UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Surficial geology of the west half of the Skykomish River quadrangle, Snohomish and King Counties, Washington

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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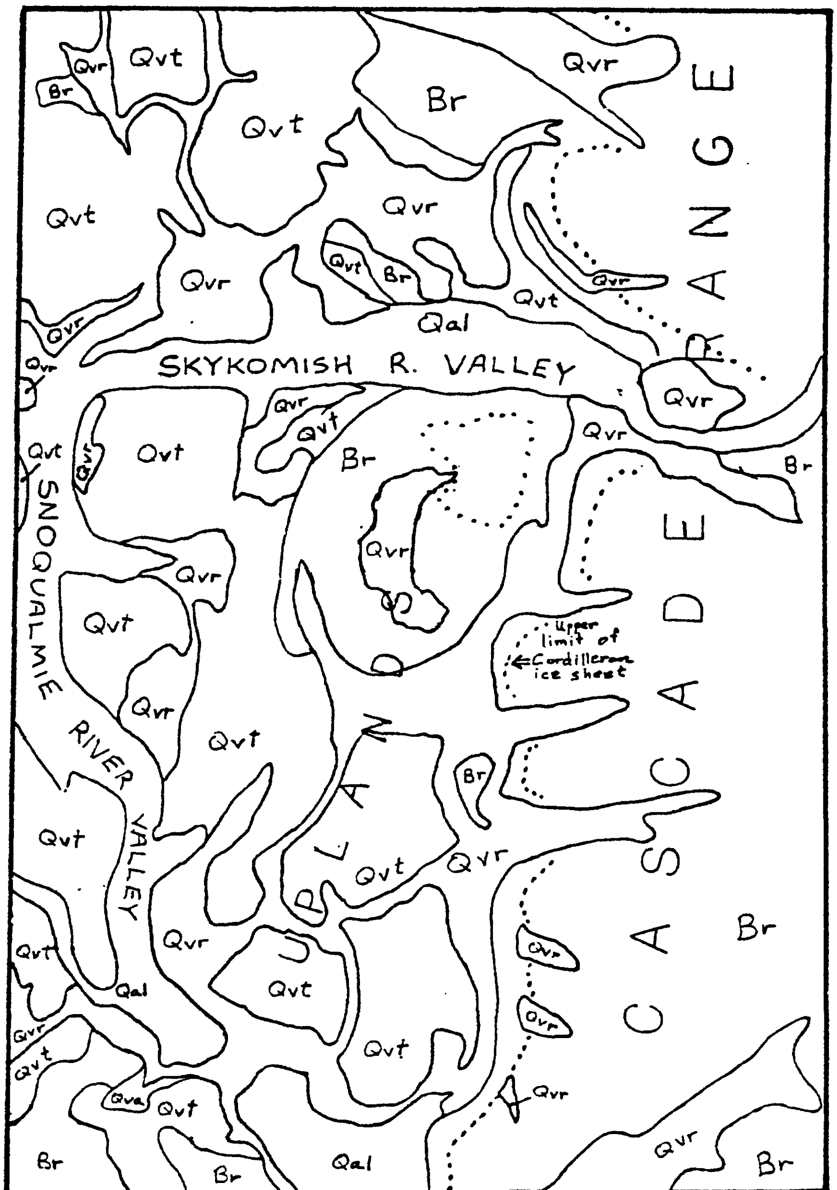
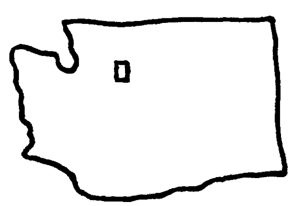


FIGURE 1. GENERALIZED GEOLOGY

20 KM

10 MI



EXPLANATION

Qal	Alluvial deposits (Holocene and Pleistocene)

Deposits of Vashon stade of Fraser glaciation of Armstrong and others (1965) (Pleistocene)--In this area, divided into:

Qvr	Recessional outwash deposits
Qvt	Till
Qva	Advance outwash deposits
Br	Bedrock (Tertiary and Mesozoic)

INTRODUCTION

This study of the surficial geology of the western half of the Skykomish River 1:100,000 quadrangle is part of a larger investigation of the geology of the Wenatchee 1^{o} by 2^{o} quadrangle (Figures 1 and 2) in west-central Washington. This specific area expresses well erosional and depositional processes of ice sheet glaciation, particularly those unique to the ice-marginal areas. Basic geologic data on the distribution and sequence of surficial deposits and the processes that have led to their formation, such as those detailed in this report, can be used to reconstruct the dynamic behavior of past ice sheets, further elucidate the Pleistocene history in western Washington, and better inform planners and engineers who must work with these deposits.

This study emphasizes the deposits associated with the most recent invasion of ice that advanced out of the mountains of British Columbia, but discusses older units as well. These older units include deposits of earlier glacial advances, local alpine glacial deposits, and bedrock. The bedrock geology of this area is discussed in greater detail by Tabor and others (1982) in a companion map of the Skykomish River quadrangle. Adjacent geological maps include the eastern half of the Skykomish River 1:100,000 quadrangle (Tabor and others, 1982), the Snohomish and Maltby 1:24,000 quadrangles to the west (Minard, 1980, 1981), and the Port Townsend 1:100,000 quadrangle to the northwest (Pessl and others, 1983; Whetten and others, 1983).

FIELDWORK AND ACKNOWLEDGMENTS

Field work for this study was accomplished from spring 1981 through winter 1983. Additional field work included a preliminary reconnaissance of the lower Skykomish River valley by R. B. Waitt Jr. in 1978. S. A. Sandberg, F. Moser, and F. Beall were able field assistants during the summer of 1981.

I would like to acknowledge the discussions and support of R. W. Tabor, R. B. Waitt Jr., Fred Pessl, Jr., V. A. Frizzell Jr., J. P. Minard, and D. P. Dethier of the U.S. Geological Survey; Bernard Hallet, S. C. Porter, C. F. Raymond, and J. D. Smith of the University of Washington; Gerald Thorsen of the Washington Department of Natural Resources; Robert Searing of the U.S. Army Corps of Engineers; and consulting geologists W. T. Laprade, Curtis Scott, M. E. Shaffer, and L. R. Lepp. J. C. Yount, E. J. Helley, Fred Pessl Jr., and R. W. Tabor provided critical review and valuable suggestions on the manuscript.

PREVIOUS WORK

Willis (1898) first described the Pleistocene stratigraphy and glaciation in the Puget Sound region. Bretz's (1913) reconnaissance emphasized the recessional lake history associated with the last glaciation of the lowland. Cary and Carlston (1937) briefly described a glaciofluvial delta that was built in the upstream direction across the South Fork of the Skykomish River. They first noted that alpine ice from the Cascades probably did not merge with the large ice sheet occupying the lowland. Mackin (1941) investigated in detail the character of deposits and drainage along the ice

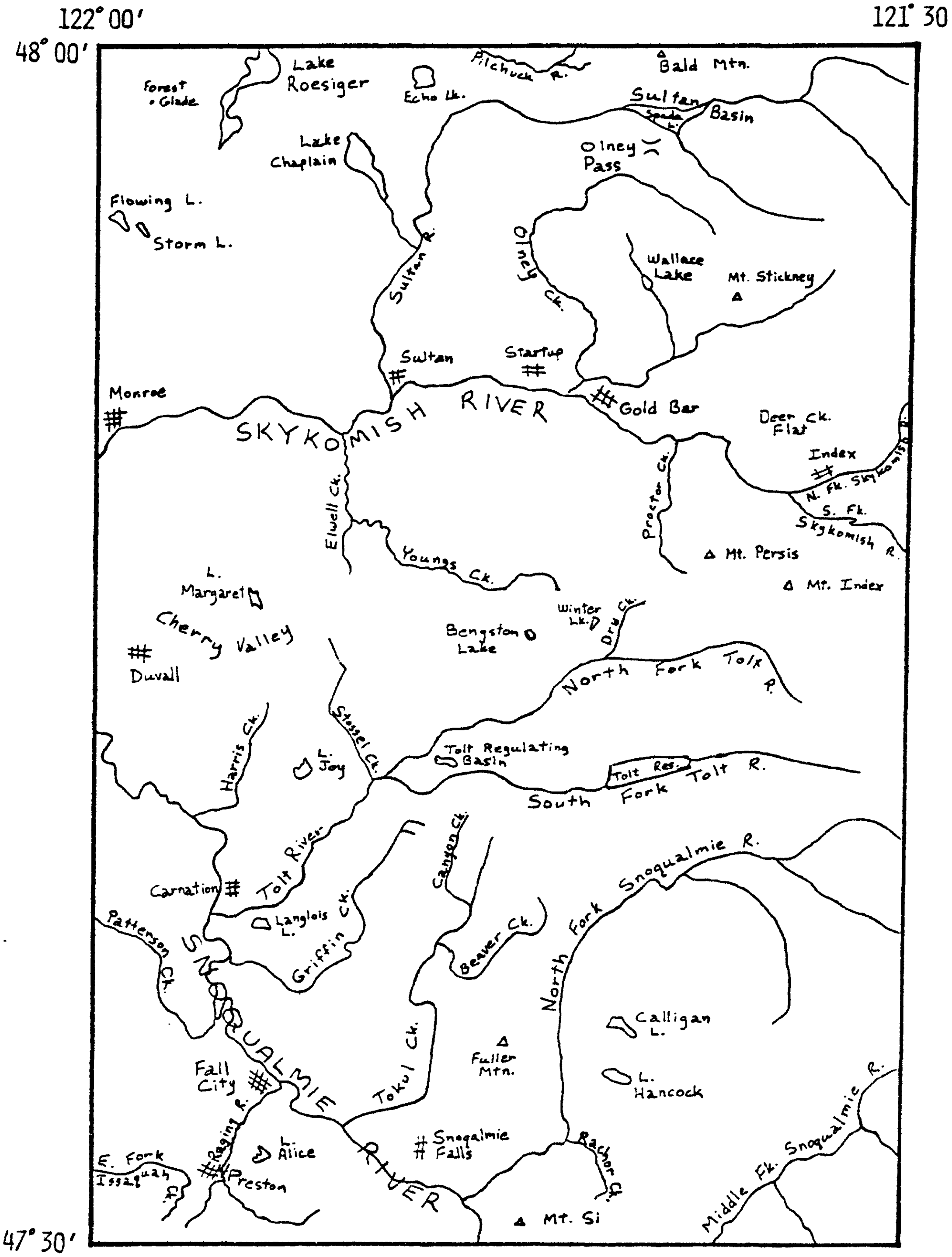


FIGURE 2. INDEX MAP OF GEOGRAPHICAL LOCALITIES

margin abutting the Cascade range front, and reconstructed some of the local details of ice recession and drainage derangement. Maps of various aspects of the surficial geology and covering parts of the study area include: Newcomb (1952) on groundwater resources, Liesch and others (1963) and Livingston (1971) as part of regional geologic compilations, Anderson (1965) and Knoll (1967) with particular emphasis on the recessional glacial history, Williams (1971) on the extent of glaciers in the Middle Fork of the Snoqualmie River, and Snyder and Wade (1972) on soils of the National Forest lands (Figure 3). Thorson (1980, 1981) expanded on the early work of Bretz to delineate a more detailed sequence of local and regional lakes during recession of the last ice sheet. He then used this information to infer amounts and rates of isostatic rebound following deglaciation.

PRE-PLEISTOCENE GEOLOGY

HISTORY

Consolidated bedrock in the area of this report consists of Mesozoic marine metasedimentary and meta-igneous rocks, overlain by lower and middle Tertiary volcanic and sedimentary rocks, and intruded by middle Tertiary batholiths. The Mesozoic metamorphic rocks underlie much of the terrain west of the Cascade range front, both north and locally south of the Skykomish River. On the basis of lithologic variation and intense deformation, Tabor and others (1982) interpret the Mesozoic rocks to be a melange. By early Tertiary time the melange had been uplifted and eroded; it was subsequently covered by volcanic flows, pyroclastic deposits, and sedimentary rocks. Concurrent in part with this volcanic activity, tonalite and granodiorite intruded the region, forming coalescing batholiths that now underlie the western ridges of the Cascade mountains. Smaller intrusions crop out as isolated bodies scattered up to 6 km (4 mi) west of the roughly NS-trending contact between the main batholiths and country rock.

Folding has warped the volcanic rocks in the western part of the quadrangle into a broad west-plunging syncline. On the northern limb of this fold, erosion has stripped away any overlying volcanic rocks, exposing a wide region of the melange covered discontinuously only by glacial drift. In the northwestern corner of the quadrangle, middle to upper Tertiary fluvial sedimentary rocks are exposed and probably overlie this eroded melange surface.

BEDROCK UNITS AND MORPHOLOGY

Melange

The Mesozoic melange consists of a pervasively sheared matrix of mostly argillite containing outcrop- to mountain-sized phacoids of sandstone, greenstone, amphibolite, metagabbro, meta-andesite, chert, marble, and metatonalite. Towards the east, the melange grades into phyllite, with well-developed foliation commonly parallel to bedding. Landforms in the Wallace Lake/Mt. Stickney area that are developed on the phyllite show strong asymmetry and orientation parallel to this foliation. Variability in

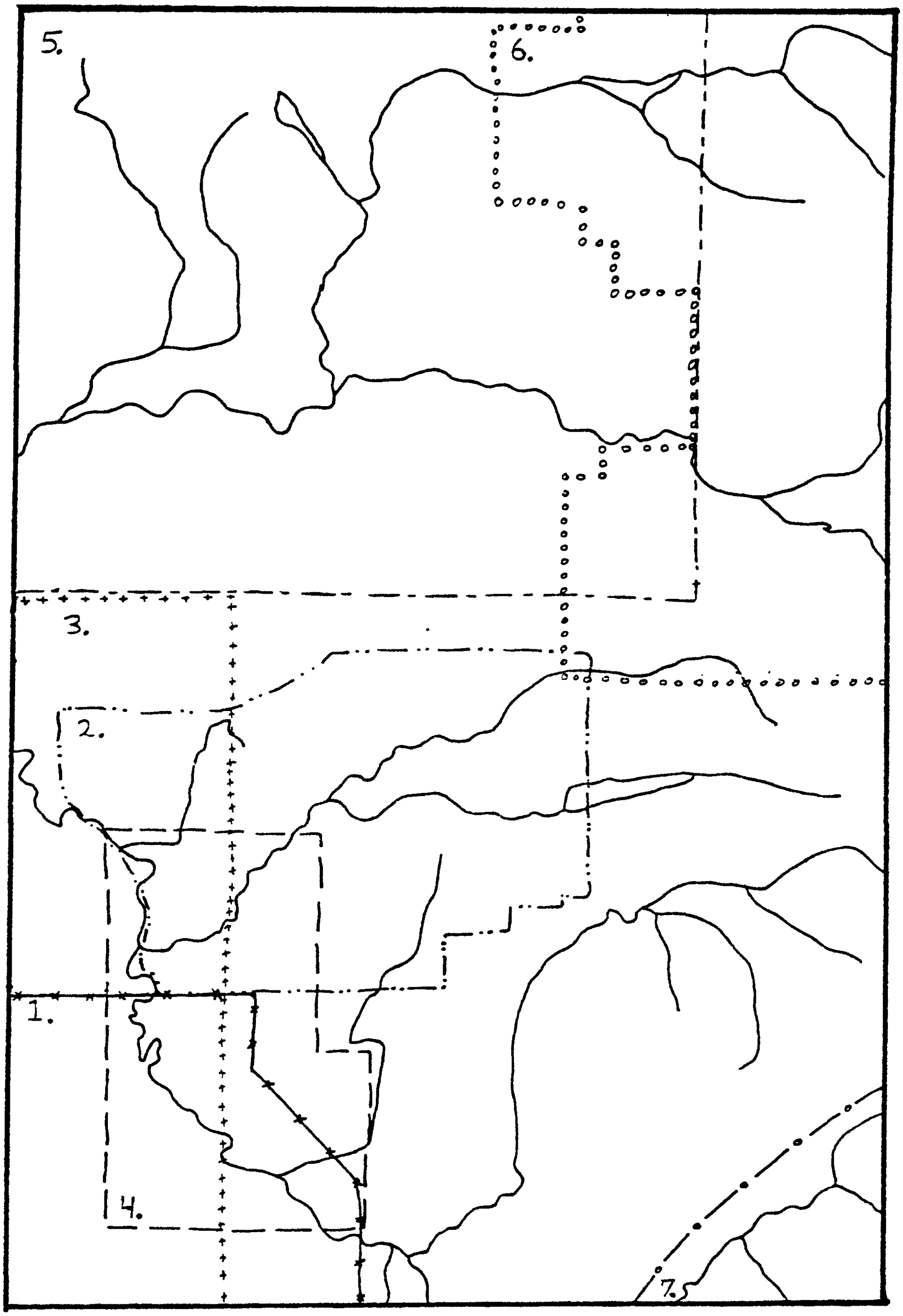


FIGURE 3.

Sources consulted extensively during map preparation:

1. Anderson, 1965
2. Knoll, 1967
3. Liesch and others, 1963
4. L. Lepp and J. Walker, written commun., 1982
5. Newcomb, 1952
6. Snyder and Wade, 1972
7. Williams, 1971

erosional resistance between components of the melange leads to numerous other instances of structural control of young landforms. A particularly good example is the enormous etched-out block of metagabbro comprising the bulk of Mount Si.

Volcanic and Sedimentary Rocks

Andesite, andesitic breccia and tuff, and minor basalt and rhyolite flows and tuffs overlie much of the melange in the area between the Skykomish and Middle Fork of the Snoqualmie Rivers. Southwest of the Snoqualmie River, more abundant sandstone, siltstone, and conglomerate crop out, along with less common volcanic flows and breccias. The northern volcanic rocks are part of the volcanic rocks of Mount Persis unit (Tabor and others, 1982), dated at about 38 m.y., and include minor interbeds of volcanic sandstone and siltstone in the upper part of the section, exposed in the western part of the map area. The sedimentary and volcanic rocks to the south correlate with the Puget Group and have roughly equivalent ages to those of the Mount Persis unit. The volcanics rocks are generally more resistant to erosion, and so often form prominent ridges and bluffs, especially well-expressed in the Lake Elsie/Elwell Creek area 5 km south of Sultan.

Intrusive Rocks

The Oligocene Index batholith and the Miocene Snoqualmie batholith constitute the bulk of Tertiary intrusions in this area. Other isolated bodies are present at the head of Youngs Creek and control the pronounced topographic form of Fuller Mountain northwest of Mount Si. Intrusive rocks north of Spada Lake include the southern part of the distinctively coarse-grained granodiorite of Bald Mountain, of unknown but possibly late Cretaceous or early Tertiary age.

Sedimentary Rocks

Lithologies in this unit vary from moderately to deeply weathered sandy pebble-conglomerate to very fine-grained sandstone. Coarser beds contain a high percentage of quartzose pebbles; finer beds contain considerable mica and lignite. Deeply weathered exposures usually can be distinquished from old glacial outwash by manganese staining on joint planes, nearly monolithologic conglomerate clasts, and the presence of organic matter. However, isolated exposures can be ambiguous, and have occasionally been identified as lake deposits of the early part of the Vashon stade (e.g., Newcomb, 1952). More extensive exposures west of the map area are considered by Minard (1981) to be Oligocene in age and lithologically similar to the Blakely Formation of Weaver (1912). To the northwest, similar rocks are described by Danner (1957) and assigned an Oligocene age based on fossils.

PLEISTOCENE DEPOSITS

REGIONAL SETTING

The Puget Sound lowland extends as a structural and topographic basin between the Olympic Mountains on the west and the Cascade Range on the east. Less pronounced uplands define its southern boundary, and it extends northward into southern British Columbia as part of the Fraser River valley and the Strait of Georgia. The basin's persistence through time is shown by the great thickness of upper Tertiary and Pleistocene sedimentary deposits that fill it (Glover, 1936; Weaver, 1937; Mullineaux, 1970; Hall and Othberg, 1974). Fault-bounded crustal blocks beneath the sedimentary materials may be responsible for the basin (Danes and others, 1965; Stuart, 1961; Gower, 1978; Thorson, 1981).

Multiple advances of ice originating in the mountains of British Columbia have invaded the Puget lowland, leaving a discontinuous record of early(?) to late Pleistocene glacial and interglacial periods (Crandell and others, 1958; Armstrong and others, 1965; Easterbrook and others, 1967). This ice was part of the Cordilleran ice sheet covering western North America that advanced into the lowland as a broad piedmont lobe, referred to as the "Puget lobe" by many authors since Bretz (1913). The extent of this lobe was limited by the net flux of ice from British Columbia, ablation in the lowland, and the mountains surrounding the lowland itself.

These mountains were local sources of glaciers as well. Sufficient periodic cooling coupled with the relative proximity of marine moisture generated multiple advances of Olympic and Cascade alpine glaciers (Crandell and Miller, 1974; Porter, 1976), whose relatively feeble remnants still cling to the slopes of the highest peaks and ridges. The most recent major advance of the Puget lobe, at its maximum stand, probably did not coalesce with alpine ice originating in the Cascades. Speculation on the cause of this lack of synchrony has focused on the shadowing effect of a continental ice sheet on eastward storm tracks, starving the Cascade glaciers and forcing their retreat.

In this quadrangle, post-glacial modification following the most recent occupation by the Cordilleran ice sheet has been dominated by the reestablishment of the major drainages from their alpine headwaters into Puget Sound, across the deranged glaciated lowlands. The advance of thick, active ice sheets forced initial rerouting of these rivers from their preglacial lowland paths into more easterly, south-trending valleys. This diversion often became permanent even after deglaciation, as suggested in this quadrangle by the probable southern diversions of the North Fork of the Snoqualmie River or further south by the present course of the Cedar River (Mackin, 1941). Subsequent fluvial activity has reexcavated valleys filled with glacial and lacustrine sedimentary deposits and reestablished valley-width floodplains graded with respect to modern river and sea level elevation.

SEDIMENTARY PROVENANCES

Material transported by the Cordilleran ice sheet consists of a wide range of lithologies, as debris was derived from both the more northerly alpine valleys of the Cascades and the source mountains in Canada. The amount of sedimentary material foreign to the local drainage basin commonly ranges from 5 to 15 percent. Both Crandell (1963, p. 14) and Dethier and Safioles (1981) report similar percentages of foreign material, particularly clasts of high grade metamorphic rocks, incorporated into Puget lobe till found southwest and northwest of this area. Lithologies of the remaining clasts are dominated by local upglacier bedrock. Because of the predominance of tonalite and granodiorite up most of the alpine valleys in this quadrangle, the percentage of clasts with these lithologies is often sufficient to distinguish the source of the till deposited within an alpine valley. For example, nearly adjacent exposures of inferred "continental" and "alpine" till along the northeastern shore of Calligan Lake contain 15% and 80% granitic clasts, respectively.

REGIONAL STRATIGRAPHY

Previous workers in the Puget lowland have developed a formal Pleistocene stratigraphy for both alpine and Cordilleran glacial and non-glacial deposits, summarized in Table 1. The youngest glaciation has been named the Fraser glaciation by Armstrong and others (1965) who included the Evans Creek stade, associated with the advance of alpine glaciers in the Cascades, and the Vashon stade, associated with the Puget lobe advance. The limiting dates on the Vashon glacial advance in the Seattle area, near the latitude of this quadrangle, include a maximum arrival date for the ice lobe of 15,100 ± 600 ^{14}C years B.P. (W-1305) (Mullineaux and others, 1965), and minimum retreat date of 13,650 ± 550 ^{14}C years B.P. (L-346) (Rigg and Gould, 1957). The ages of earlier glaciations are much more poorly constrained, and have been vigorously debated as well (Stuiver and others, 1978; Easterbrook and others, 1981). Because current terminology is unsettled, I make no attempt in this report to correlate pre-Vashon continental glacial deposits with established stratigraphic nomenclature. Such usage in prior local studies has complicated attempts at correlation across the lowland based on physical parameters, such as weathering characteristics and relative geographic extent, and may require extensive renaming as subsequent absolute ages are obtained.

NON-GLACIAL AND GLACIAL DEPOSITS

Glacial and non-glacial sedimentary deposits of pre-Fraser glaciation age (Pleistocene)

Throughout this quadrangle, only scattered exposures of pre-Fraser deposits exist. Commonly, younger drift is found directly overlying bedrock. This contrasts to the greater prevalence of older deposits preserved in other glaciated terrains that were also occupied by Late Wisconsin ice sheets, including more central areas of the Puget lowland (e.g., Crandell, 1963) and the Great Plains of the mid-continent. The scarcity of pre-Fraser sedimentary deposits in this region therefore suggests that most of them have been eroded away in the inter-glacial interval(s) prior to the most recent Cordilleran ice advance. This conclusion was also reached in a similar setting by Coates and Kirkland (1974) in the Appalachian Plateau.

Description and Weathering Characteristics

Older drifts are identified on the basis of particular weathering characteristics not shared by Vashon-age deposits. In outcrop they are generally oxidized throughout the full thickness of the exposure to either a mottled gray and orange or a more uniform orange brown. In less weathered deposits included within this unit, clasts stand out from the face of the exposure and evidence of clay translocation is visible in the matrix. Weathering rinds are seen on most clasts, and measure 1 to 3 mm on fine-grained volcanic rocks. Granitic clasts are often completely grussified, although some show only minimal decomposition.

In more intensely weathered exposures, clasts are generally flush with the surface of the exposure and can be easily cut with a shovel. This degree of weathering often makes lithologic identification of the clasts uncertain. These deposits are largely clay, and so are usually quite unstable on steep natural or artificial slopes.

Found within these deposits are both matrix-supported diamictons and bedded clast-supported fluvial gravel and sand. Clast lithologies, where identifiable, usually require pre-Vashon age continental glaciation events for their emplacement. The wide range of weathering intensity observed in these deposits probably indicates material derived from at least two, and possibly more, pre-Fraser glacial and/or interglacial periods, despite likely variations between local wathering environments.

Distribution

Older drift is generally found above the maximum altitude of Vashon ice, or beneath Vashon-age deposits where stream incision has exposed the older material. Above the Vashon ice limit, older drift of continental provenance is exposed in a highly discontinuous belt, never more than 50 m (160 ft) elevation above the inferred younger ice sheet. Older drift of distinctly alpine provenance occurs both below and well above this level, and is discussed in a later section. Below the Vashon ice limit, the best and most extensive exposures of pre-Fraser sedimentary deposits are found in the South Fork and main branch of the Tolt River, where incised meanders and consequent landsliding have exposed over 100 m (330 ft) of older drift beneath Vashon-age deposits. Although these exposures are predominantly weathered continental till, locally derived sand, gravel, and minor silt is exposed 1.04 km (0.65 mi) downstream of the Tolt regulating basin, lying above a weathered diamicton and directly below Vashon till. Clast lithologies in this fluvial deposit are consistent with a local source area. Wood in the lower part of this fluvial section yielded a ^{14}C date of 25,600 ± 320 years B.P. (USGS 1625).

Transitional Beds

Along the lower reaches of the Skykomish and Snoqualmie Rivers, lacustrine sedimentary materials are exposed stratigraphically beneath Vashon till. In this area and generally to the west as well (Minard, 1980, 1981), these deposits are not found above 60 m (200 ft) in elevation. The sedimentary deposits are gray silty clay and clay, firm, with virtually no oxidation coloration, and horizontally laminated except where loading has produced dipping or contorted bedding. They are both impermeable and quite unstable, giving rise to numerous slope failures particularly along the north side of U.S. Highway 2 east of Monroe. These deposits correlate with parts of the Admiralty Clay of Newcomb (1952), and the Pilchuck Clay Member and Lawton Clay Member of the Vashon Drift (Newcomb, 1952; Mullineaux and others, 1965), which have been described as lakebed deposits laid down in standing water ponded by the advancing Vashon ice sheet.

Following Minard (1980, 1981), I map these sedimentary deposits as the transitional beds. They span a period of sedimentation prior to and including the early advance of the Vashon ice sheet. The base of this unit is not exposed in this area, but the top is clearly marked either by the appearance of sand and gravel of the advance outwash or by the presence of lodgement till.

GLACIAL DEPOSITS

Deposits of the Vashon Stade of the Fraser Glaciation of Armstrong and others (1965)

The majority of Pleistocene deposits exposed in the quadrangle were directly or indirectly derived from the lobe of the Cordilleran ice sheet that occupied the Puget lowland about 14,000 years ago. The lowermost sedimentary deposits are lacustrine and fluvial, derived from the advancing ice. These deposits were largely removed by the ice or covered by till, which was itself incised or covered in part by meltwater and associated deposits during both the maximum and recessional stages of glaciation.

Advance Outwash Deposits

Description

Exposed discontinuously beneath Vashon till are sand and gravel deposited by meltwater from the advancing glacier. The sand is commonly cross-bedded and tend to grade upward into more gravelly layers. In most exposures, these deposits are almost completely unoxidized and, where undisturbed, are almost always compact. The base of this unit is marked by the first appearance of sand above the silt and clay of the transitional beds. This contact may be gradational, representing continuous sedimentation throughout the ice sheet advance. In most exposures the unit is overlain by lodgement till. The contact between outwash and till is locally transitional over as much as a meter, but usually this boundary is rather abrupt over less than a few centimeters.

The thickness of the advance outwash is highly variable and completely exposed in only a few areas. Maximum observed thickness occurs west of Duvall, on the west side of the Snoqualmie River, where over 100 m (330 ft) of sand and gravel with deltaic forset beds is exposed between capping lodgement till and river level. A nearby diapire of pebbly silty clay, apparently forced up into the sand from below, suggests the close proximity of the base of the advance outwash. East of Monroe the advance outwash is present only as a discontinuous, contorted stratum between Vashon till and the transitional beds, never exceeding a meter in thickness.

Engineering Properties

Where exposed or otherwise inferred to underlie younger deposits, the advance outwash is a promising source of relatively shallow groundwater. Newcomb (1952) reports recharge, permeability, and water quality as quite good. However, because this potential aquifer is frequently isolated from contamination by only a thin blanket of till, care must be taken in construction projects not to penetrate this cover. The advance outwash deposits stand on moderate slopes with only minor ravelling. They are a good source of clean sand, although their high degree of consolidation and limited extent have apparently discouraged major exploitation in this quadrangle.

Till

Description

Vashon till is mainly a tough, unoxidized diamicton with a silty sand matrix and with sub- to well-rounded clasts composing approximately 20% of the deposit. The deposit ranges from a thin cover of less than a meter in thickness to several tens of meters thick. In some exposures the diamicton appears to have two distinct facies: the lower is tough and unoxidized, with a fine-grained matrix; and the upper is looser, more sandy, and commonly lightly oxidized. Although in most localities the upper layer is probably weathered till, originally identical to the lower, in some exposures this top layer is more likey melt-out or ablation till from debris released by the melting ice during deglaciation. In these areas it commonly grades into more distinctly water-worked recessional stratified drift, which in turn is found as a discontinuous cover over much of the areas of the mapped till.

Lithology

The clast composition of Vashon till is dominated by the bedrock lithology present immediately upglacier from it. Observations in many exposures suggest that the majority of clasts in the lodgement till were transported only a few kilometers. There are, however, almost always a few exotic clasts whose presence distinguishes continentally-derived deposits from their alpine counterparts. Clast lithologies found along the South Fork of the Skykomish River, above the North Fork of the Tolt River upstream of Dry Creek, along the south shore of the Tolt Reservoir, and near the eastern end of Calligan Lake are exotic to the basins themselves, and so reveal former tongues or bergs of continental ice up each of these drainages.

Weathering

Weathering of Vashon till is very slight in most exposures. Weathering rinds on fine-grained volcanic rocks are much less than a millimeter in thickness. Oxidation effects, if present at all, extend at most a meter into the deposit, and there is no evidence for significant clay translocation. Only some granitic clasts show a significant degree of decomposition, which can be quite variable even within a single outcrop. Detailed studies of the weathering of Vashon till by Peter Lea (written commun., 1982), Colman and Pierce (1981), and Carson (1970) show mean weathering-rind thicknesses from the southern Puget lowland of 0.5 mm or less, oxidation depths of 0.5 m, and no significant matrix alteration.

Distribution and Topographic Expression

Vashon till mantles most of the rolling uplands above the Skykomish and Snoqualmie River valleys. Recessional deposits are largely channelized through this topography and do not obscure it. However, the distribution of pre-Vashon deposits and bedrock indicates that Vashon till largely blanketed a pre-existing topography that was not greatly altered by the passage of the ice. The till is significantly thinner on the upglacier side of hills that have at least a few tens of meters of relief, such as around Lake Roesinger, Forest Glade, and Lake Chaplain (all north of the Skykomish River); along the south side of the Skykomish River; and southeast of Cherry Valley. Mullineaux (1970, p. 44-45) and an analysis by Nancy Brown (written commun., 1983) of well data recorded in Liesch and others (1963) show a similar pattern of till deposition to the south and west of this quadrangle.

The till surface is marked by numerous linear depressions and elongate ridges, which define consistent ice flow directions over much of the area. These linear features also align well with striations on bedrock, and, in two localities, with pronounced till fabric. The depressions are generally a few meters deep, roughly ten meters wide, and may traverse the countryside for several kilometers. They are often poorly drained, and the vegetation that thrives in this boggy environment highlights these features on aerial photographs. Wider depressions are well-expressed by the orientation of Storm and Flowing Lakes, Lake Margaret, and Lake Alice. Elongate ridges may be composed either wholly of till or bedrock, or a mantling of till over bedrock.

Towards the margin of the ice sheet, patchy till exposures give way to a scattering of rounded pebbles that thins upslope, commonly over an increase in elevation of roughly 30 m (100 ft). Benches, breaks in slope, and infrequent moraines are other indicators that define the most probable ice limit of the Vashon ice sheet.

Intra-Till Stratified Sedimentary Deposits

In some exposures, Vashon till is comprised of tough, compact crudely to well-bedded clast-supported deposit with widely variable proportions of silty matrix. These deposits are commonly in close proximity with more characteristic lodgement till. The sedimentary materials include sorted sand or gravel interstratified with diamicton, commonly in geographic or stratigraphic locations far from plausible long-term ice margins. They are therefore probably not flowtills associated with subaerial ice-contact environments. I interpret these materials to be subglacial fluvial deposits, repesenting either the reworking of recently deposited basal till or the sediment actively transported in subglacial or englacial passageways. Similar material is described and similarly interpreted by Eyles and others (1982) as part of their "lodgement till complex." Exposures of these deposits can be seen in the Monroe-Sultan area on the south side of the Skykomish River, along the lower reaches of Proctor Creek (W.T. Laprade, oral commun., 1982), and along some of the south-trending channels in the upland area east of Lake Joy.

Engineering Properties

Vashon till is the "hardpan" of local experience and terminology. It drains poorly, has a very low permeability and water content, is relatively stable on moderate slopes where not immediately underlain by less competent deposits, and has good undisturbed bearing strength for roads and foundations. Since it is of only limited thickness, however, the ground stability in the proximity of long steep slopes merely capped by the till will often be more dependent upon the underlying geologic material. Management of the runoff from the nearly impervious till surface then becomes critical in maintaining that stability (Tubbs, 1974).

Ice-Contact Deposits

Depositional Environments

Continual melting of ice at a glacier's surface, coupled with the flow of new ice and entrained debris from within the ice out to its edges, provides a steady flux of both sedimentary materials and meltwater to the ice margin. The morphology of the sedimentary materials deposited in this environment will depend in large measure upon the geometry of the land surface and drainage system adjacent to the ice margin (Flint, 1971). Of particular relevance to the area of this report is the situation where an ice tongue extends up a river valley or completely blocks its mouth. Sediment released from the melting ice will thus aggrade into that valley. As the sediment is transported further from the ice margin, the resultant deposit will take on more typical fluvial characteristics; and if the ice has impounded a lake in the valley, the distal deposits will form a delta whose most distal facies will consist of fine-grained lacustrine sedimentary materials. The deposit therefore may grade into a fluvial or lacustrine deposit indistinguishable from those derived from non-ice-contact sources. In such situations the contact between the distinctly ice-contact and strictly fluvial or lacustrine deposit will be gradational. These deposits are, however, contemporaneous and so are mapped as the same time-stratigraphic unit, or morphosequence (Koteff and Pessl, 1981).

Distribution

Ice-contact deposits occur along the maximum or near-maximum position of the former ice sheet, and along the eastern wall of the Snoqualmie River valley where a tongue of ice must have persisted for some time during deglaciation. Additional smaller deposits are present where active ice lobes were stable for long enough to deposit significant amounts of debris. The best example is in the Bengston Lake area north of the Tolt River, where two nested moraines loop across the upland plain, marking the location of a near-maximum recessional ice stand.

Great embankments of ice-contact deposits are found filling the mouths of west-draining alpine valleys along the margin of the Vashon ice sheet. Clast lithologies and occasional foreset beds indicate that these materials originated from outside of the local drainage basins, and were deposited by ice and water flowing up the present river valleys. Almost all of the major alpine valleys (Sultan, Olney, Wallace, Skykomish, Proctor, South Fork of the Tolt, North Fork of the Snoqualmie, Calligan, and Hancock) are partially or completely blocked by such an embankment. The valley mouth of the North Fork of the Tolt River is also choked by Vashon-age deposits, but here the material is exclusively well-sorted fluvial sand and gravel; it is discussed in the section on recessional history.

Sedimentary and Morphological Characteristics

These deposits show wide variation in both sedimentary materials and morphology. They are comprised predominantly of fluvial gravel and sand, commonly with local foreset bedding. However, lenses and thick layers of flowtill and probable lodgement till are also found in many exposures, particularly in the morainal embankments. Till lenses are exposed in the creek cuts of the Hancock and Calligan Lake outlets, and are the primary sedimentary deposits encountered in test borings through the embankment just west of Spada Lake (Converse Ward Davis Dixon, 1979) and north of the Tolt dam (Shannon and Wilson, 1959). Roadcuts along the eastern, distal slope of the South Fork of the Tolt River embankment, just north of the dam, also expose till up to at least 560 m elevation (1840 ft). Excavations through the middle of this embankment reveal a thin layer (1-2 m) of distinctly fluvial material overlying 50 m (160 ft) of moderately consolidated, crudely-bedded, unoxidized, matrix-rich gravel and sandy silt and clay. The deposit is locally clast-supported along subhorizontal layers. The texture is similar to that of lodgement till found thoughout the area but includes a greater amount of clay in the matrix. The origin of a similar deposit has been debated by Evenson and others (1977), favoring subaqueous flowtill melted off the glacier snout; and Gibbard (1980), favoring subglacial melt-out till beneath a floating ice tongue. Other descriptions of glacial sedimentation into lacustrine environments (Eyles and Eyles, 1983) that apply closely to this locality suggest that subglacial meltout is the source of this deposit.

Along the near-maximum ice margin, the morainal embankments were built into lakes impounded by either the ice sheet or by the sedimentary deposits themselves. Any sedimentary materials transported well beyond the ice margin by fluvial processes tend to grade into a delta, although the bulk of the embankment is not necessarily deltaic. Rarely, a discrete source of water and sedimentary materials can be traced upglacier along the margin of the ice as a terrace surface graded to the level of the embankment. North of the Pilchuck embankment such a terrace can be followed from the upper surface of the embankment to a pronounced bedrock notch at 750 m (2500 ft) elevation, just north of the map boundary. However, the previously referenced borings show that over much of the embankment this fluvial surface is only a thin cap, less than 10 m (30 ft) thick, overlying at least 60 m (200 ft) of till. A less well-defined channel occupying an analogous position is present northwest of Deer Creek Flat, the embankment at the mouth of the Skykomish River valley.

Engineering Properties

The multiple modes of deposition of these ice-contact sedimentary materials yield deposits whose engineering properties vary over short distances. Although reasonably well-sorted fluvial gravel and sand may be expected in their distal reaches, showing many of the engineering properties of the recessional outwash, deposits proximal to the ice-contact surface often show abrupt and unpredictable grain size variations. Boulders in excess of a meter in diameter are not uncommon. Till lenses and larger masses may also be encountered. The two major reservoirs in the area demonstrate the relative impermeability of the morainal embankments behind which they are impounded, but detailed subsurface exploration of each has demonstrated their variability as well.

Recessional Outwash Deposits

Description

Fluvial sedimentary materials, deposited by meltwater during retreat of the ice, mantle much of the terrain. They range in thickness from a thin cover of less than a meter to over 100 m (330 ft) in large deltas such as those along the east side of the Snoqualmie River valley. Characteristically the sedimentary deposits are comprised of an interbedded mixture of sand and sub- to well-rounded gravel with clasts up to 30 cm in diameter. A light-orange oxidation color on otherwise fresh clasts is present for the full depth of exposure. Except for occasional minor iron oxide cementation, the sedimentary deposits are easily excavated with a hand shovel. Lithologies are characteristic of the Vashon Drift as a whole; although showing a preponderance of local types, they almost invariably have an easily identified exotic component. One might expect the deposits to fine upward, reflecting retreat of the ice margin, but this is rarely observed here. Neither cross-bedding, nor very fine-grained sand and silt, are as common in these fluvial recessional deposits as in fluvial deposits of the advance outwash.

The major variability between exposures of recessional outwash is in the maximum and mean grain sizes. Although 30 cm represents a common maximum boulder diameter, some deposits have significantly smaller or larger clasts. In particular, extremely coarse boulders (2-3 m diameter) crop out just north of the North Fork of the Tolt River, south of Winter Lake; and along Youngs Creek, 4 km (2.5 mi) above its confluence with Elwell Creek south of Sultan.

Lacustrine sedimentary deposits associated with the recession of the ice sheet are deposits generally composed of silt to very fine sand, often thinly laminated in fresh exposures. Rare dropstones are present in many exposures. In the North Fork of the Snoqualmie River valley, lacustrine sedimentary deposits are distinctly coarser than in the other alpine valleys. Medium-grained sand is common here and silt is rather rare, suggesting a rapidly aggrading valley in which deposition kept pace with rising base level.

Distribution

The greatest volumes of recessional outwash sand and gravel are present as deltas built into a recessional lake formed in the Snoqualmie River valley. The deposits are present at the mouths of streams that drain the uplands to the east, and whose valleys provided routes for meltwater released at the retreating ice margin. The Tolt River valley displays well the downstream transition from a kettled outwash plain through a series of channelized gravels and sands to a corresponding series of deltas built into the Snoqualmie valley. A similar system of deltas just north of Monroe shows the influence of falling lake levels in the Skykomish River valley, and the successive activity of several distinct meltwater channels from the north.

Marginal Lacustrine Deposits

The Vashon ice sheet impounded lakes in many of the alpine valleys. The maximum elevation of the ensuing lake deposits, commonly well-correlated with corresponding morainal embankment elevations, and the paucity of ice-rafted pebbles suggest that some of these embankments dammed their valleys well into the post-glacial period. Exposures of Vashon till in the Sultan Basin, the South Fork of the Skykomish River valley, the South Fork of the Tolt River valley, and above the northeast shore of Lake Calligan confirm that parts of these lacustrine deposits are recessional. Both advancing and receding ice, however, would have been equally effective in damming these valleys as long as the ice at their mouths was sufficiently thick.

Engineering Properties

The recessional outwash deposits provide most of the sand and gravel used for construction, which according to Livington (1971) is the most valuable mineral resource of western Washington. In the Snoqualmie and Skykomish River valleys, most of the large deltas, and many of the smaller ones, are actively mined. Although shifting channels that transported the material produce variability in grain size along any given section, within beds the sorting is likely to be quite good. Overall, these bodies show grain sizes commonly ranging commonly from medium grained sand through 20 cm diameter cobbles. Fine-grained materials are rare in the main body of the deltas. Upstream along the channels, grain size variability and maximum grain size commonly increase since proximity to the ice margin results in locally higher flow gradients and more common ice-rafted boulders. Many of these channel deposits are veneers over subglacially-deposited material. This underlying material is more poorly sorted and more compact, making its commercial evaluation difficult.

Permeability is high, stability is good, and settlement should be negligible. Areas underlain by sufficiently thick accumulations of recessional outwash should be well-drained, but because in many (if not most) localities the deposit is underlain by lodgement till or impermeable bedrock, perched groundwater is possible. Since it is not generally overlain by younger deposits, shallow wells in the recessional outwash are prone to seasonal fluctuations and contamination. Nevertheless, it is an important groundwater source throughout the area (Newcomb, 1952).

In contrast, recessional lacustrine deposits are both weak and impermeable. Poor surface drainage, together with low slope stability and bearing strength, make those areas underlain by this deposit particularly ill-suited for most types of development.

Alpine Drifts and Related Deposits

Older alpine drift, undivided

Deposits above the limit of Vashon ice on the interfluves between west-draining alpine valleys, particularly south of the North Fork of the Tolt River, were left by ice originating from the direction of the Cascade crest. They form low-relief surfaces above roughly 1000 m (3300 ft) elevation. Weathering rinds on fine-grained clasts measure from one to eight millimeters thick, and granitic clasts are generally decomposed to grus completely. Oxidation effects are variable, but they are always more intense than in either continental or alpine deposits associated with the last major ice advance. Lithologies usually specify an alpine source, with granitic clasts common even in those deposits found far west of any granitic bedrock exposures.

Alpine drift of Mt. Stickney

West of Mt. Stickney, till and stratified drift mantle the bedrock ridges as a broad, gently sloping surface with a pronounced morainal crest. The lithology of the drift, eighty to ninety percent granitic clasts, indicates transport by alpine ice from granitic bedrock east of Mt. Stickney. This drift is largely above the limit of continental ice, although in one area above Wallace Lake some of this material has been reworked by the Vashon-age continental ice sheet. Modern U-shaped alpine valley floors, cut hundreds of meters into the upland surface, were occupied by younger isolated valley glaciers. Thus the glacier responsible for this deposit must have formed a widespread icecap, covering all but the highest peaks and ridges. Evidence for the extent of this ice north and west into the lowlands has been completely obscured by younger deposits.

Weathering rinds on fine-grained volcanic clasts on the constructional surface of the deposit measure 1 to 3 mm, and granitic clasts show a wide range of decomposition with slightly grussified stones predominating. Material exposed and reworked by continental ice is generally much fresher, indicating its long isolation from weathering while deep beneath the original depositional surface.

Alpine till

Deposits mapped as alpine till are loose to compact diamictons, with angular to subrounded clasts supported by a silt or sand-rich matrix. Clast size is variable, but generally less than 30 cm. Oxidation is generally absent, and clasts are uniformly fresh. Counts of clast lithologies specify upvalley sources. This unit includes only those few deposits sufficiently continuous and well-exposed to map.

Alpine glacial deposits, undivided

Thick vegetation cover coupled with sporadic exposures and poor road access up most of the alpine valleys render the identification, subdivision, and delineation of the limits of alpine glacial deposits virtually impossible. Such deposits, therefore, are inferred primarily from aerial photographs and occasional field exposures. They also include significant amounts of talus, colluvium, alluvial fans, modern valley-bottom alluvium, and bedrock. Contacts with mapped bedrock upslope may be gradational and only approximately located. The weathering chracteristics and topographic position of most of the glacial deposits included here are similar to those mapped more specifically as the alpine till unit.

Glacial and talus deposits

Some talus deposits observed on aerial photographs show ridged, lobate lower boundaries, suggesting deposition at the base of small glaciers. All are unvegetated and are found only on north-facing slopes in areas above 1200 m (4000 ft) elevation. Their distinct morphology and lack of vegetation suggest a late Holocene age.

CORRELATION OF PLEISTOCENE DEPOSITS

Cordilleran Ice Sheet Advances

Although previous studies in the central Puget lowland have documented multiple advances of continental glaciers, such evidence is rather sparse in this quadrangle. Older drift, however, is found discontinuously up to 50 m (160 ft) above the maximum elevation of Vashon ice, along much of the ice margin here. The weathering characteristics and relative topographic position are consistent with those deposits reported by Carson (1970) and Peter Lea (oral commun., 1982) in the southwestern and southern lowland, and so provide additional evidence for a more voluminous pre-Vashon advance. Carson (1970) correlated this maximum continental ice advance with the Salmon Springs glaciation of Crandell and others (1958). Correlation of this stand with previously named deposits, however, is probably premature, and must await additional age data.

Alpine Glacial Advances

The current stratigraphic framework for alpine deposits on the western slopes of the Cascade range is given by Crandell and Miller (1974). Although speculative, correlation between deposits found near Mount Rainer and those in this quadrangle, 110 km (70 mi) further north, are suggested by certain topographic and weathering characteristics. The degree of weathering and lack of morphology associated with the deposits mapped here as the undivided older alpine drift clearly indicate a pre-Evans Creek age. In addition, this unit includes deposits that more specifically share weathering and morphologic characteristics described by Crandell and Miller (1974, p. 19) for Wingate Hill Drift. Weathering rinds on clasts in the alpine drift of Mt. Stickney also indicate a pre-Evans Creek age (Colman and Pierce, 1981). The degree of weathering and loss of constructional morphology, however, is consistently less than in most of the deposits mapped here as undifferentiated older drift. These characteristics invite comparison with the Hayden Creek drift of Crandell and Miller (1974, p. 21-22) and suggest possibilities for future investigation.

Less weathered deposits constitute the remainder of alpine drift found in this area. One deposit in particular, damming a bog 2 km south of Lake Hancock, shows a distinct morainal form, and permits estimation of the equilibrium line altitude (ELA) of the glacier that formed it. Reconstructing the aerial extent of this glacier by making reasonable assumptions about its gradient and source area, and applying methods of ELA estimation described in Porter (1975) and Pierce (1979), yield an ELA of approximately 1000 m (3300 ft). This compares closely to values obtained by inspecting Crandell and Miller's map (1974, Plate 1) showing Evans Creek glaciers in the Mount Rainier area, and by calculations performed by Williams (1971) for the Middle Fork of the Snoqualmie River basin and assigned by him to glaciers of the Evans Creek stade. The absence of absolute age control, however, permits only a late-glacial age assignment.

No evidence for the merging of late Wisconsin-age alpine and continental glaciers was found in this area. The presence of marginal lacustrine deposits in the alpine valleys confirms the retreat of alpine glaciers prior to the continental ice sheet's final retreat, but sheds no additional light on their relative timing or interaction. Williams (1971) reported deltaic deposits at the upper end of the Vashon-age lake in the Middle Fork of the Snoqualmie River valley, but field work for this report disclosed only abundant Holocene alluvial fan deposits along the steep valley walls.

NON-GLACIAL DEPOSITS

Older Alluvium

Fluvial gravel and sand above the level of the modern floodplains can be mostly assigned to a recessional interval during the last ice retreat. However, the topographic position of some deposits makes this interpretation doubtful. For example, along the upper Raging River south of Preston, terrace remnants stand at 200 m (660 ft) elevation, 10 m (30 ft) above the level of the modern streambanks. Projection of this terrace west down the channel now occupied by the East Fork of Issaquah Creek, a path for recessional meltwaters, indicates that it stands at too low a level to correspond with the Vashon recessional terraces there. Instead, it was probably deposited by the Raging River during or preceding its active incision of the canyon north of Preston. A similar series of three broad terraces along the Skykomish River near Gold Bar cannot be unequivocably assigned to any of the recessional stages in the valley. Indeed, their surfaces project downstream on reasonable gradients to levels well below those associated with deposits produced during deglaciation. The terraces are numbered on the map from 1 through 3, indicating successively younger intervals of deposition.

Younger Alluvium

Recently transported sand and gravel is present along all of the major streams and rivers in the area, generally forming a surface without major topographic scarps and devoid of mature vegetation. Although the age of these surfaces are inferred from vegetation and morphology to be measurable by years or decades at most, this unit includes some deposits equivalent in age to mapped older alluvium but lacking any observed topographic demarcation.

Bog Deposits

Poorly drained depressions are common throughout much of this area. Identification of bog deposits include topography, vegetation characteristic of wet environments, and the presence of standing water. Bogs are also common in valleys occupied in part by flowing streams, and thus may be gradational with modern alluvium. In many such instances, the form and gradient of the channel has been inherited from glacial activity, with the stream passing through both alluvial reaches and nearly standing water. Peat is common in many of these bogs (Rigg, 1958).

Alluvial Fan Deposits

Where tributary streams join with larger valleys having a lower gradient, some portion of the tributary sediment load is deposited as an alluvial fan at the mouth of the stream. Ephemeral streams on steep sideslopes also transport material downslope for varying distances, and this material can coalesce into an entire hillside of fan deposits. The deposit is generally composed of poorly to moderately sorted rock debris and reworked glacial deposits.

Although truly gradational with talus and certain other mass wastage deposits, the alluvial fan deposits are distinguished by their characteristic lobate morphology at low hillslope gradients and by the presence of stream channels on steeper slopes.

Talus Deposits

Sub-angular to very angular blocks of local bedrock mantle hillslopes below steep rock cliffs. They are most pronounced above 1000 m (3300 ft) elevation and on north-facing slopes where frost action is most effective. I mapped most deposits from aerial photographs on the basis of surface texture, the absence of vegetation, and topographic position.

Mass Wastage Deposits

On hillslopes of any non-zero gradient, the surface material is in sporadic downhill motion by a wide variety of processes dependent on local failures in the soil or underlying rocks, expansion and contraction of the surface material, or biological activity. I mapped mass wastage deposits where they are sufficiently thick and continuous to obscure both the underlying material and any characteristic topographic features that might serve to identify them.

Landslide Deposits (Undivided)

I identified landslide deposits largely from characteristic hummocky topography, distinct scarps, or anomalous closed depressions that are not associated with collapse features of ice-contact deposits. They are gradational with the mass wastage deposits but generally involve larger, more coherent blocks of surficial material or bedrock. Contacts may include not only the failed material itself, but also the slide scarp if its expression is relatively fresh and the material there is potentially unstable as well. Non-horizontal dips in fine-grained sedimentary deposits that are inferred to be undisturbed by glacial action also indicate downslope mass failure by rotation of coherent blocks, particularly if adjacent to actively downcutting streams. Instability is indicated not only by the surface form and presence of discrete scarps and fissures in the ground surface, but also by the character of the vegetation, which commonly includes trees canted irregularly downslope.

Modified Land

Modified land mapped in this area includes the three major dams in the area, cuts for a powerhouse on the Sultan River, and extensive grading and filling for a power substation northeast of Monroe. Transportation corridors involving the placement of fill on or alongside of Skykomish and Snoqualmie River alluvium are shown only when their width is easily represented at this scale of mapping.

CHANNELWAYS

A variety of troughs and valleys incise the till and bedrock landscape, particularly in the uplands east of the Snoqualmie valley. Although some are easily explained by the scouring action of ice or the exploitation by subaerial recessional meltwater, other valleys discussed here as "channelways" instead reflect the occupation and erosion by subglacial meltwater. On the the map, channelways often appear as narrow sinuous to linear valleys occupied by lakes, bogs, or underfit streams. Their sidewalls are often steep, with relief of ten to over one hundred meters. In addition to bog deposits and modern alluvium, till and recessional outwash deposits are occasionally exposed but only rarely can be differentiated at this map scale. These features bear many topographic similarities to "overflow channels" and "sluiceways" named by Coates and Kirkland (1974) in the Appalachian Plateau and attributed primarily to proglacial fluvial erosion. However, the channelways differ fundamentally in owing their origin and position to subglacial processes. They functioned only incidentally (if at all) as spillways or outwash channels during ice retreat.

Criteria for identifying the subglacial origin of these features divide into two groups: those which suggest the implausibility of other, more familiar processes, and those which demonstrate evidence of subglacial processes directly. The characteristics particularly inconsistent with a subaerial fluvial origin include:

1) "humped" or "up-and-down" longitudinal profiles (Peel, 1956);
2) abrupt channel termini without deltas or fans (Sissons, 1958);
3) multiple intakes and outflows (Derbyshire, 1961);
4) till or other ice-contact sedimentary deposits occasionally exposed in the troughs; and
5) perched topographic position without significant drainage area.

Other characteristics are more specifically suggestive of a subglacial origin. In particular, channelways are usually aligned subparallel to ice surface gradients, which correspond to the expected average flow direction of subglacial water and ice. On the map, this is most easily seen by the general parallelism between channelways and ice flow indicators, used to infer the probable direction of the ice surface gradient. Where channelways are used as directional indicators themselves (particularly well-expressed north and east of Lake Joy), other nearby directional indicators, such as elongate bedrock ridges and the regional pattern of ice flow, strongly support this interpretation. Such correspondence is consistent with a subglacial origin and provides a rational explanation for many of the "anomalous" features listed above. In particular, the present topographic position of these valleys and lack of subaerial drainage, which renders a subaerial origin unlikely, reflects instead the distribution and flow of subglacial water. This water experiences a radically different hydraulic gradient regime from surface flow determined primarily by the ice surface slope (Shreve, 1972). Although ice-marginal stream channels may also have insignificant drainage area following deglaciation, channelways generally cross-cut likely ice margin positions. Thus, under roughly uniform ice margin retreat rates, they would have diverted through them only minor volumes of water in this environment. The "up-and-down" profile of channelways with respect to the modern topography, unlikely under any subaerial regime, can be shown to yield monotonically decreasing hydraulic potentials under any substantial thickness of sloping ice.

In these channels, the relatively small width, occasional obliquity to ice flow indicators, and sinuosity reduce the likelihood of significant erosion by the ice itself. The added drag of the valley walls on the ice should locally reduce basal sliding rates and thus abrasion that is specifically due to ice motion (Rothlisberger, 1968). These features can therefore grow subglacially only by the direct or indirect (Weertman, 1979) action of water. Channelway locations are also consistent with other predicted patterns of subglacial water flow. Under actively flowing ice, the lee side of obstacles would be zones of relatively lower pressure and thus lower hydraulic potential. Subglacial water channels would tend to migrate to these locations, cross-cutting regional gradients and local ice flow directions alike. This is well-illustrated in the area 5 km (3 mi) north of the Tolt regulating basin and probably accounts for the generally symmetrical landforms in this area.

Inspection of the distribution of channelways across the map shows that they are particularly prevalent across the major bedrock spurs that extend west from the mountain front. They therefore tend to transect and behead these spurs, leaving an often bizarre topography of isolated bedrock knobs separated by single or anastomosing steep-sided, flat-floored valleys. Because any sufficiently extensive ice sheet advance would have covered this channelway system, they presumably owe their present form to multiple glaciations and a far longer period of activity than the duration of the Vashon-age glaciation in this area alone. They display a progressive development that reflects relative subglacial drainage areas, local bedrock resistance, and potential for expansion to a point that active ice flow can take a significant role in their continued shaping, equivalent to Coates and Kirkland's (1974) "through valley" stage.

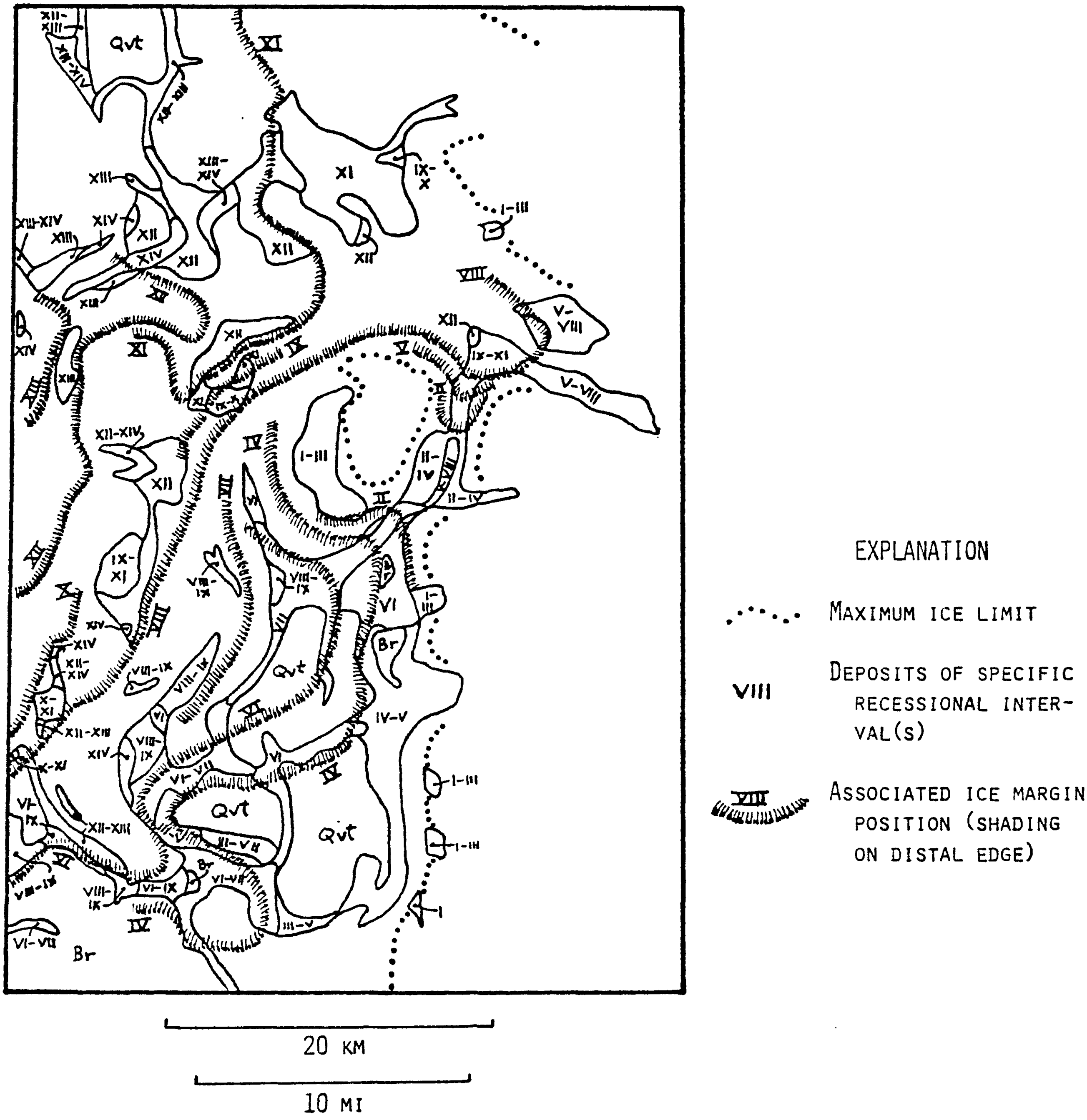


Figure 4.

Distribution and sequence of the recessional outwash deposits of the Vashon stade of Armstrong and others (1965). Numbers refer to deposits of specific recessional intervals (I, the oldest; XIV, the youngest). Qvt = Vashon till (Pleistocene); Br = bedrock (Tertiary and Mesozoic)

VASHON-AGE RECESSIONAL HISTORY

As the scoured and channelized topography of the lowland emerged from beneath the retreating ice sheet, a complex of interconnected meltwater channels and lakes formed. Earlier workers have stressed either the local (Anderson, 1965; Knoll, 1967) or the regional (e.g., Bretz, 1913) character and sequence of these features. The recent study of Thorson (1981), however, provides a far more complete framework of the deglaciation sequence for defining more detailed, localized stratigraphy.

In the study area, the postglacial topography naturally divides the region into three distinct areas: 1) the Snoqualmie valley, 2) the Skykomish valley and its northern tributary valleys, and 3) the upland valleys and channels lying east of the Snoqualmie River. Throughout most of the recessional period, meltwater activity followed a rather simple and consistent pattern. Water draining marginally and submarginally from the north was impounded in a lake occupying the Skykomish valley, and spilled southward first through the broad trough south of Gold Bar, and then through the valley south of Sultan. This water thus entered the upland channel system, combined with additional water derived from the gradually retreating ice margin in this area, and flowed south and southwest into the Snoqualmie valley. The bulk of the ice sheet, blocking the northerly drainage of this valley, impounded a series of lakes that drained into yet other, lower water bodies to the south and west beyond the limits of the quadrangle. Spillways that controlled the altitude of such lakes in both the Snoqualmie and Skykomish River valleys can be identified. It is the presence of stream deposits, deltas, and lake-bottom deposits associated with these altitudes that form the basis for time-stratigraphic assignment and correlation of the recessional deposits.

To elucidate these relationships, time intervals within the recession are numbered sequentially. Their boundaries are defined either precisely by the opening of a specific spillway or more indefinitely by the position and altitude of particular recessional deposits (Figure 4). Because the three major topographic areas are only indirectly connected, events defining a particular time boundary would not simultaneously affect every site of sedimentation throughout the quadrangle. Thus individual recessional deposits and active meltwater routes often include more than one time interval. In the following discussion, Roman numerals in parentheses refer to the time-stratigraphic assignments (I being the oldest), whose relationships can be seen more concisely on the chart of recessional intervals (Figure 5). When correlating spatially separated features, we can compensate for the systematic increase in present-day elevations northward due to isostatic rebound since deglaciation by using Thorson's gradient of 0.9 m/km (1979, Figures 17 and 23) along a roughly north-trending transect. This correction appears to be applicable even this close to the edge of the lowland.

Uplands

Early recessional deposits preserved along the ice margin are limited to moraines and morainal embankments blocking alpine valleys (I-III). Their variable surface elevations, at very different altitudes below their local ice maximum limits, require that their formation was not simultaneous. They must, however, have preceded the deglaciation of all channels further west.

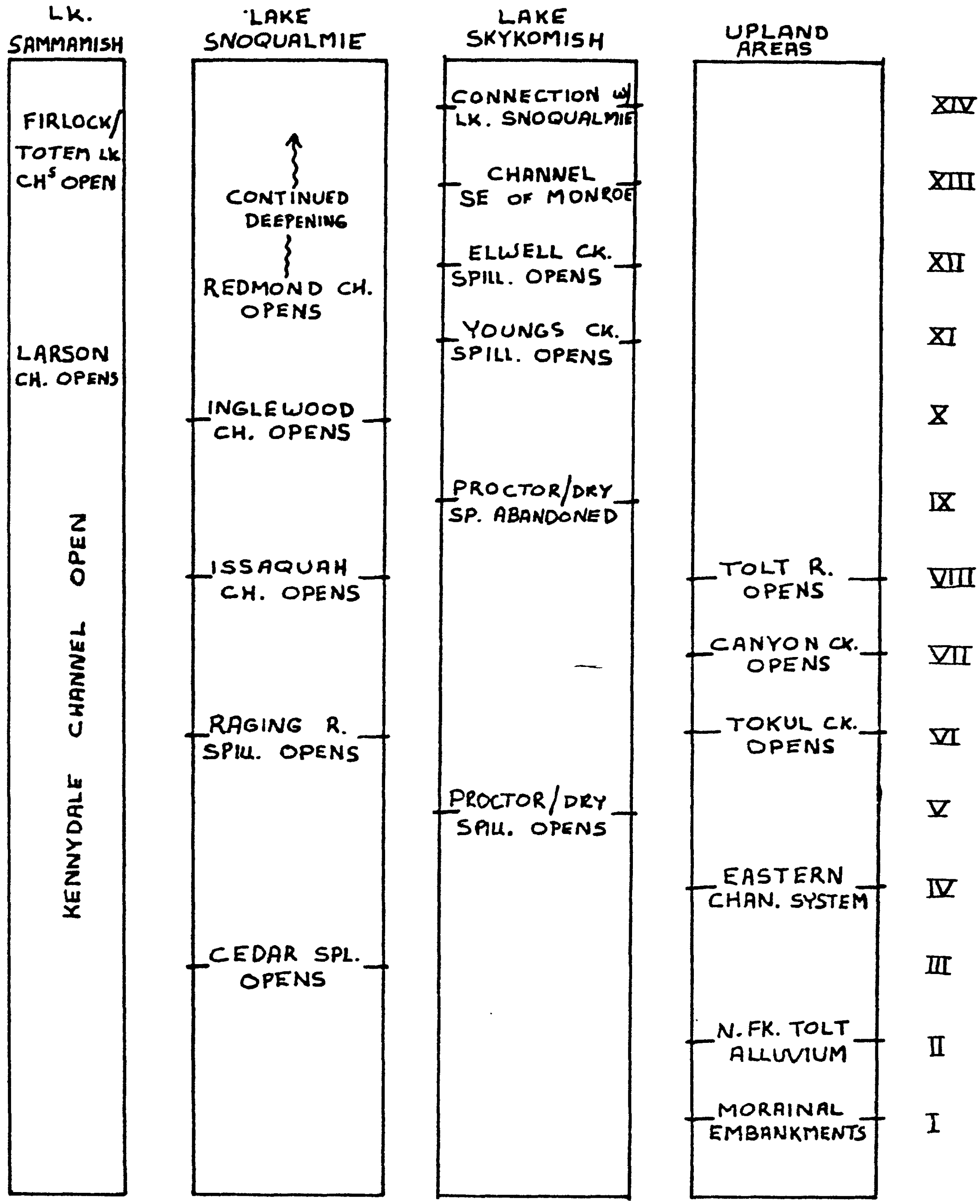


FIGURE 5. Recesional intervals (I-XIV) of the Vashon stade of Armstrong and others (1965)

Poor exposure and later erosion inhibit interpreting the morphology of these embankments. In the Calligan-Hancock area, Mackin (1941) first noted that each valley drains around the south edge of the embankment that blocks it. He suggested the presence of a great ice-marginal river that carried the water from each of the blocked drainages southward, dumping sediments into each valley in turn on their north side and draining off to the south. Yet neither coarse-grained fluvial deposits nor deeply scoured continuous channels, plausible remnants of such an hypothesized torrent, can be found at or near the level of these embankments. Such fluvial features, however, are found roughly 200 m (600 ft) below the level of these marginal embankments, on the floor of the upland surface now occupied by the North Fork of the Snoqualmie River. Analysis of the subglacial hydraulic potential in this area, following Shreve (1972) or Nye (1976), confirms that instead of draining subaerially at the ice margin, water would tend to occupy this lower, subglacial position. The surface topographies of these embankments generally do not reflect aggradation from the north by river-transported sedimentary materials. At Lake Calligan, for example, the high point lies along the central E-W axis of the embankment. Finally, exposures and borings through several of the embankments show that till is common or even dominant relative to fluvial deposits. This suggests that material was water-transported only locally off the ice surface.

Emergence of subaerial channels in the upland region followed formation of these embankments, as the ice margin began retreating from the mountain front. The highest and easternmost of these channels (IV-V) began as a set of now-beheaded valleys just south of the South Fork of the Tolt River. They continued south as anastomosing channels in marginal or near-marginal positions and finally built a broad outwash plain, whose base level was fixed by the earliest lake to occupy the Snoqualmie valley (see III, below). The bedrock and till that emerged from beneath the ice in this area is now largely submerged by these deposits.

Further north, an alluvial deposit chokes the valley of Dry Creek and the North Fork of the Tolt River, with associated lake deposits present further up the North Fork valley (II-IV). The surface elevation of this deposit and its isolated position indicate its deposition relatively early in the recession, while ice still covered both the Proctor Creek valley just north of it and the lower upland channels to the west. Its continuity with the early outwash surface to the south (IV-V), discussed above, is ambiguous. Much of the drainage both into and out of this area may have been through subglacial passageways, and therefore diagnostic depositional surfaces are absent.

Continued withdrawal of the ice margin from the upland area allowed the primary routes of meltwater drainage to migrate westward. Although evidence is lacking for any standstill of the ice margin during this time, the presence of spillways permits assigning discrete intervals within this period. The subaerial emergence of Tokul Creek, Canyon Creek, and the Tolt River define three such intervals (VI, VII, and VIII). Terraces and channels found near Beaver Creek suggest an early connection (VI) between the older "eastern" channels and Tokul Creek. Each of the three main stream channels lies roughly perpendicular to ice flow indicators and so all were probably marginal or near-marginal streams during their successive activity. Only the Tolt has maintained significant Holocene flow, as it forms the lowest, western-most outlet for a basin otherwise bounded by bedrock divides. Tokul and Canyon

Creeks are perched well above this basin and therefore required ice diversion of meltwater for their supply. This is confirmed by the proximity of ice-contact deposits. During their respective occupation by outflow, the basin upstream of the outlet channels aggraded with fluvial sedimentary materials to concordant elevations. The thickness of these deposits, roughly 30 m (100 ft), coupled with likely rates of ice retreat required by the maximum 1500 year occupation time of the ice (Rigg and Gould, 1957; Mullineaux and others, 1965) testify to a remarkably high flux of sediment during this time.

Knoll (1967) proposed an equivalent sequence of recessional stages in the Tolt River area, but he included Griffin Creek as an additional important channel. Griffin Creek, however, has an extremely low gradient at 150 m (500 ft) elevation, 4 km (2.5 mi) dowstream of a plausible spillway out of the Tolt basin, and shows no major accumulation of sediment. Since only minor sediment transport could have occurred downstream of this point, significant meltwater occupation of Griffin Creek must have been very short-lived (during VIII).

Skykomish River Valley

The high bedrock divide just south of the Skykomish River permitted relatively few drainage routes across it. The highest, most easterly, and longest occupied route is the broad south-trending trough south of Gold Bar, now occupied by Proctor and Dry Creeks (V-VIII). Its location is structurally controlled by a fault line scarp between resistent Tertiary volcanic rocks and the easily eroded Mesozoic argillite-rich melange. This passageway formed the only drainage route for the entire Skykomish valley during most of the Vashon-age glaciation. It would have been equally favorable as a subglacial drainage route, both at ice maximum and for as long during retreat as ice was sufficiently thick to prevent subglacial drainage farther west (e.g., the Elwell Creek valley south of Sultan). All water at the ice margin or subglacially within several tens of kilometers from it, collected from west-flowing alpine valleys and submarginal drainage further north, would thus have been channeled through here. As a subsequent subaerial drainage route, it provided much of the water and sediment for those southern channels closer to the maximum ice margin (V) and for the water and sediment that later entered the Tolt basin (VI-VIII). The top of the Skykomish River morainal embankment and the upper limit of lake deposits found further upstream (V-VIII) are roughly graded to the subaerial elevation of this trough as well (490 m, 1600 ft) (Cary and Carlston, 1937; W. T. Laprade, oral commun., 1982).

Continued ice thinning eventually would have allowed subglacial drainage farther west (IX-X) under a lower hydraulic potential than the now-subaerial Proctor trough. Base level of the Skykomish lake then fell continuously as the ice thinned; therefore, no discrete intermediate intervals can be defined. Once the spillway at Youngs Creek (XI) was exposed south of Sultan, the lake level stabilized again and a set of identifiable lacustrine deposits, terraces, and outwash plains graded to 180 m (600 ft) developed. Flow over Olney Pass from water impounded in the Sultan Basin, and from an ice margin near Lake Chaplain and Echo Lake, contributed to the formation of the large outwash plain north of Startup. A somewhat perplexing problem is the relatively short distance of ice margin retreat required to open a yet lower path, contrasted with the apparent large volume of sedimentary material graded to the Youngs Creek spillway. The lower spillway, exposed at Elwell Creek

(130 m, 430 ft) (XII), allowed another drop in lake elevation. The location of deposits graded to this base level attests to the ice margin's continued westward retreat out of the Skykomish valley. Final retreat from this valley created a penultimate level of water and deposits (XIII) before the valley merged with the regional lake system, as discussed in the next section.

Snoqualmie River Valley

Five distinct spillways link the Snoqualmie valley with the rest of the lowland to the south and west (Figure 6). Continuous ice retreat impounded a discrete sequence of lakes whose levels were controlled by the currently lowest and most northerly of these spillways, successively exposed from beneath the retreating ice margin. Lake levels are marked particularly well by the elevations of alluvium and deltas deposited during simultaneous drainage from the upland channel system. Because the Snoqualmie valley trends north-south, features distributed along the valley associated with a single late-glacial water plane will now stand at different elevations, owing to isostatic rebound since the ice retreated. In particular, initially level features now stand higher to the north since thicker overriding ice ultimately resulted in greater amounts of rebound to the north. To facilitate comparisons, elevations are given with both the present values and the correction required to compensate for rebound relative to Monroe. This arbitrary datum is chosen because the amount of rebound at Monroe is roughly equivalent to that of the entire Skykomish valley and because it coincidentally matches the rebound of the last regional-lake spillway of the entire Puget Sound region (the Leland spillway, discussed below). Estimates of the correction can be made for unspecified features by inspecting Thorson (1979, Plate 1) or, more crudely, by adding 9 m elevation for each 10 km distance (5 ft/mi) south of Monroe.

The broad valley of the Snoqualmie River terminates approximately 8 km (5 mi) south of the map, at the foot of a broad trough (the Cedar spillway) between Rattlesnake Mountain and the Cascade range front. This trough probably acted as a subglacial meltwater passage. As the ice margin retreated north, it became a subaerial spillway with an elevation of 280/+45 m (920/+150 ft), impounding a proglacial lake between it and the ice (III-V). Both Bretz (1910) and Thorson (1981) called this body Lake Snohomish. Fluvial deposits in the lower North Fork of the Snoqualmie River valley, associated with the upland channel sequence (IV-V), must have in part built into this lake.

Opening of a spillway southwest of Fall City over the divide between the Raging River and the East Fork of Issaquah Creek (158/+36 m, 520/+120 ft) appears to have been roughly synchronous with the opening of Tokul Creek as the primary upland drainage path. Evidence includes the absence of 280 m level deposits at Tokul Creek or 158 m level deposits along the lower North Fork of the Snoqualmie River (VI-VII). Drainage to the west was into Glacial Lake Sammamish, whose elevation at this time was controlled by the Kenneydale channel (91/+37 m, 300/+120 ft), located southwest of this quadrangle. The initial diversion of water east of the town indicates an ice margin position close to Snoqualmie Falls, while the multiple levels of the delta at Tokul Creek show active downcutting of the controlling spillway. Voluminous ice-contact fluvial deposits just north, along the east wall of the Snoqualmie valley, show that a tongue of ice entended down the late glacial precursor of the modern valley both before and during drainage via the Raging River. The

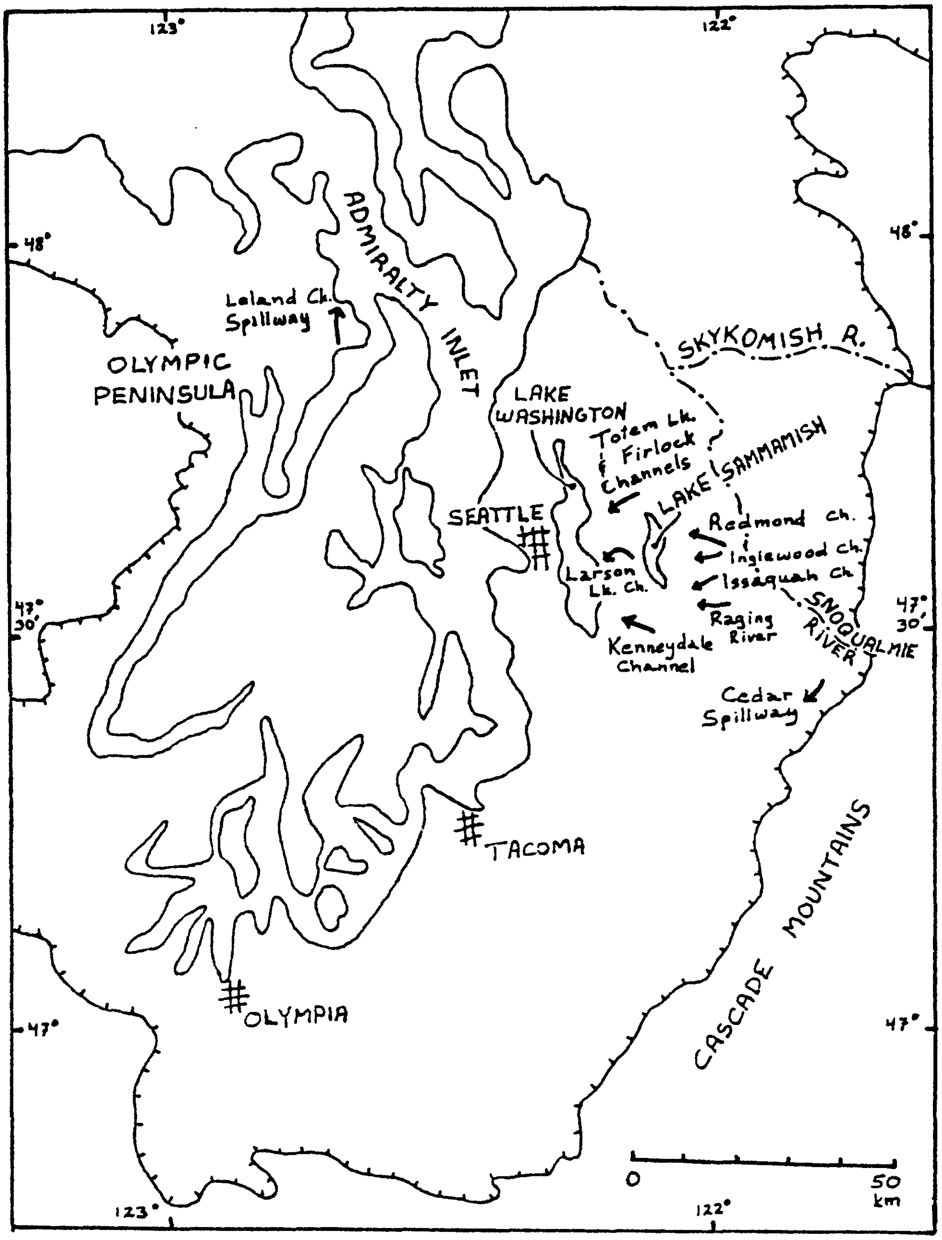


FIGURE 6. Puget lowland localities discussed in text. Hachured line indicates position of Puget lobe ice limit (from Thorson, 1980) during the Vashon stade of Armstrong and others (1965).

low gradient of Griffin Creek at 150 m (500 ft) is easily explained by water and sediment flow from this ice tongue up the modern valley, leaving a gradation from coarse to fine-grained alluvium from the Snoqualmie valley to the large Griffin Creek bogs.

Continued margin retreat opened in succession two channels northwest of Fall City, which also drained west into Glacial Lake Sammamish. Associated with the Issasquah channel (110/+34 m, 360/+110 ft) are ice-contact deposits just north of it, indicating the probable ice margin position at this time; and deposits of the Tolt River delta, including its southern end where fluvial material buried the stagnant tip of the Snoqualmie valley ice tongue (VIII-X). Occupation of the Inglewood channel (107/+31 m, 350/+100 ft) was briefer (X-XI), as only a minor shift of the ice margin position west of the quadrangle exposed a much lower drainage route.

The Redmond channel, 5 km (3 mi) southwest of Carnation, provided the lowest route south of Monroe for drainage to the west. It is therefore the most northerly of the Snoqualmie spillways. The level of deposits in the main valley indicates that their elevation was controlled by the level of Glacial Lake Sammamish, and thus the sequence of spillways identified by Thorson (1980) for that lake are applicable to this valley as well. At the first exposure of the Redmond channel, water level in the Snoqualmie valley fell from its Inglewood channel level. Evidence from the deposits north of the Tolt River, at Harris Creek, and from a plausible reconstruction of the ice margin location west of the map area all indicate with excellent agreement that the Larson channel of Glacial Lake Sammamish (76/+33 m, 250/+110 ft), west of this quadrangle, was active at this time (XII-XIII). Consequently, continued retreat of the ice in the map area affected only the location of sedimentation in the lake; the lake elevation itself was controlled by the retreat much further west. Lake-bottom silts that form constructional terraces along the sides of the Redmond channel are below the level of this stage (XII-XIII) but above that of the subsequent stage (XIV), necessitating their deposition during this time as well. Although the Redmond channel itself must have deepened as water from the Snoqualmie valley flowed through it, its early recessional existence and exploitation are required by the recessional deposits found within it. Since till caps the surface on either side of the channel and does not appear to drape down into it, the channel was unlikely to be a primary preglacial or subglacial feature. Thus its formation must have been relatively rapid, undoubtedly aided by the easily eroded advance outwash deposits present in great thicknesses beneath a relatively thin resistant cover of till.

The next lowest channels draining Glacial Lake Sammamish (Firlock and Totem Lake) allowed the lake to merge with Lake Bretz (Waitt and Thorson, 1983), identified by Thorson (1981) as the last and largest glacial lake to occupy central Puget Sound. Its elevation was fixed by the Leland Creek spillway (68/+0 m, 225/+0 ft) (XIV), on the northeast corner of the Olympic Peninsula, and it persisted until ice margin retreat permitted drainage through Admiralty Inlet. Deposits within the map area, whose elevations indicate deposition contemporaneous with this stage of recession, include the deltas at Monroe, Stillwater (3 km, 2 mi north of Carnation), and near Griffin Creek (3 km south of Carnation).

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DESCRIPTIONS OF MAP UNITS

NON-GLACIAL DEPOSITS

m MODIFIED LAND (HOLOCENE)--Gravel or diamicton as fill, or extensively graded natural deposits

LANDSLIDE DEPOSITS (HOLOCENE)--Divided into:

Ql Landslide deposits--Diamicton of angular clasts of bedrock and surficial deposits derived from upslope locales. Many shown with no letter symbol, only arrows denoting downslope direction of movement

Qlra Rock avalanche deposits--Huge angular boulders on or at the base of steep slopes

Qmw MASS WASTAGE DEPOSITS (HOLOCENE)--Colluvium, soil, or landslide debris with indistinct morphology, mapped where sufficiently continuous and thick to obscure underlying material. Deposits are gradational with units Qf and Ql

Qt TALUS DEPOSITS--(HOLOCENE) Non-sorted angular boulder gravel to boulder diamicton. At lower elevations, gradational with unit Qf. At higher elevations, includes small rock avalanche deposits as well as some Holocene moraines, rock glaciers, and protalus rampart deposits that lack characteristic morphology. Generally unvegetated surfaces

Qf ALLUVIAL FAN DEPOSITS (HOLOCENE)--Poorly sorted cobble to boulder gravel, deposited as either a discrete lobe at the intersection of a steep stream with a valley floor of lower gradient, or as a broad apron of coalescing fluvial material on steep sideslopes

Qb BOG DEPOSITS (HOLOCENE)--Peat and Alluvium. Poorly drained and at least intermittently wet annually. Grades into unit Qyal

Qyal YOUNGER ALLUVIUM (HOLOCENE)--Moderately sorted deposits of cobble-gravel to pebbly sand along rivers and streams. Generally unvegetated surfaces; gradational with both units Qf and Qb

Qoal OLDER ALLUVIUM (HOLOCENE AND PLEISTOCENE)--Similar material to unit Qyal, but standing above modern floodplain level and generally separated from it by a distinct topographic scarp. In the Sykomish River valley, terrace sequence is indicated by subscripts, from 1 (oldest) to 3 (youngest)

GLACIAL DEPOSITS

ALPINE DRIFTS AND RELATED DEPOSITS (HOLOCENE AND PLEISTOCENE)--Divided into:

Qgt GLACIAL AND TALUS DEPOSITS--Similar material to unit Qt but showing distinct lobate form indicating deposition at terminus of small glacier or permanent snowfield, or an active rock glacier. Generally unvegetated surface

Qag ALPINE GLACIAL DEPOSITS--Ranges from till in uplands and upvalley to gravelly outwash on broad valley floors. On valley sides includes areas veneered with drift but also showing bedrock, alluvial fans, colluvium, or talus deposits. On valley floors may also include small fans, bog deposits, and modern stream alluvium. Areas of thin, sparse drift with sporadic bedrock exposures generally included in this unit as well. In the headward reaches of alpine streams, grades into unit Qgt

Qat ALPINE TILL--Fresh diamicton of locally derived lithologies, similar to till mapped as part of unit Qag

Qams ALPINE DRIFT OF MT. STICKNEY--Till and stratified drift forming a broad morainal ridge extending northwest from Mt. Stickney

Qoad OLDER ALPINE DRIFT, UNDIVIDED--Moderately to strongly weathered older diamicton. The lithologic composition indicates transport by alpine glaciers

DEPOSITS OF THE VASHON STADE OF THE FRASER GLACIATION OF ARMSTRONG AND OTHERS (1965) (PLEISTOCENE)--Divided into:

Qvr RECESSIONAL OUTWASH DEPOSITS--Stratified sand and gravel, moderately- to well-sorted, and well-bedded silty sand to silty clay. Roman numeral subscripts (shown on geologic map) distinguish successively younger deposits, with Roman numeral I the oldest. Multiple subscripts, or their absence, indicate increasingly indeterminant ages. These deposits represent predominantly outwash plain and valley train environments in the lowland areas that may locally be divided into:

Qvrs Sand-dominated recessional outwash deposits

Qvrg Gravel-dominated recessional outwash deposits

Qvrl Fine grained deposits of ice-dammed lakes associated with specific recessional intervals

Qvrm Deposits associated with marginal lakes dammed by ice or debris in the major west-draining alpine valleys

Where units Qvr and Qvt are mapped together, topographic form of composite unit is controlled by the underlying till, but with a near-continuous blanket of outwash. Gradational with both units Qvr and Qvt

Qvic ICE-CONTACT DEPOSITS--Deposits are often similar in texture to unit Qvr but show structures or morphology that indicate deposition in close proximity to active or stagnant ice. Roman numeral subscripts (shown on geologic map) follow same conventions as for the recessional outwash deposits units (see footnote on correlation diagram). Locally divided into:

$Qvic_k$ Kame and kettle deposits--Underlie areas with characteristic topographic form indicative of deposition around or above stagnant ice

$Qvic_m$ Moraines and morainal embankment deposits--May include a high percentage of loose to compact diamicton beneath and interstratified with fluvial materials, deposited at or near active ice margins

Qvt TILL--Mainly compact diamicton with subangular to rounded clasts, glacially transported and deposited. In ice-marginal areas or where covered by a thin layer of recessional outwash, contact with unit Qvic or Qvr is gradational

In certain areas where both till and bedrock are mapped together, overall topographic form of unit is controlled by bedrock, with exposures of both materials present. Composite unit includes areas with colluvium of angular clasts and uniform lithology in close proximity to till, with or without corresponding bedrock exposures. Also locally includes:

Qvts Intra-till stratified sedimentary deposits--Minor deposits of stratified sedimentary material of inferred subglacial fluvial origin. Usually interbedded with till (Qvt)

Qva ADVANCE OUTWASH DEPOSITS--Well-bedded gravelly sand to fine-grained sand, generally firm and unoxidized; deposited by proglacial streams

Qvu DRIFT, UNDIVIDED

NON-GLACIAL AND GLACIAL DEPOSITS

Qtb TRANSITIONAL BEDS (PLEISTOCENE)--Pre-Vashon and early Vashon-age deposits of laminated clayey silt to clay; occasional dropstones present. Grades upward into unit Qva

Qpf GLACIAL AND NON-GLACIAL SEDIMENTARY DEPOSITS OF PRE-FRASER GLACIATION AGE (PLEISTOCENE)--Deeply weathered stratified sand and gravel, or clay-rich diamicton. Strong in-place weathering is indicated by oxidation, grussification, rind development, and clay mineral development throughout the depth of exposure. Consists of deposits with a wide age range (predating the Fraser glaciation)

Qtu TILL, UNDIVIDED (PLEISTOCENE)--Compact diamicton for which weathering and stratigraphic position are insufficient to assign to either unit Qvt or Qpf. On the western edge of the map, may include small areas of non-glacial sedimentary deposits

Qdu GLACIAL DRIFT, UNDIVIDED (PLEISTOCENE)

BEDROCK

Ts SEDIMENTARY ROCKS (TERTIARY)--Moderately to deeply weathered sandy pebble-conglomerate to fine-grained sandstone. Quartzose pebbles common in coarser-grained deposits; mica common in finer-grained sand

Ti INTRUSIVE ROCKS (TERTIARY)--Mostly biotite-hornblende and hornblende-biotite granodiorite and tonalite, but locally includes quartz diorite, quartz monzonite, and granite

Tvs VOLCANIC AND SEDIMENTARY ROCKS (TERTIARY)--Mostly andesite and andesitic breccias and tuffs with minor basalt, dacite, and rhyolite. Southwest of the Snoqualmie River, sandstone, siltsone, and conglomerate predominate

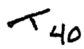
Br BEDROCK, UNDIVIDED (TERTIARY AND MESOZOIC)--Consists variably of a single bedrock unit (as listed herein) or a composite of several separate bedrock units, in combination with one or more non-bedrock units

Mm MELANGE (MESOZOIC)--Argillite, phyllite, graywacke, chert, greenstone, marble, amphibolite, metatonalite, and metagabbro; pervasively sheared and disrupted. Sheared argillite commonly forms a matrix for blocks whose dimensions may range from one to thousands of meters

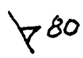
MAP SYMBOLS

Contact

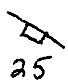
High angle fault--bar and ball on downthrown side



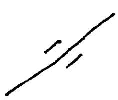
Strike and dip of bedding



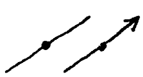
Strike and dip of foliation in metamorphic rocks



Strike and dip of bedding in glacial outwash deposits

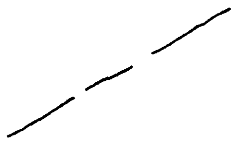


Till fabric--symbol aligned with consistent horizontal trend of the long axis of pebbles



Striation--direction of motion indicated by arrow head

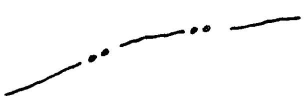
Flow of glacial meltwater inferred from surface morphology



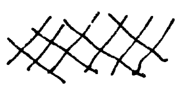
Ice flow indicator--elongated hills, valleys, and closed depressions inferred to show direction of basal ice motion

Approximate limit of continental ice sheet

Crest of moraine associated with continental ice sheet

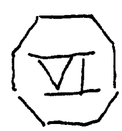


Crest of moraine associated with alpine glaciers



Channelway

Direction of landslide motion



Spillway controlling elevation of impounded recessional meltwater (Roman numeral corresponds to recessional interval)

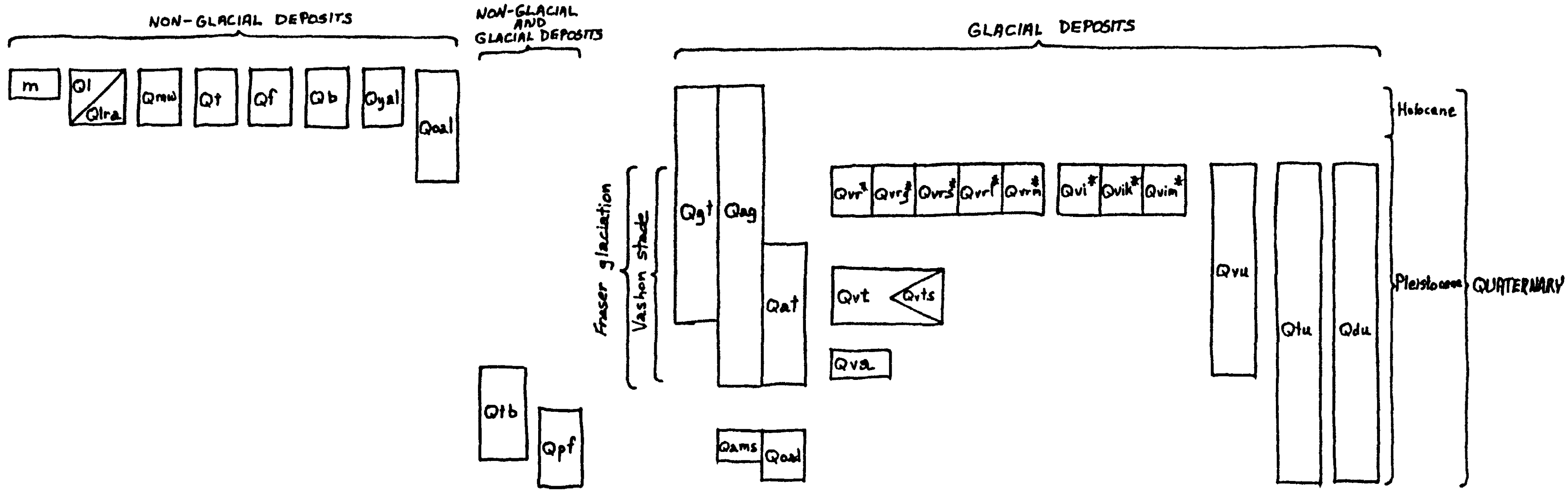
Tacoma quad & adjacent district	Southeastern part	Puget lowland area	Central part (Seattle area)	Southeastern part (Mt. Rainier area)
Modified from Willis (1898)	Modified from Crandell & others (1958)	Modified from Armstrong & others (1965)	Modified from Mullineaux & others (1965)	From Crandell and Miller (1974) *Alpine glacial advances*
Vashon glaciation	Vashon glaciation	Fraser Glaciation: ·Sumas stade ·Everson interst. ·Vashon stade ·Evans Ck. stade	Vashon Drift: ·Recessional outwash deposits ·Till ·Advance outwash deposits: ·Esperance Sand Member ·Lawton Clay Member	Evans Ck. Drift
	Interglacial (unnamed)			Hayden Ck. Drift
Puyallup interglacial	Salmon Springs glaciation			
	Puyallup interglacial			Wingate Hill Drift
Admiralty glacial epoch	Stuck glaciation			
	Alderton interglacial			
	Orting glaciation			

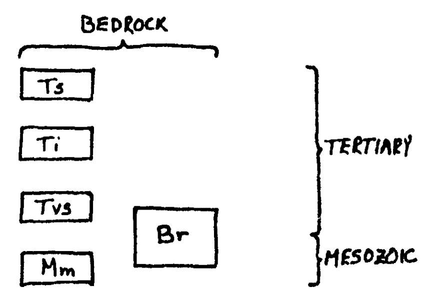
Late Pleistocene ? (bracket beside Vashon glaciation and Puyallup interglacial, Tacoma column)

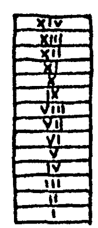
Late Pleistocene ? (bracket beside Evans Ck. Drift and Hayden Ck. Drift, Mt. Rainier column)

TABLE 1. Summary of Pleistocene staratigraphy of Puget lowland

CORRELATION OF MAP UNITS







* Subscript numbers in map unit symbol represent specific recessional intervals I-XIV (I being the oldest interval) that are shown by the separate unit symbols. Multiple subscripts indicate deposits spanning more than one interval; absence of subscript indicates an indeterminant age.