landing. Cobbles 20 to 30 cm in diameter are common in parts of the gravel sequence. The composition of Partridge outwash clasts is varied, with common occurrences of Canadian provenance granitic rocks. Because a varied clast composition is widely used to identify sediment derived from the Cordilleran Ice Sheet, the conclusion that Partridge outwash was shed off the Cordilleran Ice Sheet follows. In some exposures between West Beach and Point Partridge, the outwash is only crudely stratified (Fig 5-11). The entire thickness of Partridge outwash in the western high terrace exhibits a large-scale coarsening-up sequence.

Well-sorted, fine-grained sediments are also present in Partridge outwash. These fine-grained sediments were deposited as bottomset beds in a prograding delta environment.

Figure 5-8 Southeast-dipping foreset beds, Point Partridge. Dip at this location was measured at 25 degrees to the southeast.

Figure 5-9 Front of foreset beds shown in Figure 5-8 at Point Partridge.

Figure 5-10 South-dipping foreset bed in Partridge gravel. Exposure is at large gravel pit west of Coupeville (shown in Figure 1-2). Measured dip at this location was 24 degrees to the south.

Figure 5-11 Partridge outwash south of West Beach. Note the more chaotic nature of the gravel here when contrasted with the exposures shown in Figures 5-8 and 5-9.

This interpretation is based on observations of foreset bedding grading into the fine-grained Partridge outwash sediments. The bottomset bed interpretation is also supported by the presence of sedimentary structures, such as flame structures, typically found in a prodelta environment. Figures 5-12 through 5-15 show sedimentary structures common in the fine-grained Partridge outwash layers.

Pumice and coal are found throughout the section in gravelly sand and sand layers, in both the western and eastern high terraces (Fig. 5-16). These components are clearly waterlaid, incorporated into the normal sediment load carried by the meltwater streams and sorted by density. Shell fragments have only been found in gravel in the western terrace and only near the top of the section (elevation approximately 55 meters).

5.4.2.2 Distribution and Stratigraphic Relationships

The lower contact of the Partridge outwash is rarely exposed. Partridge outwash can be seen to overlie Vashon till at two places, in a sea-cliff exposure just north of West Beach on the west coast of Whidbey Island, and in a sea-cliff exposure on the south shore of Penn Cove. Where Vashon till is absent from the pre-recessional topography, Partridge outwash overlies the Whidbey Formation.

The upper contact of Partridge outwash is also visible in only a few places. At the type locality just south of West Beach, Everson glaciomarine drift can be seen to overlie Partridge outwash in a sea-cliff exposure. In another sea-cliff exposure at Rodena Beach, Everson glaciomarine drift can be seen to overlie stratified sand considered correlative

Figure 5-12 Well-sorted, rippled sand of the Partridge outwash showing scour-and-fill structures. Ripples indicate current to the south. This exposure is located between Point Partridge and Ebey's Landing.

Figure 5-13 Well-sorted sand of the Partridge outwash at Rodena Beach, eastern high terrace. Partridge outwash is overlain by Everson glaciomarine drift at this location (arrows at contact).

Figure 5-14 En-echelon faulting in Partridge outwash at Point Partridge.

Figure 5-15 Flame structures in silty sand of Partridge outwash at Point Partridge.

Figure 5-16 Pumice and coal lenses in Partridge outwash at Point Partridge.

with Partridge outwash (Figs. 5-13, 5-17, 5-18). This exposure is interpreted to be a record of transgressive marine deposits. A gravel lag is exposed at the contact, 30 meters above sea level.

In most places on the high terraces, the upper surface of the Partridge outwash forms the present-day topography. In some locations, especially along the coastline on the western high terrace, Partridge outwash is capped by dune sand (Fig. 5-19). Where sand dunes are present, the surface of the top of the terrace gravel is very flat at 60 meters above sea level. The contact between Partridge outwash and dune sand typically shows oxidation. Rubble from Partridge outwash is commonly incorporated in the lower 10 cm of dune sand (Figs. 5-19, 5-20).

Figures 5-21 and 5-22 show the top of the Partridge outwash between Lovejoy and Long Points on the eastern high terrace. Partridge outwash here is composed of stratified sand and gravel, finer than at most places on the western terrace. At this location, the stratified sand and gravel is capped by a meter of thinly bedded silty sand. Because no marine shells were found in the silty sand, and the stratified sand and gravel of the Partridge outwash appears to be a terrestrial deposit, the thinly-bedded silty sand was probably deposited in a pond occupying a depression on the delta plain.

The distribution of Partridge outwash was mapped during this investigation. The outwash occurs throughout the areas previously identified in this document as the "kettled topography" and both "high terraces".

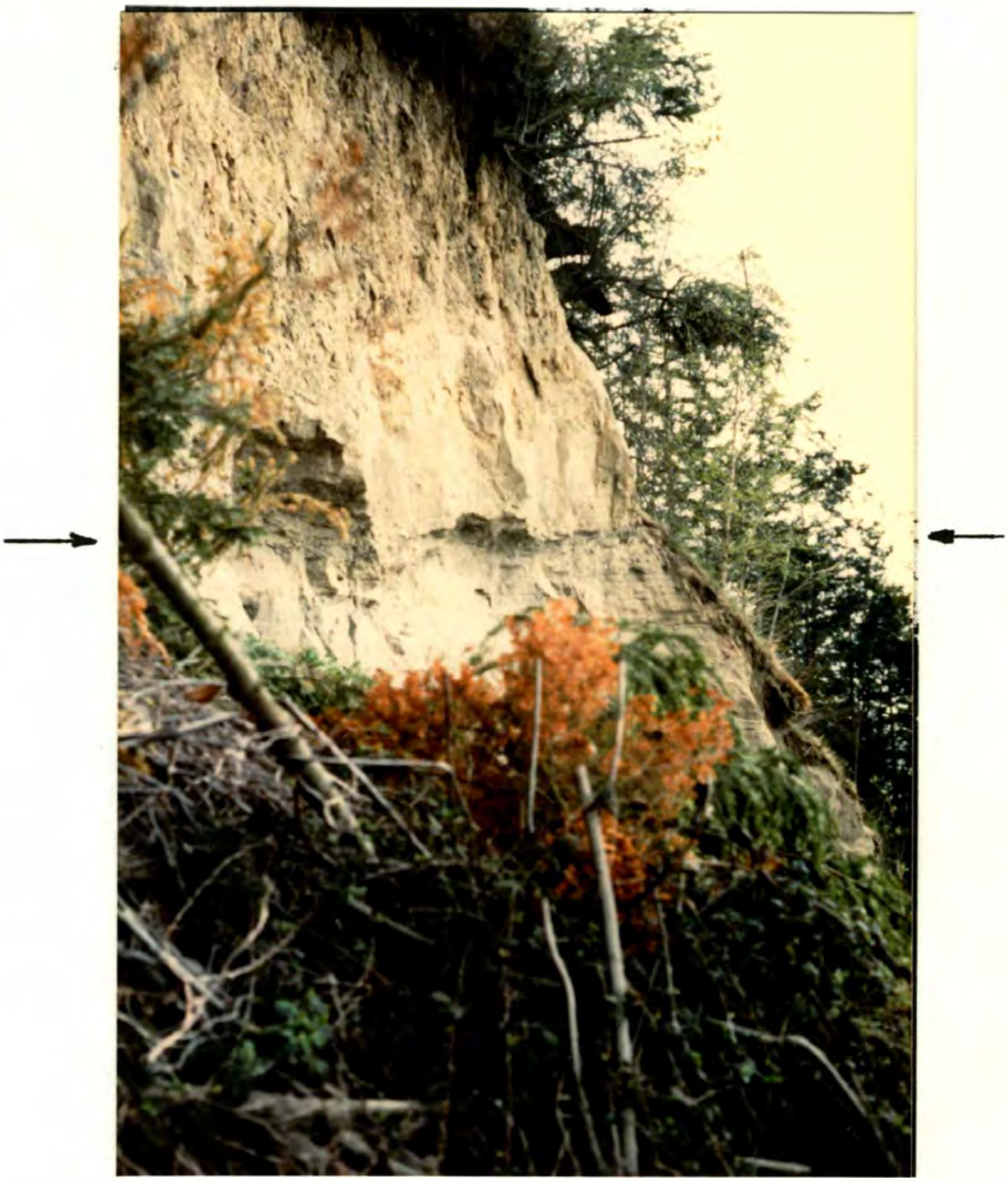

Figure 5-17 The upper contact of Partridge outwash at Rodena Beach. The outwash is overlain by Everson glaciomarine drift at this location. See Figure 5-18 for a close-up of the contact zone.

Figure 5-18 Contact between Partridge outwash and overlying Everson glaciomarine drift near Rodena Beach. See Figure 5-17 for a more distant view.

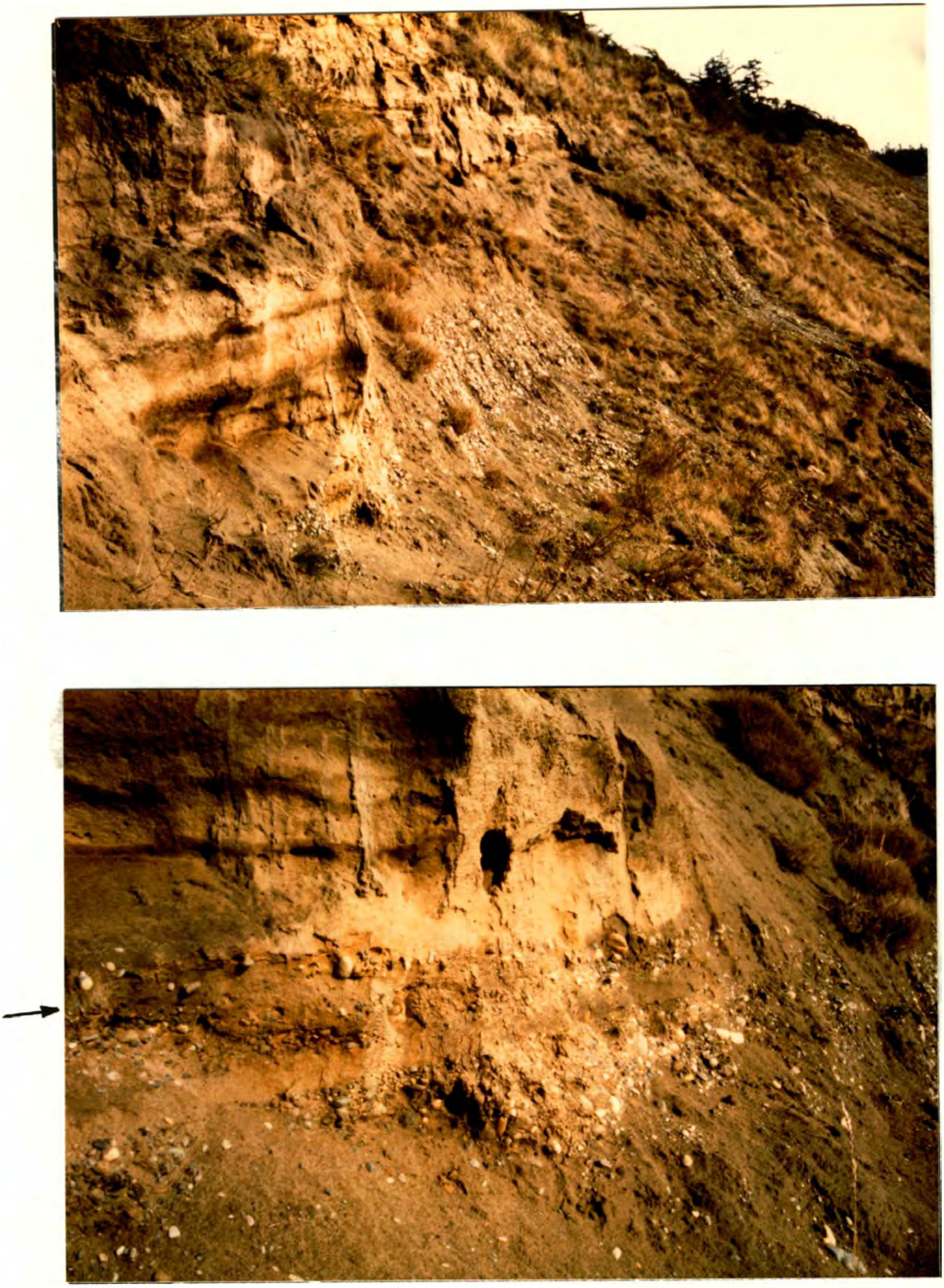

Figure 5-19 Upper contact of Partridge outwash with overlying dune sand at Point Partridge. Contact is shown with arrows.

Figure 5-20 Upper contact of the Partridge outwash with overlying dune sand near Point Partridge (contact shown with arrows). Note cross-stratification in the Partridge outwash and rubble incorporated into the dune sand.

Figure 5-21 Partridge outwash at the top of the eastern high terrace, between Lovejoy and Long Points on Penn Cove. Note thinly bedded silty sand overlying stratified sand and gravel (contact shown with arrows). See Figure 5-22 for a close-up view of the silty sand.

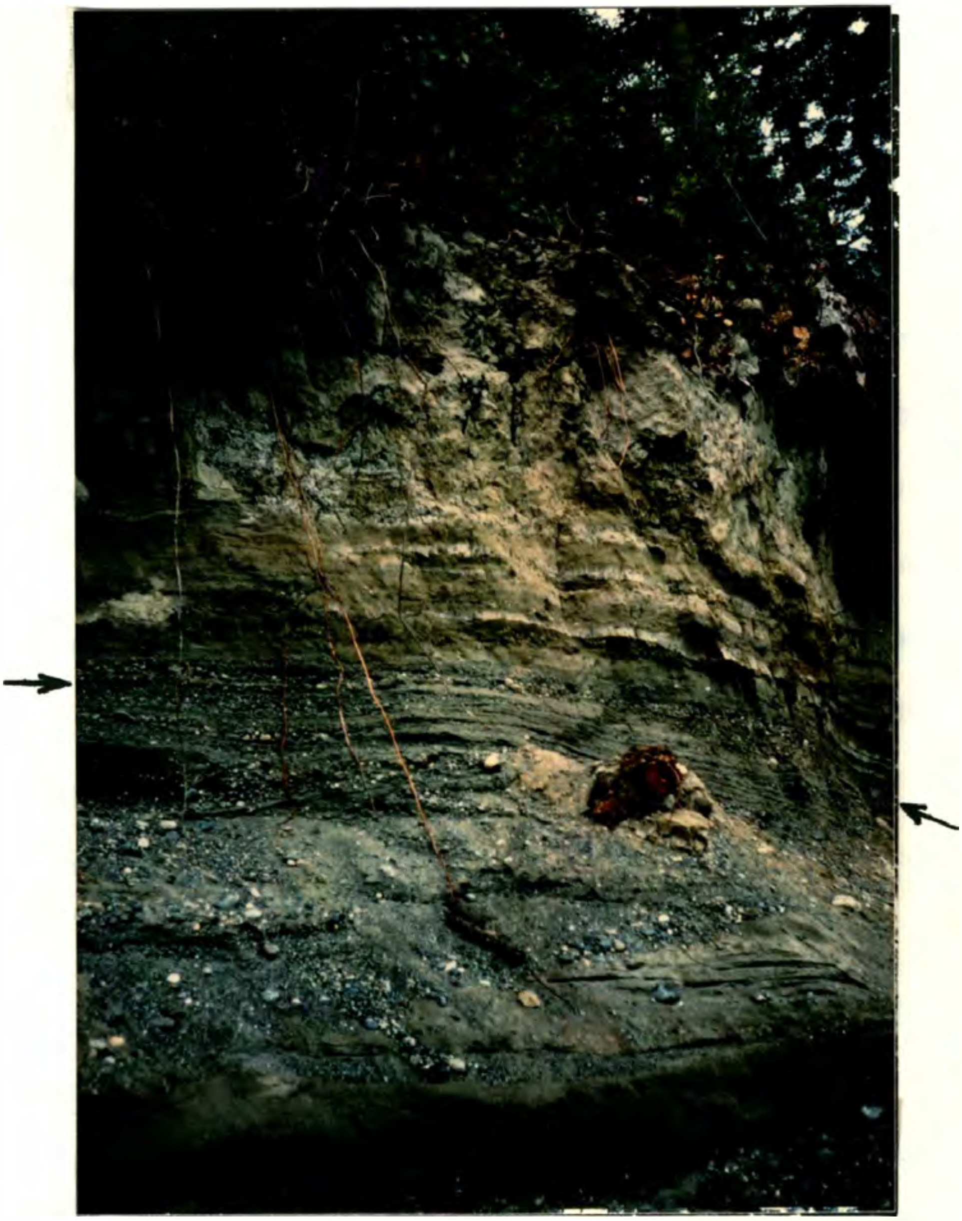

Figure 5-22 Partridge outwash at the top of the eastern high terrace, between Lovejoy and Long Points on Penn Cove. Note thinly-bedded silty sand overlying stratified sand and gravel (contact at arrows). See Figure 5-21 for a larger-scale view of this exposure.

Kettled Topography

Partridge outwash was originally identified by Easterbrook (1968) in the sea-cliffs near Point Partridge. This narrow part of Whidbey Island is characterized by hummocky topography interpreted by Easterbrook (1966, 1968) to be kettles developed in recessional outwash shed off a lobe of ice occupying Penn Cove during the waning stages of the Vashon Glaciation.

Except for the sea-cliff exposures on the west coast of Whidbey Island, exposure in the kettle topography is poor. Available information about the geologic composition of the interior of the kettled region consists of water-well logs, accounts of exposures that were fresh when the main highway (Highway 20) was constructed through the eastern portion of the kettle region (Easterbrook, personal communication, 1991), and knowledge of depositional environments commonly associated with kettle formation. Analysis of water-well records (Washington Department of Ecology, 1987) in the kettled topography suggests Partridge outwash was encountered in the kettle topography region from the surface to as low as 41 meters below sea-level. Fresh roadcuts during highway construction revealed sandy gravel with collapse features visible in many locations (Easterbrook, personal communication, 1991). Based upon the information presented here and the consistency of this information with a typical depositional model for kettle formation, a reasonable conclusion is that this hummocky topography was formed when numerous blocks of ice were buried in recessional outwash deposits and then melted.

High Terraces

Partridge outwash makes up the entire thickness of the western high terrace as documented by field mapping and well-log analysis. In general, a coarsening-up sequence exists in the western high terrace. A succession of stratified sand and gravel, showing ripples, ripple cross-lamination, and scour and fill structures, is overlain by cobble foreset beds. The uppermost gravel layers are characterized by boulder-size blocks of clay and coarse cross-stratification. Lower sections of the Partridge outwash, visible at beach level in several places, are fine-grained, primarily fine sand with silt lamination showing well-preserved flame structures and rip-up clasts.

In the eastern high terrace, Partridge outwash makes up the upper portion of the landform everywhere. Unlike the contact in the western high terrace, the contact between the Partridge outwash and the underlying units is exposed above sea-level in several places.

5.4.2.3 Age and Correlation

The age of Partridge outwash has previously been recognized by Easterbrook (1968) as constrained between the retreat of the Vashon ice sheet from this region and the deposition of Everson glaciomarine drift, dated in this area at between 12,535 and 13,600 years b.p. (Easterbrook, 1968; Pessl and others, 1989; Dethier and others, in review). One of the objectives of this investigation was to obtain an absolute date for deposition of the Partridge outwash. Lenses of tephra (dominantly lapilli-size) and carbonaceous material originally believed to be charcoal are common throughout most Partridge outwash. Shell fragments are also incorporated in the sand and gravel in some places. At the onset of this investigation some of this material was hoped to be useful for numerical dating purposes, but analytical results were unenlightening.

A twofold approach was taken to acquiring dateable material from the Partridge outwash. First, material originally believed to be charcoal was collected for radiocarbon dating. Second, tephra from Partridge outwash was collected and an attempt made to correlate it with a known (and dated) volcanic eruption.

Radiocarbon Dating

Charcoal was believed to be present in the Partridge outwash. Upon closer examination, the material believed to be charcoal turned out to be clasts of low-grade coal. The coal was not radiocarbon-dated for this investigation because its age would not help tie down the age of the Partridge outwash. The coal was likely eroded from some older geologic unit and redeposited with Partridge outwash.

Marine shell fragments can be found dispersed throughout the Partridge outwash. A concerted digging and sieving effort might produce enough shell material from the Partridge outwash to obtain a radiocarbon date. Radiocarbon dates on shells are usually considered to be less accurate than dates on woody material because of the tendency for carbon exchange to occur with the outer portion of the shells. This problem becomes significant particularly for shells older than about 20,000 years. Dates on shells in the range of 10 to 15,000 years have corroborated dates on wood from the same deposits (Easterbrook, oral communication, 1992). Unfortunately, because of time constraints, pursuing radiocarbon dating of shell material in Partridge outwash was not possible during the course of this project.

Tephra Correlation

Tephra from Partridge outwash was analyzed geochemically, in the hope that it could be correlated with a volcanic eruption known to have occurred during the period when these sediments were being deposited. Although the tephra had been reworked by fluvial processes, the date of the eruption would have narrowed the date of deposition of the Partridge outwash. The source for the tephra was originally thought to be Glacier Peak, which is located almost directly east of the study area. Glacier Peak was active during the late Pleistocene, and the geochemistry of various Glacier Peak ashes has been well documented.

Westgate and Gorton (1980) recommend a multiple-criteria approach to tephra characterization and caution against the correlation of tephra units based on less than complete evidence. They recommend (p. 76) that "equivalence of samples should only be considered firmly established if: (1) their stratigraphic, palaeontologic, paleomagnetic, and radiometric age relations are compatible, (2) properties of the glass shards and phenocrysts agree, and (3) the combination of these characteristics is distinctive from that of other tephra beds in the area." They do favor the use of major element composition determined by electron microprobe technique because of its ability to distinguish minor variation in the chemistry of the glasses and because of the grain-discrete nature of the procedure. Because the chemistry of a single grain is determined by electron microprobe technique, contamination is not a problem.

Tephra was collected from Partridge outwash at two locations within the study area for geochemical analysis. The first sample, PP-1, was collected from Partridge outwash at Point Partridge at approximately 55 meters elevation. The second sample, RB-1, was collected from Rodena Beach, on the east side of Whidbey Island, from well-sorted sand of the Partridge outwash at beach level. Major element chemistry was determined on the glass by the tephra chronology lab at Washington State University. Analytical results were good, and although based on only two samples, speculation about implications from the geochemical data is possible.

Based on the geochemical results, a Glacier Peak source is unlikely. The results from the tephra geochemical analysis provide only limited useful information concerning the age and origin of the Partridge outwash. Glass chemistry is tabulated in Table 5-2 and compared to Lake Tapps tephra and Glacier Peak Layer G. Although the most likely source for this tephra had seemed to be Glacier Peak because of its proximity and because Glacier Peak was active in the 11,000-to-12,000-year time span, the major-element chemistry appears to match best with the Lake Tapps tephra described by Westgate and others (1987). The Lake Tapps tephra has not been linked to a volcanic center but is believed to be 1.0 million years old, based on fission track dating. In addition, a recent laser-Argon date of 1.0 my has been obtained from detrital pumice on Camano Island (Easterbrook and others, in press).

The suggestion that tephra in Partridge outwash is correlative with Lake Tapps tephra leads to two interesting observations. The first is that Partridge outwash, a unit which must be between 12,500 and 14,000 years old, may contain significant quantities of

Table 5-2 Volcanic Glass Chemistry of Partridge Outwash Tephra

Oxide	RB-1 Wt. %	PP-1 Wt. %	Lake Tapps Wt. % *	Glacier Peak G Wt. %
SiO_2	77.70 (20)**	77.66 (16)	78.2 (4)	77.73 (72)
Al_2O_3	12.52 (12)	12.53 (8)	12.6 (2)	12.76 (16)
Fe_2O_3	0.99 (8)	0.99 (10)	0.84 (7)	1.19 (14)
TiO_2	0.17 (6)	0.15 (3)	0.19 (3)	0.19 (3)
Na_2O	3.70 (9)	3.72 (12)	3.5 (4)	3.04 (25)
K_2O	3.85 (14)	3.90 (12)	3.7 (1)	3.17 (9)
MgO	0.17 (3)	0.16 (3)	ND	0.27 (2)
CaO	0.81 (5)	0.77 (3)	0.80 (10)	1.21 (5)
Cl	0.10 (5)	0.11 (9)	0.15 (3)	0.18 (3)
Total	100 n=22	100 n=21	100 N=33	100 N=25
Key Atom Percentages				
Ca	13.0 (0.8)	12.3 (0.5)	13.5 (1.7)	20.8 (0.8)
K	71.6 (2.6)	72.3 (2.2)	72.6 (2.0)	60.8 (1.7)
Fe	15.4 (1.3)	15.4 (1.6)	13.9 (1.2)	19.2 (2.3)
K/Fe	4.6 (0.4)	4.7 (0.5)	5.2 (0.5)	3.2 (0.4)

* data from Westgate and others, (1987) Quaternary Research, 28, 340-355

** standard deviations in parentheses (in hundredths of a percent)

n = number of point analyses averaged

waterlaid 1.0 million year old tephra. This depositional scenario would require a prolific source area for the reworked tephra in addition to a fortuitous situation incorporating the 1.0 million year old tephra into this recessional outwash sand and gravel. While the above situation is not impossible, the fact that tephra deposits of that age (1.0 m.y.) have not previously been recognized in this region of the Puget Lowland is curious.

The second observation based on the geochemical results is the possibility that there may be Lake Tapps tephra in the central Puget Lowland. Up to now, Lake Tapps tephra has only been described in the southern Puget Lowland, where it occurs as fine-grained ash in early Pleistocene lacustrine deposits (Westgate and others, 1987). Based on the larger grain size of the tephra in Partridge outwash relative to that found in the southern Puget Lowland, future research efforts focused on the source for the Lake Tapps tephra should consider north Cascade volcanic centers.

The tephra in Partridge outwash could be equivalent to Glacier Peak Layer G; if so, because of the limited nature of analysis of the tephra in this investigation, the proper correlation may not have been made, but that is unlikely. Recent investigations into the age of Glacier Peak Layer B and Layer G tephras have revised the age of Layer G to around 11,200 years b.p. rather than >12,000 yrs b.p. as previously thought (Mehringer and others, 1984). Prior to Mehringer and others (1984), the two most commonly cited radiocarbon dates for Glacier Peak layer G were 12,750 ± 350 yr B.P. (W-1644; Diversion Lake, Sun River, Montana) (Porter, 1978) and 12,000 ± 310 yr B.P. (WSU-155; Lower Grand Coulee, Washington) (Lemke and others, 1975), suggesting that Glacier Peak was active over a thousand year period in the late Pleistocene. Mehringer and others (1984) believe that these dates could be revised downward based on laboratory inaccuracies and poor sample quality. If Mehringer and others (1984) are correct and Glacier Peak layers B and G are as young as 11,200 yr b.p., they would be too young to be incorporated into Partridge outwash. The date of 12,535 on shells in the Everson glaciomarine drift at West Beach places a limiting date on deposition of Partridge outwash that is 1000 years prior to Glacier Peak eruptions (if Mehringer and others (1984) are correct).

The possibility also exists that the tephra in Partridge outwash is derived from another, as yet unrecognized, eruption of Glacier Peak or Mt. Baker. No additional information is available at this time to support such a contention.

Partridge outwash is probably correlative with recessional outwash deposits described by Dethier and others (in review) on northern Whidbey Island, on the San Juan Islands, and near Sequim on the Olympic Peninsula. All of these recessional outwash deposits may have been deposited almost synchronously in front of a very irregular Vashon ice sheet or isolated lobe of the ice sheet. The possibility also exists that these gravel deposits are time-transgressive features, representing progressive locations of the ice-sheet terminus.

5.4.3 Everson Glaciomarine drift

5.4.3.1 Description

Glaciomarine sediments deposited from floating ice during retreat of the Vashon ice sheet have been included in the Everson Interstade (Armstrong and others, 1965; Armstrong and Brown, 1954; Easterbrook, 1963). Domack (1982, 1983) conducted a detailed sedimentological study of deposits identified as Everson glaciomarine drift by Easterbrook (1968) in the Penn Cove region of Whidbey Island. Domack found the following six major lithofacies within these deposits: (1) lithofacies consisting of stratified and convoluted beds of diamicton that exhibit sedimentary characteristics indicative of mass flow processes, (2) silty sand which he interpreted to be deposited in a delta-like sequence, (3) overlying pebbly silt, (4) pebbly mud, (5) massive fossiliferous diamicton, and a capping (6) gravel lag. The thickness of the unit is generally not great, usually about 2 to 6 meters. The maximum observed thickness is about 12 meters (Domack, 1982).

The detailed work conducted by Domack in the vicinity of Penn Cove provides much useful information concerning the variability of deposits from the Everson Interstade. Many of the structures he documented around Penn Cove have not been identified elsewhere in the Puget Lowland. The lack of such structures suggests that the environment at Penn Cove during deposition of Everson glaciomarine drift was not present elsewhere in the Puget Lowland.

5.4.3.2 Distribution and Stratigraphic Relationships

Massive, fossiliferous diamictons (Domack, 1982) are the most widespread and recognizable facies of Everson glaciomarine drift, having been identified in an area of approximately 18,000 square kilometers in the northern Puget Lowland and southwestern British Columbia (Easterbrook and others, in press; Blunt and others, 1987). This unit tends to develop a blocky weathering habit on exposed surfaces, a characteristic that is useful in distinguishing Everson glaciomarine drift from Vashon till in exposures lacking shells.

On Whidbey Island, Everson glaciomarine drift is present as the uppermost unit in many sea-cliffs but is absent on the higher parts of the island. Where the deposits occur in bluffs near sea-level, they typically thin progressively as the top of the sea cliffs becomes higher, leaving the impression that Everson glaciomarine drift was draped over existing topography.

The complex relationship between Everson glaciomarine drift and Partridge outwash is one of the most significant findings of this investigation. The Partridge outwash is considered a facies equivalent of Everson glaciomarine drift. Sea level was approximately 55-meters above present-day sea-level during early deposition of Partridge outwash and formation of the high terraces. No Everson glaciomarine drift is present above a 37 meter elevation in the study region, suggesting that Everson glaciomarine drift was not being deposited here during the early stages of Partridge outwash deposition. Later, during the time when Everson glaciomarine drift was deposited in the study area, the depositional environment of the study area was one where Partridge outwash was being deposited in some areas, while glaciomarine drift was being deposited in other areas. This relationship becomes evident after analyzing the two regions within the study area described below.

The first region is the Penn Cove and West Beach region. Everson glaciomarine drift can clearly be seen to overlie Partridge outwash in this region, but it is restricted to elevations below 37 meters. At one location (Rodena Beach, Fig. 5-13), Everson glaciomarine drift overlies a gravel lag deposit, interpreted here to be a transgressive surface on Partridge outwash. Apparently, once Partridge outwash deposition ceased in the Penn Cove area, sea level had dropped to approximately 37 meters above present-day sea-level. The lower section of Partridge outwash was below sea level. Narrow marine terraces were etched out of Partridge outwash deposits around Penn Cove and glaciomarine drift was deposited on those surfaces.

The second region where the Partridge outwash/Everson glaciomarine drift relationship is highlighted is Ebey's Landing. Continuous exposures in the sea-cliffs between Point Partridge and Ebey's Landing show Partridge outwash sand and gravel at Point Partridge grading into silty clay at Ebey's Landing. The sediments at Ebey's Landing are lithologically similar to Everson glaciomarine drift, except that they seem to be devoid of pebbles. Because one can follow the southward-fining Partridge outwash sequence between Point Partridge and Ebey's Landing, the silty clay at Ebey's Landing seems to be a result of Partridge outwash distal deposition rather than a separate glaciomarine deposition.

The conclusion that these two depositional environments occurred simultaneously in the study area is documented here. Everson glaciomarine drift is present in the Coupeville area up to elevations of 37 meters. If the Coupeville area was submerged up to 37 meters above present sea level, Ebey's Landing had to also be below sea level during the same time period. The absence of a contact between Partridge outwash and Everson glaciomarine drift at Ebey's Landing, such as the contact that exists between those two units at Rodena Beach, suggests that the depositional processes taking place at Ebey's Landing during this time period were a continuation of the depositional environment of the Partridge outwash deposition. Apparently, deposition of outwash sand and gravel had ceased in the Coupeville area before deposition of these sediments ceased at Ebey's Landing.

5.4.3.3 Age

Everson glaciomarine drift has been radiocarbon-dated extensively. More than 80 radiocarbon dates on glaciomarine drift have been obtained in Washington and British Columbia, all placing the age between 11,000 and 13,500 years. Three radiocarbon dates, 12,535 at West Beach (Easterbrook, 1966; 1968) and two dates of 13,600 from glaciomarine drift on the north side of Penn Cove (Pessl and others, 1989), have been obtained by previous investigators in the study area.

5.5 Holocene Dune Sand

The western high terrace is capped in many places by well-sorted sand. The sand appears to be structureless in most exposures, although, at one exposure where it partially fills a kettle, stratification parallel to the slope of the kettle is apparent. The contact between the sand and the underlying Partridge outwash is oxidized. Fine gravel and coarse sand, derived from the underlying Partridge outwash, is common in the lower portion of the sand unit.

This sand cap is interpreted to be windblown sand. Grain-size analysis (Figure 5-23) is consistent with this interpretation. According to Collinson (1986), the normal size range for windblown sand bedload is 0.1 mm to 1 mm. A modal size of approximately 0.3 mm is characteristic. The bulk of the sample analyzed for this investigation fell within the 0.1 to 1.0 mm size range. The modal size for the sample was the 0.20 to 0.30 mm size fraction. Silt and fine sand have been reported overlying gravelly beach deposits at other locations on northern Whidbey Island and at Cattle Point on San Juan Island and have been interpreted by Dethier and others (in review) as having an eolian origin.

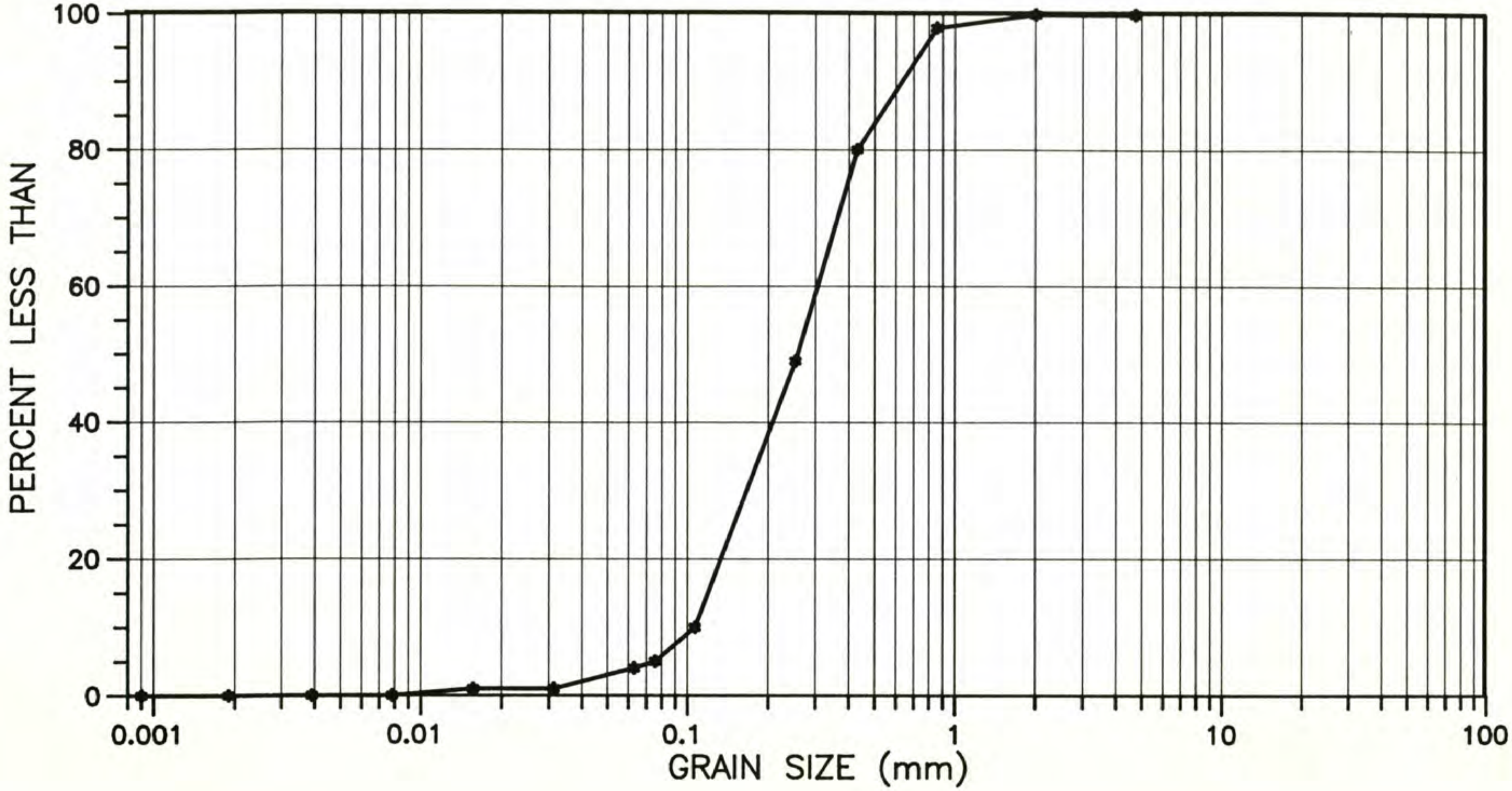

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FIGURE 5–23

GRAIN–SIZE DISTRIBUTION
FOR SAND UNIT AT TOP OF BLUFF
POINT PARTRIDGE, WHIDBEY ISLAND

6.0 QUATERNARY GEOLOGIC HISTORY AND GEOMORPHIC DEVELOPMENT

6.1 Early Pleistocene (pre-Vashon)

The geologic record for the Puget Lowland during the Pleistocene calls for at least six separate glaciations, including the Vashon Stade (Easterbrook and others, 1981). Aside from the Vashon deposits, which are the dominant geologic units in the study area today, remnants of two earlier glaciations (the Double Bluff and Possession) and one interglacial period (the Whidbey) are present on central Whidbey Island.

The Whidbey Formation overlies Double Bluff Drift unconformably and is also present near sea-level at places along the south shore of Penn Cove. During the Whidbey Interglaciation, this region was apparently occupied by the floodplain of one or more large rivers. The most likely river systems to have occupied this region, assuming drainage configurations of west-slope Cascade Range rivers have not been altered dramatically during the late Pleistocene, are the Skagit and Stillaguamish Rivers (Figure 6-1). The floodplain of either of these two rivers can be imagined to have reached as far west as Whidbey Island if the present-day Puget Sound troughs in that vicinity did not exist. The study area during that period would have been a floodplain with very low relief and abundant marshy areas.

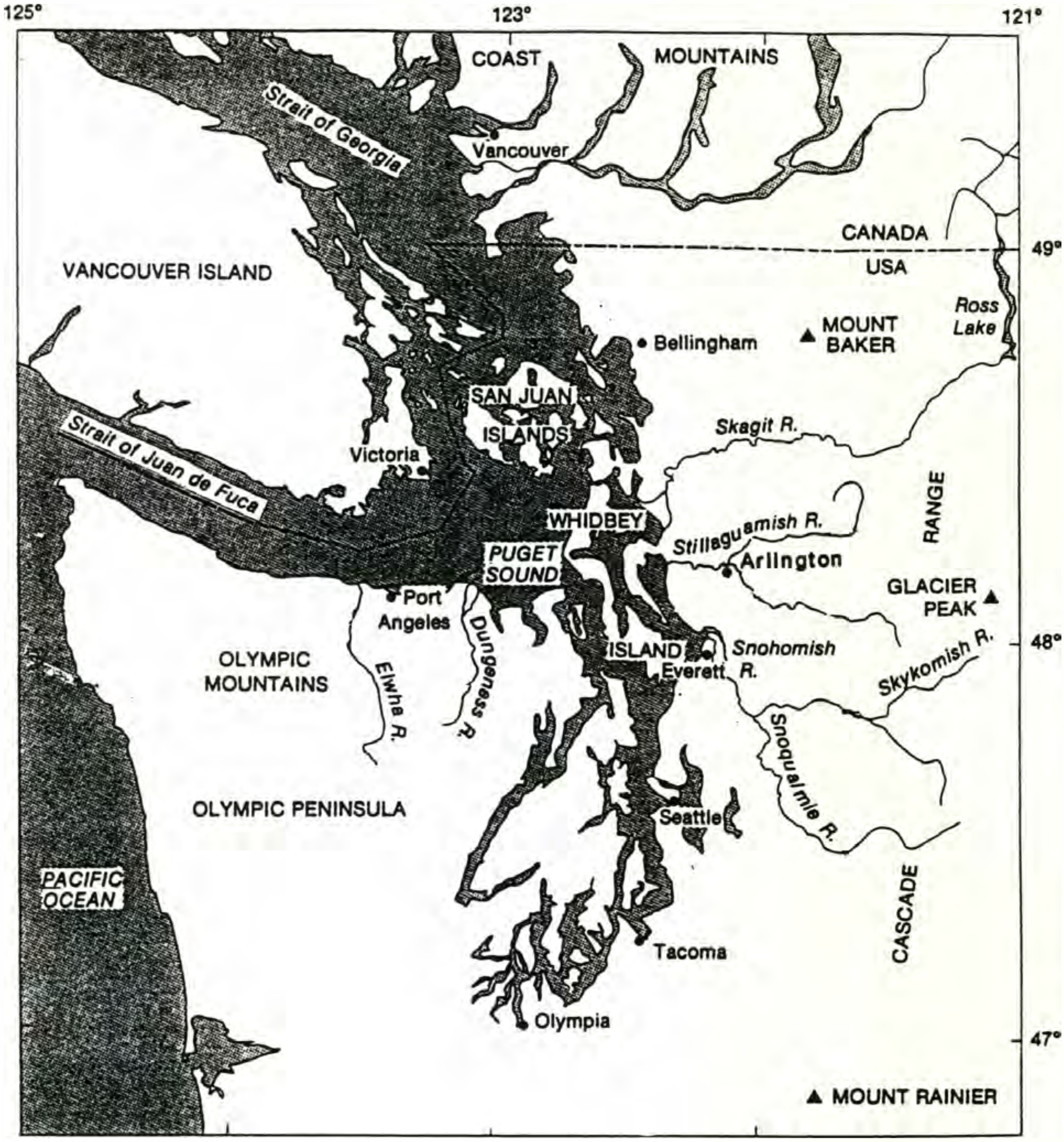


Figure 6-1 Regional map showing locations of the Skagit and Stillaguamish Rivers and Glacier Peak relative to the project area.

Between the Whidbey Interglacial and the beginning of the Vashon Stade, another glacial period, the Possession, occurred. Although Possession glacial deposits have been documented north of the study area at Blower's Bluff (Easterbrook, 1968), and surely affected the study area, no Possession deposits have been identified within the study area.

Much of the sculpting of the land surface in the study area probably occurred during the Vashon glaciation as documented for elsewhere in the Puget Lowland (Bretz, 1913; Crandell and others, 1965). Some of the work of transforming the flat, low-lying landscape of the Whidbey Interglacial into rolling hills could have occurred during the Possession glaciation, but there is no evidence in the study area to suggest so. Where present in the study area, the contact between the Whidbey Formation and overlying Esperance sand is unconformable but fairly flat. This relationship is visible on the west shore of Whidbey Island north of West Beach and south of Ebey's Landing. Based on these observations, the Possession glacier apparently did not significantly alter the flat-lying landscape of the Whidbey Interglacial in the study area.

6.2 Vashon Advance

The Vashon ice sheet crossed the Canada/United States border about 18,000 years ago (Clague, 1980; Armstrong and others, 1965; Hicock and others, 1982; Hicock and Armstrong, 1985; Easterbrook, 1969). The ice sheet split into two lobes, the Juan de Fuca lobe, flowing westward out the Strait of Juan de Fuca, and the Puget lobe, flowing southward into the Puget Lowland. As the Puget lobe moved south, it entered a northward-draining fluvial system that occupied the Puget Lowland during the Olympia nonglacial period. Olympia nonglacial sediments are common in the southern and central Puget Lowland but not abundant in the northern Puget Lowland. No geologic unit correlative with Olympia nonglacial sediments was identified in the study area during the course of this investigation.

As the ice sheet advanced southward past the Strait of Juan de Fuca it blocked the Puget Lowland drainage system, and proglacial lakes were impounded in the stream valleys. These lakes are represented by units such as the Lawton clay, present in the Seattle area. In front of the southward-advancing ice of the Puget lobe, outwash sand and gravel of the Esperance sand filled earlier-formed lakes and spread an apron in front of the advancing ice (Newcomb, 1952; Mullineaux and others, 1965).

As the Puget lobe of the Vashon ice sheet advanced over its own outwash, it sometimes rode over the older units and sometimes scoured sharply through the older units and dove below present-day sea-level. The glacier left patches of till in many places. The Vashon glacier scoured the pre-existing stream valleys and is responsible for the existence of the troughs which Puget Sound occupies (Crandell, 1965; Easterbrook, 1969).

The flat, low-lying landscape of the Whidbey Interglacial was sculpted into undulating hills with up to 60-meters of relief before the end of the Vashon glaciation. The timing of transformation is demonstrated by the present-day topography in three places in the study area. The Town of Coupeville is situated around two 43-meter hills cored with the

Whidbey Formation (Figure 1-3). The topographic relief of these hills has been preserved because they are composed of the relatively resistant Whidbey Formation . The same situation exists at the knob between Ebey's Landing and Fort Casey. This knob is cored with Whidbey Formation overlying Double Bluff Drift and has a cap of Vashon till and Everson glaciomarine drift in places. The topographic relief of the knob and the two hills at Coupeville is caused by the thickness of the Whidbey Formation. The present-day topography in the three locations described was formed primarily before removal of the Vashon ice-sheet. This interpretation is supported by the presence of thicker Whidbey Formation exposures than elsewhere, and by the cap of Vashon till and Everson glaciomarine drift that appear to mantle pre-existing topography in the Whidbey Formation.

6.3 Vashon Maximum

The Puget lobe of the Vashon ice sheet reached its maximum geographic extent just south of Olympia about 15,000 years ago. It apparently did not remain there long, as not much of an end moraine was built (Bretz, 1913; Mackin, 1941; Crandell, 1963; Carson, 1970; Porter and Carson, 1971; Lea, 1984).

6.4 Vashon Recession

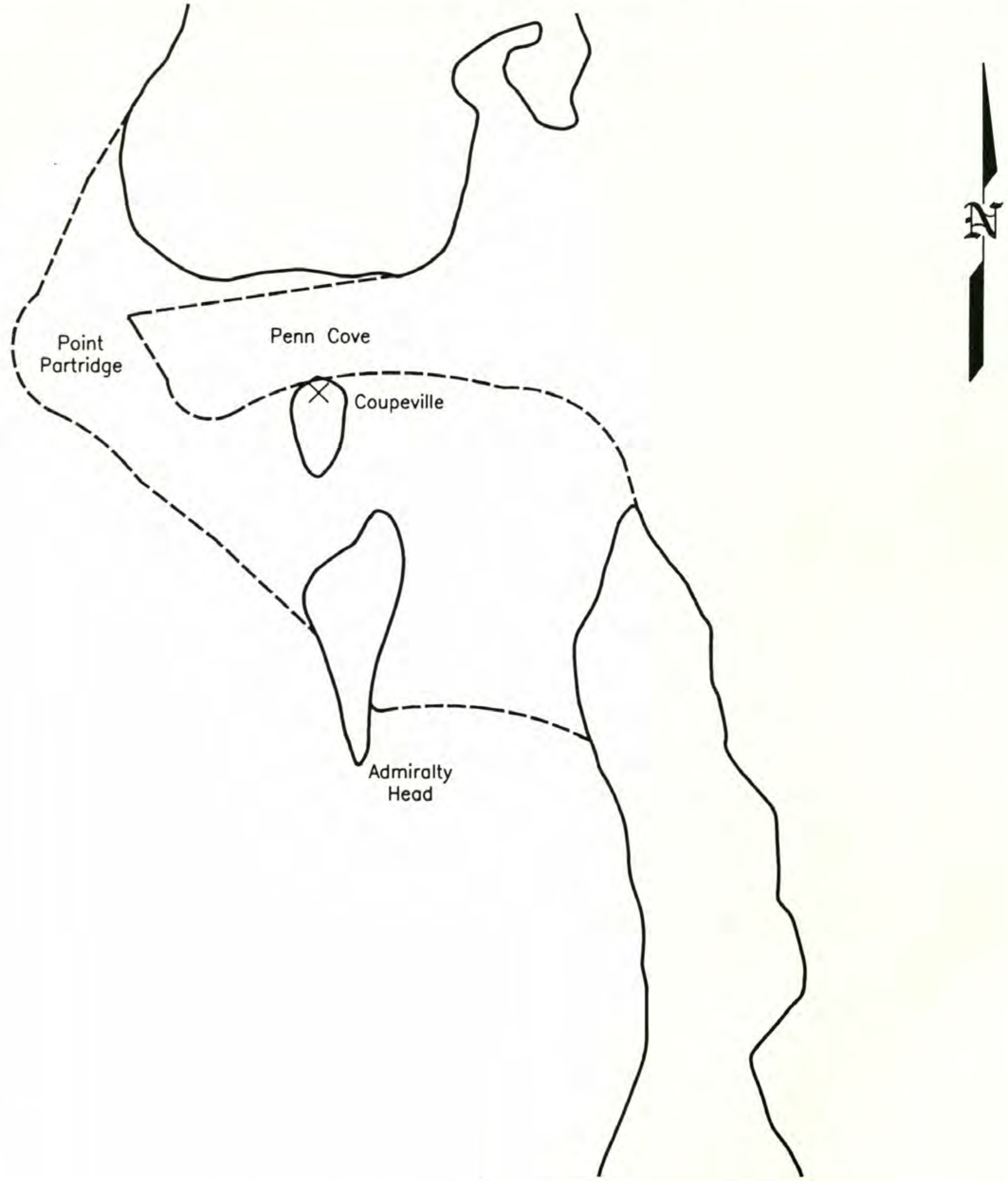
By 13,500-14,000 years ago, the ice sheet had receded to north of Seattle, based on two radiocarbon dates, one at 13,650 ± 550 from peat at the base of Lake Washington (Rigg and Gould, 1957) and one at 13,570 ± 130 years (UW-35) from late-glacial sediments in the Snoqualmie valley (Porter, 1976). With the ice sheet receding, the troughs of Puget Sound first became ice-free and available for fluvial and lacustrine activity while the outlet at the Strait of Juan de Fuca was still blocked, preventing sea water from entering. Proglacial lakes were once again impounded in the Puget Lowland (Bretz, 1913; Curran, 1965; Mackin, 1941; Thorson, 1980, 1981). Drainage was to the south, out the Chehalis River valley.

The timing of retreat of the Juan de Fuca lobe has historically been the subject of some debate. Thorson (1980, 1981) argues that the Juan de Fuca lobe, calving in deep marine water, retreated much more rapidly than the Puget lobe until it had reached a bedrock sill. Booth (1987) calculated a minimum rate of retreat for the Juan de Fuca lobe of 200 meters per year based on radiocarbon dates. Thorson based his interpretation on features he believed to be northward-draining outwash channels in the northeast corner of the Olympic Peninsula (northwest Puget Lowland). Because ice was still present in the Puget Lowland during the time that, according to Thorson, these channels were active, the channels could only have been draining northward if the Strait of Juan de Fuca was ice-free by that time. Other researchers (Heusser, 1973a; 1973b; 1982; Easterbrook and others, in press) cited radiocarbon and palynological evidence supporting the hypothesis that the Juan de Fuca lobe had retreated from the western Olympic Peninsula between 12,020 and 14,460 years b.p. (Heusser, 1973a), suggesting a more synchronous retreat of the two ice-sheet lobes.

6.5 Everson Interstade

When the Puget lobe retreated and thinned to north of Seattle, marine water was finally free to flow into the troughs of Puget Sound again (Blunt and others, 1987). Timing of the marine incursion is bracketed by the time that ice is known to have been still in the Strait of Juan de Fuca and Puget Lowland and dates on Everson glaciomarine drift. These two limitations require the marine incursion to have been between 12,535 (Easterbrook, 1966) and 13,600 years b.p. (Pessl and others, 1989) in the study area. Between the beginning of marine influence in the Puget Lowland and final disappearance of ice in the region, the major landforms and geologic deposits were formed in the study area.

A map reconstruction of the study area can be generated that shows how the land surface would have appeared immediately following removal of the Vashon ice sheet (Fig. 6-2). Figure 6-2 was drawn based on the distribution and thickness of sediments that post-date Vashon till. When these post-Vashon till deposits are removed from the stratigraphy, the resulting map shows the configuration of Whidbey Island in the study area immediately after recession of the Vashon ice-sheet. This reconstruction is helpful to understanding the distribution of ice-recessional units in the study area. Two useful observations are immediately apparent from Figure 6-2. The first is that most of present-day Whidbey Island in the vicinity of Point Partridge and Smith Prairie did not exist prior to Vashon recession. Today, the east-west orientation of Penn Cove appears to be an anomaly in the Puget Lowland, where most of the topography has a north-south orientation streamlined during the Vashon glaciation. However, prior to deposition of ice-



- - - - - - Present Day Whidbey Island Coastline

——— Coastline Prior to Deposition of Recessional Units

FIGURE 6–2

Reconstruction of Pre–Vashon Recession Topography in Project Area

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recessional sediments, landforms in the study area had a dominantly north-south orientation just as in other areas of the Puget Lowland. The second observation is that the two high terraces on which Partridge outwash now is found were actually basins before the Vashon recession. The present-day low area around Coupeville was a topographic high at that time.

6.5.1 Problem of the Origin of the Terraces

During the course of this investigation, a multiple-working-hypothesis approach was taken to evaluating the origin of the terraces in the study area. Several combinations of potential origins exist for the two terrace levels, with different implications for sea-level and deglaciation. The terraces may be either constructional or erosional landforms, formed by either marine of fluvial processes. For each theory, four questions must be answered about the terraces:

(1) What geomorphic processes formed them;

(2) Were they formed at the same time;

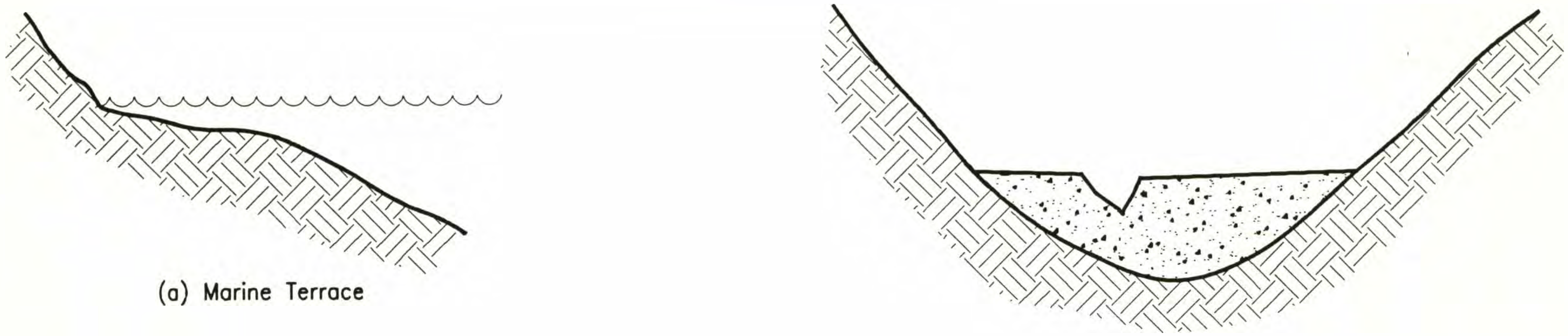
(3) What does their origin reveal about sea-level at the time of their formation; and

(4) What are their ages?

Table 6-1 and Figure 6-3 summarize the origins considered for the terraces.

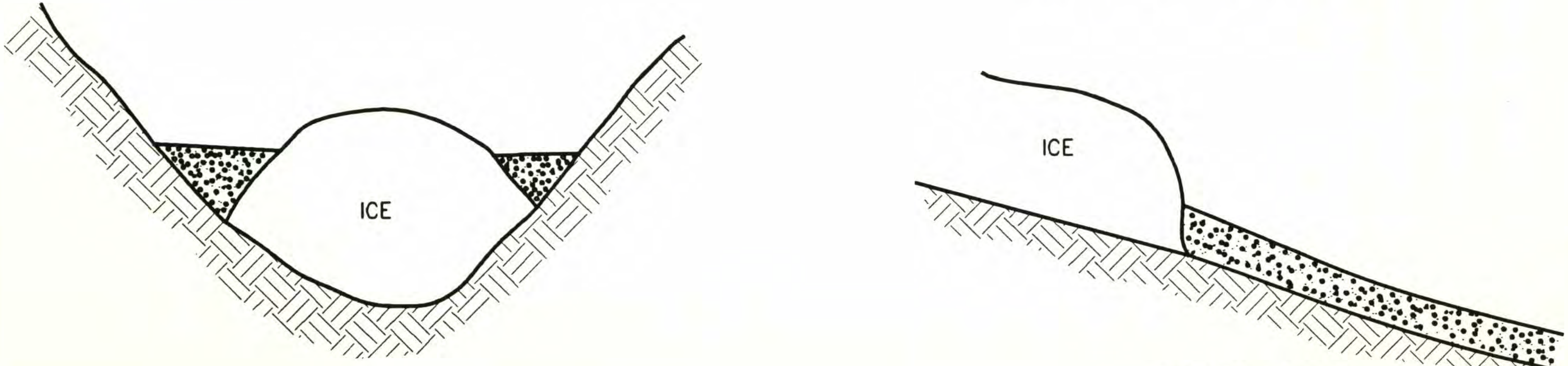
Table 6-1 Origins Considered for Terraces in Study Area

Origin	Sea-Level Implication	Geologic Evidence
Marine (wave-cut)	Sea-level at terrace-level	Erosional surface - surface may crosscut structure of underlying geologic unit. Width of terrace related to erodibility of geologic unit and duration of sea level at that elevation
Nonglacial fluvial	No direct sea-level implication - terrace would have been higher than the contemporary sea-level.	Must be postglacial Possibility of large river in area Sedimentary structures, alluvial deposits
Kame Terrace	No sea level implication	Ice-contact features Sedimentary structures Cross-stratification
Outwash Plain	No direct sea-level implication - terrace would have been higher than the contemporary sea-level.	Remnants of dissected outwash plain in other locations at similar elevations Sedimentary structures Cross-stratification
Marine Delta	Approximately one meter above topset/forset bed contact	Sedimentary structures Forset bedding Large-scale coarsening-up sequence
Kame Delta	If marine, sea-level would have been approximately one meter above the topset/foreset bed contact. If freshwater, contemporary sea-level would have been lower than the delta.	Sedimentary structures Foreset bedding Large-scale coarsening-up sequence Ice-contact features



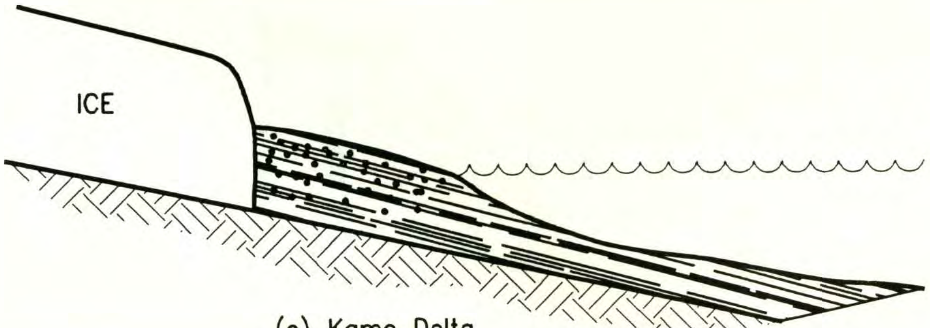
(a) Marine Terrace

(b) Nonglacial Fluvial Terrace



(c) Kame Terrace

(d) Outwash Plain



(e) Kame Delta

FIGURE 6–3

Origins Considered for
Terraces in the
Study Area

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6.5.1.1 Marine (wave-cut) Terraces

A marine terrace origin (wave-cut terrace) was initially considered for both terrace levels in this investigation. Terraces formed by marine processes would be erosional surfaces. Under this scenario, the material in which the terraces are cut would be older than the surfaces themselves, and there should be evidence of an erosional surface at or near the terrace tops. If this origin were demonstrated, the implication would be that relative sea-level stood at approximately 60 meters above present level as the Vashon ice sheet was initially retreating, forming the high terraces in previously deposited material. If the lower terrace was also an erosional marine terrace, relative sea-level would have dropped to approximately 30-meters above the present level by the time of lower terrace formation. This relative sea-level drop would likely have been caused by isostatic rebound of the land as the weight of the ice was removed. If Easterbrook (1966) is correct that Everson glaciomarine drift was deposited on the lower terrace but not on the upper terraces, than the period of formation of the lower terrace may be equivalent to the deposition period for Everson glaciomarine drift.

6.5.1.2 Nonglacial Fluvial Terraces

A fluvial origin for one or both terrace levels was initially considered. The eastern high terrace slopes to the southwest with a drop of 6 meters in its 5 km length, a slope of 0.0012 (1.2 m/km), discernable on a 1:24,000 scale topographic map. The low (Ebey's Prairie) terrace slopes to the southwest with a drop of 12 meters in 2.4 km, a slope of 0.005 (5 m/km). No slope is discernable on the western high terrace. The terraces could be normal fluvial terraces, unrelated to glaciation, formed in the floodplain of an ancestral river and later left abandoned and elevated.

This hypothesis was abandoned for three reasons. First, both terrace levels are composed of Vashon recessional deposits. Second, the presence of kettles in the high terrace requires a glacial origin. Third, no major river systems exist on Whidbey Island today. Because the Puget Sound troughs had to be carved before the end of the Vashon Stade (Bretz, 1913; Crandell and others, 1965; Easterbrook, 1968, 1969), the study region could not have been part of a major river floodplain once the Puget Sound troughs became ice-free.

6.5.1.3 Kame Terraces

A kame terrace, a fluvial surface formed by water flowing on or banked against ice, is a second possible fluvial origin. Kame terraces are also, by definition, banked against a valley side. The kettle topography west of Penn Cove requires ice to have been nearby when the Partridge outwash was deposited. Ice (at least icebergs) continued to occupy the vicinity until approximately 12,500 years ago while Everson glaciomarine drift was being deposited. A kame terrace origin was ruled out for the terraces in the study area because no valley walls exist for the terraces to be banked against. The high terraces are the highest topography in the study area.

6.5.1.4 Outwash Plain

The terraces could be remnants of an outwash plain, formed by streams issuing from the terminus of the ice sheet. The sediments composing the high terrace (upper level outwash plain) would have been dissected subsequently under this scenario. This origin would imply a sea-level somewhat lower than the terrace level at time of formation.

If either or both of the terrace levels were part of formerly more extensive outwash plains, remnants of this surface and associated deposits would be expected elsewhere at similar elevations. This is not the case. The highland area north of Penn Cove and the region south of the study area are composed mostly of older glacial and interglacial units (Double Bluff Drift, Whidbey Formation, Esperance sand, Vashon till). Based on this observation, the high terraces were determined to not be part of a formerly-more-extensive outwash plain. The low terrace level, which is composed primarily of glaciomarine drift, is not a fluvial surface.

6.5.1.5 Marine Delta

A delta plain, the upper surface of a delta, is the last potential origin considered for the terraces in the study area. The high terraces could be one dissected delta or two undissected deltas. In this situation, the high terrace surface would be a delta plain, formed by advancing delta topset beds. if the delta were a marine delta, sea-level at that time would have been near the topset/foreset bed contact.

The origin of the lower terrace is speculative under the delta hypothesis. It could be the deposits on the floor of the basin into which the delta(s) were advancing, or a marine terrace, representing sea-level at a time subsequent to delta formation. If the low terrace represented the basin into which a marine delta was advancing, it wouldn't necessarily have been a flat surface originally, but would have became flatter as a result of the deposition of nearly horizontal bottomset beds.

The presence of deltas in proglacial lakes occupying the Puget Sound basin as the Vashon ice sheet backwasted has been discussed by Bretz (1913) and Thorson (1980; 1981; 1989). Raised marine deltas have also been identified that date from Vashon recessional times (Thorson, 1980). Alley and Chatwin (1979) and Armstrong (1981) have described deltaic features associated with Vashon recessional deposits on southwest Vancouver Island and the Fraser Lowland. Results from this investigation show that formation of two marine deltas did play a role in the origin of the terraces in the study area.

6.5.2 Preferred Explanation: Formation of Kame-Delta Complex

Consideration of the hypotheses described in the previous section led to the following interpretation for the origin of the terraces. After marine water had re-entered Puget Sound, the study area was subjected to rapid deposition of coarse outwash gravel into a marine environment. The source for the large volumes of sand and gravel was the deteriorating Cordilleran Ice Sheet. Sediment-laden outwash streams formed two separate coarse kame-delta complexes in the study area. Figures 6-4 and 6-5 depict this

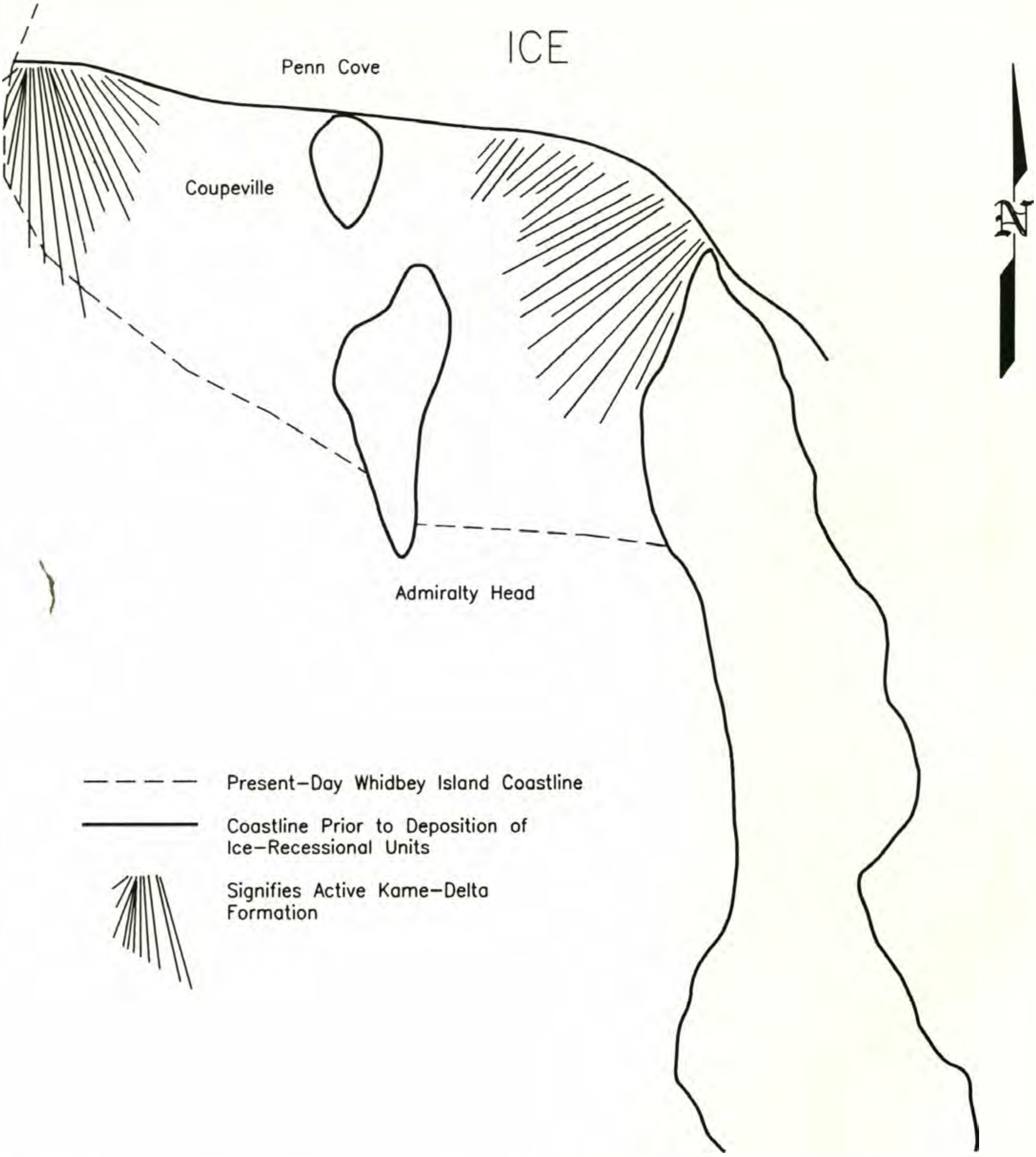

FIGURE 6-4

Map Reconstruction of Project Area During Formation of Kame Delta Complexes

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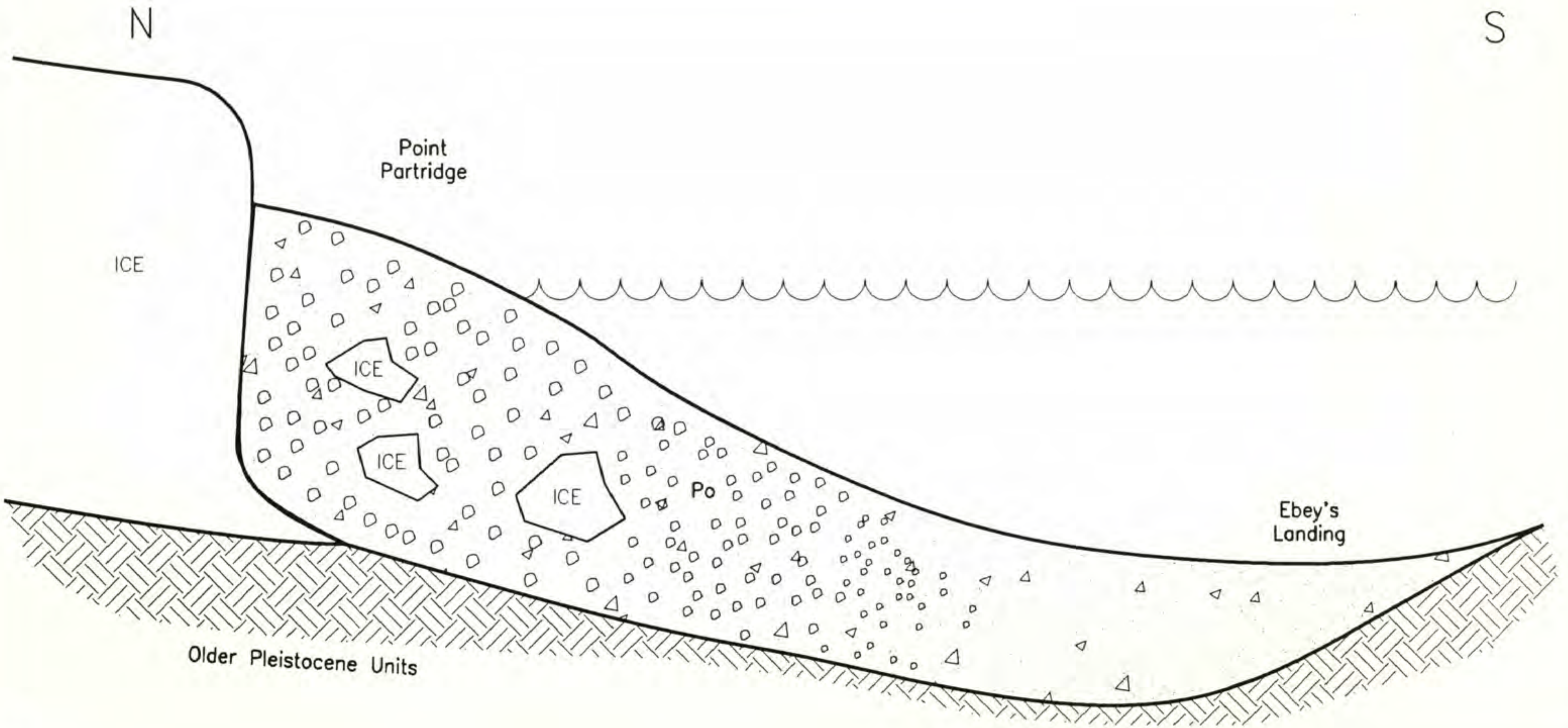

Po = Partridge Outwash

No Vertical Exaggeration

FIGURE 6–5

Depositional Setting for Kame Delta Formation

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scene. This constructional process of kame-delta formation, resulted in the present-day surfaces of both high terraces and the Ebey's Prairie low terrace. The scarps that elevate the high terraces above Ebey's Prairie are the delta fronts. This interpretation is based on the following geologic evidence:

(1) Both high terraces are composed of Partridge outwash, which was derived from the Cordilleran Ice Sheet (based on clast lithologies). The entire thickness of the outwash exhibits a large-scale coarsening-up sequence, characteristic of an advancing delta,

(2) Foreset bedding is common in Partridge outwash in both high terraces,

(3) In beach exposures between Point Partridge and Ebey's Landing, the cobble foreset beds within the western high terrace can be seen grading into sandy bottomset beds towards Ebey's Landing. The sediment in the lower section is finer than farther north, and the dip of the bedding becomes more gentle, from 25 to 4 degrees to the southeast. This is consistent with the scarp being the delta front. The slope of the scarp, measured off a topographic map, is approximately 12 degrees.

(4) The 55-meter knob, to the north of Fort Casey, located geographically between the two high terraces (Fig. 1-2), contains no Partridge outwash. It is composed entirely of older Pleistocene units (Vashon till, Whidbey Formation, and Double Bluff Drift). If the two high terraces were once

continuous, Partridge outwash, which makes up most of the stratigraphic section of both high terraces, would have been deposited on top of the 55 meter knob and should have been left as a remnant when the 30-meter terrace was cut at a later time.

(5) All current indicators, including ripples, foreset beds, and cross-stratification, support the idea that flow was toward the scarps. In the western high terrace, measurements of the dip of foreset beds ranged from 24 degrees south, in the large gravel pit near Coupeville, to 25 degrees to the southeast at Point Partridge. A foreset bed dip of 25 degrees to the southwest was measured from Partridge outwash north of Harrington Lagoon on the eastern high terrace.

(6) Relict channels on the eastern high terrace surface, visible on air-photos (Fig. 6-6), appear to flow toward the scarp. The eastern high terrace has a shallow inclination toward the scarp.

(7) No contact between Partridge outwash and Everson glaciomarine drift, or any other deposit, can be found at Ebey's Landing. The sediments composing Ebey's Landing are fine grained (Fig. 6-7) and are interpreted to be bottomset beds, deposited in a prodeltaic environment.

Figure 6-6 Air photograph of Smith Prairie showing relict channels.

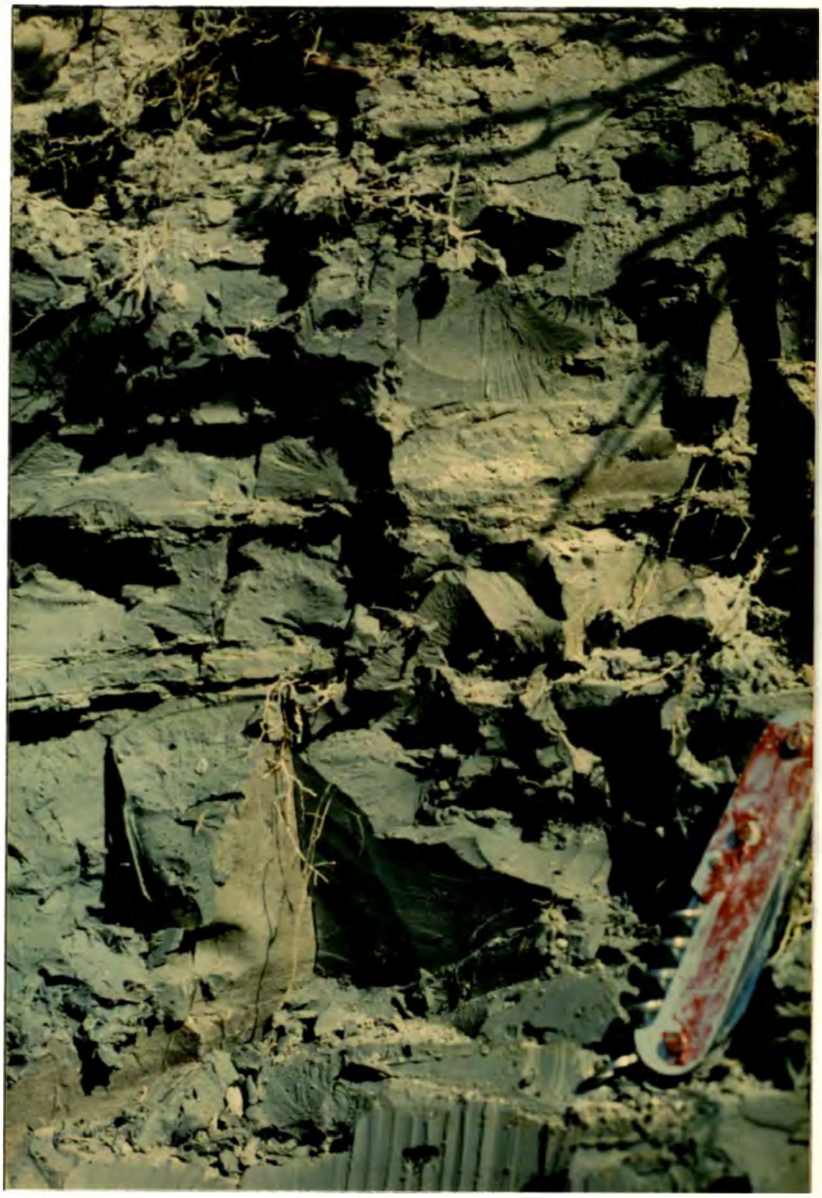


Figure 6-7 Silty clay that makes up the sea-cliff at Ebey's Landing. These sediments are interpreted to be prodelta deposits.

(8) The presence of ice in the area is confirmed by kettles in the Point Partridge area and isolated kettles in the eastern high terrace. Partridge outwash contains collapse structures in the vicinity of these depressions, supporting the interpretation of these depressions as kettles.

6.5.3 Intermediate Sea-level Stillstands

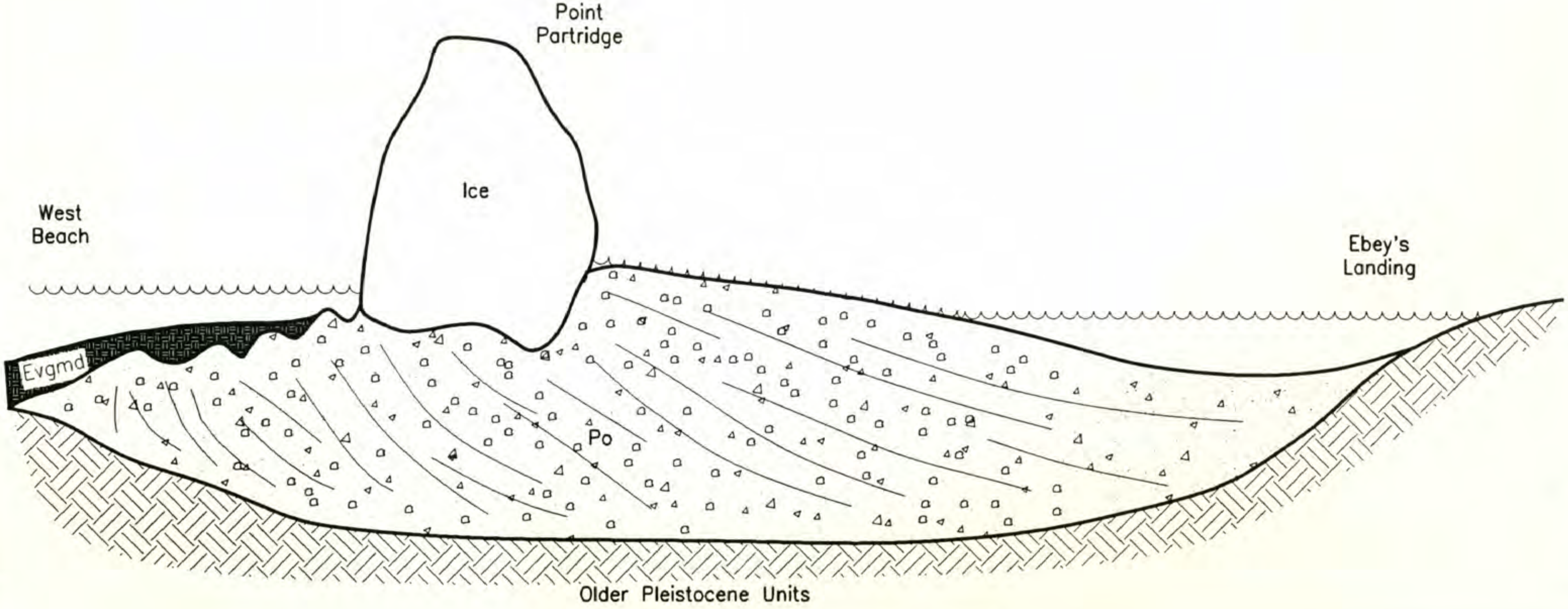
Figures 6-8 and 6-9 show strandlines visible on air photographs of the study area. These strandlines, not visible on topographic maps, record sea-levels that were intermediate between sea-level when the kame delta complex was most actively forming and a later time when sea-level was at approximately 37-meters in elevation (discussed later). Four sets of strandlines are visible on the photographs at 40, 46, 49, and 52 meters. In the field, these strandlines are marked by thin gravel-lag deposits. Strandlines are only preserved on the knob of older Pleistocene deposits, not on the high terraces composed of Partridge outwash. This differential preservation is probably the result of the different erodibility of Partridge outwash and older Pleistocene units. Narrow strandlines cut into Partridge outwash wouldn't persist as topographic features because this unit is more erodible.

6.5.4 Formation of Marine Terraces around Penn Cove

After sea-level had dropped to around 30 meters, the main era of deposition of Everson glaciomarine drift began. Figure 6-10 depicts the study region during this time. A narrow marine terrace was cut around the margin of Penn Cove at 30-meters. An excellent

Figure 6-8 Strandlines on knob north of Fort Casey. See Figure 6-9 for exact location of photograph. North is to the right in this photo.

Figure 6-9 Strandlines (highlighted) on knob north of Fort Casey



Po = Partridge Outwash

Evgmd = Everson Glaciomarine Drift

No Vertical Exaggeration

FIGURE 6–10

Depositional Scenario During Main Period of Everson Glaciomarine Drift Deposition, Sea Level at Approximately 37 Meters

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exposure of the transgressive surface, showing sand of Partridge outwash overlain by Everson glaciomarine drift with the two units separated by a gravel lag, can be seen at Rodena Beach (Figs. 5-13, 5-17, 5-18).

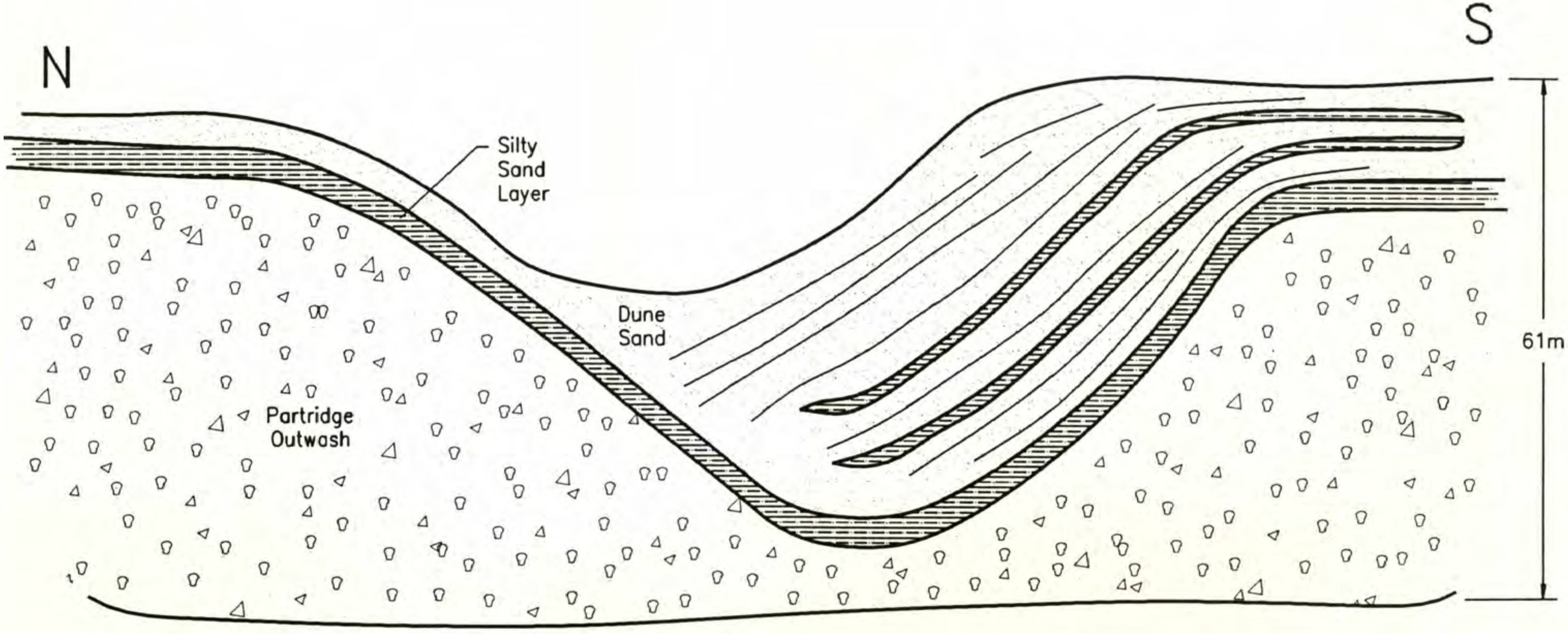
6.5.5 Relationship of Partridge Outwash and Everson Glaciomarine Drift

The relationship between Partridge outwash and Everson glaciomarine drift is central to understanding the geologic history of the study area. The stratigraphy at three locations in the study area supports my interpretation of that relationship.

6.5.5.1 Kettle Cross Sections

Two stratigraphic sections are important in highlighting the relationship of the Everson glaciomarine drift to the kettles in Partridge outwash. At West Beach, undeformed Everson glaciomarine drift laps into a kettle in the Partridge outwash. The kettle morphology must have formed before sea water had access to this kettle and before Everson glaciomarine drift was deposited. Sea water must have had access to the kettle to allow deposition of glaciomarine drift in the kettle.

At an exposure farther south, south of Point Partridge, the sea-cliff exposes a cross-section through another kettle. A drawing of this section is shown in Figure 6-11. Well developed collapse features are visible in the Partridge outwash on both sides of the kettle. Above Partridge gravel, a 1-meter-thick layer of undeformed fine sandy silt drapes down into the kettle. This sandy silt layer is continuous with the top of the terrace gravel



No Vertical Exaggeration

FIGURE 6–11

Kettle Cross Section at Point Partridge

to the south at an elevation of 60 meters. To the north, the contact is not well exposed. The sandy silt layer shows evidence of weathering (oxidized zone at contact with gravel) and is dark colored (enriched in organic material) where it is exposed at the topographic bottom of the kettle. Well-sorted, rippled sand is present below the organic-rich zone on the south side of the kettle. On the north side, the soil layer is in direct contact with Partridge outwash below. The sandy silt layer is uniform in thickness; it does not appear to thicken in the low area of the kettle. A higher rippled sand with bedding planes parallel to the sandy silt layer below is present in the southern part of the exposure. At least two additional sandy silt layers are present above the lowest one. Both show evidence of weathering (oxidized zone at base). Capping the exposure and filling most of the original kettle is more crossbedded sand.

The kettle cross-section described above is interpreted to record the following events:

(1) A large volume of Partridge outwash was shed off a lobe of stagnating ice northwest of this location. The northwest source for the outwash is required by the southeast-dipping foreset beds at this location. A block of ice was buried in Partridge outwash at this site, as were many others in this region.

(2) As the block of ice melted, the Partridge outwash collapsed into the depression, forming a kettle.

(3) Windblown sand, driven by prevailing southwest winds, began to fill the depression. The dunes draped into the kettle from the southwest. Coarser material, derived as slopewash from Partridge outwash, became incorporated in the lower layer of sand.

(4) Fine sediment, dominantly silt-size, became available to the wind and was deposited uniformly over the terrace surface. The reason that this material was distributed uniformly across the Partridge gravel, rather than collecting in low areas as was the windblown sand deposited in the kettle earlier, may be related to the high cohesive properties of the finer material. High cohesion of the silt might have made it possible for these grains to accumulate on the uphill slope of the kettle.

Apparently the topographic low in the bottom of the kettle was more conducive to vegetation growth, which has left an organic-rich zone in this location. This area may have been more moist than adjacent higher locations because water collected here or because the water table was close to the surface here.

(5) Subsequent to the formation of this ancient soil, deposition of windblown sand from the southwest resumed and continued until the kettle was nearly filled, leaving only a remnant of the original depression. Why deposition of the windblown sand was interrupted for a period during soil

formation is a mystery. It could simply be related to the availability of sand that could be transported by the wind.

In contrast to the first kettle cross-section described, the second kettle contains no glaciomarine drift even though the bottom of the depression is only approximately 6 meters above mean sea-level today and glaciomarine drift is found up to 30-meters high in this area. This lack of glaciomarine drift can be explained two ways:

(1) the depression caused by melting of the buried block of ice did not form until after glaciomarine drift deposition had ceased; or

(2) even though this depression would have been low enough for glaciomarine drift to be deposited here, the surrounding land surface was too high to allow marine water to enter the depression.

Hypothesis (2) seems more likely for two reasons. First, large differences in the rate of ice meltout in similar deposits located so close together, buried to similar depths and in similar proximity to the ice sheet seem unreasonable. Second, the rate of sea-cliff retreat in this area is high because the cliffs are exposed directly to waves off the Strait of Juan de Fuca and the unconsolidated nature of Partridge outwash makes it very erodible material. High erosion rates are evident today, particularly in the vicinity of military gun emplacements (circa 1930) near Point Partridge. Many of these gun emplacements have been completely eroded out of the sea-cliffs. Substantial sea-cliff retreat has probably occurred since the end of the Pleistocene. This kettle could easily have been isolated from sea water by higher terrain to the west.

The problem with hypothesis (2) is that with highly permeable material such as Partridge outwash, a water-table lake would be expected to have occupied the kettle while sea-level was above the bottom of the kettle and the kettle was in proximity to the shoreline.

6.5.5.2 Penn Cove Marine Terraces

The narrow marine terrace cut around the perimeter of Penn Cove and the kettle section at West Beach are the only locations in the study area where glaciomarine drift overlies Partridge outwash. The association of the glaciomarine drift with this marine terrace and with a lower sea-level than during earlier Partridge-outwash deposition suggests that this terrace formed in Partridge outwash and glaciomarine drift was deposited on it at elevations below 37 meters, during the very latest glacial period in this region.

6.5.5.3 Ebey's Landing

If Partridge outwash and Everson glaciomarine drift were truly two sequential units, with deposition of glaciomarine drift beginning after cessation of Partridge outwash deposition, a clear contact should be visible between Partridge outwash and Everson glaciomarine drift at Ebey's Landing. Ebey' s Landing is low enough in elevation to have experienced glaciomarine conditions. Instead, the stratigraphic sections at Ebey's Landing show a gradation from Partridge outwash to finer material, with a gravel lag at the top of the section (Fig. 6-12), interpreted to be a regressive beach deposit. This sequence suggests the facies relationship between Partridge outwash and Everson glaciomarine drift described in detail in Section 5.4.3.2.

Figure 6-12 Regressive beach deposit at Ebey's Landing.

6.6 Holocene

The youngest deposit in the study area is the dune sand that caps the western high terrace on the west coast of Whidbey Island. The dunes were probably deposited by winds off the beach. They are completely vegetated with mature trees. Easterbrook obtained a date of 700 years from a piece of wood in silt associated with this deposit (oral communication, 1987).

7.0 IMPLICATIONS FOR DEGLACIATION AND SEA-LEVEL FLUCTUATION

7.1 Glacial Stillstand or Stagnation

The geologic record of glaciation, subaerial outwash, and glaciomarine deposition preserved in the study area has not been recognized elsewhere in the Puget Lowland. Exploring reasons why preservation of that record has occurred in the study area is the subject for this section.

Previous research has described the rapid, chaotic decay of the Cordilleran Ice Sheet once the ice was subjected to marine influence (Pessl and others, 1989; Booth, 1987, Thorson, 1981; 1989). These interpretations have been based on the general lack of ice-recessional deposits in the northeast corner of the Olympic Peninsula.

In the study area for this investigation, the most striking geologic features are the large volumes of recessional sediment and well-preserved recessional landforms. The presence of these features necessitates a grounded ice source area and one of:

(1) availability of large volumes of sediment and the capability for meltwater streams to transport the sediment. Deposition would have had to be extremely rapid for these large morphological features to form in front of a retreating ice front;

(2) a glacial stillstand or stagnation in this region long enough to create the landforms present in the study area today; or

(3) an isolated piece of the ice sheet that lingered in the localized area of Penn Cove/Point Partridge. This isolated piece of ice would have needed access to the large volumes of Partridge outwash seen in the study area today. A prominent submarine platform, Dallas, Partridge, Eastern, and McArthur Banks, and Admiralty Sill is present in the eastern Strait of Juan de Fuca (Fig 7-1). Water depths in this area are generally less than 50 meters in contrast to water depths of more than 80 to 100 meters that are common farther west and within the Puget Sound troughs. This area of shallow water may have allowed grounded ice to persist in the area west of the study area while ice was floating in other, deeper areas of Puget Sound.

A short glacial stillstand or final stagnation of the Vashon ice sheet is the favored scenario, supported by the following additional geologic evidence:

(1) Glacial stillstands have been proposed by Alley and Chatwin (1979) for southwest Vancouver Island and Dethier and others (in review) for the Arlington area. Both of these interpretations are based on ice-marginal landforms, including kame terraces similar to those found in the study area. Imagining an ice front position that would have passed near all three of these locations is not difficult (Fig. 6-1).