PROPOSED REVISION OF NOMENCLATURE FOR THE PLEISTOCENE STRATIGRAPHY OF COASTAL PIERCE COUNTY, WASHINGTON

by

JOHN B. NOBLE
Robinson and Noble, Inc.
Tacoma, Washington

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

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Brian Boyle · Commissioner of Public Lands
Art Stearns · Supervisor

Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

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By John B. Noble
Robinson and Noble, Inc.
Tacoma, Washington

ABSTRACT

The stratigraphic sequence of Pleistocene sediments in the southern Puget Sound basin is now known to be far more complex than that which has been described in the literature. Furthermore, some usages of the established nomenclature have been found to be in error. Erroneous application of the term Salmon Springs Drift is a prime example.

Since 1983 I have been involved with a series of hydrogeologic studies in the southern Puget Lowland, focusing on coastal Pierce County, during which the logs for many scores of deep water wells were evaluated. I personally logged the lithology in many of these wells. The evaluation allowed the establishment of a stratigraphic sequence independent of and differing from earlier descriptions.

The proposed revised and new informal nomenclature for the Pleistocene sediments of coastal Pierce County and adjacent areas, from younger to older, is: Vashon Drift (no change proposed); Discovery nonglacial unit (for nonglacial deposits of Olympia time); Narrows glacial unit (a newly named glacial unit); Kitsap Formation (still a reliable map unit but reassigned from Olympia time to a "Kitsap" nonglacial episode); Flett Creek glacial unit (described from well log data but may locally crop out above sea level); Clover Park nonglacial unit (a widespread nonglacial unit described from well logs); Lakewood glacial unit (described from well logs); Gravelly Lake nonglacial unit (a nonglacial deposit described from well logs); Lone Star glacial unit (the oldest glacial deposit confidently recognized in well logs); and older and unnamed Pleistocene sediments which may or may not include glacial drift.

The newly named units are likely to be correlative to previously named pre-Vashon units, especially those of Crandell and others (1958). However, such correlations are not proposed herein because of lack of supporting evidence.

INTRODUCTION

The southern Puget Sound basin contains a sequence of unconsolidated Pleistocene sediments in excess of 2,000 feet thick. Many of these sediments result from advance and wasting of continental glaciers, whereas other parts of the sequence consist of lacustrine and fluvial sediments deposited during interglacial episodes. The glacial deposits are typically from high-energy environments, whereas the nonglacial deposits are typically sediments from

slower flowing streams or slack water. The relative volumes of each are roughly equal--therefore, the interglacial times must have been of much longer duration than the glacial times.

Of the more than 2,000 feet of sediment, stratigraphic nomenclature has been applied only to those portions exposed above sea level. This has allowed the identification of at least four continental glaciations in the southern Puget Sound lowland. The current nomenclature has been in part independently established for the northern and southern parts of the basin (Fig. 1). Correlations between the northern and southern sections of the Puget Sound area have not been confidently established. Furthermore, correlations between the type sections in the eastern part of the southern basin and mapped deposits in the southern basin near the Puget Sound shorelines are almost certainly in error.

During the last two decades the "practical" geologists, principally engineering geologists and hydrogeologists, have probably misapplied the stratigraphic nomenclature throughout the southern Puget Sound lowlands. For example, there has been a nearly universal tendency to name as Salmon Springs any glacial unit that appears to be both older than Vashon and also near or above sea level. This has been done with no supporting evidence for a direct correlation with Salmon Springs Drift sediments at the type sections. As further discussed, such correlations are unlikely to be valid. Compounding the probable misnaming of the unit, consulting geologists in private reports have commonly used the term "Salmon Springs Aquifer". The error here is that stratigraphic units, in themselves, do not constitute aquifers. Permeable zones within stratigraphic units may constitute aquifers.

In recent years I have preferred the use of local, but not stratigraphic names, for aquifers. An example is the Redondo-Milton channel aquifer at Federal Way (Robinson and Noble, Inc., 1987) which has a mapped areal extent and for which there is a definition of the stratigraphic units containing and confining it. However, those same stratigraphic units extend beyond the boundary of the aquifer.

In contrast to the "practical" geologists, the "academic" geologists have established numerous type and reference stratigraphic sections for the region's Pleistocene units. However, they have been unable to confidently correlate these units beyond their study areas.

In the early 1960s I began with the academic geologic approach to areal stratigraphy, but I gravitated toward the practical applications of geology after becoming hopelessly confused with the former. During my academically oriented years, mapping for the Washington Division of Water Resources in cooperation with the U.S. Geological Survey, I contributed to some of the problems. Subsequently, as a consulting geologist, I made observations during the drilling of scores of thousands of feet of deep wells in the region and

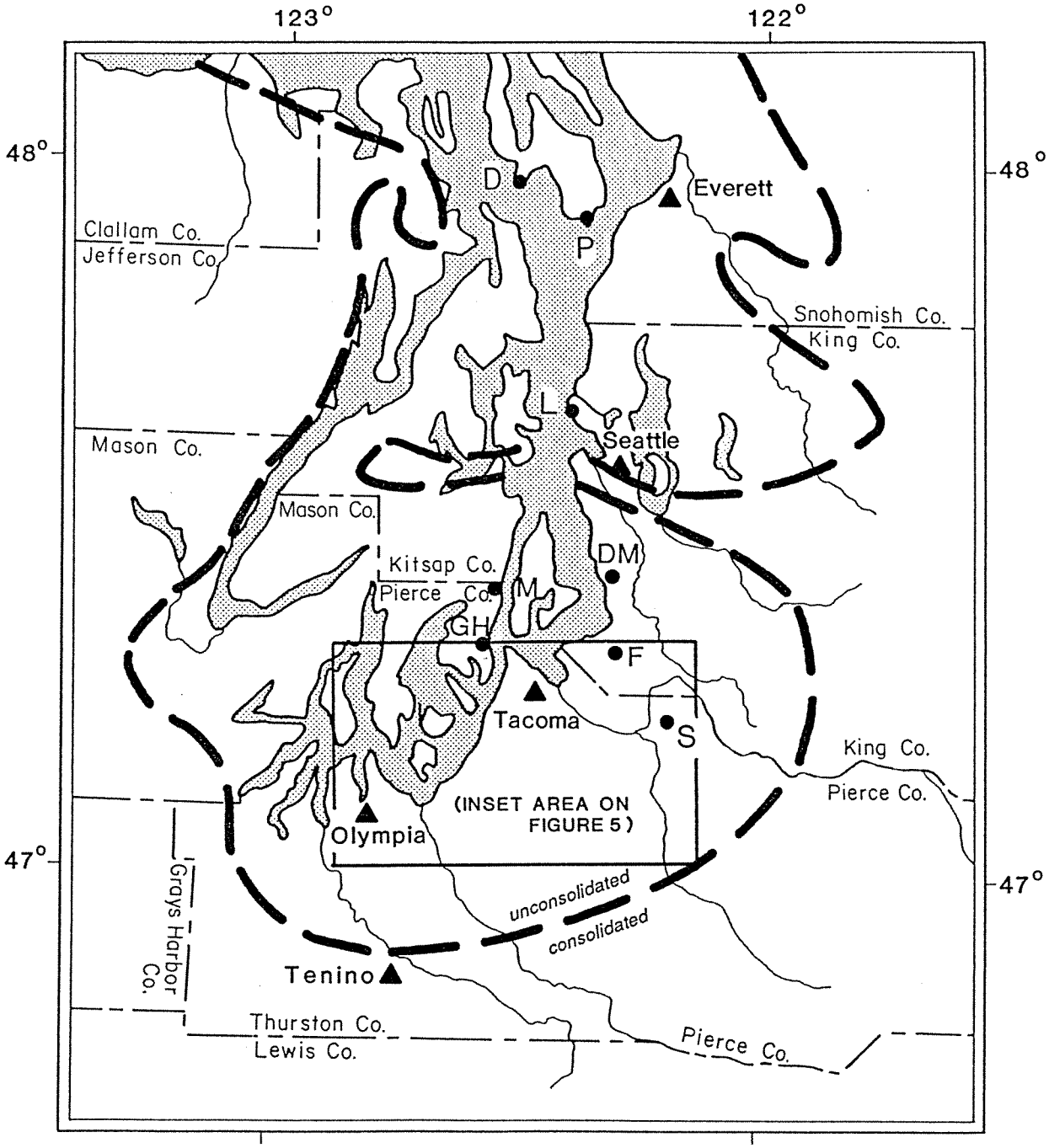

Figure 1. Index map of Puget Sound area showing type locations of earlier studies. D, Double Bluff; P, Possession Point; L, Ft. Lawton; S, Salmon Springs; GH, Gig Harbor; F, Federal Way; DM, Des Moines; M, Maplewood. **Heavy line,** approximate boundary between surficial outcrops of unconsolidated and consolidated rocks.

formed some concepts that may be useful for obtaining a fuller and more accurate regional understanding of the Pleistocene geologic history of the southern Puget Sound area.

The basic purpose of this paper is to propose a revised, informal stratigraphic nomenclature for deposits already mapped in the southern Puget Sound coastal areas, particularly in coastal Pierce County. Ideally, correlations can be carried to or from these newly named deposits, which can then be established as concordant with the type sections. If convincingly done, the informal names proposed herein would die by priority rules. Thus, if old name A = new name B, then the unit name is obviously A. However, where the name A in one place is incorrectly given to a unit assumed to be A in another place, then it is useful to have the name B, at least for the nonce.

Additionally, I am proposing informal names for the parts of the sequence that are present only below sea level in the coastal Pierce County area. Some of these units may be correlative with those in the type sections, but others may not be. These deeper strata are recognized solely from lithologic descriptions of drill hole samples.

SELECTED TERMINOLOGY

A few stratigraphic terms are used in Pleistocene glacial geology that are not frequently used in the general earth sciences. These are:

Drift -- the general term for all rock material deposited by glacial action, either directly by the ice or indirectly by meltwater from the glacier. Thus, drift can contain particle sizes from clay through boulders and range from unsorted to well sorted. "Drift" has been applied as a stratigraphic formation designator, i.e., Vashon Drift, which is the total set of material deposited during and as a result of the Vashon glaciation.

Till -- a special component or member of a drift that consists of material deposited directly by a glacier with minimal reworking by water. As such, till is essentially an unsorted mixture of all sizes and is usually densely compacted (in the case of subglacial till) as a result of the overriding ice's weight. Ablation till (as opposed to subglacial till) is not compacted and is a residual deposit of all detritus let down on the surface as ice melts away.

Stade -- a glacio-climatic episode within a longer glacial time. In this paper the term is used only for the Vashon Stade of the Fraser Glaciation.

Formation -- the basic stratigraphic unit for mappable deposits. (See Bates and Jackson, 1987.) In the local Pleistocene stratigraphy the term has become limited to mappable stratigraphic units of nonglacial or interglacial sediments as opposed to the glacial deposits which are designated as drifts.

As an example, the Puyallup Formation (nonglacial) conformably underlies the Salmon Springs Drift (glacial).

Unit -- as used herein, a geologic unit is synonymous with formation except for the formal acceptance of the name through the codes for stratigraphic nomenclature. In this report, the adjective "glacial" or "nonglacial" has been applied to each newly named unit.

PREVIOUS STUDIES

Bailey Willis (1898) was the first to describe a sequence of glaciations in the Puget Sound region, naming the Vashon glaciation and an older (Admiralty) glaciation. These basic terms and the concept of two and only two continental Pleistocene glaciations survived at least into the late 1940s when it became apparent that glacial history was more complex. Even J Harlen Bretz in his brilliant 1913 book, Glaciation of the Puget Sound Region, recognized only the two glaciations, although he suspected the possibility of a double advance of the Vashon.

The Admiralty glaciation concept was finally laid to rest by Crandell and others (1958) when they described a sequence of four continental (Puget lobe) glaciations and intervening nonglacial episodes. The Vashon remained as the youngest of the glaciations, whereas the Admiralty did not fit into their system. Type localities of that study are shown on Figure 1, where "Salmon Springs" is noted. (See also Fig. 5.) Table 1 shows Crandell's stratigraphic sequence and climatic episodes. This sequence is definitely valid at the type areas. However, correlations to the west have now been found to be faulty.

In the early 1960s a series of coordinated mapping projects was done in the lowlands of Thurston, Mason, Kitsap, and Pierce Counties. The resulting publications were: Molenaar (1965) for the Kitsap Peninsula portions of Pierce and Kitsap Counties; Noble and Wallace (1966) for Thurston County; Walters and Kimmel (1968) for central Pierce County; and Molenaar and Noble (1970) for western Mason County. These authors agreed to redefine Sceva's (1957) "Kitsap Clay Member of the Orting Gravel" as a nonglacial unit deposited during the unnamed interval between the Vashon and Salmon Springs Glaciations. The redefinition was published by Molenaar (1965). The Kitsap Formation of those studies is a valid, mappable unit; however, its position in those authors' chronology is now known to be in error, and the resulting misapplication of its chronology has caused considerable confusion to date.

The Kitsap Formation was believed by the above-mentioned workers to belong to the unnamed pre-Vashon interglacial episode by virtue of finite radiocarbon dates ranging from 26,000 to 36,000 years BP (Noble and Wallace, 1966, p. 35). After publication, those authors were notified by the dating agency (Univ. of Washington) that the laboratory hydrogen used in the process was contaminated by radioactive tritium resulting from the many nuclear tests

Table 1 -- First major revisions of Pleistocene stratigraphy in the southern Puget Sound area

Formations (east*)	Climatic episode	Formations (west**)
Vashon Drift	Vashon Glaciation	Vashon Drift
(None shown)	Unnamed interglaciation	Kitsap Formation
Salmon Springs Drift***	Salmon Springs Glaciation	Salmon Springs(?) Drift
Puyallup Formation	Puyallup Interglaciation	None mapped
Stuck Drift	Stuck Glaciation	None mapped
Alderton Formation	Alderton Interglaciation	None mapped
Orting Drift	Orting Glaciation	None mapped

* Crandell and others (1958)
** Molenaar (1965); Noble and Wallace (1966); Walters and Kimmel (1968), coastal Pierce County only
***At the type section the Salmon Springs includes a thin nonglacial unit.

Table 2 -- Second major revision of Pleistocene stratigraphy by Armstrong and others (1965)

Climatic episode	Formation in southern Puget Sound
Fraser Glaciation	
Sumas Stade	None
Everson Interstade	None
Vashon Stade	Vashon Drift
Olympia Interglaciation*	Kitsap Formation
Salmon Springs(?) Glaciation	Salmon Springs Drift

* The Kitsap Formation is now known to be older than the Olympia Interglaciation.

of the 1950s and 1960s. Later samples from the Kitsap, including several obtained by Walters and Kimmel, all yielded radiocarbon ages greater than 38,000 years BP and possibly much greater.

Beginning in 1965, after I moved to a consulting career in ground water, I was shown and accumulated a diverse set of geologic evidence showing that a post-Kitsap, pre-Vashon drift unit was present in the south Puget Sound area. This evidence was difficult to accept because it broke down an accepted "fact". The description and new informal names of these immediately pre-Vashon stratigraphic units are presented herein. They are key to the revision of the entire stratigraphic sequence.

In the mid-1960s, Mullineaux and others (1965) obtained radiocarbon dates from wood in sediments immediately beneath the Lawton Clay. These deposits conformably lie below sand and clay deposited during the advance of the Vashon glacier. This section is exposed in the sea cliff at Seattle's Fort Lawton, now Discovery Park. The ages range from 17,400 to 23,200 years. Also about this time, D. J. Easterbrook (Whatcom County) and J. E. Armstrong (southwest British Columbia) recognized a post-Vashon glaciation that barely entered the U.S.

By now, the Crandell sequence (Table 1) could be expanded by naming the pre-Vashon climatic episode and by recognizing that the Vashon was succeeded by a younger drift sheet. Accordingly, in Armstrong and others (1965), Armstrong, Crandell, Easterbrook, and Noble added two new names to the chronology. They first coined the term "Fraser Glaciation" with a "Sumas Stade", an "Everson Interstade", and a "Vashon Stade". The term "Vashon Drift" remains valid and includes numerous members. Second, they named the previously unnamed interglacial episode immediately before the Vashon Glaciation. They chose the term "Olympia" after the city near where the Kitsap Formation is widely exposed. D. R. Crandell, as advised by D. R. Mullineaux, urged that the type locality for Olympia-age sediments be at Seattle's Fort Lawton for which Mullineaux had radiocarbon dates, and not near Olympia where the radiocarbon dates were questioned. Hindsight shows that the first interglacial should have a more meaningful name than Olympia. Table 2 shows the revised or "Armstrong and others" stratigraphic set.

While Walters and Kimmel, Noble, and Molenaar were mapping with and expanding the 1958 "Crandell" stratigraphy in the southern Puget Sound region, Easterbrook was mapping to the north in Whatcom and Island Counties and using names that he developed. Easterbrook's (1968) principal units, as they apply to this paper, included Vashon Drift. His new nomenclature also included Possession Drift, Whidbey Formation, and Double Bluff Drift. Easterbrook's units are well identified on the south part of Whidbey Island, which is only 5 miles from the north end of Kitsap County where Molenaar used the "southern" stratigraphic scheme. To date, correlation from north to south has been unsuccessful, although Deeter (1979) prepared an ambitious master's thesis that made a reasonable attempt to do so. However, he was not able to clearly distinguish between Kitsap and Whidbey. Table 3 shows Easterbrook's original

Table 3 -- Easterbrook's (1968) stratigraphy of the northern area and correlation with that of the southern area; Based on Blunt and others (1987, p. 324)

Formations (north)	Climatic episode	Formations (south)
Sumas Drift	Fraser Glaciation	None
Everson Drift	Fraser Glaciation	None
Vashon Drift	Fraser Glaciation	Vashon Drift
None named*	Olympia Interglaciation	None
Possession Drift	Possession Glaciation	None
Whidbey Formation	Whidbey Interglaciation	None
Double Bluff Formation	Double Bluff Glaciation	None
--- Hiatus from 250,000 to 800,000 years BP** ---		
None	Salmon Springs Glaciation	Salmon Springs Drift
None	Puyallup Interglaciation	Puyallup Formation
None	Stuck Glaciation	Stuck Drift
None	Alderton Interglaciation	Alderton Formation
None	Orting Glaciation	Orting Drift

* Blunt and others (1987) cite numerous samples with radiocarbon dates in the Olympia time interval, but no associated units are named.

** Blunt and others (1987) implied the likely existence of exposures for this time, but knew of none.

(1968) stratigraphy with subsequent revisions by Blunt and others (1987). Note that Table 3 omits reference to the Kitsap Formation and shows the Salmon Springs to be much older than previously surmised.

The Whidbey Formation is widespread on Whidbey Island and is a classic representation of a nonglacial unit. In the southern Puget Sound region the lithologies of the Kitsap Formation record a similar depositional environment, and the unit seems to have a similar stratigraphic position. Easterbrook's Possession Drift, however, is not nearly as well exposed as the Whidbey, being sporadic in occurrence. During a 1964 field trip with me, Easterbrook referred to it as the "phantom till".

PROBLEMS WITH REGIONAL CORRELATION

Vashon Drift is a recognizable and widespread formation throughout the Puget Sound lowland. This drift sheet extended, as part of deposits of the Cordilleran glacier, south into Washington to a definite end moraine terminus in eastern Washington. In western Washington the terminal position is not precise, but all agree the maximum extent was south of Olympia, near Tenino (Fig. 1).

Olympia Time-Rock Problems and Proposed Naming of the Discovery Nonglacial Unit

Stratigraphic problems begin when one attempts to match rock units with events during the interglacial episode immediately prior to the Vashon glacial stade (about 20,000 years BP). That interglacial time, as explained above, has been called Olympia. The principal, widespread pre-Vashon nonglacial formations that have been mapped are the Whidbey (north) and the Kitsap (south). Radiocarbon dates now confirm that both predate Olympia time, although the Kitsap was erroneously reported to be of Olympia age, as explained earlier.

Mullineaux and others (1965) established a radiocarbon age for the Olympia interglacial interval from samples immediately and conformably below what they redefined as the Lawton Clay Member of the Vashon Drift. They proposed removing this bed of nonglacial sand, silt, and clay from the earlier, informally described Lawton formation (Mackin and others, 1950) and leaving the nonglacial unit unnamed. They restricted the use of the term Lawton Clay Member to the proglacial clayey deposits of the Vashon Drift. However, as these nonglacial sediments immediately below the Lawton represent the earliest described and dated unit for Olympia-age materials, they deserve a distinct nomenclature. For this, I here propose the informal term Discovery nonglacial unit (after Discovery Park). The suitable section for defining this unit is in sec. 16, T. 25 N., R. 3 E., beds 1 through 8 of Mullineaux and others (1965, p. 3-5). Figure 2 is derived from that paper.

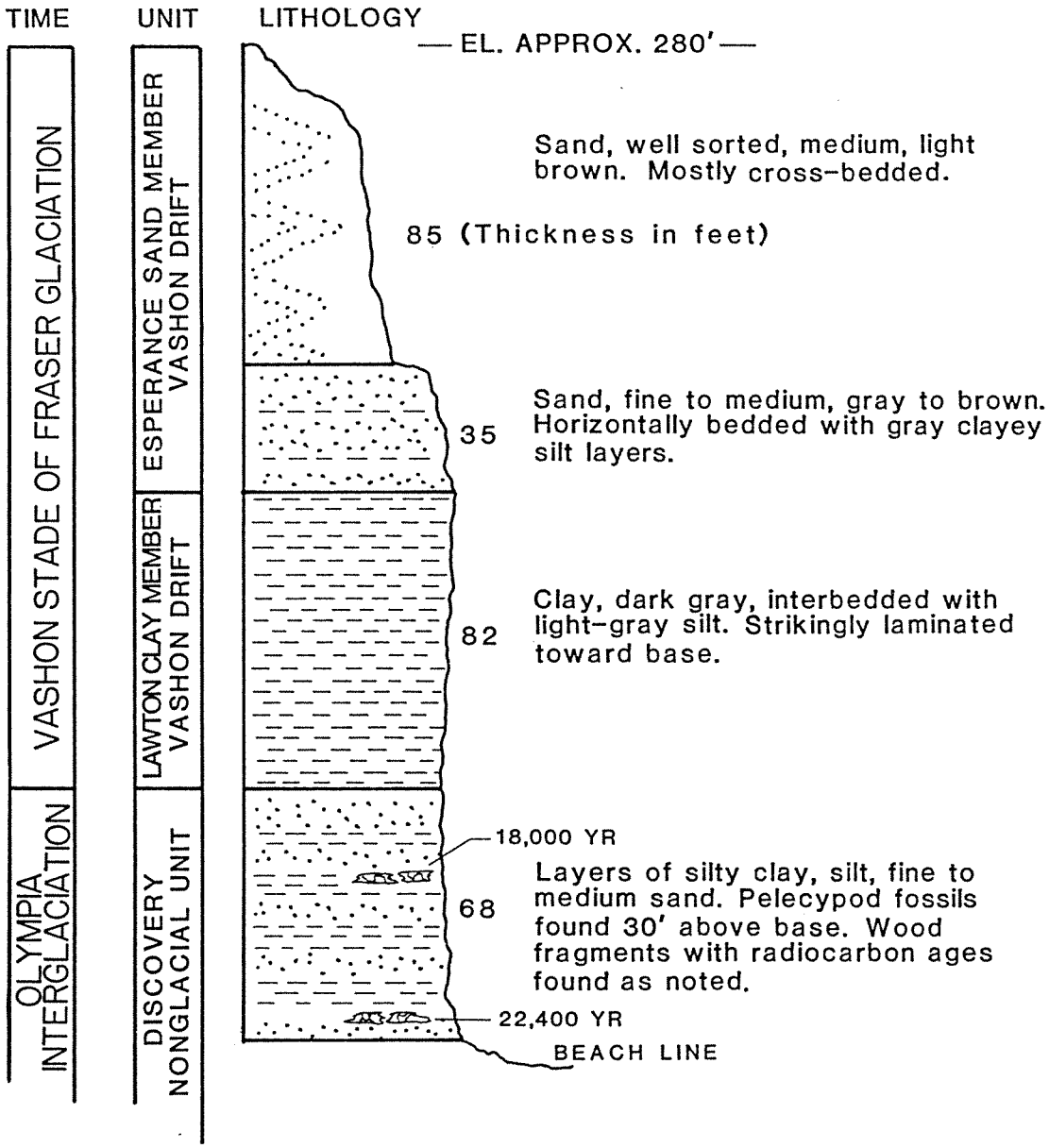

Figure 2. Proposed "type" section of the informal Discovery nonglacial unit based on and summarized from Mullineaux and others (1965). Section is 2,500 to 3,500 feet southeast of West Point Lighthouse, Discovery Park, Seattle.

Salmon Springs and Other Time-Rock Problems

A second major stratigraphic/nomenclature problem is the relation of the Possession Drift to the Salmon Springs Drift. Easterbrook and others (1981, for the northern part of the sound) and I (unpublished, for the southern part) have independently concluded that the Salmon Springs and Possession are not time correlative, and that the Salmon Springs is older than the Possession. Further studies by Blunt and others (1987) provide evidence of a time gap of more than half a million years between the two drifts.

The nonequivalence of Possession and Salmon Springs strata raises the problem of the relation of Kitsap to Whidbey strata. Easterbrook's Whidbey is below the Possession, whereas in the south the Kitsap lies above deposits mapped as Salmon Springs. Both Kitsap and Whidbey are mappable across widespread areas, and each appears to represent a major nonglacial episode in which fluvial filling of the lowlands from the surrounding uplands was occurring. I here suggest that the Kitsap and the Whidbey may be time equivalent, but this is a preliminary suggestion and it requires more support before the units can be redefined.

Easterbrook's Double Bluff Drift lies stratigraphically below the Whidbey. His stratigraphic section effectively ends at sea level, and reliable deeper (subsurface) data are lacking. In that the Double Bluff is below the Whidbey, it could follow, through "layercake" analysis, that the Salmon Springs is equivalent to the Double Bluff as it lies below the Kitsap, if Kitsap is equivalent to Whidbey. This rationale may break down as the term "Salmon Springs" is further examined below.

Crandell and others (1958, p. 394) named the Salmon Springs Drift from and established the type section at Salmon Springs, the City of Sumner's water source in the south-central part of sec. 18, T. 20 N., R. 5 E. Crandell also noted an intradrift, nonglacial, organic-rich silt, clay, and ash that led him to believe the glaciation was interrupted by a recession and readvance. Perhaps, instead of the single glaciation with a minor interruption, the type section for Salmon Springs represents two distinct glaciations and a major nonglacial episode that is poorly represented at the type section. In the 1970s I applied that concept to local studies (unpublished) in which upper and lower Salmon Springs units separated by the Kitsap Formation were suggested. That usage implied the upper Salmon Springs was equivalent to Possession. I now believe this to be erroneous.

Walters and Kimmel (1968), following the lead of Waldron (1961), mapped the Salmon Springs Drift to the coastline of central Pierce County. I, in Thurston County, and Molenaar, on the Kitsap Peninsula, extended the terminology to the widespread, oxidized gravelly glacial deposits beneath the Vashon. During the 1960s none of us considered the possibility of the unit being divided into two glacial deposits separated by a nonglacial deposit. I now concur with Easterbrook that the use of Salmon Springs nomenclature should

be discontinued until further proven in the western lowlands beyond localities mapped by Crandell (1963).

The Puyallup Formation underlies the Salmon Springs at the type sections of Crandell and others (1958). On the basis of its position, Waldron (1961), in coastal King County near Des Moines, mapped the Puyallup below what may be erroneously called the Salmon Springs. In numerous unpublished technical reports, I have previously used the term Puyallup for an easily recognized nonglacial unit below the possibly erroneously named Salmon Springs. If the previously mapped Salmon Springs of the coastal area is misidentified, then the underlying nonglacial formation cannot be called Puyallup on the basis of stratigraphic position.

Still older formations in the Crandell sequence (representing Stuck glacial, Alderton interglacial, and Orting glacial episodes) are not exposed above sea level along the Puget Sound coastline. The correlations are very likely erroneous, as further shown.

Summary of Stratigraphic Problems

There is general concurrence in the mapping and the stratigraphic positioning of the Vashon Stade of the Fraser Glaciation. However, in the coastal areas of southern Puget Sound the mapping of deposits older than Vashon till calls into question correct nomenclature, relative chronology, or both. The problems I have recognized are:

- The Olympia Interglaciation is represented by no mapped units in coastal Pierce County if the Kitsap Formation is removed from that time, as it should be.

- The Possession Drift has heretofore not been mapped south of the central part of the Puget Sound basin. Several workers believe its terminus may have been at about the latitude of Seattle, but no firm evidence has been found.

- The Whidbey Formation may be correlative with the Kitsap Formation. The Whidbey is confidently placed as stratigraphically between the Possession and Double Bluff Drifts, whereas the Kitsap lies generally between the Vashon and "Salmon Springs" Drifts.

- According to Easterbrook, the Double Bluff Drift is stratigraphically below the Whidbey, but the Double Bluff is not equivalent to the Salmon Springs.

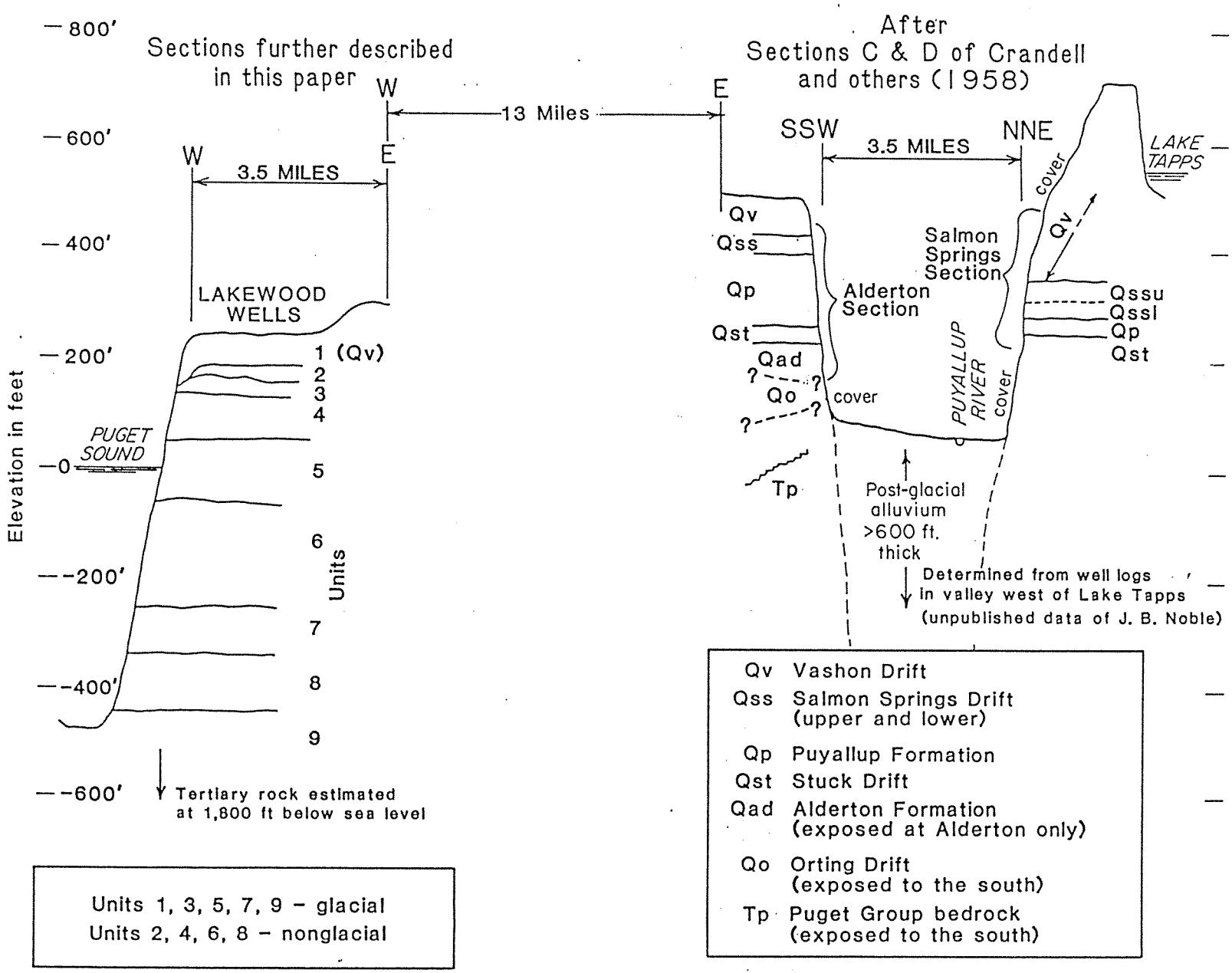

Figure 3. Schematic relation between type section of Crandell and others (1958) and sections described in this paper.

- The "Salmon Springs" Drift of coastal Pierce and Thurston Counties is a mapped unit below the Kitsap Formation, but the term "Salmon Springs" should be discontinued in this area because of the questioned correlation with the type sections.

- Near-sea-level and sub-sea-level units below what has been mapped as Salmon Springs in the coastal lowlands should not be assigned the nomenclature developed by Crandell and others (1958).

Figure 3 schematically shows sections C and D of Crandell and others (1958) on the walls of the Puyallup-White valley. The figure also shows for comparison the subsurface sections in the Lakewood area as developed for this paper. For the purposes of the drawing, units in the Lakewood section are numbered 1 through 9 rather than named. The difficulties in correlating from east to west are obvious when seen in this perspective, yet correlations were in fact made by the several authors mentioned earlier. In the 1960s we did correlate what is diagrammatically shown as unit 5 with the Salmon Springs and unit 6 with the Puyallup. (Units 2 and 3 were not then recognized).

Note that at Crandell's Salmon Springs section there is an implied 350 feet of undescribed material above the Salmon Springs Drift representing Vashon and Olympia time. This relatively great thickness of sediment for those periods appears unlikely to me. Other units younger than Salmon Springs and older than Olympia could very well be "hiding out" in that section. The reported antiquity of the Salmon Springs (1.0 million years) as determined by Easterbrook and others (1981) and Blunt and others (1987) supports the concept of "missing" units above the Salmon Springs in its type section.

NEW FINDINGS IN STRATIGRAPHY FOR THE SOUTHERN PUGET SOUND LOWLANDS

Field mappers of the Puget Sound valleys and coastline have been frustrated in finding good sections where tops and bottoms of stratigraphic units can be confidently described. Most sections are partly covered by vegetation, talus, or landslides; there is also a confusing possibility of "overdrape" of the Vashon till. The very locations of exposed sections are commonly due to the presence of geologic changes or "weak spots" responsible for the valley or bluff where the exposure is visible.

Conversely, I believe the subsurface geologic section at inland locations to be regionally more representative of the total Pleistocene geology than the sections at the sea cliffs. That is, sequential deposition of materials across a surface of gentle relief is more uniform than deposition into a highly eroded landscape. However, at the inland locations the subsurface descriptions can be derived from drill-hole data only. J. W. Robinson (of Robinson and Noble, Inc.), since the 1940s, and I, since 1965,

have had the opportunity to personally inspect lithology from hundreds of well drilling projects in parts of the lowlands in King, Pierce, Kitsap, and Thurston Counties. This experience is the basis for the proposed revision of stratigraphic nomenclature.

The distinctions between glacial and nonglacial units have been made by us on the basis of both texture and lithology. Texture alone (i.e., gravel or clay) does not provide a fully valid distinction. The combination of lithology and texture usually does. In the south-central lowland the Puyallup and Nisqually Rivers were the predominant fluvial sources of sediments during nonglacial times, as they are today. These rivers, rising on Mount Rainier, carry a large amount of andesitic gravel and hypersthene-rich sand that give the fine fractions of their deposits a pink or lavender color and the entire section a generally dark appearance. Sands tend to be "black" rather than the "salt and pepper" color typical of (glacial) sand from northern sources. These dark colors are used by us as nonglacial indicators, as are beds or seams of peat and wood and/or ash. In contrast, continental glacial materials have gravel fractions that contain clasts of true granites and metamorphic rocks that do not occur in the local drainage basin. The provenance of the true granites and metamorphic rocks lies in the Cascade Range north of Snoqualmie Pass and on into British Columbia. In areas north of the Puyallup River basin, to which Mount Rainier has not supplied detritus, these simple lithologic distinctions cannot be made. In these areas, of which Whidbey Island is one, lithologic distinction between glacial and nonglacial deposits can be impossible.

The natural gamma log also provides some meaningful radiation distinction between varying lithologic suites in both cased and uncased boreholes. The natural gamma logger is sensitive to gamma radiation, which is generally considered to emanate from potassium during its natural break down. As such, the gamma log is influenced by the relative amounts of potassium in the unit, so should be influenced by mineralogical changes when potassium is included. Local experience has shown that the gamma log commonly shows anomalies independent of changes in texture. As such, mineral changes within units of similar textures are the probable cause. The data set of these logs is sparse, but increasing use of gamma logs will be helpful in refining correlations between drill holes, especially where distances between sites is less than about a mile.

Electric logs are less frequently run in the study area because their use is limited to uncased boreholes, whereas most wells are drilled as casing is concurrently advanced. The several electric logs examined from deep uncased rotary borings do not appear to be useful for stratigraphic correlation.

In 1983, a series of engineering studies was started in which Robinson and Noble, Inc., was contracted to describe the hydrostratigraphy of central and southern Puget Sound areas. In the first of these studies, in the Clover Creek basin of Pierce County (Brown and Caldwell, 1985), I developed a simple,

nine-layer stratigraphic sequence where alternate letters (A, C, E, G, I) designate glacial units and the intervening letters (B, D, F, H) designate nonglacial units. Layer A included the sediments of the youngest (Vashon) glaciation and Layer I, those of the oldest. During this process, and after the lettered sequence was already "frozen", I identified a distinct nonglacial unit in the "A" part of the section in part of the study area. This unit became "Layer A1", and, as it is a nonglacial unit above B, which is equivalent to the mapped Kitsap Formation, it would presumably have been deposited during the Olympia interglacial interval. Thus, the A deposits below A1 and above B must belong to a pre-Vashon glaciation younger than the Kitsap. A single date, 26,000 yearS BP, from wood in A1 was obtained from a commercial laboratory by Shannon and Wilson, Inc. (D. K. Balmer, oral commun., 1989). This sample came from a depth of 60 feet below grade, on Fort Lewis in the SW1/4 NE1/4 sec. 28, T. 19 N., R. 2 E. (The log of that well is shown in the basic data section of this paper and also indicated on Figure 7.)

For the Brown and Caldwell (1985) study (also see West and Noble, 1989), I prepared base-of-unit contours on all discernible units from A and A1 through F. The most confidently identified of these units is layer D, which is an exceptionally distinct nonglacial unit beneath the Lakewood district of Pierce County. This unit is thick, widespread, and has the typical nonglacial lithology described above. Because B is the mapped Kitsap Formation, nonglacial unit D was correlated with the Puyallup Formation and the intervening C glaciation was correlated with the Salmon Springs. (These correlations are no longer recommended.)

Expansion of the first hydrostratigraphic study in central Pierce County has now been made into the Federal Way area of King County, the Gig Harbor Peninsula of Pierce County, and all of Kitsap County. It has become apparent that the A, B, C, D system is invalid regionally, and that use of the older, conventional stratigraphic names is probably erroneous.

PROPOSED STRATIGRAPHIC NOMENCLATURE FOR COASTAL PIERCE COUNTY

Given all the problems and confusions that have developed in the Quaternary stratigraphic descriptions of the entire Puget Lowland, I here propose a revised stratigraphic sequence for coastal Pierce County. Figure 5 (which accompanies the basic data section) shows a broader area where the informally named sequence is also believed to be valid. Ideally, some of the proposed names will not survive because confident correlation will be made between a unit informally named herein and a previously named unit. The informal nomenclature of units for which regional correlation cannot be made should serve as a base for future studies in which formal names are provided. The proposed units and climatic-time episodes are as noted in Table 4.

Table 4 -- Proposed revised stratigraphy for coastal Pierce County

Formation/Symbol*	Remarks
Vashon Drift/Qv	No change from prior studies
Discovery nonglacial unit/Qd	Based on section by Mullineaux and others (1965) This formation inferred to be of the Olympia Interglaciation
Narrows glacial unit/Qn	Based on section found by author--likely correlative with Possession Drift
Kitsap Formation/Qk	No change in mapped position; chronology moved from Olympia time
Flett Creek glacial unit/Qfc	Third drift sequence recognized
Clover Park nonglacial unit/Qcp	Pre-Kitsap nonglacial unit, relatively thick and widespread
Lakewood glacial unit/Qlk	Fourth drift sequence recognized; weathered clasts imply great age
Gravelly Lake nonglacial unit/Qgl	Pre-Clover Park nonglacial unit recognized in many deep wells
Lone Star glacial unit/Qls	Fifth drift sequence recognized; seen in some deep well logs
Unnamed	Logs of deep wells show thick fluvial section below Lone Star

* Symbols used in Figures 7 through 9

Vashon Drift consists of many members, including the Steilacoom gravel, the till, and the Esperance or Colvos Sand. The till and other members of the Vashon Drift mantle the majority of the Puget Sound lowland. Blunt and others (1987) suggest an absolute age range of about 20,000 to 13,000 years BP for the Vashon Glaciation.

Discovery nonglacial unit is the term I here propose for all nonglacial sediments deposited during Olympia time. The type locality (Fort Lawton) (Figs. 1 and 2) should be that for the deposits below the Lawton Clay described by Mullineaux and others (1965) at Seattle. Most of the Discovery sediments may have been deposited on topography similar to today's -- that is, on an eroded drift surface across which there are a few major valleys. Consequently, the largest areas of Discovery alluviation have been overridden and removed by Vashon glaciation or subsequent valley cutting. The areas where Discovery sediments may remain appear to be limited. Blunt and others (1987) suggest an absolute age range of 28,000 to 20,000 years BP for the Olympia Interglacial episode.

In western Pierce County the top and bottom of the Discovery nonglacial unit defined "Layer A1" beneath the upland north of Lakewood and generally around University Place (Brown and Caldwell, 1985, fig. 5-13). University Place is an unincorporated area south of the Narrows Bridge. Lakewood is a larger unincorporated area south of University Place. "Mount Rainier"-lithology sediments have been reported in some subsurface data, indicating an ancestral Puyallup or Nisqually river source. Elevations of the base of the unit range from about 100 to 200 feet above mean sea level. Logs of wells believed to penetrate the Discovery nonglacial unit south of where it is mapped in the Brown and Caldwell report are presented in the basic data section of this paper.

Narrows glacial unit is the informal name here introduced for a drift unit below the Discovery nonglacial unit and above the Kitsap Formation. The unit has not been previously recognized and, where exposed, has been included with either the Vashon or Salmon Springs on geologic maps. The unit shares the phantomlike characteristics of Easterbrook's Possession Drift as noted earlier. They may be correlatives.

A suitable section from which to define the drift is a dense till in a heavily wooded gully on the eastern bluff of the Tacoma Narrows below the residence at 2318 North Harmon in Tacoma (NW1/4 NE1/4 sec. 34, T. 21 N., R. 2 E.). I first saw this exposure in 1976 during a slope stability study at that address. Figure 4 is the field sketch of the observed section. This midcliff till is overlain by sandy outwash mapped as Colvos Sand by Walters and Kimmel (1968). I believe that assignment is valid. Vashon till is not present at the section, but glacial erratics rested on the undeveloped lot above the cliff, and Vashon till is exposed at the surface a short distance farther to the east.

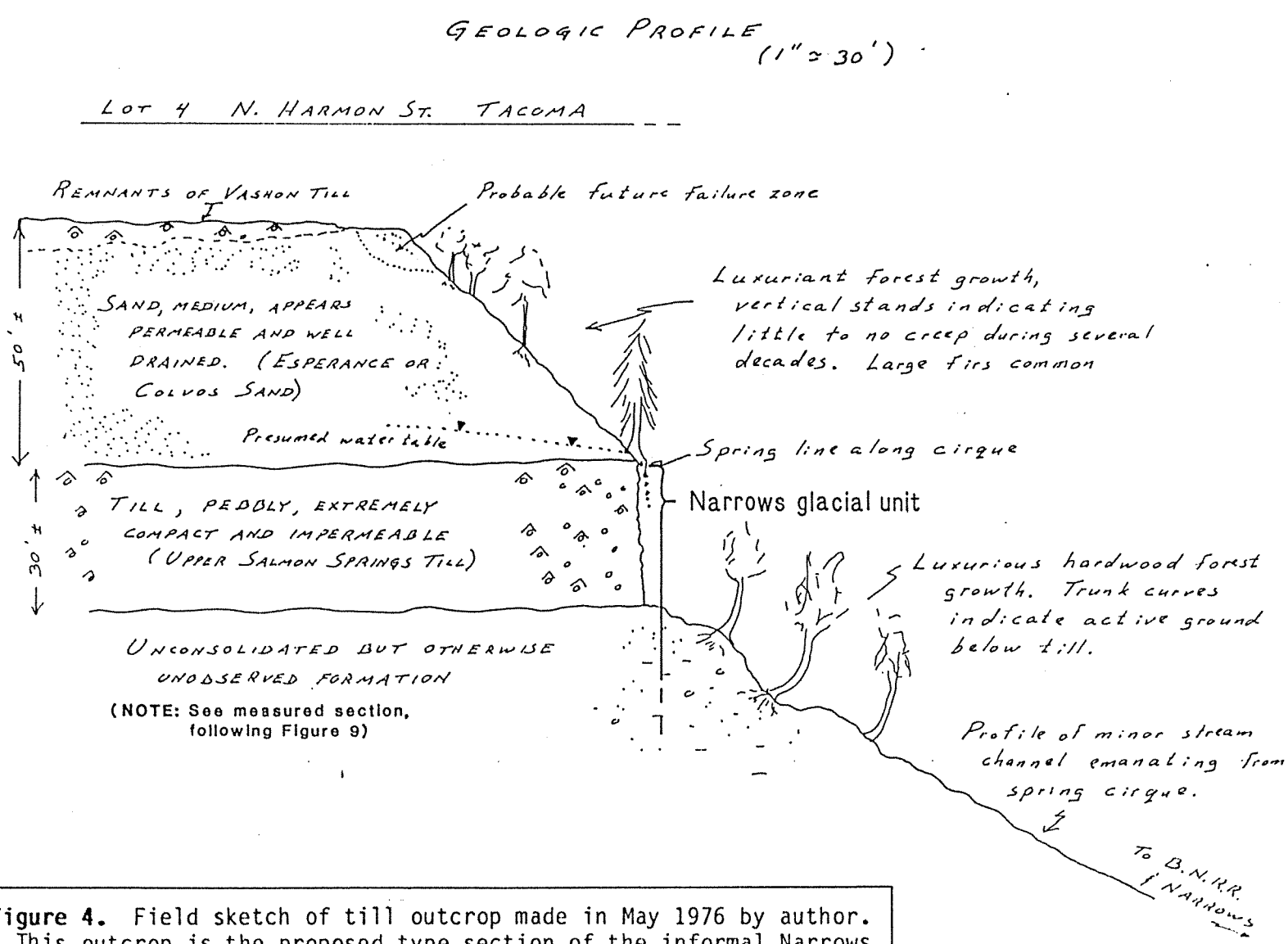

Figure 4. Field sketch of till outcrop made in May 1976 by author. This outcrop is the proposed type section of the informal Narrows glacial unit described herein. Note that the till was believed to be Salmon Springs in 1976.

Gravelly outwash deposits that are almost certainly Narrows glacial unit crop out on the western bluff of Point Defiance. Here, a few feet below the top of the bluff is a distinct break between fresh, gray gravels of Vashon Drift and lower oxidized gravels assigned to the Narrows glacial unit. This entire section of sand and gravel was mapped as Colvos Sand by Walters and Kimmel, but there is no reason to expect a weathered surface to exist within the Colvos section. The base of the bluff below the drift unit is a very firm clay, unnamed by Walters and Kimmel. This clay is of unknown age.

Across the Narrows at Point Fosdick (sec. 5, T. 20 N., R. 2 E.) is another bluff consisting of rudely stratified oxidized glacial outwash. This too has the characteristics of the Narrows glacial unit seen at Point Defiance. It was mapped as Salmon Springs by Molenaar (1965).

The assignment of the Narrows glacial unit as a pre-Vashon, post-Kitsap glacial deposit is based on the observed stratigraphic position and by the relatively greater degree of oxidation weathering of the materials below the nearby unweathered Vashon. No absolute ages have been determined. However, Blunt and others (1987) suggest an absolute age range of 90,000 to 28,000 years BP for the Possession Glaciation, which may well be correlative to the Narrows. Well logs showing the interpreted presence of the Narrows glacial unit are included in the basic data section. A section measured in 1989 by J. W. Purdy of Robinson and Noble, Inc., is also included.

Kitsap Formation is the nonglacial unit below the Narrows glacial unit. It is found near sea level along tens of miles of shoreline through Pierce, Thurston, and Mason Counties. Excellent exposures of the Kitsap Formation can be seen, where not overridden by Vashon deposits, from south of Point Defiance to the Nisqually River floodplain, thence from the Nisqually River floodplain north along Nisqually Reach to Johnson Point in Thurston County. Outcrops continue westward across Hartstene Island in Mason County and are also evident on the Longbranch Peninsula, Anderson Island, and McNeil Island (Fig. 5).

The Kitsap Formation in southern Puget Sound localities is typically a brown to gray, clayey and sandy silt with a suggestion of lavender color. Peat beds and fossil wood are common. Particularly gravelly sections occur near Chambers Bay and between Steilacoom and Solo Point in Fort Lewis. These gravels are of "Mount Rainier" lithology and lack granitic and metamorphic clasts.

The type section of the Kitsap Formation (Sceva, 1957) is at Maplewood on Colvos Passage on the Pierce County side of the Kitsap County-Pierce County boundary. This is an extremely complex and controversial section. The Kitsap Formation should have a more representative type section.

The Kitsap Formation was mapped as "Layer B" in the Brown and Caldwell (1985) report, but I now think some of that unit was misassigned from part of "Layer A1" (the Discovery nonglacial unit). Well logs showing the interpreted presence of the Kitsap Formation are included in the basic data section.

Flett Creek glacial unit is here introduced as the informal term for the drift deposits stratigraphically below the Kitsap Formation. The purpose of introducing this term is to locally dispense with the term Salmon Springs and to avoid the problem of an erroneous correlation. Essentially all drift near sea level and stratigraphically below the Kitsap that has previously been mapped as Salmon Springs is included with the Flett Creek glacial unit. For the purpose of this paper we tried to find a suitable type section for the Flett Creek glacial unit within areas mapped as Salmon Springs by Molenaar (1965) and Walters and Kimmel (1968). The type section should, at the least, show a definite contact with the overlying Kitsap Formation. However, we found no such exposure. Specific descriptions for the Flett Creek glacial unit are found in logs of Lakewood Water District wells shown in the basic data section.

The Flett Creek glacial unit is also correlative with "Layer C" of Brown and Caldwell (1985). Maps in that report indicate a top-of-unit elevation near Puget Sound ranging from about 100 feet above sea level to 100 feet below sea level. The unit's base in the same area ranges from about 30 to 180 feet below sea level

Clover Park nonglacial unit is the informal name here proposed for a nonglacial unit that may be equivalent to the Puyallup Formation as mapped by Walters and Kimmel (1968) and Waldron (1961). Use of the term Puyallup Formation is no longer recommended. South of those mapped exposures the unit is present only below sea level. In drilling samples the unit is typified by "black" sands, "lavender" silts, and appreciable amounts of peat and wood. The sediment is distinctly rich in Mount Rainier material. Ash is noted in many logs.

The texture and lithology of the Clover Park nonglacial unit are very similar to those of the Kitsap Formation. The Clover Park is distinguished from the Kitsap solely by its stratigraphic position below the Kitsap Formation. Correlation with the Puyallup Formation is not advised because the Puyallup Formation is defined, in part, as underlying the Salmon Springs Drift -- and the latter is a term that must be avoided here as previously explained. The type descriptions for the Puyallup Formation (Crandell and others, 1958) refer to appreciable amounts of mudflow deposits. Such deposits are not reported in the well logs, nor would they be expected at the greater distance from the mountain front.

I have a great deal of confidence in the subsurface mapping of the Clover Park nonglacial unit as depicted in Brown and Caldwell (1985, fig. 5-16). These base-of-unit contours show a widespread area of gentle topography suggesting a major erosion surface over which the unit was deposited. The name "Clover Park" is from the Clover Park School District, which serves much of western Pierce County south of Tacoma. The well logs from which the Clover Park nonglacial unit was identified are included in the basic data section.

Lakewood glacial unit is the informal name here proposed for the glacial unit below the Clover Park nonglacial unit. (Lakewood is an unincorporated, urbanized district south of Tacoma, most of which is served by the Lakewood Water District.) The Lakewood drift is reasonably well identified as "Layer E" in Brown and Caldwell (1985, fig. 5-17) In the drill holes, gravels of this unit commonly have a green, clay-rich matrix. In many instances the gravel clasts have been noted to be clay-weathered to a depth of several millimeters. These characteristics and the drift's position below the Clover Park nonglacial unit suggest a fairly great age. Well logs showing descriptions of the Lakewood glacial unit are included in the basic data section.

Gravelly Lake nonglacial unit is the informal name proposed for the sediments below the Lakewood glacial unit. As with the Clover Park and Kitsap, the sediments have the mineralogy, lithology, and coloration typical of Mount Rainier provenance. Peat and wood are commonly present. The four Lakewood well logs in the basic data section show descriptions of this formation, although only two wells (T-1 and T-2) appear to fully penetrate it.

The Gravelly Lake nonglacial unit is correlative with "Layer F" of Brown and Caldwell (1985). The base of that layer is identified by about 20 deep wells referenced in that report.

Lone Star glacial unit is the deepest of the drift units recognized and is the least confidently identified. It is named from the deep, northern provenance gravels found in Lone Star Well 2 (log R-1, basic data section), from which a tentative correlation has been made to wells T-1 and T-2. The Lone Star glacial unit is correlative with "Layer G" of Brown and Caldwell (1985); the base of that layer was not mapped but is noted in some of the cross sections in that report.

Other and older formations are noted in about a dozen well logs in coastal Pierce County. Three of the six reference logs in the basic data section show examples of these. The log R-1 and the logs of nearshore wells to the south show a thick section of clay believed to be of glaciolacustrine origin. This clay is not present to the east or on the islands to the west. Its base is more than 600 feet below sea level, and its top has a subjectively interpreted cover of fine Clover Park sediments. The implication is that a deep channel was cut through the Lakewood and Gravelly Lake sediments in this area, then filled with clay. Presumably the clay was deposited in a proglacial lake during the onset of the Lakewood glaciation. The channel's location appears to be parallel to and east of the southern end of the Tacoma Narrows and could be termed an ancestral Narrows.

Also below the Lone Star glacial unit is a sequence which I have interpreted to be mostly of fluvial origin and which has no distinct indication of tills or northern rock types. Still deeper wells on Fort Lewis (Walters and Kimmel, 1968) have logs indicating a continuation of these probably fluvial sediments to nearly 1,800 feet below sea level. These deep unconsolidated sediments are also unnamed.

INTERPRETED PLEISTOCENE HISTORY

The interpreted history is based on the observations of the sediments and their apparent stratigraphic relations. The referred climatic episodes are informal and simply relate to the unit name given herein.

To my knowledge, there was no marine water occupancy during the pre-Vashon Pleistocene time south of Seattle, as indicated by the bedrock rise in Figure 1. My assumption is based on the lack of marine fossils in outcrop or well cuttings. There must have been a major valley system, however, to contain the accumulation of as much as 1,000 feet of fluvial sediments. These sediments, thickly covered by younger deposits, may all be of nonglacial origin. Mount Rainier was in existence during at least part of this period of valley aggradation.

The earliest drift noted with reasonable confidence, because of the presence of northern provenance gravels, is the Lone Star glacial unit. No suggestion of its age is implied here, though it must be very old because of its position below the also very old Lakewood glacial unit. Weathering of clasts seen in samples of Lakewood deposits suggest a pre-Wisconsin age.

The Gravelly Lake nonglacial sediments were deposited on the ancient Lone Star glacial unit surface by ancestral Puyallup and Nisqually rivers, at least in part. The topography at the end of Gravelly Lake time appears to have been a fairly planar surface dipping northwestward at about 30 to 50 feet per mile. (This topography and that for units described below are interpreted from the base-of-unit maps in Brown and Caldwell, 1985.)

If the sequence interpretation is correct, the Lakewood glacier carved the deep ancestral Narrows (noted earlier) through the Gravelly Lake nonglacial unit. This channel, because it is far deeper than any other clay-filled channel noted from drilling logs, yet is less than a mile wide, must have been directly carved by the advancing ice -- much as the Vashon glacier did in Wisconsin time.

The Lakewood glaciation also deposited drift on the plain developed during Gravelly Lake time. The remains of the Lakewood glacial unit appear to be rather uniform in thickness (about 100 feet). The uniformity of its upper surface and the pronounced weathering of some of the gravel clasts suggest a considerable period of erosion and subareal exposure, perhaps a major interglacial period prior to the onset of Clover Park alluviation. The apparent disconformity between the Lakewood and Clover Park sediments suggests a major change of regional base level occurred during Clover Park time but before Clover Park sedimentation.

After the long (inferred) erosional interval, the ancestral Nisqually and Puyallup rivers began depositing sediments of the Clover Park unit. These sediments are thicker than those of the preceding and succeeding interglacial times, so a relatively long span of deposition might also be inferred for the

Clover Park nonglacial interval, especially if rates of sedimentation were uniform.

The onset of the Flett Creek glaciation appears to have caused west-trending erosional incision on the Clover Park surface. This eroded surface was then covered with glacial drift. Well logs suggest many glacial lakes or ponds in the area during this time, as indicated by sporadic, intermittent lenses or pods of silt and clay incorporated in the otherwise gravelly section.

During the Flett Creek glaciation the topography was complexly sculptured into a drumloidal pattern as evidenced by the contours developed by mapping the base of the Kitsap Formation. The elevation of much of this sculptured surface was low enough to become alluviated by ancestral Puyallup and Nisqually rivers during the following Kitsap interglaciation. Kitsap deposits are widespread across the Flett Creek drift plain.

The Kitsap interglacial time ended with the onset of the Narrows glaciation. My observations of the contact between Narrows and Kitsap are very limited. However, the contacts in logs appear to be conformable, implying that cessation of Kitsap deposition was immediately followed by the deposition of Puget lobe glacial detritus.

The Narrows glacial unit sediments are sporadic and tend to be thin where seen. On the basis of the degree of oxidation of the gravels believed to be of Narrows age, I infer that the topography at the close of Narrows time was an erosion surface that remained exposed longer than the approximately 13,000 years of subareal exposure during post-Vashon time. (The Vashon sands and gravels demonstrate less oxidation.)

Olympia time began when the Narrows glacier wasted away. The region was probably somewhat as it is today in that most areas were subjected to erosion instead of deposition. The Olympia-age Discovery nonglacial unit is sporadic in occurrence and of irregular thickness. Its radiocarbon age is from about 20,000 to more than 30,000 years, based on Mullineaux and others (1965) and the 26,000 yr BP date reported by D. L. Balmer of Shannon and Wilson, Inc.

About 20,000 years ago Vashon ice entered the area and began depositing sediments. In its southward advance it gouged through preceding deposits to a depth of more than 500 feet below sea level in Puget Sound west of Steilacoom. Concurrently, it left a till mantle on the adjacent higher ground. The topography at the close of Vashon glaciation was essentially as it is today with the exception of the post-glacial filling of the Puyallup and Nisqually estuaries. Marine waters entered the southern sound for the first time as Vashon ice wasted in the north, opening the Strait of Juan De Fuca. Vashon recessional history is covered in detail by other authors such as Bretz (1913), Walters and Kimmel (1968), and Booth (1987).

SIGNIFICANCE OF THE STRATIGRAPHIC SEQUENCE

This revised stratigraphic sequence proposes informal names for four pre-Vashon Puget Lobe glacial units. The sequence also informally names four interglacial units. For the most part these are names that can be applied to the sequence near the Puget Sound shoreline between Tacoma and Olympia and westward to Hartstene Island.

Further studies will demonstrate which of these units can be confidently correlated with previously named units. When that is done, the terminology can be simplified to describe more accurately the Pleistocene history of the area.

An improved understanding of the sequence should also enhance knowledge and management of ground-water resources. Ground-water travel is controlled in large part by the permeability of the materials; furthermore, horizontal permeability greatly exceeds vertical permeability. In general (but with considerable exception), the glacial units have higher permeability than the nonglacial units; therefore, ground-water flow has a strong horizontal component in the glacial deposits and is impeded by the overlying and underlying nonglacial deposits. These conditions influence potentiometric heads in the aquifers and also influence the rate and areal extent of recharge to the deeper aquifers. In the description of the significant aquifer zones, it becomes useful to not only understand their origins and distribution but also to name them by their sedimentary origins and relations.

In the area of the well logs presented in the basic data section, hydrologic properties are generally as shown on Table 5.

BASIC DATA

In the preparation of the report by Brown and Caldwell (1985) approximately 300 well logs were reviewed and analyzed to develop the layer sequence of A to I. Of these, four Lakewood Water District wells have been selected for this paper to serve as "typical data points" for the stratigraphic sequence below the Kitsap Formation. Additionally, the Lone Star well shows deeper parts of the section. Still other wells shown are: Madigan Well 6, a sample from which yielded a radiocarbon date for the Discovery nonglacial unit; Kopachuck Well 2, which shows a western extent of the deep units; Gig Harbor Well 3, which shows a northern extent; Fort Lewis Sequalichew Well 1, which shows a southern extent; and Glacier Park's Hawks Prairie well, which shows the sequence in Thurston County. These additional wells are here designated "reference data points" to show supporting data beyond the core "type area" in Lakewood. The "typical" well logs are designated by a "T", the reference logs by an "R".

I personally logged some or all of the materials drilled at all but the Kopachuck well and developed preliminary concepts of the stratigraphy in the

Table 5 -- Hydrologic properties of stratigraphic units in coastal areas of Pierce County

Unit	Properties
Vashon Drift	Where saturated, outwash members yield varying amounts of water. Some very high transmissivities locally; most of unit moderate to low transmissivity
Discovery nonglacial unit	Presumably serves as a weak aquitard
Narrows glacial unit	No major well yields known
Kitsap Formation	Serves as a regional aquitard between younger and older deposits. Some wells yield moderate amounts of water from sands and gravels
Flett Creek glacial unit	Transmissive zones serve as major aquifers in the Lakewood area; some wells are "dry" in this unit
Clover Park nonglacial unit	Serves as a broad confining unit Sandy zones yield moderate supplies to some wells
Lakewood glacial unit	Transmissive zones are major aquifers in the Lakewood area
Gravelly Lake nonglacial unit	Serves as an aquitard
Lone Star glacial unit	Several very deep wells obtain water from transmissive zones within this ancient drift unit
Older units	Aquifers are noted at various depths in the few very deep wells penetrating these units

process. The log descriptions are newly written for this paper and are not identical to previously recorded logs for the same wells. Some of the new descriptions are condensed (by combining notes for similar continuous units into a single unit), and other parts are expanded to indicate lithologic provenance on the basis of review of the project field books. In the well logs where quotes (as "purple") are used, the quoted notations are as written in the field books of the observing geologist and imply a field impression to be noted, not necessarily a technical description. It should be emphasized that the well log descriptions were developed to describe verbally observations made during drilling for water and not to establish purely geologic descriptions.

Locations of the logs and the measured section for the Narrows glacial unit are shown on Figure 5. Cross sections including the wells are shown on Figures 6 through 9. All the logs have the owner's name or number plus the coded local number of the U.S. Geological Survey usage, as 20/2E-27M. In that example, the well's location is in T. 20 N., R. 2 E., sec. 27 and 1/16th section "M" which is the NW1/4 SW1/4 of said section.

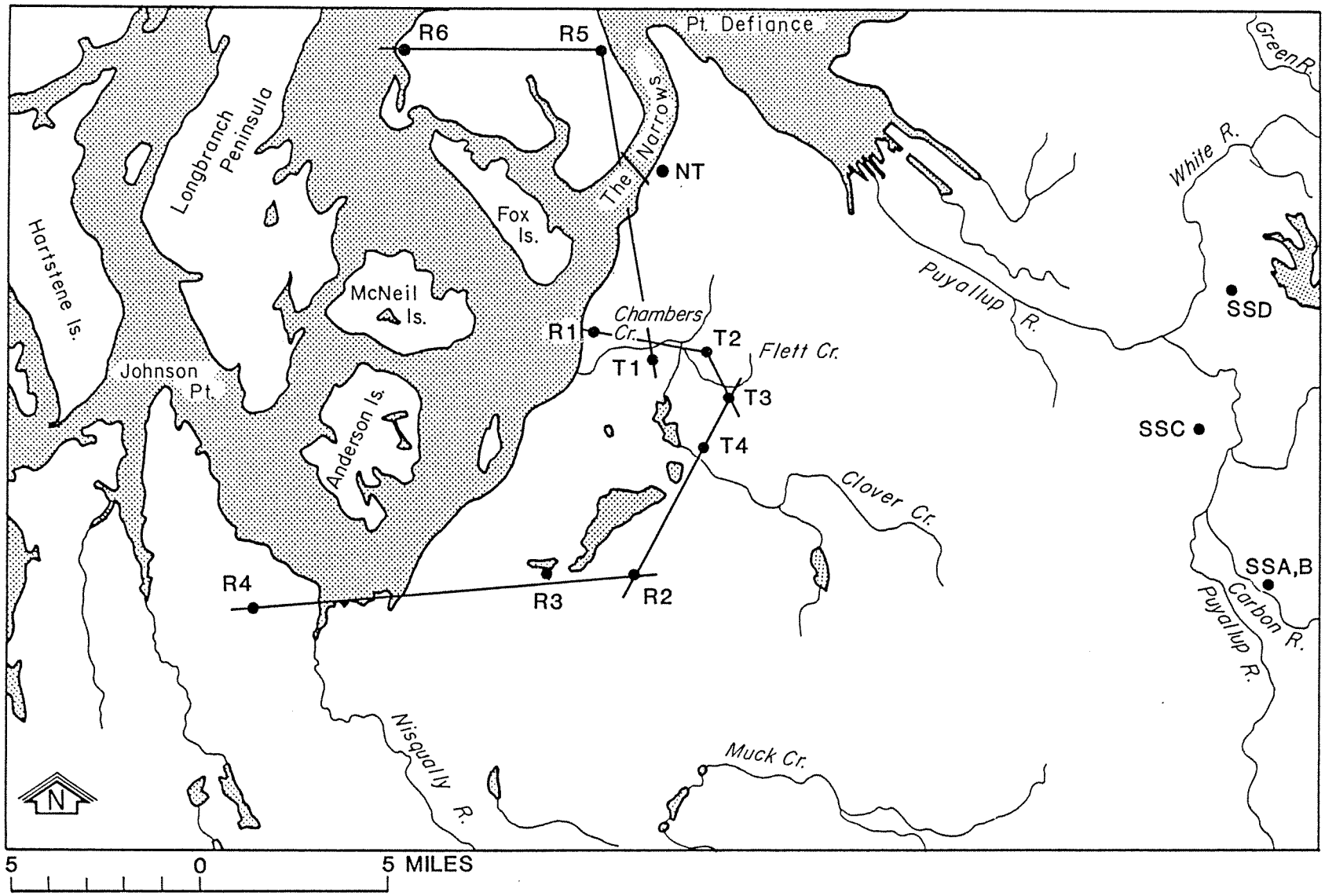

Figure 5. Location of "type section" (NT), "type" wells (T), and "reference" wells (R) for this study. Also shown are locations of Crandell and others'; (1958) type sections (SS) along Puyallup Valley.

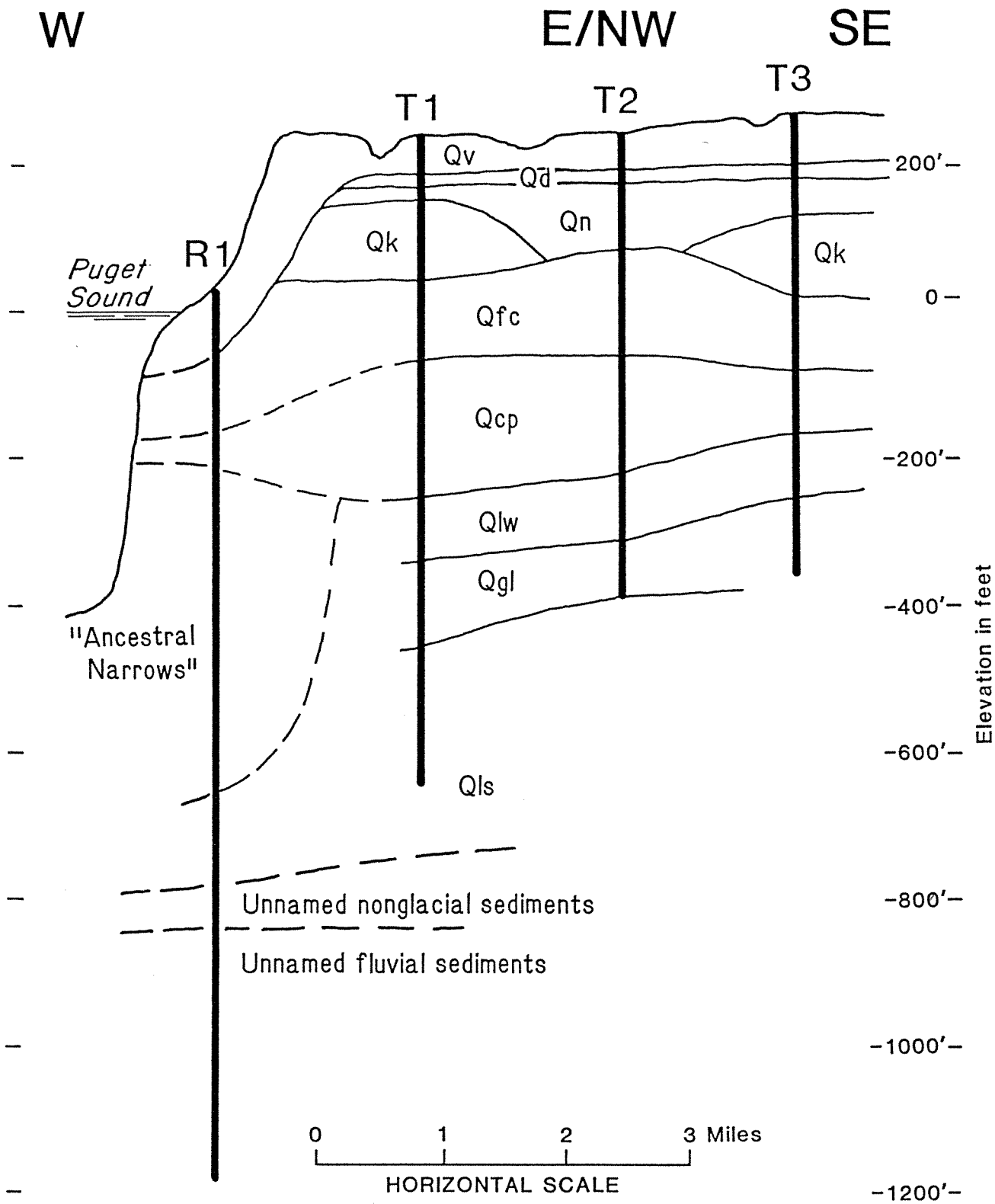

Figure 6. Cross section, R1 to T3. (See Fig. 5.) Explanation of symbols is on Table 4.

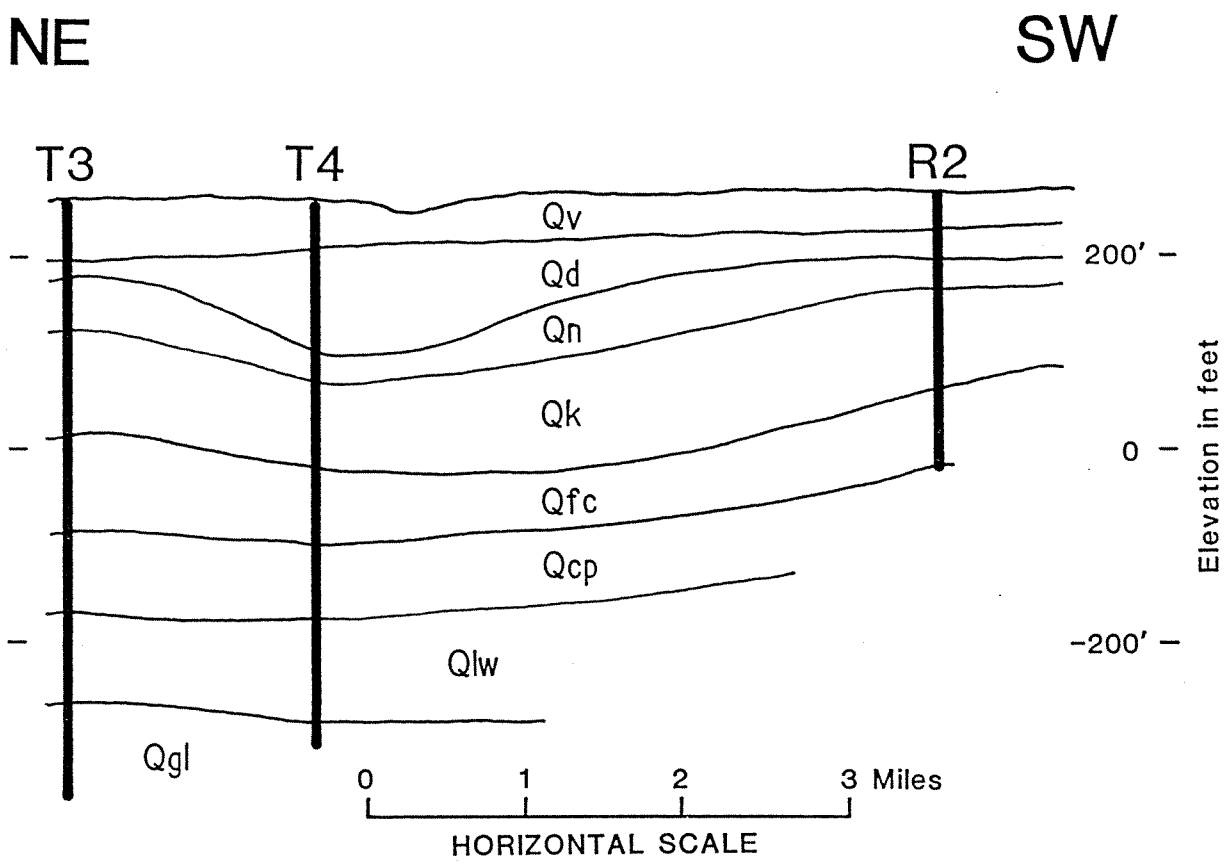

Figure 7. Cross section, T3 to R2. (See Fig. 5.) Explanation of symbols is on Table 4.

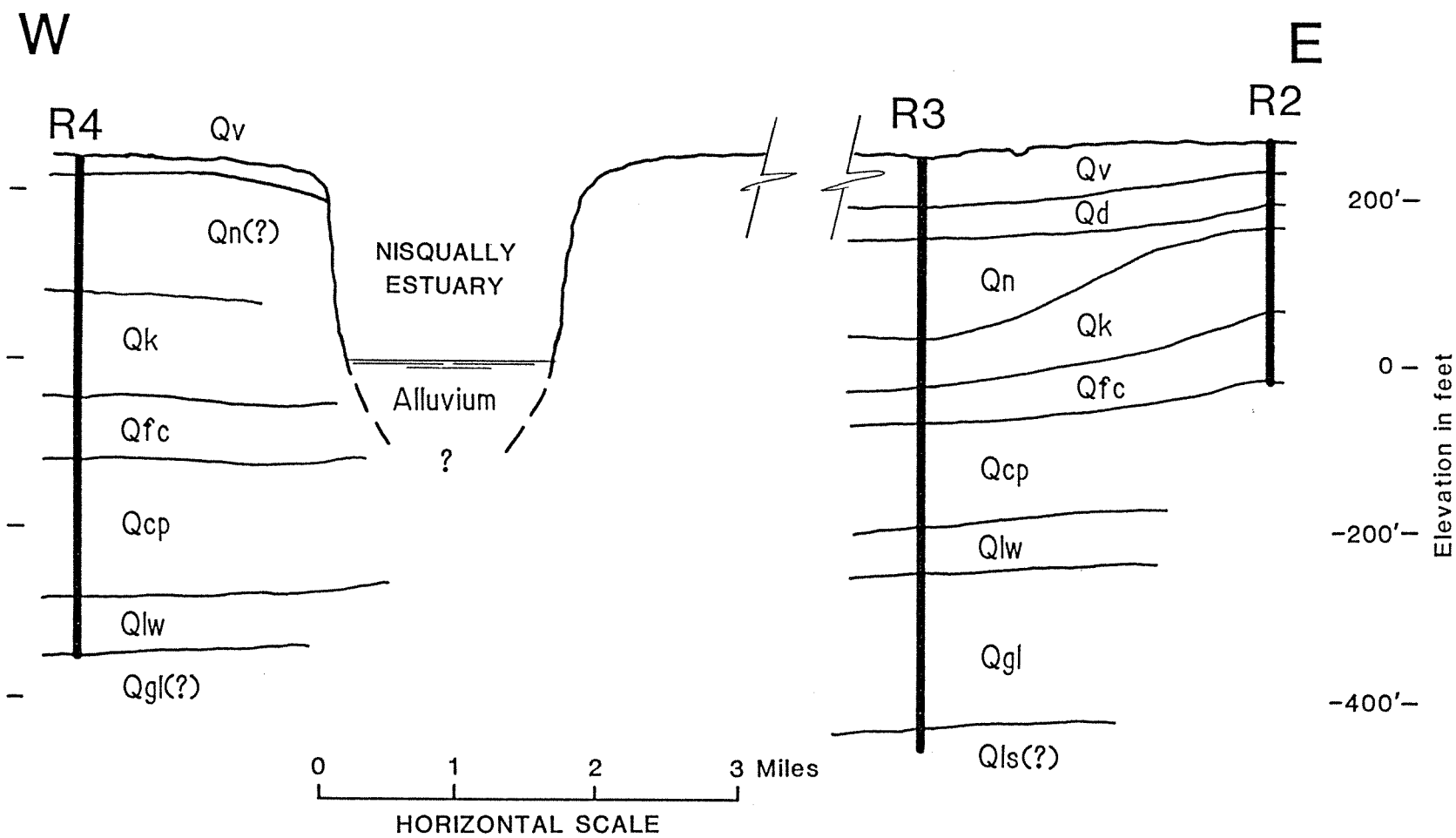

Figure 8. Cross section, R4 to R2. (See Fig. 5.)
Explanation of symbols is on Table 4.

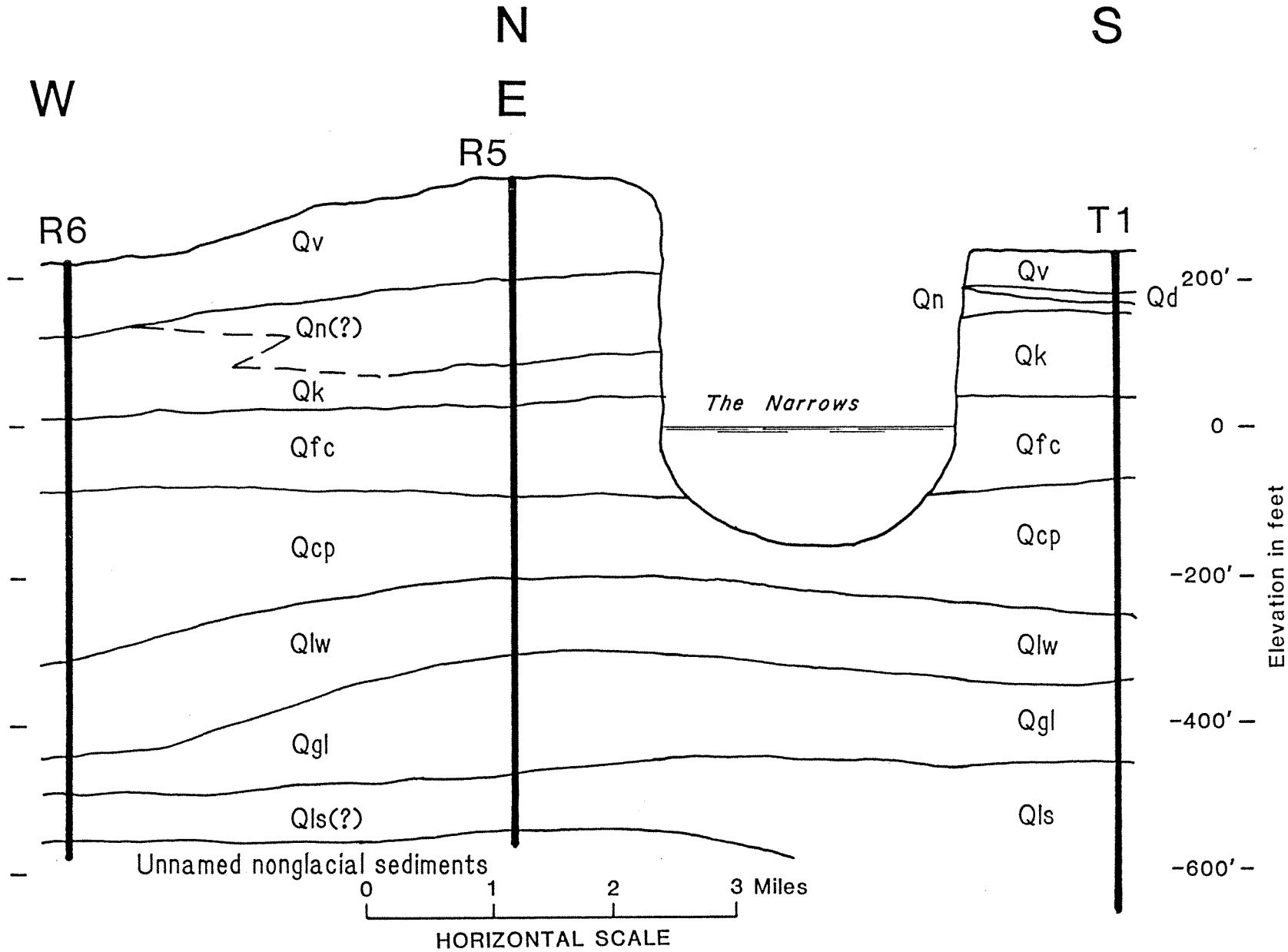

Figure 9. Cross section, R6 to T1. (See Fig. 5.)
Explanation of symbols is on Table 4.

OUTCROP SHOWING NARROWS GLACIAL UNIT

Measured section near The Narrows
(21/2E-34B) Behind the residence at 2318 North Harmon, Tacoma, WA. Section measured on March 24, 1989, by Joel W. Purdy. Top of section approximately 190 feet above sea level. (See Fig. 4.)

	Thickness (ft)
Esperance Sand Member of Vashon Drift	
Brown sand, scattered boulders as float.	50
Narrows glacial unit	
Battleship-gray till, pebbles, and cobbles in matrix of gray sand and clay. Upper 15 feet of the unit is a competent cliff-forming deposit with no visible stratification. The unit becomes more sandy below.	30
Dark brown, oxidized sand with some pebbles.	15

BASIC DATA LOG T-1

Log of Lakewood Water District Well O-1
(20/2E-27M) Altitude at surface is 240 feet

Altitude of base (ft)		Thickness (ft)
	Vashon Drift	
181	Sand and gravel; includes some cobbles.	59
	Discovery nonglacial unit	
169	Silt, blue-green, peaty.	12
	Narrows glacial unit	
149	Sand and gravel.	20
	Kitsap Formation	
69	Fine sand, "black with numerous red grains" layered with blue-green peaty clay.	80
57	Sand and gravel, clasts as much as 3-in. diameter.	12
39	Silt, brown-gray, with peat layers.	18
	Flett Creek glacial unit	
-22	Gravel and sand, gray-green, grading to sand with some gravel.	61
-28	Clay, sandy, gray.	6
-72	Sand, gray, fine to medium.	44
	Clover Park nonglacial unit	
-208	Clay; some gravel near base.	136

-249	Sand, fine to medium, with gravelly zones at top and bottom.	41
-256	Silt, blue-green, peaty.	7
	Lakewood glacial unit	
-329	Brown gravel and sand; contains zones of greenish silt binder.	73
-341	Fine sand.	12
	Gravelly Lake nonglacial unit	
-447	Sand, silty, "black"; wood pieces noted.	106
	Lone Star glacial unit(?)	
-452	Sand and gravel.	5
-465	Silt and sand	13
-486	"Hardpan" (gravelly diamicton).	21
-515	Clay and silt, gray, grades to brown.	29
-548	Layered sand and gravel and gravelly diamicton.	33
	Unassigned	
-583	Sand and gravel, "loose", "blue".	35
-649	Sand, medium, "blue".	66
-654	Clay, light brown.	5

BASIC DATA LOG T-2

Log of Lakewood Water District Test Well T-16
(20/2E-26K) Altitude at surface is 240 feet

Altitude of base (ft)		Thickness (ft)
	Vashon Drift	
192	Gravels, sands and gravels.	48
	Discovery nonglacial unit	
176	Sand and clay; fossil log at base.	16
	Narrows glacial unit	
141	Gravel and sand, grading downward to sand.	35
98	Sand and gravel with clay binder.	43
	Narrows or Flett Creek glacial unit	
87	Gravelly diamicton (till?).	11
	Flett Creek glacial unit	
-32	Gravel and sand alternating with clay-bound gravel and sand. Gravel contains granitic and metamorphic rock types.	119
-49	Gravelly, brown-green diamicton (till?).	17
-61	Gravel grading down to sand.	12
	Clover Park nonglacial unit	
-90	Sand, blue-green, with silt beds.	29
-187	Beds of silt, sand, and clay, some	97

	gravelly zones. Generally blue to green with the diagnostic "purple" color of Mt. Rainier provenance. Peat.	
-222	Cobbly gravel, sand, silt, and clay with "purple" sand.	35
	Lakewood glacial unit	
-248	Gravelly green diamicton.	26
-274	Alternating cemented and "loose" sand and gravel.	26
-291	Green "till".	17
-311	Sand and gravel; contains abundant granitic and metamorphic clast types.	20
	Gravelly Lake nonglacial unit	
-327	Sand and gravel; Mt. Rainier clast types prevalent.	16
-350	Silty clay, layers of sand. Some carbonaceous material.	23
-380	Sands and gravel, "dark-to-black", peaty clay seams.	30
-388	Silty clay and black wood. Deeply weathered pebbles in clay.	8

At -388 Deeply weathered pebbles in clay matrix.

BASIC DATA LOG T-3

Log of Lakewood Water District Well P-1R
(20/2E-36M) Altitude at surface is 265 feet

Altitude of base (ft)		Thickness (ft)
	Steilacoom Gravel Member of Vashon Drift	
252	Brown gravel.	13
	Vashon Drift	
211	Brown gravel, sand, clay.	41
201	Brown sand and gravel; water bearing.	10
	Discovery nonglacial unit	
181	Brown silty sand over sandy clay.	20
	Narrows glacial unit	
161	Brown gravel, sand, clay.	20
130	Brown sand and gravel.	31
	Kitsap Formation	
128	Brown silt.	2
108	Gray gravel, sand, clay.	20
65	Gray clay.	43
18	Gray silty sand and silty clay.	47
	Flett Creek glacial unit	
-5	Gray gravel, sand and silty clay.	23
-17	Gray gravel and sand, "dirty".	12

-49	Gray gravel, sand, silt, and clay (as hard till).	32
-54	Gray sand and gravel.	5
-81	Gray sand, gravel, silt.	27
	Clover Park nonglacial unit	
-122	Gray silty sand, clay layers; wood noted.	41
-141	Gray to brown silty sand and gravel.	19
-169	Sand, gravel, and clay with wood.	28
	Lakewood glacial unit	
-174	Yellow-gray gravelly till.	5
-239	Layered sand and gravel and sand-gravel with green silt-clay matrix.	65
-255	Weathered, green gravel, silt, clay.	16

*Below altitude -262, log is from Well P-1 which is 20 feet north of well P-1R.

	Gravelly Lake nonglacial unit	
-275	Gray-green silty clay.	20
-293	Green sandy clay with peat seams.	18
-306	Dark gray sticky clay and sandy clay.	13
-316	"Dark colored" sand with ash or pumice.	10
-361	Gray silty clay with peat.	45

BASIC DATA LOG T-4

Log of Lakewood Water District Well R-1
(19/2E-11C) Altitude at surface is 260 feet.

Altitude of base (ft)		Thickness (ft)
	Steilacoom Gravel Member of Vashon Drift	
251	Gravel and sand, brown.	9
	Vashon till	
222	Brown-gray diamicton of gravel, sand, silt, and clay.	29
	Vashon advance outwash	
212	Brown sand and gravel; water bearing.	10
208	Gravel, sand, silt.	4
	Discovery nonglacial unit	
163	Brown, grading to very dark gray gravel and sand with organic silt layers.	45
91	Gray to gray-brown silt and clay; scattered gravel and organic seams.	72
	Narrows glacial unit	
73	Gravel, silt, and clay, diamicton, possibly till.	18
68	Sand and gravel, poorly sorted.	5
	Kitsap Formation	
24	Green-gray sand, gravel, silt, and clay; central Cascade clast lithologies.	44

-22	Green-gray silt and silty clay.	46
	Flett Creek glacial unit	
-50	Green-gray gravelly diamicton, possibly till.	28
-98	Green-gray gravelly diamicton, "looser" than above.	48
	Clover Park nonglacial unit	
-108	Gray silt with peat.	10
-147	Black silty sand with gravel (Mt. Rainier provenance).	39
-167	Brown-gray dense silt.	20
	Lakewood glacial unit	
-232	Gravelly diamicton with matrix of multicolored sand, clay and silt, possibly till. Markedly weathered.	65
-293	Brown gravel and sand 18 feet thick over coarse sand 16 feet thick. Bottom 27 feet is bimodal sand and gravel. Heavily iron stained.	61
	Gravelly Lake nonglacial unit	
-309	Green-gray silty sand with minor gravel. (Base of unit not penetrated.)	16

BASIC DATA LOG R-1

Log of Lone Star Well 2
(20/2E-20Q) Altitude at surface is 25 feet.

Altitude of base (ft)		Thickness (ft)
	Steilacoom Gravel Member of Vashon Drift (Steilacoom delta front)	
-57	Sand and gravel, gray-brown; northern provenance.	82
	Flett Creek glacial unit(?)	
-137	Blue sticky clay.	80
-154	Gravel and sand.	17
	Clover Park nonglacial unit	
-183	Clay, some admixed gravel; woody fragments in bottom 7 feet.	29
-209	Clay with admixed gravel.	26
-224	Sand and gravel with clay layers.	15
	Glacial lake sediments of "ancestral Narrows"	
-270	Silty clay.	46
-372	Silty clay and sticky blue clay.	102
	Lone Star glacial unit	
-744	Sand and gravel of northern provenance.	97
-783	Blue clay with thin sand seams.	39
	Unnamed nonglacial sediments	

-796	Clay and thin sand lenses with lavender coloration.	13
-807	Cemented gravel and clay; possibly a mudflow.	11
-837	Sand layered with clay, lavender coloration.	30

Unnamed fluvial sediments of central Cascade provenance

-999	Medium to very coarse sand with granules, and pebbles.	162
-1186	Well layered sequence of clay, sand, sandy silt and minor sand and gravel. Organic seams and woody material. Greenish-gray color predominant.	187

BASIC DATA LOG R-2

Composite Logs for Wells 4 and 6, New Madigan Hospital (19/2E-28H) Wells are 1,200 feet apart, altitude at surface is 270 feet.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift, Steilacoom Gravel Member	
230	Brown-gray cobbly gravel (to 10-in. diameter) with some sand and silt.	40
	Discovery nonglacial unit	
217	Brown medium sand, silty; some gravel; some thin silt layers.	13
203	Brown sandy, silty gravel, with cobbles to 10-in. diameter and embedded wood and peat. Has mudflow texture. Mt. Rainier clast types predominant. Wood radiocarbon dated at 25,100 +/- 600 yr (D. K. Balmer, oral commun., 1989).	14
195	Brown, fine to medium, silty sand.	8
	Narrows glacial unit	
186	Red-brown sand.	9
177	Brown sand-gravel diamicton (till?).	9
168	Brown, small gravel and coarse sand.	9
163	Brown, sandy, silty gravel.	5
	Kitsap Formation	
126	Brown, silty sand, silty clay, some gravel. Laminations noted.	37

119	Brown silt and sand with ash partings.	7
67	Brown, iron-stained and iron-cemented sand and gravel with wood pieces.	52
	Flett Creek glacial unit.	
63	Gray gravel, sand, silt, clay (till).	4
40	Gray silt, sandy, clayey gravel with boulders.	23
14	Brown and gray (layered) silty sand and gravel.	26
3	As in overlying interval, but with notable coal detritus.	11
-20	"Clean" well-sorted sand and gravel with notable coal detritus.	23
-22	Brown gravelly coarse sand.	2
	Clover Park nonglacial unit(?)	
-25	Brown, fine to medium sand.	3

(Base not penetrated.)

BASIC DATA LOG R-3

Log of Fort Lewis Sequalitchew Well 1 (19/2E-30B)
Altitude at surface is 250 feet.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift	
231	Bouldery gravel; some sand.	19
190	Brown gravel, sand; some silt.	41
	Discovery nonglacial unit	
162	Brown sand, grades finer and siltier downward. Increasing amounts of wood fragments downward. Silty, peaty seams at base.	28
154	Sand with silt layers; some gravel.	8
	Narrows glacial unit	
113	Brown gravel and sand with silty beds; iron stained at top. Appears to be of Puget lobe provenance.	41
31	Gray and brown gravel, sand, and silt diamicton. Distinctly till from depth 190 ft to 200 ft. Wood fibers throughout.	82
	Kitsap Formation(?)	
-31	Brown to brown-gray gravelly sand with wood and disseminated peat. Iron cementing common. Clasts of central Cascade provenance. (Unit is similar to Kitsap outcrop at Solo Point.)	62
	Flett Creek glacial unit(?)	

-70	Sand, gravel, and some cobbles in green-gray silty matrix. Probably till toward base.	39
	Clover Park nonglacial unit	
-77	Gray gravel, sand, wood. Mt. Rainier provenance.	7
-196	Layers of clay, silt, sand, varicolored (brown, red-brown, green, and lavender). Peat seams and wood throughout. All clasts of Mt. Rainier provenance.	119
	Lakewood glacial unit	
-198	Yellow, coarse sand and gravel.	2
-247	Yellow-brown sand, gravel, and silt diamicton, probably till.	49
	Gravelly Lake nonglacial unit	
-343	Gray to green-gray sand and silt and clayey silt, minor gravel.	96
-361	Sand and gravel of Mt. Rainier provenance.	18
-436	Sand and silty sand and silt beds with some peat. Color grades downward from brown to dark brown to lavender-brown; some green.	75
	Unnamed older units (undifferentiated)	
-457	Greenish-gray gravel and sand; central Cascade provenance.	21
-462	Brown silt and sand; some gravel. Mt. Rainier provenance.	5

BASIC DATA LOG R-4

Log of Hawks Prairie Well 1 owned by Glacier Park Co.
(19/1W-35G) Altitude at surface is 245 feet.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift (recessional outwash)	
226	Gravel and sand, loose, brown.	19
	Vashon Drift and/or Narrows glacial unit	
130	Gravel and sand with greenish silty binder.	96
83	Cobbles with sand, grading sandier downward.	47
81	Gray gravel-sand diamicton (till?).	2
	Kitsap Formation	
-1	Layered silt, sand, some pebbles, gray-green-tan-lavender; some peat; Mt. Rainier lithology. (The Kitsap Formation is mapped on nearby coastlines at sea level.)	82
-19	Sand and gravel; contains silt layers.	18
-42	"Lavender" silt layered with "black" sand and gravel.	23
	Flett Creek glacial unit	
-81	Sand and gravel, some silt binder, some silt layers.	39
-98	Brown sand, medium to very coarse.	17
-110	Sandy silt, green-gray.	12
-119	Sand with some gravel.	9

	Clover Park nonglacial unit	
-198	Layered silt, fine sand, clay, and some gravel, some ash noted. Tan-green-gray.	79
-282	Sand, "black"; silty layers toward bottom.	84
	Lakewood glacial unit	
-345	Gray sand, medium to very coarse; amount of gravel increases at depth. Pumice (central Cascade provenance).	63
	Gravelly Lake nonglacial unit(?)	
-355	Clay, sandy.	10

BASIC DATA LOG R-5

Log of City of Gig Harbor Water District Well 3 (21/2-17F2)
Altitude at surface is 341 feet. Modified from Drost, 1982.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift	
311	Till.	30
204	Brown sand; sand and gravel.	107
	Narrows glacial unit or Vashon Drift	
102	Sand; sand and gravel.	102
85	Gravelly hardpan.	17
	Kitsap Formation	
34	Gravelly and sandy clay.	51
	Flett Creek glacial unit	
-99	Fine to medium sand and gravel.	133
	Clover Park nonglacial unit	
-199	Gray and blue clay and silt with some wood.	100
	Lakewood glacial unit	
-304	Brown and gray-brown clay and silt with some wood.	100
	Gravelly Lake nonglacial unit	
-450	Sand; sand and gravel.	146

	Unnamed older units	
-560	Sand and gravel with thin layers of green clay and peat.	96

BASIC DATA LOG R-6

Log of Kopachuck State Park Well 2
(21/1E-16K) Altitude of surface is 217 feet.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift	
126	Brown fine to very fine silty sand.	91
	Kitsap Formation	
14	Gray silt and silty clay.	112
	Flett Creek glacial unit	
-83	Poorly sorted silt, sand, and gravel.	97
	Clover Park nonglacial unit	
-252	Gray clay and silt.	169
-307	Gray-brown silt with layers of coarse sand and gravel.	55
	Lakewood glacial unit	
-440	Fine to medium sand.	133
	Gravelly Lake nonglacial unit	
-481	Silt, clay, sand, and peat.	41
	Unnamed older units	
-522	Sand and gravel.	41
-553	Gray fine sand.	31
-579	Brown silt and clay with peat layers.	26

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