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CONTENTS (continued)

CHRONOLOGY OF PLEISTOCENE SEDIMENTS IN THE PUGET LOWLAND, WASHINGTON

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ABSTRACT

The early Pleistocene history of the Puget Lowland is marked by repeated advances of the Cordilleran ice sheet into the southern Puget Lowland where deposits of at least three glaciations older than 0.8 million years are recognized: the Orting, Stuck, and Salmon Springs, separated by the interglacial Alderton and Puyallup Formations. Until 1981, the chronology of these stratigraphic units was unknown, and correlations were based entirely on relative age considerations. Paleomagnetic, fission-track, and tephra analyses now provide a basis for establishing the chronology of the type sections of these stratigraphic units and to develop a standard for correlations throughout the Puget Lowland. Reversed magnetic polarity and fission-track ages of 800,000-900,000 years from Lake Tapps tephra at three localities indicate that the Orting Drift, Alderton Formation, Stuck Drift, Puyallup Formation, and Salmon Springs Drift were all deposited during the Matuyama Reversed Polarity Epoch, which began about 2.48 million years ago and ended about 0.73 million years ago. Many of the correlations previously made with Salmon Springs Drift and older units in the Puget Lowland are no longer viable in view of the antiquity of the Salmon Springs, Puyallup, Stuck, Alderton, and Orting sediments. A chronologic gap between 200,000 and 800,000 years ago is now apparent in the Pleistocene stratigraphic record of the Puget Lowland.

The chronology of Double Bluff Drift, Whidbey Formation, and Possession Drift has been determined by amino acid analyses of shells and wood. Amino acid age estimates for marine shells in Double Bluff glaciomarine drift suggest an age of 110,000-178,000 years, but the ages could be as old as about 250,000 years. The age of shells in sediments of the Whidbey Formation is calculated as 96,000 ± 35,000 years by leucine and 107,000 ± 9,000 years by alloisoleucine/isoleucine D/L ratios. Marine shells in Possession glaciomarine drift give estimated amino acid ages of 80,000 ± 22,000 years.

Amino acid analyses of wood associated with shells in Double Bluff Drift, Whidbey sediments, and Possession Drift and of younger wood dated by radiocarbon were made to determine if wood could be used for amino acid age determinations. Most of the wood analyses gave consistent results, but some samples gave widely disparate results for reasons which were not readily apparent. Age calculations for wood were not made because kinetic models of racemization in wood are not yet well understood. The results of amino acid analyses in wood look encouraging, but additional data are needed before the method can be used with confidence.

The chronology of late Pleistocene sediments in the Puget Lowland is well established with many radiocarbon dates. An early advance of ice into the Fraser Lowland of British Columbia between 18,000 and 21,500 years ago that may be equivalent to the Evans Creek Drift in the Cascade Mountains apparently did not reach the Puget Lowland of Washington. The Cordilleran ice sheet advanced across the international boundary shortly after 18,000 years ago. The Puget lobe and the Juan de Fuca lobe apparently advanced synchronously. The Juan de Fuca lobe retreated from the western part of the strait shortly before 14,500 years ago, and the Puget lobe retreated from its terminus to the vicinity of Seattle by 14,000 years ago. Shortly thereafter, the ice sheet thinned sufficiently to allow marine water into the Puget Lowland, and floating of the remaining ice and its progessive melting resulted in deposition of Everson glaciomarine drift over an area of about 18,000 square kilometers. More than 80 radiocarbon dates from shells and wood in Everson glaciomarine drift show that the drift was deposited nearly contemporaneously from berg ice over the whole region, rather than transgressively from a retreating, calving ice front.

Cordilleran ice readvanced a short distance into the northern Puget Lowland during the Sumas Stade about 11,500 years ago and disappeared by 10,000 years ago.

INTRODUCTION

Construction of the stratigraphic framework of Pleistocene sediments in Washington was initiated by Willis (1898) and Bretz (1913). Willis recognized two glaciations in the Puget Lowland, which he named the Vashon and Admiralty, separated by the Puyallup Interglaciation. Additional pre-Vashon glacial sediments were included by Bretz in the Admiralty Glaciation. Hansen and Mackin (1949) were the first to document more than one pre-Vashon glaciation by identifying two tills, separated by interglacial sediments, beneath 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 (Fig. 1). Pleistocene deposits beyond the range of radiocarbon dating were correlated throughout the region entirely on the basis of relative stratigraphic position and comparison with previously defined stratigraphic units.

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. A radiocarbon date of 71,500 years ago from the type locality of the Salmon Springs glaciation (Stuiver and others, 1978) suggested that it was early Wisconsin in age, and deposits of the next-to-last glaciation elsewhere in the Puget Lowland, which had previously been widely correlated with the Salmon Springs Drift, were also assumed to be the same age. However, the demonstration by Easterbrook and others (1981) that the Salmon Springs Drift at its type locality was about 850,000 years old made most previous correlations with the Salmon Springs Drift invalid and left the regional chronology of pre-Fraser deposits in need of extensive revision. This conclusion followed the discovery of reversely magnetized silt at Auburn (Othberg, 1973) and at the Salmon Springs type locality (Easterbrook and Othberg, 1976) and a zircon fission-track age of 0.84 ± 0.21 m.y. from tephra immediately below the silt (Easterbrook and Briggs, 1979; Easterbrook and others, 1981). The reversed polarity and fission-track age at the type locality place the Salmon Springs Drift within the Matuyama Reversed Polarity Chron. The revised stratigraphic sequence in the Puget Lowland is shown in Table 1.

Recent paleomagnetic investigations have shown that the pre-Salmon Springs stratigraphic units are also reversely magnetized at their type localities and are thus between about 800,000 and 2.4 m.y. old (Roland, 1984; Easterbrook, in press). The paleomagnetic and fission-track studies have thus shown a gap in the Pleistocene chronology of the Puget Lowland between about 250,000 and 850,000 years ago (Easterbrook, in press).

In order to better establish correlation and chronology of pre-Fraser–Salmon Springs sediments, amino acids in shells and wood from a number of critical localities in the northern and central Puget Lowland were analyzed (Fig. 2). Enantiomeric ratios of amino acids in fossil mollusk shells from the west coast of North America have been utilized by many workers in the past few years as an aid in correlation of geological units and to determine ages (Karrow and Bada, 1980; Kennedy, 1978; Kennedy and others, 1982; Kvenvolden and Blunt, 1980; Kvenvolden and others, 1979a, b, 1980; Masters and Bada, 1977; Miller and Hare, 1980; Rutter and others, 1979; Schroeder and Bada, 1976; Atwater and others, 1981; Wehmiller and others, 1977; Williams and Smith, 1977). In most instances, correlation using amino acids has been successful, whereas dating has been hampered by difficulty in obtaining the average temperature history of the specimen, a necessary requisite for accurate results.

Amino acid geochemistry of fossil wood has potential applicability to problems of geochronology, but details of amino acid reactions in wood are not well known. Although much less work has been done on wood than on shells, results obtained so far on wood look encouraging for correlation purposes (Easterbrook and others, 1982; Engel and others, 1977, 1979; Lee and others, 1976; Rutter and others, 1980; Rutter and Crawford, 1983). However, more data on kinetic modeling and paleotemperature effects are necessary before dates on wood become consistent and reliable.

Shells and wood were analyzed by gas chromatography (Fig. 3) at the laboratory of the U.S. Geological Survey; many of the wood samples were analyzed at the amino acid laboratory of the University of Alberta. Both laboratories followed essentially the same analyt-

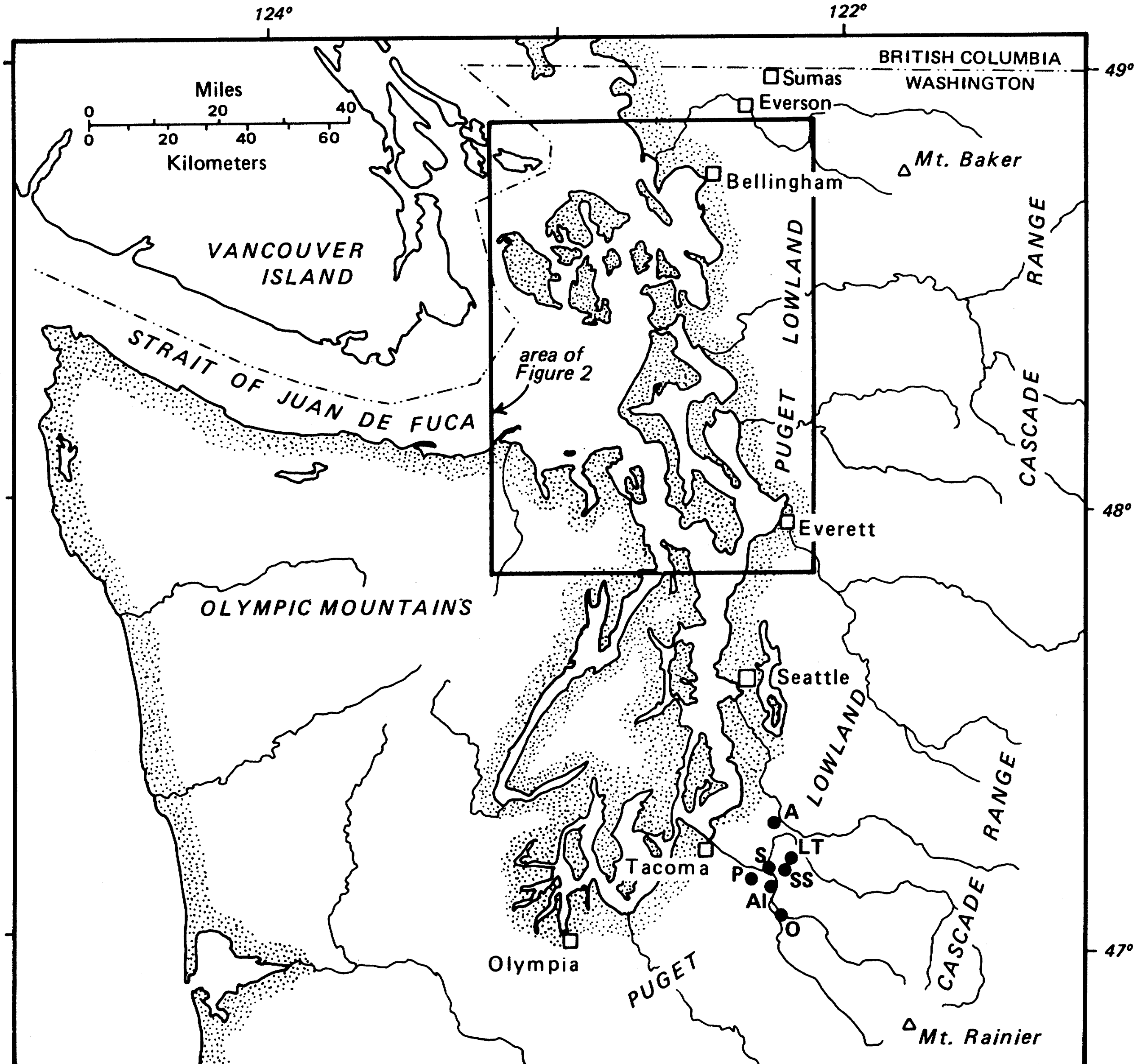


Figure 1.–Index map of the Puget Lowland. A, Auburn; Al, Alderton; LT, Lake Tapps; O, Orting; P, Puyallup; S, Sumner; SS, Salmon Springs.

ical procedures outlined by Hare (1969) and Kvenvolden (1975). Some shells were also analyzed by the University of Colorado laboratory. Details of analytical procedures are given in the Appendix.

STRATIGRAPHY AND CHRONOLOGY

Early Pleistocene Sediments

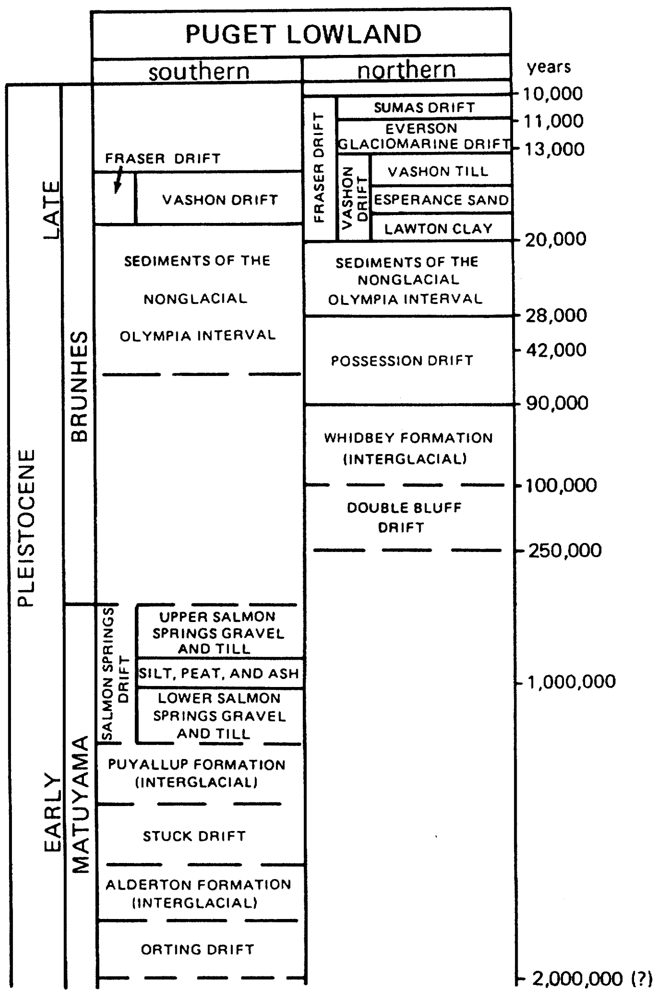
Introduction

Early Pleistocene deposits in the Puget Lowland are characterized by interbedded glacial and nonglacial sediments. Glacial lobes of the Cordilleran ice sheet extended southward from the Canadian border, splitting into two main lobes. The Juan de Fuca lobe flowed westward out the Strait of Juan de Fuca, while the Puget Lobe advanced southward across the central and southern Puget Lowland. The maximum extent of pre-Wisconsin glaciations is difficult to determine because those deposits were buried by younger sediments. No early Pleistocene deposits have been documented from the Juan de Fuca lobe.

Orting Drift

The oldest glacial unit recognized in the Puget Lowland, the Orting Drift, occurs in a few outcrops in

Table 1.–Stratigraphic sequence in the Puget Lowland



the Puyallup valley south of Seattle. Willis (1898) first used the name Orting for gravel exposed near the town of Orting. Later, Crandell and others (1958) identified at least three tills within the Orting gravel and redefined it as Orting Drift, consisting of a thick basal gravel deposited by westward-flowing streams from the Cascade Range prior to the beginning of volcanism at Mount Rainier and overlain by till and gravel of the Puget lobe. The tills are compact, unstratified, poorly sorted diamictons containing 10 to 15 percent clasts of northern provenance and 5 to 15 percent garnet in the heavy-mineral fraction. Stratified gravel and sand not closely associated with till are usually of central Cascade origin but lack clasts from Mount Rainier, presumably because the deposit predates Mount Rainier.

Orting Drift commonly occurs as continuous outcrops as much as 60 m thick and reaches a maximum thickness of 79 m. Tills less than 8 m thick occur at more than one horizon but are interpreted to be oscillations of a single major glaciation because the tills are not laterally continuous and no significant unconformities have been found (Crandell and others, 1958; Crandell, 1963).

Orting drift lies on upper Tertiary rocks and is overlain unconformably by sediments of the Alderton Formation. The drift has long been considered the oldest Pleistocene glacial deposit in the Puget Lowland on the basis of its intense oxidation, but no numerical ages have been available until recently.

Alderton Formation

The Alderton Formation lies unconformably above the Orting Drift and is named for exposures along the west wall of the Puyallup valley near the town of Alderton (Crandell and others, 1958). It consists of interbedded mudflows, lahars, alluvium, lake sediments, peat, and volcanic ash derived from an active ancestral Mount Rainier volcano that predated the modern cone. Mudflows consist of very compact, angular to subrounded pebbles and boulders of hornblende-hypersthene andesite in a sandy clay matrix. Thicknesses of individual mudflows vary from 1 to 8 m.

The predominance of Mount Rainier lithologies in the Alderton sediments and the absence of northern-provenance components are interpreted to indicate that the Alderton is interglacial. Englemann spruce pollen from the lower part of a peat bed in the unit represents a climate somewhat cooler than at present, whereas the upper part of the same peat contains large amounts of Douglas fir and alder pollen, indicative of a climate similar to that of the present (Leopold and Crandell, 1957; Crandell and others, 1958). Pollen from other peat and silt beds suggest climatic conditions ranging from cool and moist to warmer and drier than the present (Heusser, 1977), but most of the Alderton exposures are now covered with vegetation, limiting opportunities for reconstruction of the climate for the Alderton as a whole.

No numerical dates have been obtained for the Alderton Formation, but recent paleomagnetic studies have shown that the geomagnetic polarity of the Alderton at its type locality is reversed with an average declination of 176° and an average inclination of -50° (Roland, 1984; Easterbrook and others, unpub. data, 1986). The reversed polarity has been overprinted with a viscous normal remanent magnetism that can be removed with high alternating field demagnetization. Additional paleomagnetic measurements of samples at an exposure 645 m from the type section gave an average declination of 170° and inclination of -65° at the 500-oersted level of demagnetization.

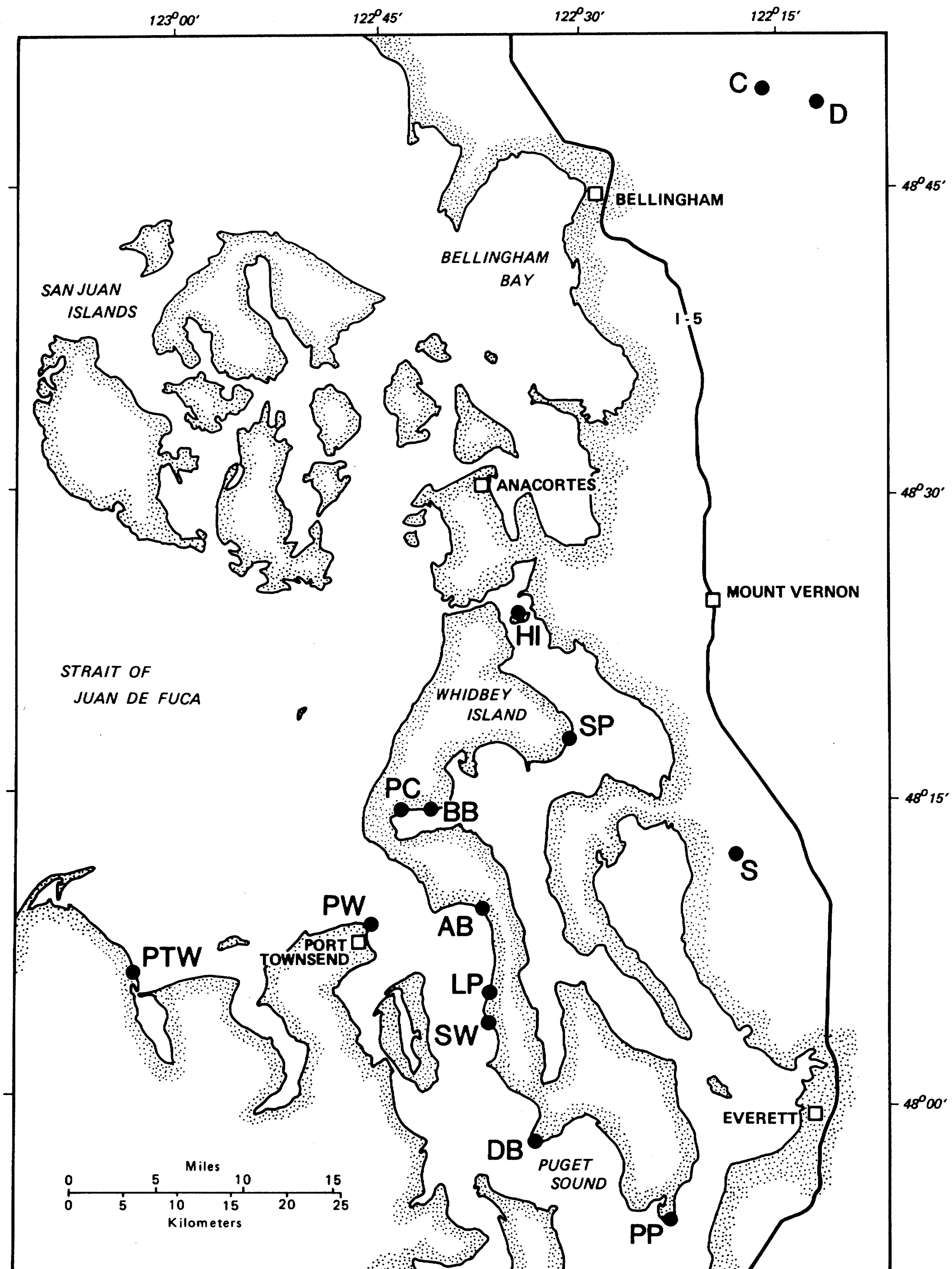
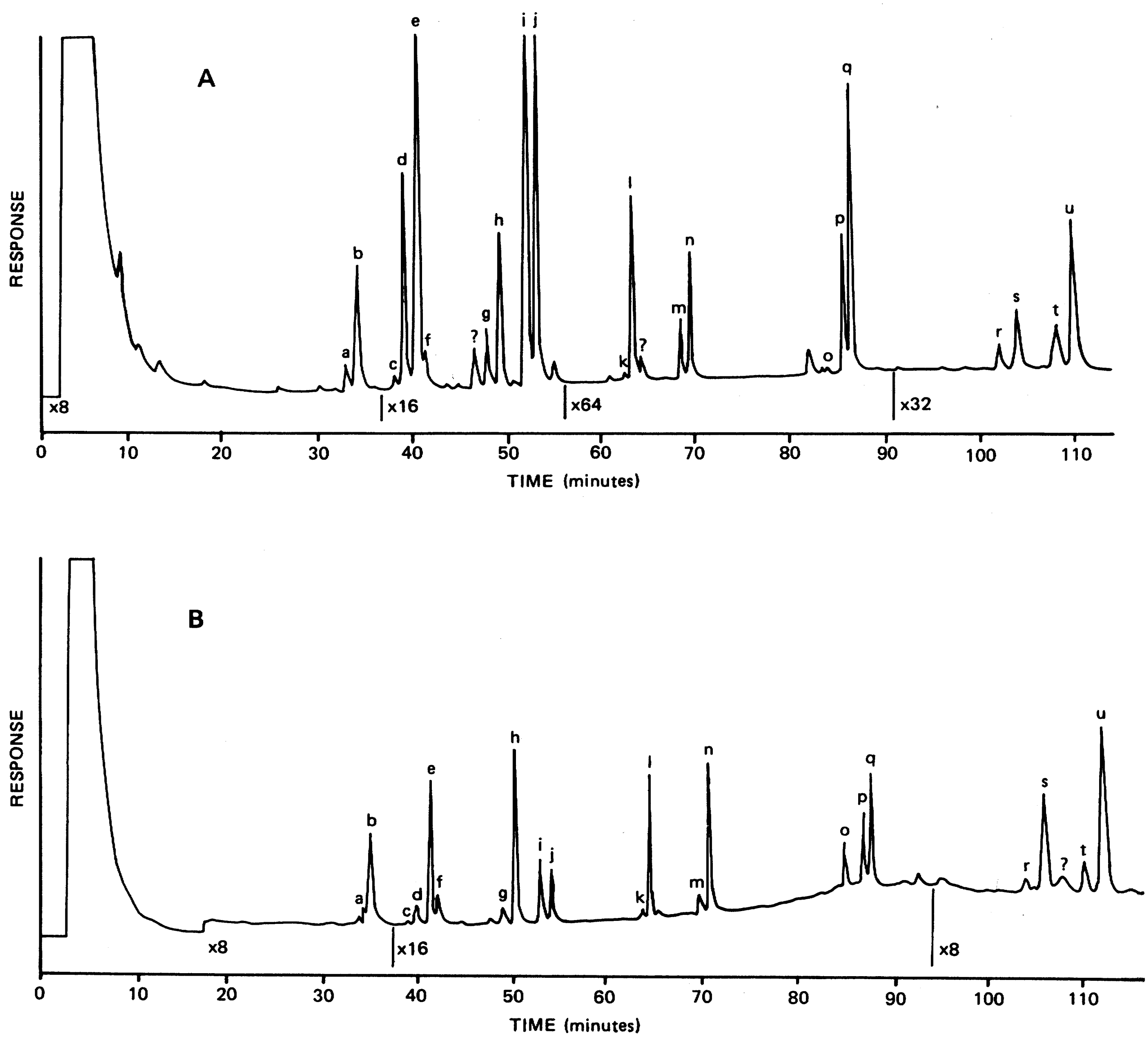


Figure 2.–Index map of the northern and central Puget Lowland. D, Deming; C, Cedarville; HI, Hope Island; SP, Strawberry Point; PC, Penn Cove; BB, Blowers Bluff; AB, Admiralty Bay; SW, South Whidbey; LP, Lagoon Point; DB, Double Bluff; PP, Point Possession; S, Stillaguamish; PW, Point Wilson; PTW, Port Williams. (Modified from USGS 1:250,000 topographic base map).



a D-valine
b L-valine
c D-alloisoleucine
d D-alanine
e L-alanine
f L-isoleucine
g D-leucine
h L-leucine (nonleucine)
i D-alpha amino-n-caproic acid
j L-alpha amino-n-caproic acid
k β-alanine
l glycine
m D-proline
n L-proline
o γ-aminobutyric acid
p D-aspartic acid
q L-aspartic acid
r D-phenylamine
s L-phenylamine
t D-glutamic acid
u L-glutamic acid

Figure 3.–A. Gas chromatographic trace of amino acids in fossil *Saxidomus giganteus*, sample 80-83c from interglacial deposits at Admiralty Bay, Washington. B. Gas chromatographic trace of amino acids in fossil wood sample 80-22 from interglacial clay deposits at South Whidbey State Park, Washington. See key for amino acid peak identifications.

The reversed remanent magnetism of the Alderton Formation and its stratigraphic position below the Salmon Springs Drift and its ≈800,000-yr fission-track dates places its age within the Matuyama Reversed Polarity Chron between 0.8 and 2.4 m.y. Volcanic ash in the Alderton sediments is presently being examined for possible fission-track dating.

Stuck Drift

Stuck Drift is defined on the basis of oxidized till, containing 10 to 15 percent clasts of rock types transported from the north by the Cordilleran ice sheet, interbedded with oxidized sand and gravel which overlies the Alderton Formation southwest of the town of Alderton (Crandell and others, 1958). In the type area, Stuck Drift consists of a single till between outwash sand and gravel, but elsewhere, two tills are separated by 15 to 50 m of lacustrine and fluvial silt, sand, and gravel (Crandell, 1963; Mullineaux, 1970). Clasts in the alluvium are derived from the Cascade Mountains to the east, indicating that the Cordilleran ice sheet had retreated sufficiently to permit re-establishment of westward-flowing drainage from the mountains. Exposures of Stuck Drift are found only along the walls of the Puyallup valley, so the southern extent of Stuck Glaciation is not known and correlation with deposits elsewhere in the Puget Lowland has not been made. Poor exposures in the area prevent lateral tracing of deposits to determine whether the Stuck Drift includes two tills separated by a nonglacial interval or whether one of the tills belongs to a different glaciation.

No numerical dates have been obtained from the Stuck Drift, but recent paleomagnetic studies have shown that silt in the Stuck near the type locality has reversed geomagnetic polarity. The mean magnetic declination calculated at the 700-oersted demagnetization level is 183°, and the mean inclination is -19°. Based on its pre-Salmon Springs stratigraphic position and reversed remanent magnetism, the Stuck Drift was deposited during the Matuyama Reversed Polarity Chron (Roland, 1984; Easterbrook and others, unpub. data, 1986).

Puyallup Formation

Nonglacial sediments in the southeastern Puget Lowland, derived mostly from ancestral Mount Rainier, were named the Puyallup Sand by Willis (1898). Crandell and others (1958) later expanded the unit to include fluvial sand and gravel, lacustrine silt and clay, peat, lahars, and mudflows which they designated the Puyallup Formation, which includes, but is not restricted to, the Puyallup Sand of Willis (1898). At its type locality in the Puyallup valley, the Puyallup Formation consists of about 41 m of lacustrine silt and sand, alluvial sand and gravel, mudflows, tephra, and peat. The mudflows, many of which contain as much as 95 percent Rainier-provenance clasts, were derived from Mount Rainier. Most gray, unoxidized sand beds in the unit are also of Rainier provenance, whereas most oxidized fluvial sand and gravel typically consist of mixed lithologies of Rainier and central Cascade provenance. Like the Alderton Formation, Puyallup sediments represent deposition along an ancestral river flowing from Mount Rainier across the southeastern Puget Lowland.

Pollen from the lower Puyallup Formation indicates an early postglacial climate followed by gradual warming. Other pollen profiles higher in the section suggest a warm climate followed by a cooling trend, but poor exposures prevent lateral tracing of sampled units, and an unknown amount of the upper part of the sediments, represented by a weathering profile and unconformity, may be missing. A major erosional unconformity, with a strong weathering profile characterized by kaolin, was recognized by Crandell and others (1958) at the top of the Puyallup Formation and interpreted to represent a long period of erosion and weathering prior to deposition of the overlying Salmon Springs Drift (Crandell, 1963; Mullineaux, 1970).

No numerical dates have yet been obtained from the Puyallup Formation, but paleomagnetic measurements from part of the original type section and from nearby exposures indicates reversed magnetic polarity with a complex magnetic overprint (Roland, 1984; Easterbrook and others, unpub. data, 1986). The remanent magnetism of sediments at another nearby section, correlated with the Puyallup on the basis of lithology and stratigraphic position, was clearly reversed. The mean magnetic declination was 183°, and mean inclination was -42° with an alpha-95 of 15° at the 700-oersted demagnetization level. The reversed magnetic polarity, together with its stratigraphic position beneath the Lake Tapps tephra, places the Puyallup Formation within the Matuyama Reversed Polarity Chron (Roland, 1984; Easterbrook and others, unpub. data, 1986).

Previous tentative correlation of the Puyallup Formation with the interglacial Whidbey Formation of the central Puget Lowland (Crandell, 1965; Easterbrook, 1969, 1976a,b) is now known to be impossible because of the reversed magnetic polarity of the Puyallup and the ≈800,000-yr fission-track age of the Lake Tapps tephra in the overlying Salmon Springs Drift (Easterbrook and others, 1981), together with the ≈100,000-yr ages estimated from amino acid analyses for the Whidbey Formation and its normal magnetic polarity (Easterbrook, 1976a).

Salmon Springs Drift

At its type locality in the Puyallup valley, the Salmon Springs Drift unconformably overlies the Puyallup Formation and is unconformably overlain by Vashon Drift (Crandell and others, 1958). Prior to 1979, the age of the Salmon Springs Drift was thought to be early Wisconsin on the basis of radiocarbon enrichment dates of 50,100 ± 400 years (GrN-4116c) (Armstrong and others, 1965) and 71,500 ± 1,700 years (Stuiver and others, 1978) from peat at the type locality, and Salmon Springs Drift was widely correlated throughout Washington on the belief that it was the next oldest drift beneath Vashon Drift. The first indication that these ages might be in error was the discovery of reversed magnetic polarity in a silt bed directly beneath the radiocarbon-dated peat bed at the Salmon Springs Drift type locality (Easterbrook and Othberg, 1976). A paleomagnetic profile from the silt included both normal and reversely polarized samples, as did two later magnetic profiles (Easterbrook and others, 1981). Because some of the samples showed high angular standard deviations for individual spin measurements and low sample stability, the validity of the normal polarities is difficult to evaluate. Strong normal magnetic overprinting has been found elsewhere in other profiles of Salmon Springs and older sediments, suggesting that the normal polarities in the Salmon Springs silt may be caused by postdepositional overprinting.

A fission-track date of 0.84 m.y. on zircon from volcanic ash that directly underlies the reversely magnetized silt at the type locality provided the conclusive evidence for the antiquity of the Salmon Springs Drift. The ash, which lies directly on lower Salmon Springs outwash gravel, grades upward into the overlying silt, which gradually increases in organic content and becomes the radiocarbon-dated peat. No break in pollen spectra is apparent at the contact between the silt and peat (Stuiver and others, 1978), further supporting the conclusion that no unconformity exists between the peat and ash. Thus, the ash-silt-peat sequence represents continuous deposition, and the radiocarbon dates are considered invalid (Easterbrook and others, 1981).

The tephra at Salmon Springs was named the Lake Tapps tephra by Easterbrook and others (1981). It has now been identified at five localities in the Puget Lowland, and additional fission-track dates of 0.87 ± 0.27, 0.84 ± 0.21, and 0.89 ± 0.29 m.y. have been obtained from it (Easterbrook and others, 1981; Naeser and others, 1984; J. A. Westgate, written commun., 1986). Reversed magnetic polarities have been measured in silt associated with the Lake Tapps tephra at all five localities, and the magnetic remanence at two of these localities is exceptionally stable and clearly reversed throughout the profiles (Easterbrook and others, unpub. data., 1986).

Thus, the Salmon Springs Drift is now firmly dated at about 800,000 years, in the latter part of the Matuyama Polarity Chron of the early Pleistocene. Because the age is established on the tephra-silt unit between the upper and lower drift units of the Salmon Springs Drift as defined by Crandell and others (1958), the age of the upper drift unit can only be stated as younger than about 800,000 years, but how much younger remains uncertain.

The discovery of the antiquity of the Salmon Springs Drift has far-reaching implications. The term Salmon Springs Drift has been widely used in the literature for pre-Vashon drifts in the southern and central Puget Lowland and the Olympic Peninsula, and correlations have been made over wide areas in the Pacific Northwest. In many instances, these interpretations have been based solely on stratigraphic position, under the assumption that the Salmon Springs Drift was the next-to-youngest glaciation in the region. Distinguishing those drift units that are truly correlative with Salmon Springs Drift from younger drifts is very difficult without dating control, and the designation of "Salmon Springs Drift" in many pre-1981 publications is very likely erroneous.

Middle Pleistocene
(800,000 to 300,000 years ago)

At present, no exposures of Pleistocene sediments between 300,000 and 800,000 years old are known in the Puget Lowland. Deposits of this interval may be present below sea level in the Puget Lowland, but they are not accessible and have not been identified in cores.

Late Pleistocene

The late Pleistocene stratigraphy and chronology of the Puget Lowland is broken down into several phases:

Pre-late Wisconsin

Double Bluff Drift (about 100,000-250,000 years ago)

Whidbey Formation (about 90,000-100,000 years ago)

Possession Drift (an early phase at about 70,000-90,000 years ago and a late phase about 35,000-50,000 years ago)

Late Wisconsin

Olympia nonglacial sediments (about 20,000-30,000 years ago)

Fraser Drift (about 10,000-20,000 years ago)

The ages of pre-late Wisconsin sediments have been determined largely by amino acid analysis, whereas the Olympia nonglacial sediments and Fraser Drift have been dated by radiocarbon. The amino acid geochronology of the Puget Lowland has not been previously published, so it is treated in somewhat more detail.

AMINO ACID GEOCHRONOLOGY

Amino acid racemization geochronology relies on the fact that almost all living organisms contain amino acids which are configured as the L-amino acid stereoisomer. Upon the death of the organism, the L-amino acid stereoisomer (enantiomer) undergoes a reversible interconversion forming the mirror image D-amino acid enantiomer by the racemization reaction:

$$\text{L-amino acid} \underset{k_D}{\overset{k_L}{\rightleftharpoons}} \text{D-amino acid}$$

where k_L and k_D are the relative rates of racemization of the L- and D-amino acid enantiomers. The sensitivity of the reaction rate to temperature and the reliability of the reaction in different species of mollusks are limiting factors in calculations of absolute ages by the method of amino acid racemization geochronology.

The amino acid racemization reaction in fossil mollusks has been applied to marine terrace, estuarine, and archaeological midden deposits along the west coast of North America. For example, Wehmiller and others (1977) have utilized the technique for correlation and determination of the chronology of Pleistocene marine terrace localities along California, Oregon, and Washington. Karrow and Bada (1980) applied the technique to marine terraces in San Diego County. Kvenvolden and others (1979a) used the method for correlation and determination of the chronology of Pleistocene estuarine assemblages at Willapa Bay, Washington. Atwater and others (1981) applied the method to buried Pleistocene estuarine assemblages in San Fransisco Bay, California. Miller and Hopkins (1980) used this method to study fossiliferous deposits in Alaska. Archaeological middens have been studied by analyzing amino acid racemization in mollusks in southern California (Masters and Bada, 1977) and in Alaska (Kvenvolden and others, 1979b). These investigations suggest that the amino acid racemization reaction in mollusks can provide meaningful information regarding the fossiliferous deposits in the Puget Sound Lowland.

Fossils and Localities

Fossil mollusks were collected in the Puget Sound Lowland during the summers of 1979 and 1980. Localities and specimens analyzed are described in Table 2. The pelecypods studied represent one genus from each of six families.

Family	Genus	Species
Veneridae	*Saxidomus*	*gigantea* (Deshayes, 1839)
Tellinidae	*Macoma*	*calcarea* (Gmelin, 1791)
Myacidae	*Mya*	*truncata* (Linné, 1758)
Nuculanidae	*Nuculana*	*fossa* (Baird, 1863)
Cardiidae	*Clinocardium*	*ciliatum* (Fabricius, 1780)
	Clinocardium	*nuttalli* (Conrad, 1837)
Hiatellidae	*Hiatella*	*artica* (Linné, 1758)

In this study, comparisons of amino acid geochemistry will be restricted to the genus level. The species reported represent only a few mollusks from glacial-marine deposits of the Fraser Glaciation, and more complete faunal lists have been reported elsewhere (Easterbrook, 1963, 1969). The localities at South Whidbey State Park, Port Williams, and Admiralty Bay do not have published descriptions of their molluskan fauna. Only a few isolated mollusks have been found in the Double Bluff drift (Easterbrook, 1968).

The application of amino acid geochemistry in fossil mollusks to problems of correlation and geochronology depends on a predictable rate of protein diagenesis that is not significantly influenced by environmental factors. Estimates of the effective temperature at which in-situ amino acid reactions occur are imprecise, and this limits the accuracy of age calculations. Determination of the kinetics of amino acid racemization in different species of mollusks is important if relative correlations and age estimates are to be reliable.

Duplicate analyses of amino acid D/L ratios for *Saxidomus*, *Macoma*, *Clinocardium*, and *Nuculana* indicate that the reproducibility of amino acid D/L ratios is variable, depending on genera and extent of individual amino acid racemization. Figure 3A is an example of the gas chromatographic trace of amino acid D- and L- abundances in fossil *Saxidomus giganteus* from intraglacial deposits at Admiralty Bay. An example of amino acid D- and L- abundances in fossil wood is discussed later in the text and is shown in Figure 3B. Laboratory procedures are described in the Appendix.

Intrageneric Relationships

The apparent amino acid racemization kinetics in fossil mollusks can be studied by comparing D/L ratios

Table 2.–Amino acid geochemistry (D/L ratios) of Pleistocene mollusks, Puget Lowland

Leu, leucine; allo/iso, alloisoleucine/isoleucine; glu, glutamic acid; asp, aspartic acid; pro, proline; nd, no data

GEOLOGIC CLIMATE UNIT GEOLOGIC UNIT LOCATION GENERA	LEU	ALLO/ISO	GLU	ASP	PRO	C-14 AGE
FRASER GLACIATION						
(Everson Interstade)						
Bellingham glaciomarine drift						
Cedarville (80-37)						11,800±400
Macoma calcarea	0.13	0.18	0.12	0.30	0.26	
Nuculana fossa	0.11	nd	0.16	0.34	0.14	
Nuculana fossa	0.11	nd	0.12	0.36	0.15	
Nuculana						
(AAL-3070A)	nd	0.086	nd	nd	nd	
(AAL-3070B)	nd	0.092	nd	nd	nd	
(AAL-3070C)	nd	0.102	nd	nd	nd	
Kulshan glaciomarine drift						
Deming (80-38)						12,970±280
Macoma calcarea	0.12	0.15	0.14	0.33	0.20	
Nuculana fossa	0.12	nd	0.11	0.34	0.14	
Everson glaciomarine drift						
Hope Island (79-11)						12,400±190
Saxidomus giganteus	0.11	0.08	0.12	0.29	0.23	
Clinocardium ciliatum	0.12	0.10	0.14	0.37	0.12	
Penn Cove (80-24)						13,010±170
Macoma sp.	0.12	0.08	0.13	0.34	0.18	
Mya truncata	0.11	0.08	0.11	0.31	0.14	
Nuculana fossa	0.14	nd	0.16	0.36	0.22	
Clinocardium nutalli	0.11	0.07	0.14	0.36	0.16	
Hiatella arctica	nd	0.08				
Hope Island						
Mya truncata						
(3071A)	nd	0.080	nd	nd	nd	
(3071B)	nd	0.083	nd	nd	nd	
(3071C)	nd	0.076	nd	nd	nd	
POSSESSION GLACIATION						
Possession glaciomarine drift						
Port Williams						
Clinocardium ciliatum						
(79-1A)	0.15	0.13	0.19	0.41	0.16	
(79-1B)	0.21	0.15	0.21	0.36	0.29	
(79-1D)	0.10	nd	0.13	0.33	0.11	
(79-1D)	0.13	0.12	0.16	0.37	0.13	
(79-1E)	0.08	0.07	0.13	0.35	0.09	
(79-1E)	0.09	0.09	0.13	0.35	0.10	
(AAL-1076A)	nd	0.063	nd	nd	nd	
(AAL-1076B)	nd	0.068	nd	nd	nd	
(AAL-1076C)	nd	0.055	nd	nd	nd	

Table 2.–Amino acid geochemistry, molluscs (continued)

GEOLOGIC CLIMATE UNIT GEOLOGIC UNIT LOCATION GENERA	LEU	ALLO/ ISO	GLU	ASP	PRO	C-14 AGE
POSSESSION GLACIATION (continued)						
Possession glaciomarine drift						
Port Williams (continued)						
Nuculana sp.						
(AAL-2939)	nd	0.20±.08				
Blowers Bluff						
Clinocardium sp.						
(AAL-1882)	nd	0.23	nd	nd	nd	
(AAL-1883)	nd	0.25	nd	nd	nd	
(AAL-1884)	nd	0.29	nd	nd	nd	
(AAL-1885)	nd	0.28	nd	nd	nd	
(AAL-1886)	nd	0.26	nd	nd	nd	
(AAL-3072A)	nd	0.138	nd	nd	nd	
(AAL-3072B)	nd	0.197	nd	nd	nd	
(AAL-3072C)	nd	0.110	nd	nd	nd	
Nuculana sp.						
(AAL-1881)	nd	0.30	nd	nd	nd	
Nuculana sp.						
(AAL-2938)	nd	0.18±.01				
Stillaguamish						
Saxidomus sp.						
(AAL-1876)	nd	0.19				
Clinocardium sp.						
(AAL-1878A)	nd	0.23				
(AAL-1878B)	nd	0.16				
Nuculana sp.						
(AAL-1877A)	nd	0.33				
(AAL-1877B)	nd	0.37				
(AAL-1877C)	nd	0.38				
Hiatella sp.	nd	0.16				
Point Wilson						
Clinocardium						
(AAL-3067A)	nd	0.094				
(AAL-3067B)	nd	0.106				
(AAL-3067C)	nd	0.067				
(AAL-3068A)	nd	0.122				
(AAL-3068B)	nd	0.106				
(AAL-3068C)	nd	0.096				
Balanus						
(AAL-3069A)	nd	0.124				
(AAL-3069B)	nd	0.124				
(AAL-3069C)	nd	0.028				
Admiralty Bay						
Saxidomus giganteus						
(79-9)	0.29	0.24	0.24	0.44	0.40	
(80-26B)	0.36	0.27	0.30	0.45	0.52	
(80-30A)	0.40	0.31	0.31	0.47	0.52	
(80-30B)	0.34	0.21	0.28	0.46	0.47	

Table 2.–Amino acid geochemistry, molluscs (continued)

GEOLOGIC CLIMATE UNIT GEOLOGIC UNIT LOCATION GENERA	LEU	ALLO/ISO	GLU	ASP	PRO	C-14 AGE
POSSESSION GLACIATION (continued)						
Admiralty Bay (continued)						
(80-30B)	0.36	0.25	0.30	0.50	0.46	
(80-30C)	0.37	0.27	0.30	0.47	0.47	
Mya truncata	0.41	0.44	0.30	0.59	0.47	
Macoma						
(80-26)	0.37	0.42	0.38	0.57	0.51	
(30-30)	0.47	0.48	0.39	0.65	0.58	
WHIDBEY INTERGLACIATION						
Whidbey Formation						
South Whidbey State Park						
Macoma						
(80-22A)	0.41	nd	0.45	0.52	0.46	
(80-22B)	0.24	nd	0.15	0.29	0.33	
(80-22C)	0.42	nd	0.33	0.54	0.51	
DOUBLE BLUFF GLACIATION						
Double Bluff glaciomarine drift						
Double Bluff						
Nuculana						
(80-27)	0.47	nd				
Foulweather Bluff						
Macoma	nd	0.34				
Mya	nd	0.34				

of different amino acids. Lajoie and others (1980) reported that intrageneric relationships (comparisons of two different amino acid D/L ratios in a single genus of mollusk) in *Saxidomus* and other fossil mollusks follow linear trends. The intrageneric relationships of alloisoleucine/isoleucine (hereafter, allo/iso) vs. D/L leucine for *Saxidomus*, *Macoma*, *Clinocardium*, *Nuculana* and *Mya* are shown on Figure 4. In general, the ratios for *Saxidomus*, *Clinocardium*, and *Nuculana* follow the same linear path, whereas data for *Macoma* show higher D/L ratios. The curve for *Mya* is intermediate between those for *Macoma* and the other genera.

Differences in amino acid D/L ratios among different genera are more obvious in samples from older sediments. For example, at Admiralty Bay, the leucine D/L ratio is about 0.37 in *Saxidomus* 0.47 in *Macoma*, and 0.41 in *Mya*. These data indicate that leucine racemization in *Macoma* tends to be slightly faster than in *Saxidomus*, as reported earlier by Wehmiller and others (1977).

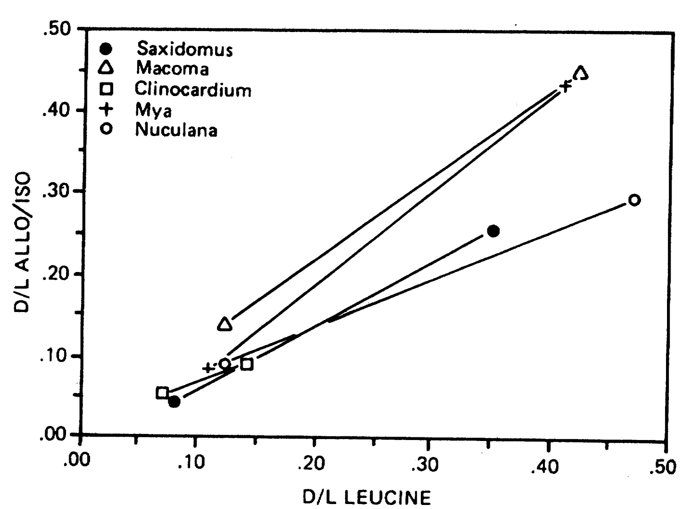


Figure 4.–Intrageneric relationships for selected mollusk genera based on leucine and allo/isoleucine D/L ratios.

Amino Acid Geochemistry of Fossil Wood

The reliable application of the amino acid racemization reaction in fossil wood to correlation and geochronology depends on the predictability of the reaction. If too many environmentally sensitive variables are involved or need to be evaluated with each sample, then the usefulness of the technique is greatly diminished. Factors that affect the racemization of amino acids in wood include temperature, moisture content, terpene abundance, formation of amino sugars, and formation of melanoidin-type substances (Lee, 1975; Zumberge, 1979; Zumberge and others, 1980). In the present study, the main factor considered was whether the racemization followed a predictable trend. Table 3 lists the amino acid D/L ratios in wood recovered from localities in the Puget Lowland.

Table 3.–Amino acid geochemistry (D/L ratios) of Pleistocene wood, Puget Lowland

GEOLOGIC CLIMATE UNIT GEOLOGIC UNIT LOCALITY SAMPLE NUMBER	ASP	PRO	GLU	LEU	C-14 AGE
FRASER GLACIATION					
(Everson Interstade)					
Bellingham glaciomarine drift					
Cedarville					
UA-1200	0.29	0.016	0.068	0.018	11,800±400
Deming Sand					
UA-1206	0.17	nd	0.054	0.017	11,640±275
UA-1207	0.21	nd	0.030	0.016	11,640±275
80-36	0.21	0.05	0.08	0.04	
OLYMPIA NONGLACIAL INTERVAL					
Strawberry Point					
UA-1195 (mid peat 6)	0.20	nd	0.059	0.018	22,700
UA-1197 (silt E, 90 cm)	0.18	nd	0.067	0.020	24,800
UA-1196 (silt E)	0.19	nd	0.067	0.020	24,800
UA-1198 (silt D, 70 cm)	0.22	nd	0.060	0.018	27,600
UA-1191 (peat 5c)	0.28	nd	0.070	0.025	27,650
POSSESSION GLACIATION					
Possession Drift					
Strawberry Point DP-37					
UA-1194 (top peat 3)	0.22	nd	0.062	0.018	34,900
UA-1192 (middle peat)	0.24	nd	0.067	0.021	35,400
UA-1190 (top peat 2)	0.25	nd	0.089	0.025	43,600
UA-1189 (peat 2)	0.30	0.029	0.072	0.029	43,900
UA-1193 (lowest peat)	0.29	nd	0.061	0.030	47,600
80-25a	0.18	0.05	0.13	0.03	
80-25b	0.25	0.07	0.11	0.06	
80-25c	0.18	0.04	0.15	0.04	
WHIDBEY INTERGLACIATION					
Whidbey Formation					
Double Bluff					
80-29	0.28	0.08	0.13	0.06	
80-28	0.25	0.09	0.12	0.07	
80-28a	0.22	0.07	0.10	0.04	
80-27b	0.37	0.06	0.09	0.04	
UA-929 (lowest peat)	0.26	0.08	0.115	0.048	
Maxwelton, Mx-10					
UA-926 (peat 5F)	0.26	0.056	0.117	0.047	
UA-927 (peat 5L)	0.24	0.032	0.156	0.040	
Strawberry Point (beach)					
UA-931	0.23	0.063	0.110	0.066	

Table 3.–Amino acid geochemistry, wood (continued)

GEOLOGIC CLIMATE UNIT GEOLOGIC UNIT LOCALITY SAMPLE NUMBER	ASP	PRO	GLU	LEU	C-14 AGE
WHIDBEY INTERGLACIATION (continued)					
Whidbey Formation (continued)					
Blowers Bluff					
UA-928 (below pumice)	0.26	0.052	0.115	0.034	
Swantown					
UA-933 (DP-25)	0.29	nd	0.104	0.042	
UA-932 (DP-29)	0.14	nd	nd	0.029	
Polnell Point					
UA-934 (DP-23)	0.28	0.041	0.137	0.041	
Freeland					
UA-935 (F-35)	0.26	0.072	0.107	0.042	
Lagoon Point					
UA-1205 (F-20)	0.42	0.097	0.174	0.050	
South Whidbey State Park					
UA-1209 (F-26)	0.13	nd	0.099	0.036	
80-22	0.65	0.12	0.19	0.07	
Camano Island					
UA-924 (L-14)	0.42	0.162	0.197	0.078	
UA-925 (L-12b)	0.22	0.197	0.208	0.090	
80-41 Pebble Beach	0.16	0.04	0.10	0.04	
Point Wilson					
80-19	0.06	0.03	0.05	0.04	
80-20	0.32	0.05	0.08	0.04	
UA-1199	0.34	nd	0.082	0.032	
Point Roberts					
UA-937	0.28	nd	0.094	0.041	
F-14					
UA-1204	0.18	0.021	0.097	0.024	
West Beach					
80-32	0.12	0.04	0.08	0.04	
80-33	0.12	0.04	0.14	0.08	
80-34	0.13	0.03	0.21	0.03	
DOUBLE BLUFF GLACIATION					
Double Bluff glaciomarine drift					
Double Bluff					
80-27a	0.30	0.13	0.22	0.07	
80-35	0.29	0.13	0.15	0.08	
80-35	0.28	0.11	0.14	0.08	
Possession Point (beneath glaciomarine drift)					
UA-1293 (Mx-20)	0.33	0.040	0.156	0.039	
UA-930 (Mx-20)	0.20	nd	0.092	0.050	
Camano Island					
80-41	0.16	0.04	0.10	0.04	
UA-1201	0.13	nd	0.257	0.021	

Aspartic Acid and Proline D/L Ratios in Wood

The trend of aspartic acid vs. proline D/L ratios in wood samples is shown on Figure 5. These two amino acids are selected because they have been used by previous workers to age-date samples of fossil wood. To be useful the trend should be linear, as demonstrated by the mollusk data. The general trend of these data points shows an increase with age for both amino acid ratios; a few data points scatter above the majority of the points. This comparison indicates that the relative kinetics of racemization between aspartic acid and proline are complex and do not follow a simple relationship. This condition has also been noted in wood samples from Willapa Bay (Blunt, 1982), where aspartic acid racemization in wood suggests non-linear kinetics at D/L values of about 0.3.

Environment of Preservation

The explanation for anomalous chemical behavior of amino acids in wood specimens includes factors of in-situ preservation. Sample W80-22 is composed of wood fragments 1 to 3 mm thick collected in silty clay of the Whidbey Formation at South Whidbey State Park. This sample has the highest measured aspartic acid D/L ratio (0.65) and the highest relative content of γ-aminobutyric acid. The non-protein γ-aminobutyric acid is common in clay, and its presence in a sample may indicate the need for additional sample cleaning (Schroeder, 1975). Non-protein amino acids are found in the mureide complex of bacterial cell walls and are considered to indicate a bacterial process in the formation of peat (Casagrande and Given, 1980).

Other wood specimens also show anomalous chemical behavior (Fig. 5). Sample W80-27b was collected in sandy silt of the Whidbey Formation at Double Bluff. This sample is from the interior of a 2-3-cm-thick wood specimen. Non-protein amino acids were not detected. Sample W80-20 was collected in sandy silt of the Whidbey Formation at Point Wilson. This sample is from the interior of a wood specimen 4 to 7 cm thick and does not have measurable quantities of γ-aminobutyric acid. Of three samples (W80-22, W80-27b, and W80-20), none have anomalously high D/L ratios of alanine or glutamic acid, a condition that could be an indication of micro-organism sources in wood (Zumberge and others, 1980). Other factors, such as the composition of the organic matrix of individual wood samples and the position of aspartic acid within peptides, need to be evaluated (Engel and others, 1979).

Identification of wood samples contaminated by micro-organisms might be accomplished through the stereochemistry of amino acids. Differences in the amino acid stereochemistry of fresh and rotten bristlecone pine have been reported by Zumberge and others (1980). According to their results, glutamic acid D/L ratios are relatively higher in the bound fraction of rotten bristlecone pine than in the bound fraction of relatively fresh wood in the same sample. Samples W80-33 and W80-34 from consolidated sand in the Whidbey Formation at West Beach have anomalously high glutamic acid D/L ratios (0.13) with respect to the D/L ratio of aspartic acid (0.12). These two samples probably have been contaminated to some extent by micro-organisms.

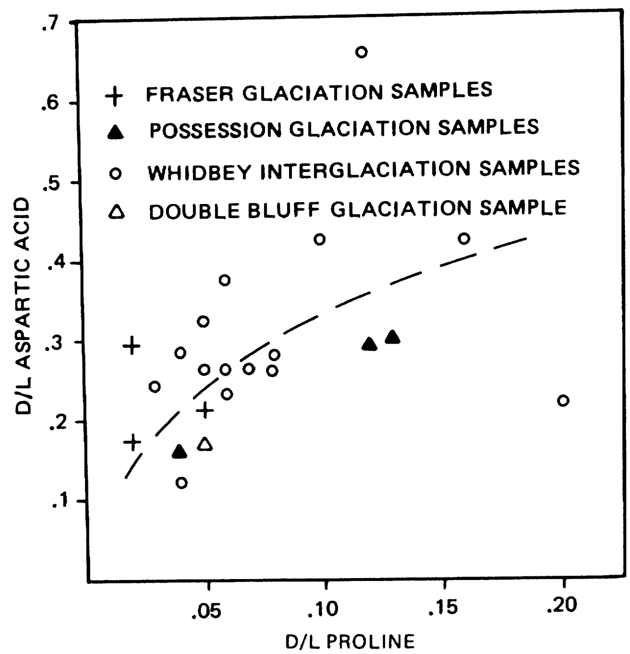


Figure 5.–Relationships of aspartic acid and proline D/L ratios in wood from Pleistocene deposits, Puget Lowland.

Amino Acid Chronology and Correlation of pre-Wisconsin Deposits

Both isoleucine and leucine have been used to correlate samples from different localities, as well as to calculate ages. The D/L ratios of leucine in *Saxidomus* have been used with some success to correlate localities in the Pacific Northwest (Wehmiller and others, 1977; Kennedy, 1978; Kvenvolden and others, 1979a; Kvenvolden and Blunt, 1980). Leucine D/L ratios of five mollusk species from the Puget Lowland (Fig. 6) cluster for species of the similar radiocarbon age. The leucine D/L ratios of *Macoma* (80-22b) and *Saxidomus* (79-1) are relatively low compared with ratios for other samples from the same locality.

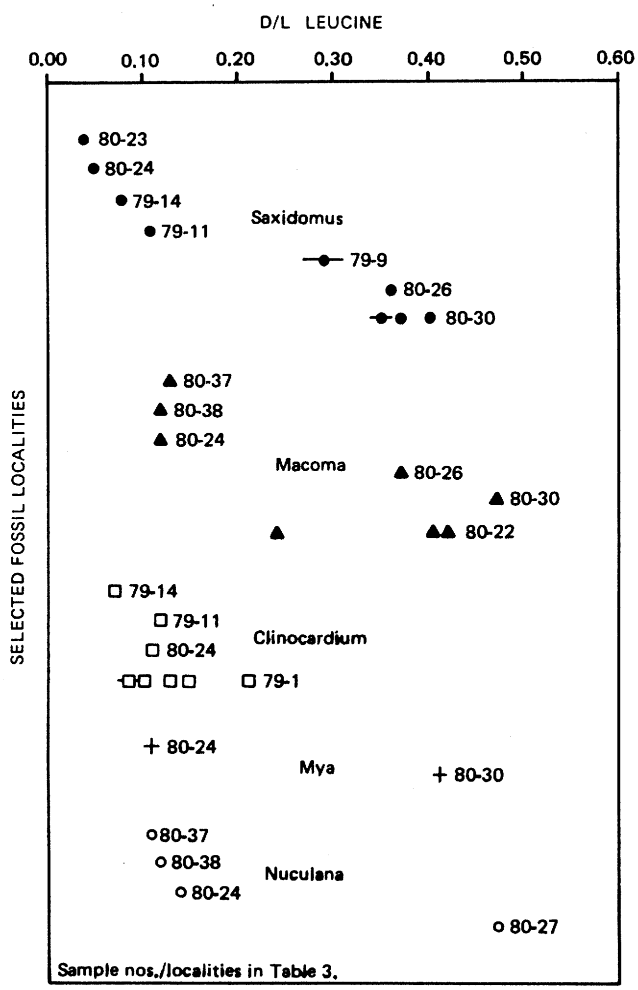


Figure 6.–Relative correlation of leucine D/L ratios in five genera of mollusk at fossil localities in the Puget Lowland.

The allo/iso D/L ratios in fossil mollusks from localities in the Puget Lowland cluster for genera of comparable age (Fig. 4 and Table 2). The allo/iso ratios in *Clinocardium* from Port Williams are not as consistent, and *Macoma* (80-22b) from South Whidbey State Park and *Saxidomus* (79-1) from Admiralty Bay have relatively low allo/iso ratios compared to other samples from the same localities.

Temperature Considerations

The rate of racemization is a function of temperature. The average effective in-situ temperature at which a fossil has been insulated during its burial history is the least reliable factor in age calculations using amino acid racemization (Wehmiller and others, 1976; Wehmiller and others, 1977; Kvenvolden and others, 1979a, b; Kvenvolden and others, 1980; Miller and Hare, 1980). Nevertheless, rate constants can be adjusted to the estimated effective diagenetic temperature conditions of a buried fossil. Adjustments of rate constants require estimating glacial temperature reductions and estimating effective temperature histories. Kvenvolden and others (1980) have employed the method of adjusting calibrated rate constants to the effective temperatures of fossil mollusks in the Puget Lowland.

Temperature reductions of as much as 4° to 6°C due to Pleistocene climatic deterioration in the Pacific Northwest have been reported from palynologic records in sediments (Heusser, 1977; Heusser and Shackleton, 1979; Heusser and Heusser, 1981) and from oxygen isotope records in calcite speleothems (Gascoyne and others, 1980). Due to the nature of palynological studies, the variations in July temperatures are usually reported. In the method established by Wehmiller and others (1976) and used by Kvenvolden and others (1980), 29 years of modern monthly air temperature variations are taken as a model of effective temperature history. The effective temperature must be adjusted downward to account for cooler Pleistocene climates. The adjusted temperature is assumed to have been the average diagenetic temperature at which the Pleistocene fossil was insulated. An average Pleistocene temperature reduction of 3.6°C for pre-Wisconsin sediments has been calculated from palynological records by Kvenvolden and others (1980).

Temperature Calibration

Temperature calibration sites listed on Table 4 were selected on the basis of proximity to radiocarbon-dated localities from which fossil mollusks were collected for analysis of leucine and glutamic acid D/L ratios. The mean annual air temperature and the effective annual air temperature were calculated from monthly air temperature data which have been averaged over the long-term recording period from 1941 to 1970 (U.S. Department of Commerce, 1975). Sediment insulation properties predict that the mean annual temperature approximates the in-situ temperature of a sample if it is buried by more than about one meter of sediment (Wehmiller and others, 1976). As the sediment cover decreases, the in-situ temperature increases and approximates the effective temperature just below the sediment surface. The effective temperatures listed in Table 4 are about 1° or 2°C higher than the mean annual temperatures because of the logarithmic increase in the calculation for warmer months (Wehmiller and others, 1976).

Table 4.–Temperature calibration localities in the Puget Lowland, Washington.

Average of monthly air temperatures (in °C) over the recording period 1941-1970 from U.S. Department of Commerce Climatological Data Annual Summary, 1975. Eff T, average effective temperature calculated using log k = 15.77 - 5939/T, following the method of Wehmiller and others (1977)

Locality	J	F	M	A	M	J	J	A	S	O	N	D	Mean	Eff T
Port Angeles	3.6	5.2	6.1	8.4	11.2	13.5	15.2	15.0	13.7	10.1	6.6	4.8	9.4	10.8
Coupeville	3.4	5.2	6.2	9.0	11.9	14.3	16.1	16.1	13.9	10.2	6.6	4.7	9.8	11.3
Anacortes	4.0	5.9	7.0	9.7	12.6	15.1	16.7	16.4	14.7	11.1	7.4	5.3	10.5	11.9
Bellingham	2.9	4.9	6.1	8.7	11.9	14.7	18.2	16.2	13.9	10.1	6.3	3.9	9.7	11.9
Sedro Woolley	3.1	5.4	6.8	9.5	12.7	15.3	17.1	16.9	14.7	10.8	6.7	4.3	10.3	12.2
Concrete	2.4	5.1	6.8	10.1	13.8	16.3	18.7	18.4	16.2	11.6	6.6	3.8	10.8	13.3

Adjustment of Racemization Rates

Leucine and glutamic acid racemization rates are adjusted to account for temperature variability using the Arrhenius relationship:

$$\ell n\,(k_2/k_1) = Ea\,(T_2 - T_1)/R(T_2T_1)$$

where k_2 and k_1 are the rates of amino acid racemization at the respective temperatures of T_2 and T_1 in degrees Kelvin; Ea is the activation energy of racemization in calories per mole; and R is the gas constant 1.987. Activation energies of amino acid racemization in fossil mollusks have been reported as 29.4 kcal $mole^{-1}$ for isoleucine in *Mercenaria* (Mitterer, 1975); 29.0 kcal $mole^{-1}$ for isoleucine in *Hiatella arctica* (Miller and Hare, 1980); and 29.4 kcal $mole^{-1}$ for an average of eight amino acids in *Saxidomus* (Blunt, 1982). The activation energy of 29.4 kcal $mole^{-1}$ is applied to leucine and isoleucine racemization in the present study.

Uncertainty in using the mean or effective temperature from Table 4 arises from the unknown insulation history of the fossils collected at each calibration locality. At Penn Cove (loc. 80-24), samples were collected within one meter of the soil surface. Near Cedarville (loc. 80-37), fossils were collected on the surface from deposits recently exposed by river erosion. The fossil mollusks collected near Deming (loc. 80-38) were from a shallow roadcut. Although these samples may have been only recently exposed, in-situ temperatures were likely warmer about 8,000 years ago during the Holocene temperature maximum (Hansen and Easterbrook, 1974; Heusser and others, 1980). Because of these uncertainties in estimating in-situ temperature histories, the average between mean annual and effective annual air temperatures is used in calculations. Samples from Admiralty Bay, South Whidbey State Park, Port Williams, and Double Bluff had more than one meter of overburden, allowing reliable use of mean annual air temperatures in calculations. (See Table 5 for method of calculation.)

Double Bluff Drift

Double Bluff Drift is named for till, glaciomarine drift, glaciofluvial sand and gravel, and glaciolacustrine silt at Double Bluff on Whidbey Island (Easterbrook and others, 1967). It occurs at or near sea level in sea cliff exposures in the central Puget Lowland, and underlying sediments are not exposed (Easterbrook, 1968). Consequently, no deposits spanning the approximately 500,000-yr gap between the Salmon Springs Drift and the Double Bluff Drift are known.

Amino acid measurements of wood and shells in Double Bluff Drift suggest an age of about 145,000 years. Three wood samples from glaciomarine drift at the type locality gave aspartic acid D/L ratios of 0.30, 0.29, and 0.28, slightly higher than typical ratios for the overlying Whidbey Formation and consistent with relative age. Proline values for the same samples were 0.13, 0.13, and 0.11, all considerably higher than those of the Whidbey Formation. Wood in silt at the base of Double Bluff glaciomarine drift at Possession Point on Whidbey Island yielded a high aspartic acid D/L ratio for one sample (0.33), but the D/L ratio for a second sample from the same site analyzed later was only 0.20, indicating that further study of species differentiation and other factors is needed.

Calculated age estimates of the Double Bluff Drift at Double Bluff were based on leucine and glutamic acid racemization in *Nuculana*. The calibration of

Table 5.–Example of time calculation

The extent of time required to achieve a given D/L ratio is a function of the specific kinetics of the amino-acid racemization (or epimerization) reaction. Linear first-order kinetics are expressed in equation (1):

$$\ln\left(\frac{1 + D/L}{1 - k'\,D/L}\right) - \ln\left(\frac{1 + D/L}{1 - k'\,D/L}\right)_{t=0} = (1 + k')kt \qquad (1)$$

where D/L is the ratio of the D- and L- amino acids

k' is inverse of the ratio of the forward and reverse rate constants at equilibrium; k' for D/L Leu = 1; K' for D-allo/L-iso at equilibrium = 0.714

k is the rate of racemization or epimerization

t is time (age of the sample)

Both the rate constant and average temperature for the "calibration site" are calculated by solving the Arrhenius expression in equation (2):

$$\ln\left(\frac{k_2}{k_1}\right) = \left(\frac{Ea}{1.987}\right)\left(\frac{T_2 - T_1}{T_2T_1}\right) \qquad (2)$$

where k_2 is calculated in equation from a site having a known radiocarbon date, measured D/L ratio, and incubation temperature (T_2)

T_2 is the average "in situ" temperature in degrees kelvin at the calibration site

T_1 is the estimated temperature at the site that includes a glacial reduction

Ea is the racemization activation energy of 29,400 calories per mole

k_1 is the rate constant of the site of unknown age.

The steps to calculate the age of fossil <u>Nuculana</u> (AAL-1877) in Possession Drift at Stillaguamish using <u>Nuculana</u> from Cedarville (C/4 = 11,640 years) are as follows:

(A) Calculate k_2 at Cedarville:

$$\frac{\ln\left(\frac{1 + 0.11}{1 - (0.714)\ 0.11}\right) - \ln\left(\frac{1 + 0.02}{1 - (0.714)\ 0.02}\right)_{t=0}}{1.714\ (11{,}640)} = k_2 = 7.6 \times 10^{-6}$$

(B) Estimate T_2 at Cedarville and T_1 at Stillaguamish using methods in Table 4:

Cedarville = 10.9°C; Stillaguamish = 9.8° - 3.6° glacial reduction = 6.2°C

(C) Calculate k_1 using equation (2):

$$\ln\left(\frac{7.6 \times 10^{-6}}{k_1}\right) = \left(\frac{29{,}400}{1.987}\right)\left(\frac{4.7}{284.05 \times 279.35}\right)$$

$k_1 = 3.2 \times 10^{-6}$

(D) Calculate the age of <u>Nuculana</u> (D-allo/L-iso = 0.36 ± 0.03) at Stillaguamish by equation (1):

$$\frac{\ln\left(\frac{1 + 0.36}{1 - (0.714)\ 0.36}\right) - \ln\left(\frac{1 + 0.02}{1 - (0.714)\ 0.02}\right)_{t=0}}{1.714\ (3.2 \times 10^{-6})} = 104{,}000 \text{ years}$$

these racemization rate constants follows the previously described procedures of Kvenvolden and others (1980). These rate constants were calibrated at radiocarbon-dated localities containing *Nuculana* at Penn Cove, Deming, and Cedarville with the temperature information from Coupeville, Bellingham, Sedro Woolley, and Concrete on Table 4. The calibrated rate constants were adjusted with a reduction of 3.6°C to the effective glacial diagenetic temperature of 6.2°C at Double Bluff. The calibrated rate constants coupled with the range of possible temperatures give a variety of calibrated rate constants at 6.2°C and a range of calculated ages. The estimated ages of the Double Bluff Drift, using leucine D/L ratios, range from 111,000 to 178,000 years. The overall age range reflects the uncertainties in the calibration method. Caution must be given to use of this tentative age estimate because only a single sample of *Nuculana* was analyzed from the Double Bluff Drift at its type locality. The age thus calculated for Double Bluff Drift may be too young because of the few samples available from the drift from throughout the area that were used for amino acid determination and the possibility of incorrect assumptions upon which computations are based. Additional samples are needed to confirm the age, but fossils are rare in this unit. D/L ratios from shells from glaciomarine drift at Foulweather Bluff also suggest relatively great antiquity for the Double Bluff Drift. Independent confirmation of the amino acid age estimates presently awaits thermoluminescence dating of clay in the Double Bluff Drift.

The remanent magnetism of Double Bluff glaciomarine drift is normal. An average declination of 1° and an average inclination of 49° were measured (Easterbrook, 1976a, 1983), providing additional evidence that the Double Bluff Drift cannot be correlative with Salmon Springs Drift in the southern Puget Lowland.

Glacial deposits stratigraphically beneath Vashon Drift (Sceva, 1957) or drift beyond the Vashon limit was commonly mapped as Salmon Springs Drift in the south-central Puget Lowland and Olympic Peninsula (Molenaar, 1965; Frisken, 1965; Noble and Wallace, 1966; Molenaar and Noble, 1970; Carson, 1970; Heusser, 1974, 1977, 1978; Gayer, 1977; Grimstad and Carson, 1981). Colman and Pierce (1981) proposed the name McCleary Drift to replace the "Salmon Springs" Drift of Carson (1970), but that drift is probably equivalent to the Double Bluff Drift. Deeter (1979) found that some of the "Salmon Springs" drifts in the southwestern Puget Lowland were in fact Double Bluff glaciomarine drift containing shells that gave amino acid racemization age estimates of about 250,000 years (Easterbrook and others, 1982). Glacial sediments extending beyond the margin of the Fraser glaciation have been tentatively correlated with the Double Bluff Drift on the basis of weathering and soil characteristics (Lea, 1984).

Whidbey Formation

Floodplain silt, sand, and peat of the Whidbey Formation accumulated during the last major interglaciation in the Puget Lowland (Easterbrook and others, 1967; Easterbrook, 1968, 1969; Hansen and Easterbrook, 1974). Pollen analyses from peat and silt indicate that Whidbey 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).

Twenty radiocarbon dates on wood and peat from the Whidbey Formation (Table 6) have yielded only infinite ages (Easterbrook, 1969, 1976a, in press).

Table 6.–Radiocarbon dates from the Whidbey Formation

>33,200	(I-1446)	>40,000	(W-1523)
>35,000	(I-1385)	>40,000	(UW-447)
>35,000	(I-1194)	>40,000	(UW-39)
>35,700	(I-1528)	>40,000	(UW-450)
>39,900	(I-2283)	>40,000	(I-10375)
>40,000	(I-974)	>42,000	(I-722)
>40,000	(I-975)	>42,000	(I-723)
>40,000	(I-1203)	>43,000	(W-1578)
>40,000	(W-1446)	>47,000	(GS-2131)
>40,000	(W-1516)	>49,400	(GRN-4971)

Six anomalous finite radiocarbon dates, ranging from 28,910 to 43,250 years reported from the Whidbey Formation (Johnson and others, 1980; Stoffel, 1980), are all considered invalid because these samples were subsequently rerun by other laboratories and found to be more than 40,000 years old. Another half dozen finite radiocarbon dates (Dorn and others, 1962), measured prior to the definition of the Whidbey Formation (but from Whidbey sediments), were also later re-analyzed and dated as older than 40,000 years. Thus, no confirmed finite radiocarbon dates are known from the Whidbey Formation.

Amino acid analyses of wood and shells in nonglacial deposits of the Whidbey Formation suggest an age of about 100,000 ± 20,000 years, well beyond the range of radiocarbon dating. Age calculations based on leucine and isoleucine racemization in *Saxidomus* were made for sediments at Admiralty Bay, Whidbey Island. Calibration of leucine and isoleucine racemization rate constants followed the method of Kvenvol-

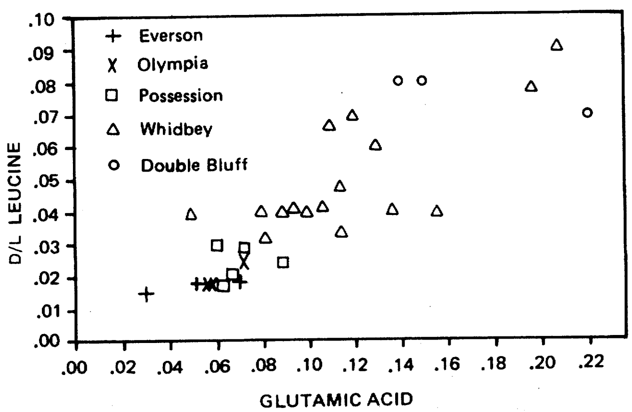


Figure 7.–Leucine and glutamic acid D/L ratios in wood from the Puget Lowland.

den and others (1980), who used Anacortes and Coupeville as temperature calibration sites and calculated an age of 77,000 years for the Admiralty Bay locality.

The calibrated rate constant (k_2) from *Saxidomus* at Hope Island and the estimated diagenetic temperature at Anacortes were used in the Arrhenius expression to calculate the rate constant (k_1) at the estimated diagenetic temperature (T_1) at Admiralty Bay. The calculated ages range from 61,000 to 131,000 years. If temperature assumptions are accurate within 0.5°C, the uncertainty in calculations is about 20 percent. The age of these deposits is here estimated as 96,000 ± 35,000 years by leucine and 107,000 ± 9,000 years by allo/iso.

The range of estimated ages for the Admiralty Bay sediments is significant because the sediments at South Whidbey State Park are correlated with those at Admiralty Bay on the basis of similar amino acid D/L ratios in *Macoma*. Fossiliferous blue clay at South Whidbey State Park was correlated on the basis of its lithology and stratigraphic position relative to the Whidbey Formation by Easterbrook (1968). The estimated amino acid age of 97,000 ± 35,000 years for these sediments appears to confirm earlier correlation of the clay with the Whidbey Formation.

Results of aspartic acid and proline measurements made on 20 wood samples from the Whidbey Formation at 11 localities (Table 3 and Fig. 5) are not as consistent as those for leucine and glutamic acid. Twelve of 19 aspartic acid measurements fall within a narrow range of values (0.20 to 0.29), but some D/L ratios of wood yielded unexpectedly higher values. Wood from shell-bearing silt and clay at South Whidbey State Park has D/L ratios of 0.65 for aspartic acid and 0.12 for proline, and wood samples from Lagoon Point and Camano Island also gave anomalous values, higher than those of Whidbey sediments elsewhere. Leucine and glutamic acid D/L ratios may be more reliable for chronostratigraphic correlation (Fig. 7). Because kinetic models are not well understood for these amino acids in wood, no ages are calculated.

Correlation of the Whidbey Formation with the Puyallup Formation in the southern Puget Lowland can be shown to be impossible because measurements of remanent magnetism of Whidbey sediments show normal polarity with declinations within 10° of north and inclinations ranging from 46° to 64° (Easterbrook, 1976b). The Puyallup Formation is reversely magnetized.

Possession Drift

Possession Drift (Easterbrook and others, 1967) occurs as discontinuous lenses in the central and southwestern Puget Lowland (Easterbrook, 1968, 1969, 1976a; Deeter, 1979). It consists of a single till sheet as much as 25 m thick at its type locality, Possession Point, but elsewhere in the lowland, Possession Drift includes glaciomarine sediments and outwash sand and gravel.

Calculations based on amino acid analyses of marine shells in Possession glaciomarine drift at several localities suggest an age of about 75,000-90,000 years (Easterbrook and Rutter, 1981, 1982). Amino acid D/L ratios were measured in shells of six mollusk genera in Possession glaciomarine drift at three localities in the Puget Lowland: Port Williams, Stillaguamish, and Blowers Bluff. Only two genera, *Nuculana* and *Clinocardium*, were found in Possession glaciomarine drift at Blowers Bluff on Whidbey Island (Fig. 8) and at Port Williams on the Olympic Peninsula (Fig. 9).

Saxidomus, Nuculana, Clinocardium, Hiatella, Mya, and *Macoma* were all present in pre-Fraser glaciomarine drift at the Stillaguamish locality (Fig. 10). The shells were radiocarbon-dated at 46,500 ± 1,100 years, but peat immediately overlying the shells was dated as older than 49,000 years (Minard, 1980). Because radiocarbon dates of shells older than about 30,000 years are much more likely to give dates to young, the peat date is believed to be more reliable, and the shells are considered older than 49,000 years. Amino acid age calculations gave a mean age of 80,000 ± 22,000 years.

Three analyses of *Nuculana* at Stillaguamish gave quite similar allo/iso ratios (0.33, 0.37, 0.38). The allo/iso ratio from the first sample analyzed from Blowers Bluff was 0.30, but ratios from seven analyses on two samples run 2 years later averaged 0.18. Analytical values for three samples from Port Williams range from 0.12 to 0.28.

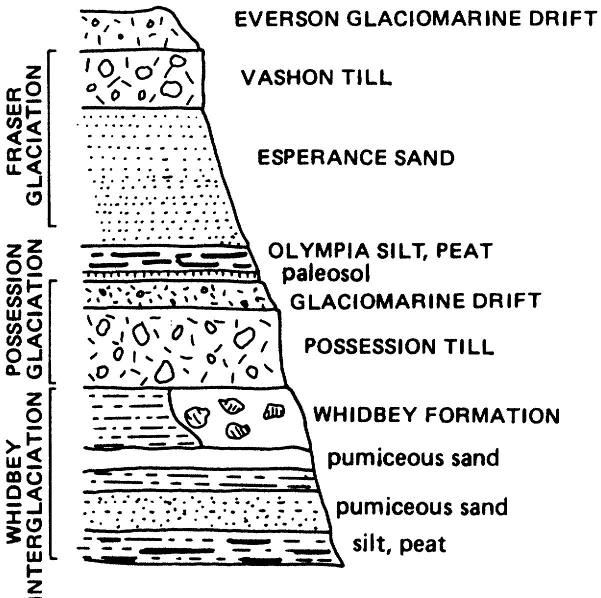


Figure 8.–Geologic section, Blowers Bluff, Whidbey Island.

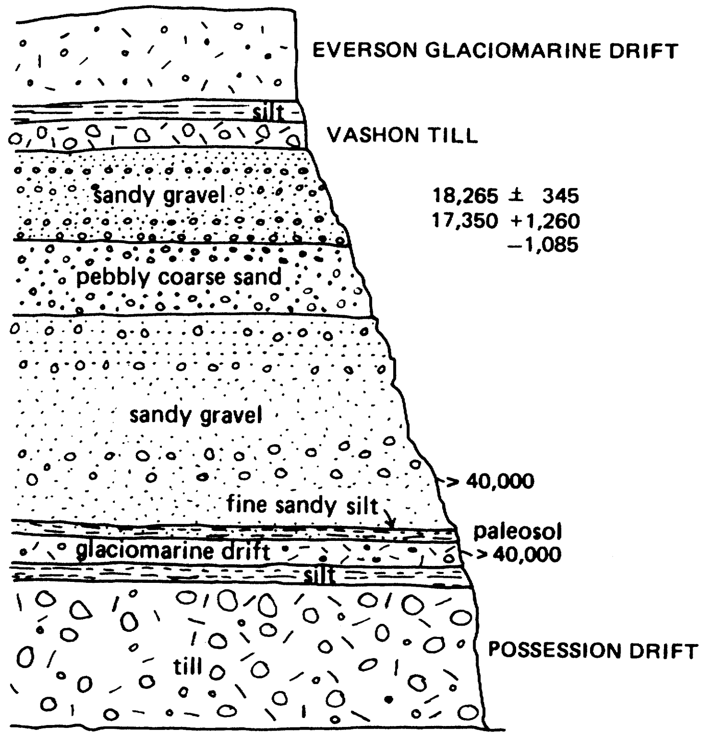


Figure 9.–Geologic section, Port Williams.

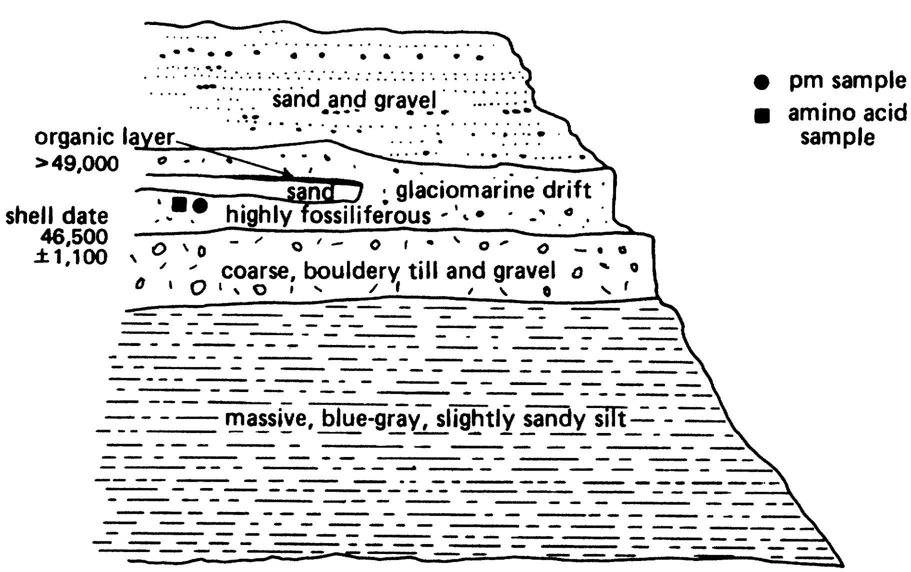


Figure 10.–Geologic section, Stillaguamish River.

At Port Williams, shell-bearing, pre-Fraser glaciomarine drift (Fig. 9) is overlain by gravel radiocarbon-dated as older than 40,000 years old. Although no direct evidence precludes that glaciomarine drift from being slightly younger than the glaciomarine drift at Stillaguamish, both occupy similar stratigraphic positions and are believed to correlate with one another. Some of the leucine and allo/iso ratios in a few *Clinocardium* from Port Williams (loc. 79-1) are similar to D/L ratios of *Clinocardium* from localities that have radiocarbon ages of about 12,000 years. However, because the fossil mollusks in the Port Williams glaciomarine drift and in the overlying gravel are radiocarbon-dated as older than 40,000 years, the Port Williams deposit cannot be correlative with such young sediments.

All radiocarbon dates on shells and wood in glaciomarine drift included in the Deception Pass Stade of the Possession Glaciation by Easterbrook (1976a) have been infinite. However, at Strawberry Point on Whidbey Island, outwash sand and gravel containing two peat beds are present between two tills. Wood in the upper of the two peats has been radiocarbon-dated at 34,900 ± 3,000 (I-1880), 35,400 ± 200 (QL-148A), and 35,600 ± 300 (QL-148B) years, and wood in the lower peat has been dated at 47,600 ± 3,300 (GrN-5257), 43,900 ± 1,000 (QL-149), and 43,600 ± 1,000 (QL-151) years (Hansen and Easterbrook, 1974; Stuiver and others, 1978). Dates of 27,600 ± 1,000 (WW-11), 27,200 ± 1,000 (I-2285), and 26,850 ± 1,700 (I-1111) years from basal peat on the upper till provide a minimum age for the upper till (Easterbrook, 1976a).

The glacial origin of these deposits is confirmed by the following evidence: (1) the upper till is compact and shows deformation structures; (2) both the till and gravel contain clasts of rock types that crop out only in Canada; (3) the gravel and till contain particles much too coarse to have been deposited in the center of the lowland by any process other than glaciation; and (4) pollen from the peat in the outwash gravel indicates a cool, tundra-like environment.

These glacial deposits provide the physical evidence for the Oak Harbor Stade of the Possession Glaciation (Easterbrook, 1976a). Pollen from the Olympic Peninsula indicates a short, cold, climatic phase from about 34,000 to 40,000 years ago (Heusser, 1977), but no evidence of glaciation during this time has been found to the north in Canada (Fulton and others, 1976) where radiocarbon dates have been measured for all but a few thousand years of the time recorded in the glacial deposits at Strawberry Point. Easterbrook (1976b,c) suggested that the Oak Harbor glacial advance occurred during a short period not covered by radiocarbon dates in Canada, but a number of recent dates from Canada coincide with those in the outwash gravel at Strawberry Point. Because the lithology of the Strawberry Point deposits precludes a glacial source in the Cascades, a very limited ice advance from British Columbia must have brought the erratic clasts.

Amino acid ratios from wood samples in late Possession and Olympia peats were measured, but no wood samples were associated with shells. All the Possession wood samples came from Strawberry Point on Whidbey Island, where radiocarbon dates were available for age comparison. The oldest wood samples at Strawberry Point were from the lowest peat in outwash gravel, dated at 47,600 years by Vogel (Hansen and Easterbrook, 1974) and 43,000 years by Stuiver, and the youngest samples were from 22,000-28,000-yr-old wood in overlying peat of the Olympia nonglacial interval (Hansen and Easterbrook, 1974). New radiocarbon dates were made from splits of the samples used for amino acid analyses and are discussed in the following section.

Aspartic acid D/L values for wood in the lowest peat, radiocarbon-dated at 47,600 years, are 0.29, 0.30, and 0.25, as compared to 0.24 for the overlying peat and 0.22 for the highest peat in the gravel (radiocarbon-dated at 34,900 years). Ratios for wood in the overlying Olympia nonglacial peat beds cluster around 0.20, although one value of 0.28 was measured. From the data collected so far, D/L ratios appear to increase with the age of the wood, but individual measurements overlap, making precise age derivations difficult.

Olympia Nonglacial Interval

Floodplain and lacustrine silt, clay, and peat of the Olympia nonglacial interval were deposited during "the climatic episode immediately preceding the last major glaciation, and represented by nonglacial strata lying beneath Vashon Drift" (Armstrong and others, 1965). Chronology of the Olympia sediments is based largely on radiocarbon dating.

Radiocarbon dates from the type locality at Fort Lawton range from 18,100 to 22,400 years (Mullineaux and others, 1965), and dates in the central Puget Lowland extend to 28,000 years (Hansen and Easterbrook, 1974; Easterbrook, 1976a). Radiocarbon dates as young as 15,000 years have been obtained from deposits immediately beneath Vashon till in the Seattle area and on the Kitsap Peninsula (Mullineaux and others, 1965; Deeter, 1979). Pollen from peat suggests that the climate during the Olympia nonglacial interval was somewhat cooler than that of the present (Hansen and Easterbrook, 1974; Alley, 1979; Clague, 1978).

RADIOCARBON CHRONOLOGY AND CORRELATION OF THE LATE WISCONSIN DEPOSITS

Coquitlam Drift

Piedmont ice which advanced into the Fraser Lowland of British Columbia late in the Olympia interval, but which apparently did not extend into Washington, deposited the Coquitlam Drift (Hicock, 1976, 1980; Armstrong, 1977; Armstrong and Hicock, 1976; Clague and others, 1980; Hicock and Armstrong, 1981; Clague and Luternauer, 1982, 1983; Armstrong and others, 1985). Wood from Coquitlam Drift in the Fraser Lowland has been radiocarbon dated at:

25,800; ± 310 (GSC-2273)
21,700 ± 240 (GSC-2235)
21,700 ± 130 (GSC-2416)
21,600 ± 200 (GSC-2203)
21,500 ± 240 (GSC-2536)
21,300 ± 250 (GSC-3305)

Mammoth tusks from Coquitlam outwash have been radiocarbon dated at:

21,400 ± 240 (SFU-65)
21,600 ± 240 (SFU-66)

Dates from overlying organic material limit the age of the Coquitlam Drift to about 18,000 years (Clague, 1980, 1981; Armstrong and others, 1985). The dates are:

18,700 ± 170 (GSC-2344)
18,600 ± 190 (GSC-2194)
18,300 ± 170 (GSC-2322)
18,700 ± 150 (GSC-2371)
17,800 ± 150 (GSC-2297)

On the basis of the range in ages, the Coquitlam Drift appears to be correlative with the Evans Creek Drift in the Cascade Mountains (deposition of which immediately preceded that of Vashon Drift), and with late Olympia nonglacial sediments in the Puget Lowland, which were deposited prior to the extension of the Cordilleran ice sheet into Washington during the Fraser glaciation (Armstrong and Clague, 1977; Easterbrook, in press).

Fulton and others (1976) have contended that the Olympia is a true interglacial period, extending from about 20,000 to beyond 59,000 years in British Columbia, but till and outwash of the Oak Harbor Stade in Washington, radiocarbon-dated between 28,000 and 35,000 years, indicate that the Olympia nonglacial interval was relatively short. Further, pollen from Olympia sediments suggests that climatic conditions were not quite as mild as at present (Hansen and Easterbrook, 1974).

Paleomagnetic data from Olympia silt indicate normal polarity with oscillatory declinations (Easterbrook, 1976a).

Fraser Drift

Fraser Drift was deposited during the last major glaciation of the Pacific Northwest by the Cordilleran ice sheet (Armstrong and others, 1965). It has been subdivided into four stades: (1) Evans Creek Drift, deposited during an early alpine phase; (2) Vashon Drift, deposited during the maximum advance 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

Vashon Drift includes (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; Mullineaux and others, 1965; Clague, 1976, 1977); (2) Vashon till (Willis, 1898; Bretz, 1913), which overlies the Esperance and Quadra units; and (3) recessional outwash sand and gravel and ice-contact deposits.

The time of advance of the Cordilleran ice sheet is limited by glaciolacustrine deposits that lie beneath Vashon till in the Fraser Lowland. The glaciolacustrine sediments have been radiocarbon dated at 18,700 ± 170 (GSC-2344) and 17,800 ± 150 (GSC-2297) years (Clague, 1980; Armstrong and others, 1985; Hicock and others, 1982; Hicock and Armstrong, 1985). Other radiocarbon dates that limit the date of the Vashon advance include: (1) 18,000 ± 400 years (I-2282) (Easterbrook, 1969) from peat in outwash sand of the Esperance Sand Member at the east end of the Strait of Juan de Fuca; (2) 16,510 ± 320 (UW-445), 15,450 ± 450 (UW-448), and 15,350 ± 210 (10374) years from floodplain sediments in the south-central Puget Lowland (Deeter, 1979); and (3) 15,000 ± 400 (W-1227), 15,100 ± 300 (W-1305), and 16,070 ± 600 (W-2125) years from organic material in the Seattle area (Mullineaux and others, 1965; Yount and others, 1980).

Waitt and Thorson (1983) proposed that the Juan de Fuca lobe (Bretz, 1920), which flowed westward out the strait to the ocean, may have been out of phase with the Puget lobe, which flowed southward down the Puget

Lowland (Fig. 11). They suggested that the Juan de Fuca lobe may have reached the western end of the strait by about 17,000 years ago, several thousand years earlier than the Puget lobe reached its maximum southern extent. However, radiocarbon dates of 17,000 ± 240 (GSC-2829) years from southeastern Vancouver Island (Keddie, 1979), 17,250 ± 1,000 from the central Strait of Juan de Fuca (Anderson, 1968); 17,350 ± 1,260 (B-1062), 18,265 ± 345 (B-1063), and 18,000 ± 400 years (I-2282) (Fig. 19) from the southeastern Strait of Juan de Fuca (Easterbrook, 1969; G. W. Thorsen, personal commun., 1981) demonstrate that the Juan de Fuca lobe did not pass the eastern part of the strait until after 17,000 years ago. Both lobes seem to have advanced synchronously.

The terminus of the Puget lobe in the southern Puget Lowland lacks a conspicuous end moraine and is marked only by patchy segments of moraines, extensive outwash deposits, and kame-kettle complexes (Bretz, 1913; Mackin, 1941; Crandell, 1963; Carson, 1970; Porter and Carson, 1971; Lea, 1983, 1984). During the interval between 13,000 and 14,500 years ago, the Puget Lobe retreated from its terminal position by backwasting, depositing recessional outwash and proglacial lacustrine sediments (Bretz, 1913; Curran, 1965; Deeter, 1979; Waitt and Thorson, 1983). The Puget Lobe had melted back from the latitude of Seattle before 14,000 ± 900 (1-330), 13,650 ± 550 (1-346A), and 13,430 ± 200 years (Rigg and Gould, 1957; Leopold and others, 1982). Wood in ice-dammed lake deposits east of Seattle was radiocarbon-dated at 13,570 ± 130 (UW-35) years, suggesting that the Puget lobe may still have occupied the Puget Lowland then.

The age of the recession of the Juan de Fuca lobe from its terminal zone is limited by radiocarbon dates of 14,460 ± 200 (Y-2452) years from a bog on Vashon Drift near the western margin of the Strait of Juan de Fuca and by the dates listed below from wood in till at five localities near the terminus of the Juan de Fuca lobe (Heusser, 1973a,b, 1982).

13,380 ± 250 (RL-140)
13,100 ± 180 (Y-2449)
13,080 ± 260 (Y-2450)
13,010 ± 240 (RL-139
12,020 ± 210 (RL-138)

Other radiocarbon dates that limit the age of retreat of the Juan de Fuca lobe include 14,400 ± 400 and 13,150 ± 400 years from bottom sediments in the Strait of Juan de Fuca (Anderson, 1968) and 12,100 ± 310 (WSU-1866) years from basal peat in a bog at a mastodon site along the southern side of the strait (Petersen and others, 1983).

Everson Glaciomarine Drift

As the Cordilleran ice sheet retreated northward from its terminus, it also thinned rapidly. Soon after it had receded northward from the Seattle area, the ice had thinned sufficiently to allow marine water to enter the Puget Lowland through the Strait of Juan de Fuca. The remaining ice floated, and progressive melting deposited Everson glaciomarine drift over a large area in the central and northern Puget Lowland (Easterbrook, 1963, 1966a, 1968, 1969, 1970, 1971, 1976a, 1979). Unbroken, articulated marine shells preserved in growth positions demonstrate that the glaciomarine drift represents in-situ deposition. More than 80 radiocarbon dates from shells and wood in Washington and British Columbia establish the age of Everson glaciomarine drift between 11,000 and 13,500 years.

Everson glaciomarine drift has been found in an area of approximately 18,000 km². It is believed to have been deposited largely from berg ice, more or less simultaneously over the central and northern Puget Lowland and southwestern British Columbia (Armstrong and Brown, 1954; Easterbrook, 1963, 1969). Pessl and others (1981) and Domack (1983) proposed the contrasting view that the Everson glaciomarine drift was deposited by calving of ice from a northward-retreating, backwasting terminus and thus is time-transgressive. Domack (1983) proposed that Everson glaciomarine drift was deposited from an adjacent, progressively retreating, ice terminus during deposition of the Everson glaciomarine drift. This type of origin requires transgressive deposition of the glaciomarine drift over a distance of more than 170 km and would mean that the glaciomarine drift in the northern part of the lowland should be younger than glaciomarine drift farther south. However, the many radiocarbon dates from Everson glaciomarine drift are not progressively younger northward. Similar ages are found for all of the Everson glaciomarine sediments, regardless of their geographic location. The southernmost radiocarbon date from Everson glaciomarine drift is 12,670 ± 90 years (USGS-64) from the southern end of Whidbey Island. Other radiocarbon dates on shells from Everson glaciomarine drift on Whidbey Island include:

11,850 ± 240 (I-1448)
12,300 ± 180 (I-2154)
12,400 ± 190 (I-2286)
12,535 ± 300 (I-1079)
13,010 ± 170 (UW-32)

Radiocarbon dates on Everson glaciomarine drift from the San Juan Islands, about in the geographic middle of the area covered by Everson glaciomarine drift are:

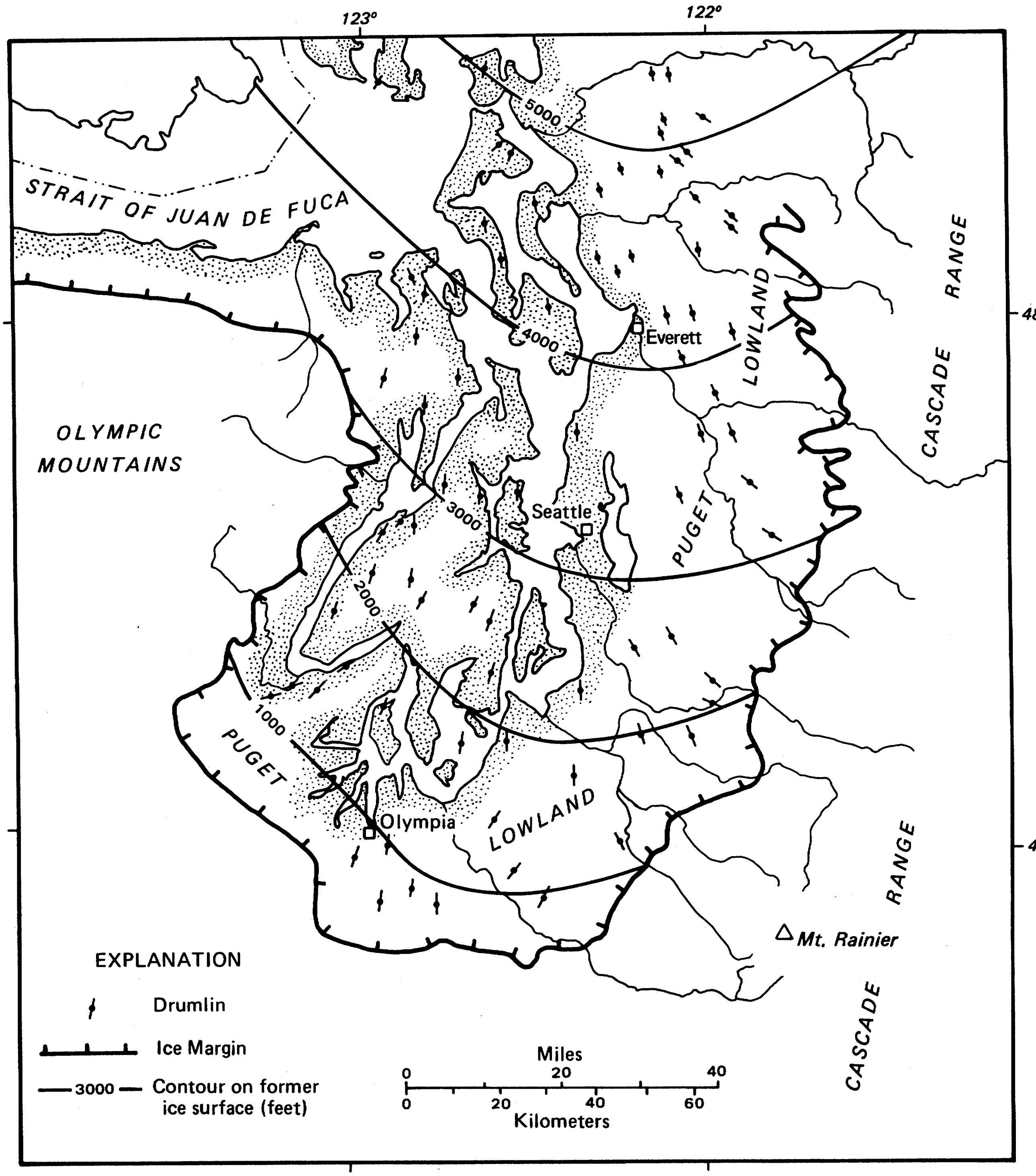


Figure 11.–The Cordilleran ice sheet in the Puget Lowland during the maximum extent of the Vashon Stade of the Fraser Glaciation (after Easterbrook, 1979).

11,900 ± 170 (I-2156)
12,000 ± 450 (I-1471)
12,160 ± 160 (I-1470)
12,350 ± 330 (I-1469)
12,350 ± 400 (I-969)
12,600 ± 190 (I-1881)

Radiocarbon dates from the northernmost Everson glaciomarine drift in Washington include 12,970 ± 280 (I-1447) and 12,090 ± 350 (W-984) years (Easterbrook, 1963, 1969) and in British Columbia, more than 20 dates range from 12,900 ± 170 to 12,000 ± 100 (GSC-2177) (Armstrong and others, 1985; Clague, 1980). The overlapping of such a large number of radiocarbon dates distributed over such a wide area and the occurrence of many old dates in the northern outcrops and young dates in the southern outcrops invalidates the Domack transgressive, calving-ice-front model for deposition of the Everson glaciomarine drift. Deposition from shelf ice is considered unlikely in view of paleoecological conditions suggested by diatoms and foraminifera in the glaciomarine drift (Crandall, 1979). Deposition largely from abundant berg ice is thus the most likely mode of origin for the glaciomarine drift.

Sumas Drift

Following deposition of Everson glaciomarine in the lowland, Cordilleran ice readvanced a short distance from British Columbia into northern Washington and deposited Sumas Drift near the international boundary (Easterbrook, 1963, 1966a,b, 1969, 1971, 1974, 1976d; Armstrong, 1977, 1981; Armstrong and others, 1965). Sumas till and ice contact deposits lie directly on post-Everson outwash, demonstrating that deposition of outwash preceded the advance of Sumas ice and that the Sumas was a subaerial advance, not just grounding of floating ice (Easterbrook, 1963). Radiocarbon dates from wood in Sumas till in southwestern British Columbia (Armstrong and others, 1965; Armstrong, 1981) include:

11,600 ± 280 (GSC-1675)
11,500 ± 1,100 (GSC-L-221D)
11,400 ± 170 (GSC-1695)

Erratics from the Fraser Canyon are frequently found associated with Sumas Drift. Radiocarbon dates (Mathews and others, 1972; Mathews and Heusser, 1981; Mathews and Rouse, 1975) from bogs in the Fraser Canyon, indicating that the canyon was ice-free at that time, include:

11,430 ± 150 (I-6057)
11,140 ± 260 (I-6058)
11,000 ± 170 (I-53460

The dates from the Fraser Canyon limit the possible thickness of ice in the canyon to 250 m at 11,430 ± 150 and 150 m at 11,140 ± 260 years ago (Clague, 1981). Sumas ice filled the Columbia Valley of Washington and the contiguous lower Chilliwack Valley of British Columbia in the Cascade Mountains with as much as to 250 m of outwash (Easterbrook, 1971). Wood in ice-contact sediments interbedded with the outwash has been radiocarbon-dated at 11,300 ± 100 (GSC-2523) (Armstrong, 1981; Clague, 1980). The time of the end of the Sumas Stade is limited by radiocarbon dates of 9,920 ± 760 (I-2280), 9,750 ± 150 (WW-6), 9,500 ± 200 (WW-8), and 9,300 ± 250 (I-2281) from the bases of peat bogs in abandoned outwash channels a few miles south of the international boundary (Easterbrook, 1969, 1971). Figure 12 summarizes the radiocarbon chronology of the late Pleistocene in the Puget Sound.

CONCLUSIONS

The chronology of early Pleistocene sediments in the Puget Lowland is based on identification and fission-track dating of the Lake Tapps tephra and paleomagnetic measurements of associated deposits. The Lake Tapps tephra, defined on the basis of outcrops at the Salmon Springs Drift type locality, is especially useful as a time-stratigraphic marker.

The ages of the Orting Drift, Alderton Formation, Stuck Drift, and Puyallup Formation are now confirmed as early Pleistocene. All lie stratigraphically beneath the Lake Tapps tephra, whose age is established as 0.8-0.9 m.y. by fission-track dating and paleomagnetic measurements. Reverse magnetization of all these stratigraphic units and the fission-track dates establish their deposition during the Matuyama Reversed Polarity Chron between 0.73 and 2.4 m.y. A numerical age for the lowermost units awaits additional dating of interbedded tephra.

Many correlations previously made with the Salmon Springs and older units in the Puget Lowland are invalidated by the antiquity of the Salmon Springs, Puyallup, Stuck, Alderton, and Orting outwash sediments. None of the Salmon Springs and older deposits can be equivalent to the Double Bluff Drift, Whidbey Formation, or Possession Drift, all of which are normally magnetized. A chronologic gap in the Pleistocene stratigraphy of the Puget Lowland is now apparent for the interval between 200,000 and 800,000 years ago.

The ages of Double Bluff Drift, the Whidbey Formation, and Possession Drift are based on amino acid analyses of shells and wood. Calculation of amino acid age estimates for marine shells in Double Bluff glaciomarine drift suggest an age of 110,000-178,000 years, but the unit could be as old as about 250,000 years. The age of shells in Whidbey sediments is calculated as 96,000 ± 35,000 years by leucine and 107,000 ± 9,000 years by allo/iso D/L ratios. Marine shells in Possession glaciomarine drift give amino-acid-estimated ages of 80,000 ± 22,000 years.

Amino acid analyses were also made on wood associated with shells in Double Bluff Drift, Whidbey sediments, and Possession Drift, as well as on younger wood dated by radiocarbon. The purpose of these analyses was to determine if wood could be used for

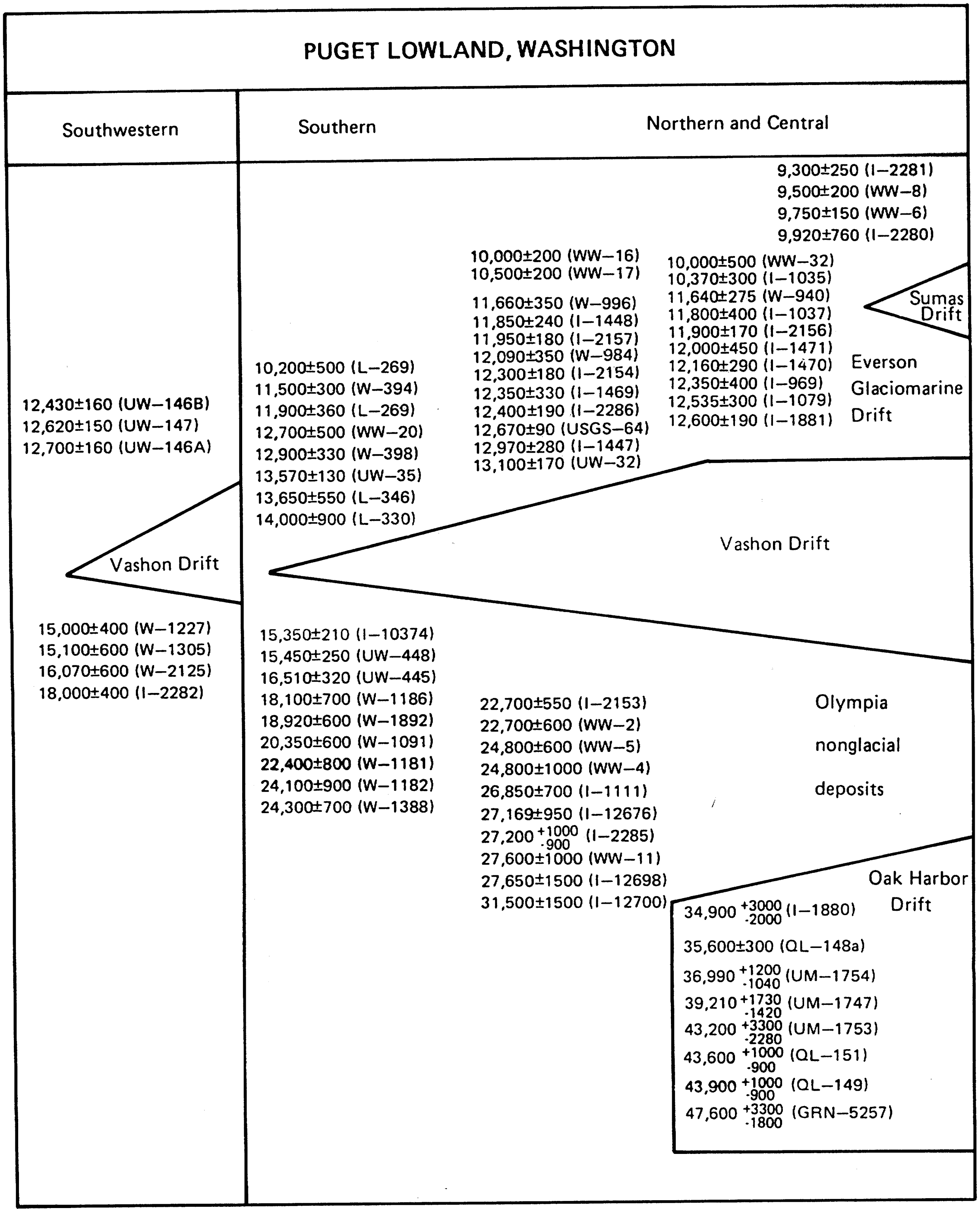


Figure 12.–Radiocarbon chronology of the late Pleistocene in the Puget Sound.

amino acid age determinations. Most of the wood analyzed gave consistent results, but some samples gave widely varying results for reasons that were not readily apparent. Age calculations for wood were not made because kinetic models of racemization in wood are not yet well understood. At this early stage in the development of amino acid age estimates in wood, results look encouraging, but additional data on variation between species and the effects of the degree of preservation of wood are needed.

The chronology of late Pleistocene sediments in the Puget Lowland has been established with numerous radiocarbon dates (Fig. 12). Advance of the Cordilleran ice sheet during the Fraser Glaciation is well documented by radiocarbon dating. An early advance of ice into the Fraser Lowland of British Columbia between 18,000 and 21,500 years ago apparently did not reach the Puget Lowland of Washington. It may be equivalent to the Evans Creek Drift in the Cascade Mountains, deposition of which also immediately preceded the main Fraser advance. The Cordilleran ice sheet advanced across the international boundary shortly after 18,000 years ago and split into two lobes at the junction of the Puget Lowland with the Strait of Juan de Fuca. Both lobes apparently advanced synchronously. The Juan de Fuca lobe retreated from the western part of the strait shortly before 14,500 years ago, and the Puget lobe retreated from its terminus to the vicinity of Seattle by 14,000 years ago. By 13,000 years ago the ice sheet had thinned sufficiently to allow incursion of marine water into the Puget Lowland, and floating of the remaining ice resulted in deposition of Everson glaciomarine drift over an area of about 18,000 km^2. More than 80 radiocarbon dates from shells and wood in Everson glaciomarine drift show that the drift was deposited nearly contemporaneously from berg ice over the whole region, rather than transgressively from a retreating, calving ice front.

Cordilleran ice readvanced a short distance into the northern Puget Lowland during the Sumas Stade about 11,500 years ago. Radiocarbon dates from basal peat in meltwater channels indicate that the Sumas ice disappeared by 10,000 years ago.

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APPENDIX

Amino Acid Geochemistry Procedures

U.S. Geological Survey Laboratory

Wood shavings were cut from the interior of each wood sample (frozen since collection) using a clean razor knife. Each shaving was immersed in 1 N HCl and sonicated for 30 sec, followed by a distilled water rinse. The pretreated shavings were dried in a vacuum oven and stored in a desiccator. Sample weights after cleaning ranged from 0.15 g to 0.70 g. Shell samples (frozen since collection) were slightly dissolved in 1 N HCl for 30 sec with sonication and rinsed in distilled water. The pretreated shell samples were dried in a vacuum oven and stored in a desiccator. Sample weights after cleaning were about 0.2 g.

Amino acids (both free and bound) were extracted from wood and shells by hydrolyzing the material in 6 N HCl at 110° C for 20 hours under nitrogen in screw-cap hydrolysis tubes. The resulting hydrolysate was evaporated to dryness, taken up in a norleucine standard at pH 1 and applied to the top of a 14 ml column of AG 50-X8 (H+) cation exchange resin. Amino acids were eluted with 2 N NH_4OH and evaporated to dryness. The amino acids were taken up in 2 ml of distilled water and split; half was acidified with 0.1 N HCl and evaporated as a salt in preparation for derivatization; the other half was evaporated to dryness and taken up on 1 ml pH 2.2 sodium citrate dilution buffer in preparation for ion-exchange chromatography. The derivatized portion is discussed in this paper.

The N-pentafluoropropionyl-amino acid-(+)-2-butyl ester derivative was resolved by gas chromatography on two different stainless steel capillary columns: 60 m x 0.08 cm coated with UCON 75-H 90,000 and 60 m x 0.12 cm coated with Carbowax 20M. Quantification of the D- and L-amino acid derivatives was made by peak-height measurement on chromatograms.

University of Alberta Laboratory

Each wood sample was thoroughly cleaned with distilled water, air dried on a plastic weighing dish, broken into small fragments, and crushed using an IKA analytical mill. The wood particles were washed twice in a plastic disposable centrifuge tube using 2 N HCl and twice with double distilled water. Between washings, the sample was sonicated, centrifuged, and decanted. The cleaned particles were transferred to a Buchner funnel connected to a water-vacuum tap and fitted with Whatman glass fiber paper (GF/A-4.25 cm) and washed several times with double-distilled water. The filtrate was discarded and the washed particles collected in small plastic vials where they were dried.

About 100 mg of washed, dried sample was placed in a glass screw-top culture tube (13 x 100 mm). About 6 to 8 ml 5.5 N HCl (constant boiling) was added and the mixture allowed to reflux at 108° C for 24 hours in a heating block. Once cooled, the supernatant liquid was evaporated to dryness in a Speed Vac Concentrator. The residue was dissolved in 1 to 2 ml double distilled water and added to freshly regenerated cation exchange resin (Dowex Ag 50W-X8, 50-100 mesh). Two bed volumes of 3 N NH_4OH were added to elute the amino acids. About 10 ml of amino acid eluate were collected in a clean 13 x 100 mm screw-top culture tube when the solvent front was about 1.5 to 2. 0 cm from the bottom of the column. Esterification was carried out by adding 0.1 ml isopropanol/3.5 N HCl to the dried eluate. This was sonicated until homogeneous, then heated at 100°C for 15 minutes in an oil bath. After evaporation to dryness, the sample was acylated by adding 0.1 ml PFPA (pentafluoropropionic anhydride) and 0.3 ml distilled CH_2Cl_2 (methylene chloride). The sample was sonicated until dissolved and then heated in an oil bath for 100 °C for 5 minutes. The excess PFPA and CH_2C_{12} were cold evaporated on a Buchi rotary evaporator using liquid N_2. Next, the sample was washed with 0.5 to 0.1 ml CH_2C_{12} and after allowing the residue to dissolve completely, it was cold evaporated to dryness using a rotary evaporator. The sample was diluted to 0.5 ml CH_2C_{12} and filtered through a Gelman alpha-200, 0.20 μ metricel filter. About 0.2 to 1.0 μl was injected onto a Hewlett-Packard Model 5840A gas chromatograph equipped with FID Detector and Chirasil-val capillary column (25 ml). The system is controlled by a digital micro-processor terminal which reports amino acid peak areas by automatic integration.

D/L ratios of alanine, glutamic acid, valine, leucine, phenylalanine, proline, aspartic acid were routinely determined in both laboratories. Aspartic acid, glutamic acid, and leucine proved to be the most useful because of their relatively fast rate of racemization and reliability. Examples of gas-chromatograms and ion-exchange chromatograms of mollusks and wood are shown on Figure 3. The leucine and alloisoleucine/isoleucine D/L ratios of fossil mollusks are reported in Table 2. The aspartic acid, glutamic acid, and leucine D/L ratios in fossil wood are reported in Table 3.

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Age of Midden Deposits at Penn Cove

The age of an archeological midden at Penn Cove on Whidbey Island was calculated using the racemization of amino acids in *Saxidomus*. Leucine and glutamic acid racemization rate constants were calibrated using data from *Saxidomus* from Bainbridge Island. The leucine D/L ratio of 0.08, the leucine time-zero correction of 0.02 and the radiocarbon age of 3,260 ± 80 years give Kleu = $(1.85 \pm 0.05) \times 10^{-5}$ yr^{-1}. The glutamic acid D/L ratio of 0.09, the glutamic acid time-zero correction of 0.03 and the radiocarbon age of 3,260 ± 80 years give Kglu = $(1.85 \pm 0.05) \times 10^{-5}$ yr^{-1}. These rate constants and the leucine and glutamic acid D/L ratios measured in *Saxidomus* 80-24m are substituted into equation (1) to give an age of 1,600 years by leucine and 1,600 years by glutamic acid. In a similar manner an age of about 1,000 years is calculated for *Saxidomus* (80-23). Subsequently, a radiocarbon age of ~ 845 years has been obtained from *Saxidomus* shells at Penn Cove, confirming the amino acid calculation.