SURFICIAL GEOLOGIC MAP OF THE SKYKOMISH AND SNOQUALMIE RIVERS AREA, SNOHOMISH AND KING COUNTIES, WASHINGTON

By Derek B. Booth

INTRODUCTION

This study of the surficial geology of the area covers the western half of the Skykomish River 1:100,000 quadrangle (figs. 1 and 2) and is part of a larger geologic investigation of the Wenatchee 1° by 2° quadrangle in west-central Washington. This particular area exemplifies the erosional and depositional processes of ice-sheet glaciation, particularly those processes unique to the ice-marginal areas. Geologic data on the distribution and sequence of surficial deposits and on the inferred processes that formed them can be used to reconstruct the dynamic behavior of past ice sheets, to elucidate further the Pleistocene history in western Washington, and to inform planners and engineers who must deal with projects involving these deposits.

This study emphasizes the deposits associated with the most recent ice advance from British Columbia (fig. 1) but addresses as well the deposits of earlier ice-sheet advances, local alpine glacial deposits, and bedrock. The bedrock geology of this area is discussed in greater detail in Tabor and others' (1982) map of the Skykomish River 1:100,000 quadrangle. Adjacent geologic maps include the Snohomish and Maltby 1:24,000 quadrangles to the west (Minard, 1985a, b), the Port Townsend 1:100,000 quadrangle to the northwest (Pessl and others, 1989; Whetten and others, in press), the Granite Falls 15-minute quadrangle to the north (Booth, 1989) and the Snoqualmie Pass 1:100,000 quadrangle to the south (Frizzell and others, 1984). The preliminary results of this study were given in Booth (1984a).

FIELDWORK AND ACKNOWLEDGMENTS

Fieldwork for this study was accomplished from spring 1981 through fall 1984. Additional fieldwork included a preliminary reconnaissance of the lower Skykomish River valley by R. B. Waitt, Jr., in 1978. S. A. Sandberg, F. C. Moser, and Fred Beall were able field assistants during the summer of 1981.

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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 Cascade Range 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 margin abutting the front of the Cascade Range and reconstructed some of the local details of ice recession and drainage derangement. Maps emphasizing various aspects of the surficial geology in parts of the study area include the following: Newcomb (1952) on groundwater resources, Liesch and others (1963) and Livingston (1971) on the regional geology, Anderson (1965) and Knoll (1967) 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 (fig. 3). Thorson (1980, 1981) expanded the early work of Bretz (1910, 1913) to delineate a 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

Bedrock in the area of this report consists of Paleozoic and Mesozoic marine metasedimentary and metaigneous rocks overlain by lower and middle Tertiary volcanic and sedimentary rocks and intruded by middle Tertiary batholiths. The pre-Tertiary metamorphic rocks underlie much of the terrain west of the Cascade rangefront both north and locally south of the Skykomish River. Because of lithologic variation and intense deformation, Tabor and others (1982) interpreted the pre-Tertiary rocks as melange. By early

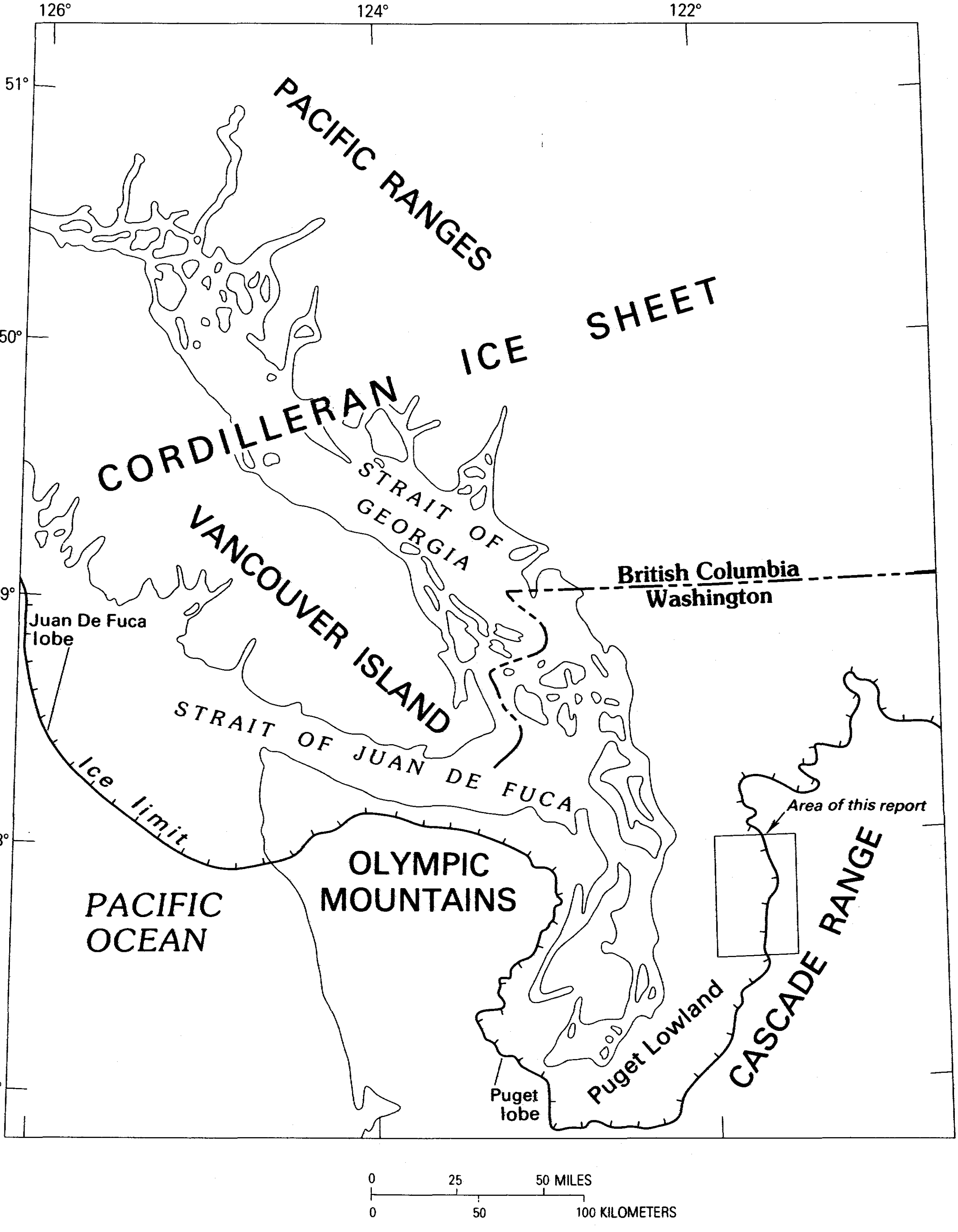

Figure 1. Maximum extent of the Cordilleran ice sheet during the last glaciation (15,000 yr B.P.). The map area straddles a portion of the former ice limit and includes parts of both the Puge Lowland and the Cascade Range.

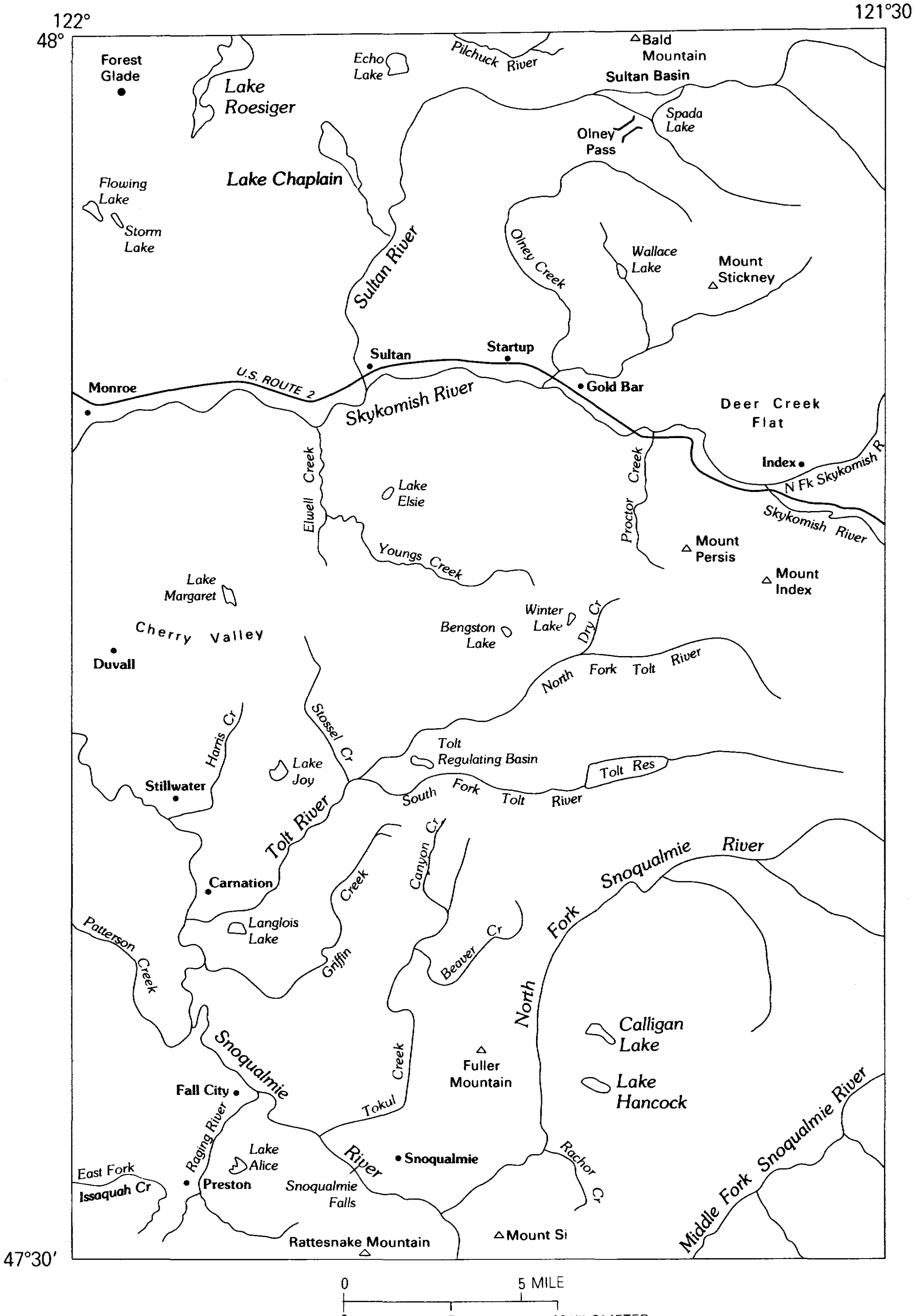

Figure 2. Index map of geographic localities used in the text.

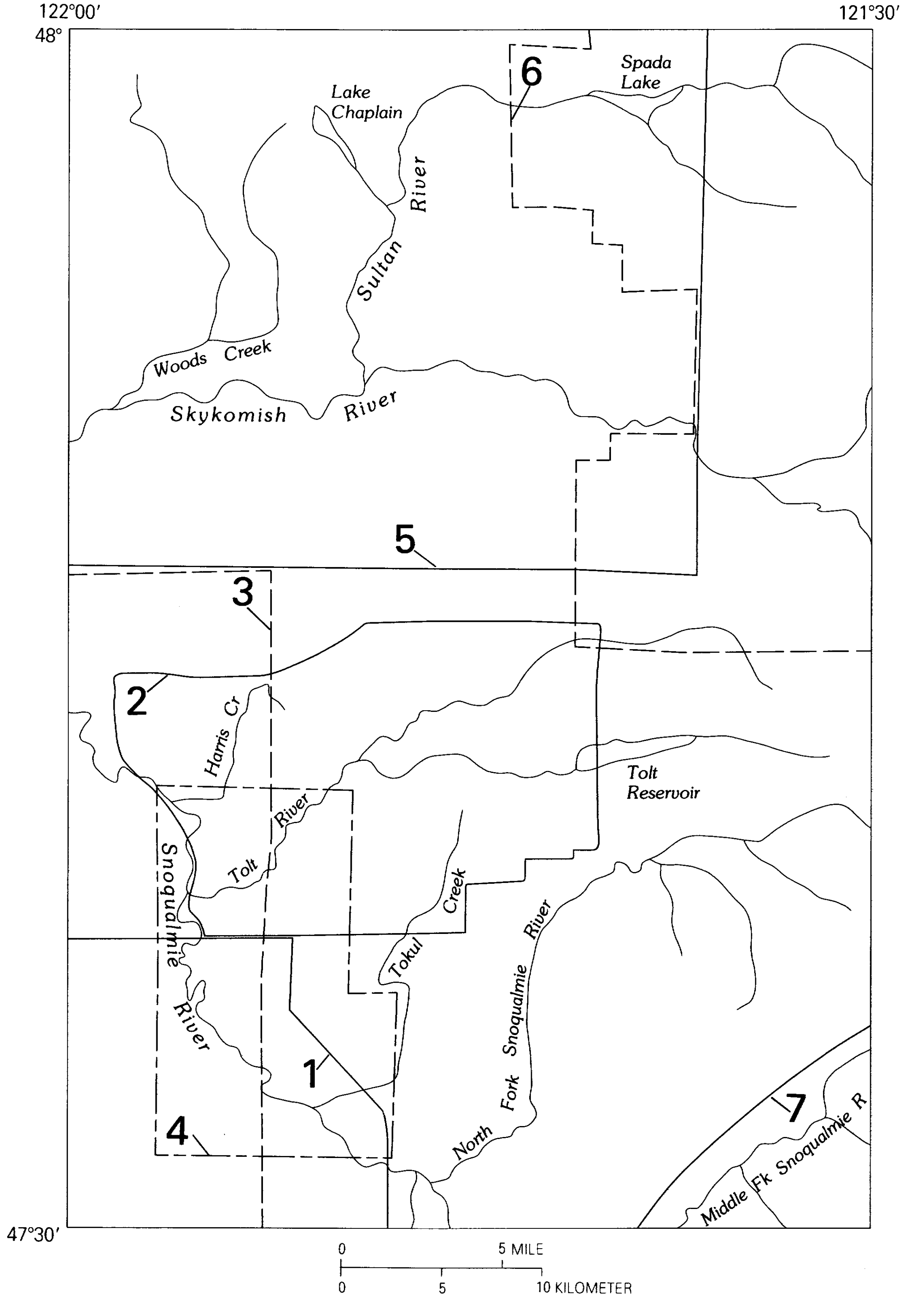

Figure 3. Index to source maps consulted during map preparation: (1) Anderson (1965), (2) Knoll (1967), (3) Liesch and others (1963), (4) L. R. Lepp and Jeff Walker (written commun., 1982), (5) Newcomb (1952), (6) Snyder and Wade (1972), (7) Williams (1971).

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 Range. Smaller intrusions crop out as isolated bodies scattered as far as 6 km (4 mi) west of the roughly north-trending contact between the main batholiths and the country rock.

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

BEDROCK

Melange

The pre-Tertiary melange consists of a pervasively sheared matrix of mostly argillite containing outcrop- to mountain-sized phacoids of sandstone, greenstone, amphibolite, metagabbro, metaandesite, chert, marble, and metatonalite. Toward the east the melange grades into phyllite, with well-developed foliation commonly parallel to bedding. Landforms that developed on the phyllite in the Wallace Lake-Mt. Stickney area are strongly asymmetrical and oriented parallel to this foliation. Variations in erosional resistance between components of the melange has produced numerous other structurally controlled landforms. A particularly good example is the enormous etched-out block of metagabbro constituting 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 River and the Middle Fork of the Snoqualmie River. Southwest of the Snoqualmie River more abundant sandstone, siltstone, and conglomerate crop out along with less common volcanic flows and breccias. The volcanic rocks in the northern part of the map area 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 sections discontinuously exposed in the western part of the map area. The sedimentary and volcanic rocks in the south correlate with the Puget Group and are about the same age as the Mount Persis unit. The volcanic rocks are generally more resistant to erosion; individval flow units form prominent ridges and bluffs, such as those in the Lake Elsie and Elwell Creek area 5 km (3 mi) 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 granitic bodies crop out at the head of Youngs Creek and control the pronounced relief 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 early Tertiary age.

Sedimentary Rocks

Lithologies in this unit vary from moderately to deeply weathered sandy pebble conglomerate to very fine grained sandstone. The conglomeratic beds contain a high percentage of quartzose pebbles; the finer grained beds contain considerable mica and lignite. Deeply weathered exposures typically can be distinguished from old glacial outwash by manganese-stained joint planes, nearly monolithologic conglomerate clasts, and the presence of organic matter. However, isolated exposures can be ambiguous and have occasionally been misidentified as lake deposits of the last glaciation (Newcomb, 1952). More extensive exposures west of the map area are considered by Minard (1985b) 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) (his Riverside unit) and Whetten and others (in press) (the Bulson Creek unit of Lovseth (1975)), which are assigned late Eocene to Oligocene ages based on fossil content.

PLEISTOCENE DEPOSITS

REGIONAL SETTING

The Puget Lowland extends as a structural and topographic basin between the Olympic Mountains on the west and the Cascade Range on the east (fig. 1). Less pronounced uplands define its southern boundary, and to the north it extends into southern British Columbia to merge with the Fraser Lowland and the Strait of Georgia. The basin has persisted for millions of years as 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 forming the basin (Stuart, 1961; Danes and others, 1965; Gower, 1978; Thorson, 1981).

Glacier ice originating in the mountains of British Columbia has invaded the Puget Lowland at least several times, leaving a discontinuous record of early(?) to late Pleistocene glacial periods (Crandell and others, 1958; Armstrong and others, 1965; Easterbrook and others, 1967). This ice was part of the Cordilleran ice sheet of northwestern North America that advanced into the lowland, referred to as the "Puget lobe" by many authors since Bretz (1913) (fig. 4). The extent of this lobe was limited by the net flux of ice from British Columbia, ablation in the lowland, and the mountainous topography surrounding the lowland itself (Booth, 1986b).

These mountains were local sources of glaciers as well. Sufficient periodic cooling coupled with the relative proximity of marine moisture (Porter, 1977)

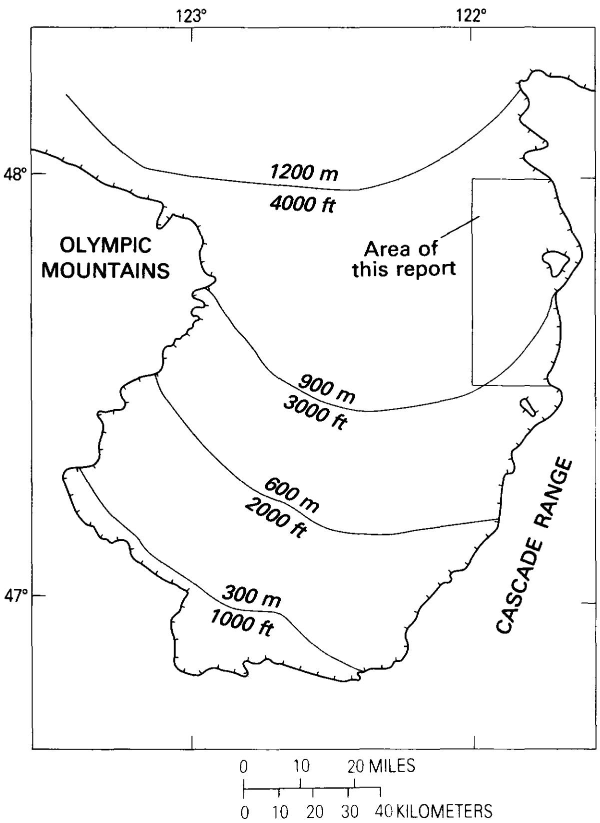

Figure 4. Reconstruction of the Puget lobe at its maximum extent during the last glaciation (data from Thorson (1980) and Booth (1984c)). Hachured lines indicate the ice limit; contour values give the ice-surface altitude above sea level, uncorrected for sea-level lowering or isostatic depression. Glaciated region within the area of this report is outlined.

generated multiple advances of Olympic and Cascade alpine glaciers (Crandell and Miller, 1974; Porter, 1976), whose comparatively feeble modern remnants still cling to the slopes of the highest peaks and ridges. During the last glaciation, the Puget-lobe maximum post-dated the alpine maximum by several thousand years. Speculation on the cause of this apparent 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 (Crandell, 1965). Porter and others (1983, p.84) have alternatively proposed that the Puget-lobe and a later alpine-ice advance were approximately simultaneous but of differing relative extents.

In the map area, postglacial modification has been dominated by the reestablishment of the major drainages from their alpine headwaters into Puget Sound across the deranged glaciated lowlands. Multiple advances of thick ice lobes initially rerouted these rivers from their preglacial lowland paths into more eastern, south-trending valleys. Many such diversions became permanent after deglaciation, as suggested in the map area by the probable southward diversion of the North Fork of the Snoqualmie River, or farther 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 has reestablished valley-wide floodplains graded with respect to modern river and sea-level altitudes.

SEDIMENTARY PROVENANCES

Sediment transported by the Cordilleran ice sheet is of diverse lithology, because debris was derived from more northerly alpine valleys of the Cascade Range and from the mountains of southwestern British Columbia. Exotic sedimentary material commonly ranges from 5 to 15 percent. Southwest and northwest of the map area, Crandell (1963, p. 14) and Dethier and others (1981) reported similar percentages of foreign sedimentary material, particularly clasts of high-grade metamorphic rocks, incorporated into Puget-lobe till. The remaining clasts are predominantly from local upglacier bedrock. Because tonalite and granodiorite are commonly in most of the alpine valleys in this area but not in the lowland, the percentage of clasts of these lithologies is usually sufficient to distinguish the source of any till deposited within a valley. For example, nearly adjacent exposures of inferred ice-sheet and alpine till along the northeastern shore of Calligan Lake contain 15 percent and 80 percent granitic clasts, respectively.

REGIONAL STRATIGRAPHY

Previous workers in the Puget Lowland developed a Pleistocene stratigraphy for both alpine and Cordilleran glaciations and interglaciations (table 1). The youngest (Fraser) glaciation (Armstrong and others, 1965) includes the Evans Creek stade, during which alpine glaciers in the Cascade Range reached their maximum extent, and the subsequent Vashon stade, inferred from the Puget-lobe advance. The limiting dates on the Vashon advance to near Seattle, at the latitude of this map area, include a maximum date of 15,100±300 years B.P. (Mullineaux and others, 1965, ^{14}C sample W–1305) and a minimum date of 13,650±550 years B.P. (Rigg and Gould, 1957, ^{14}C sample L–346). The ages of earlier glaciations are much more poorly constrained and have been recently reinterpreted (Stuiver and others, 1978; Easterbrook and others, 1981). Because current terminology is unsettled, I do not attempt in this report to correlate pre-Vashon ice-sheet deposits with established stratigraphic nomenclature. Such usage in prior local studies has complicated attempts at correlation across the Puget Lowland based on physical parameters, such as weathering characteristics and relative geographic extent, and may require extensive renaming as absolute ages become available.

NON-GLACIAL AND GLACIAL DEPOSITS

Non-glacial and glacial sedimentary deposits of pre-Fraser glaciation age

Throughout this map area, only scattered exposures of pre-Fraser glaciation deposits exist. Commonly, younger drift is found directly overlying bedrock with little evidence of removal or redeposition of pre-Fraser

Table 1 — Summary of named Pleistocene glacial intervals in the Puget Lowland

Cordilleran glacial advances				Alpine glacial advances	
Tacoma quadrangle and adjacent districts	Southeastern part	Fraser and Puget Lowland areas	Central part (Seattle area)	Southeastern part (Mt. Rainier area)	
Modified from Willis (1898)	Modified from Crandell and others (1958)	Modified from Armstrong and others (1965)	Modified from Mullineaux and others (1965)	From Crandell and Miller (1974)	
Vashon glaciation	Vashon glaciation	Fraser glaciation: Sumas stade Everson interstade Vashon stade	Deposits of the Vashon stade: **Vashon Drift, including:** Esperance Sand Member Lawton Clay Member		
		Evans Creek stade		Evans Creek glacial advance	
Puyallup interglaciation	Interglaciation (unnamed)	Olympia interglaciation			Pleistocene — QUATERNARY
	Salmon Springs glaciation			Hayden Creek glacial advance	
	Puyallup interglaciation				
	Stuck glaciation				
	Alderton interglaciation				
Admiralty glacial epoch	Orting glaciation			Wingate Hill glacial advance	

sedimentary deposits by the younger ice sheet. This contrasts to the greater prevalence of older glacial deposits preserved in other glaciated terrains that were also occupied by late-Wisconsin ice sheets (more central areas of the Puget Lowland and the Great Plains of the mid-continent). The scarcity of pre-Fraser sedimentary deposits in this area therefore suggests that most have been eroded away in the interglacial interval(s) prior to the most recent ice-sheet advance. This conclusion was also reached by Coates and Kirkland (1974) in the Appalachian Plateau, where late Wisconsin deposits of the Laurentide ice sheet also directly overlie bedrock.

Description and Weathering Characteristics

Older deposits are distinguished by greater weathering than Vashon-age deposits. In outcrop they are generally oxidized throughout the full thickness of the exposure (greater than 1–10 m (3–33 ft)) 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 an 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. Most granitic clasts are completely grussified, although some are only slightly decomposed.

In more intensely weathered exposures, clasts are generally flush with the surface of exposures and can be easily cut with a shovel. This degree of weathering commonly makes lithologic identification of such clasts uncertain. These deposits are mostly clay and so are quite unstable on steep slopes.

Matrix-supported diamicton and bedded clast-supported fluvial gravel and sand occur within these pre-Fraser deposits. Clast lithologies, where identifiable, generally imply deposition by Puget-lobe ice of pre-Vashon age. Despite likely variations between local weathering environments, the wide range of weathering intensity observed in these deposits suggests that sediment accumulated during at least two pre-Fraser glacial and interglacial periods.

Distribution

Older drift is found above the highest inferred altitude of the former Vashon ice sheet or beneath Vashon-age deposits where stream incision has exposed the older material. Above the Vashon ice limit, older drift of northern provenance is discontinuously exposed, nowhere more than 50 m (160 ft) above the inferred limit of the younger ice sheet. Older alpine drift occurs both below and well above this level.

Below the Vashon ice limit, the most extensive exposures of pre-Fraser sedimentary deposits are found along the South Fork and main branch of the Tolt River, where incised meanders and landslide scars expose over 100 m (330 ft) of older drift beneath Vashon-age deposits. Although these exposures are mainly of weathered ice-sheet till, locally derived sand, gravel, and minor silt are exposed 1.04 km (0.65 mi) downstream from the Tolt regulating basin, overlying a weathered diamicton and directly below Vashon till. Clast lithologies in this fluvial deposit are consistent with a local, upvalley source area. Wood in the lower part of this fluvial section is 25,600 ± 320 years old (^{14}C sample USGS 1625).

Transitional Beds

Along the lower reaches of the Skykomish and Snoqualmie Rivers, lacustrine sedimentary material is exposed below Vashon till. In this area and generally to the west (Minard, 1985a, b), most of these deposits lie below 60 m (200 ft) altitude. The sedimentary deposits are firm gray silty clay and clay with little or no oxidation coloration. They are horizontally laminated except where loading has produced dipping or contorted bedding. The deposits are impermeable and quite unstable, which gives 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 Admirality 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 lake-bottom deposits laid down in standing water ponded by the advancing Vashon-age ice sheet.

Following Minard (1985a, b), 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 sand and gravel of the advance outwash deposits or by lodgment till.

GLACIAL DEPOSITS

Deposits of Vashon stade of Fraser glaciation of Armstrong and others (1965)

Most Pleistocene deposits exposed in the map area were directly or indirectly derived from the Puget lobe of the Cordilleran ice sheet about 15,000–14,000 years ago. The lower sedimentary deposits are lacustrine and fluvial, deposited beyond the edge of the advancing ice. Much of these early deposits was removed by the ice or covered by till, which was subsequently incised and partially covered by meltwater and recessional outwash deposits.

Advance Outwash Deposits

Description

Sand, gravel, and minor clayey silt, probably deposited by proglacial meltwater from the advancing ice sheet, are exposed discontinuously beneath Vashon till. The sand is commonly crossbedded and tends to grade upward into more gravelly layers. In most exposures these deposits are almost completely unoxidized and compact where undisturbed. 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 lodgment till. The contact between outwash and till is locally transitional through as much as a meter but typically abrupt over less than a few centimeters.

The advance outwash greatly varies in thickness and is completely exposed in only a few areas. The maximum observed thickness occurs west of Carnation, on the west side of the Snoqualmie River, where more than 100 m (330 ft) of sand and gravel with deltaic forset beds are exposed between capping lodgment till and river level. A nearby diapir of pebbly silty clay, apparently material of the transitional beds 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 exposed only as a discontinuous contorted stratum between Vashon till and the transitional beds less than a meter in thickness. Sand and silt of the advance outwash are exposed just above the mouth of Tokul Creek, capped by loose oxidized sand of the recessional outwash. I also included in this unit nearby exposures of silt just downstream of Snoqualmie Falls, which may instead be lacustrine deposits of the recessional outwash.

Engineering Properties

Where exposed or otherwise inferred to underlie younger deposits, the advance outwash deposits are a promising source of relatively shallow ground water. Newcomb (1952) reported recharge, permeability, and water quality as quite good. However, this potential aquifer is commonly isolated from surface contamination by only a thin blanket of till, which can be breached by wells or construction projects. The advance outwash deposits stand on moderate slopes with only minor raveling. They are a good source of clean sand, although their high degree of consolidation and limited extent have apparently discouraged major exploitation in this area.

Till

Description

Vashon till is mainly a compact unoxidized diamicton composed of a silty sand matrix and approximately 20 percent subrounded to well-rounded clasts. The deposit ranges from a thin layer of less than 1 m (3 ft) to several tens of meters in thickness. In some exposures the till appears to have two distinct facies: the lower is tough and unoxidized with a fine-grained matrix, whereas 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 likely melt-out or ablation till consisting of 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 area of the mapped till.

Lithology

Clasts in Vashon till are dominated by the bedrock lithology present immediately upglacier from them. Observations in many exposures suggest that the majority of clasts in the lodgment till were transported only a few kilometers. Yet a few exotic clasts that distinguish ice-sheet deposits from their alpine counterparts are generally present. Clasts in till 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 Puget-lobe ice that moved up each of these drainages.

Weathering

In most exposures, Vashon till is only very slightly weathered. Weathering rinds on fine-grained volcanic clasts are much less than a millimeter thick. Oxidation effects, if present at all, extend less than a meter into the deposit, and significant clay translocation is not present. Only a few granitic clasts are highly decomposed, which can vary even within a single outcrop. Detailed studies of the weathering of Vashon till by Carson (1970), Colman and Pierce (1981), and Lea (1984) show mean weathering-rind thicknesses on volcanic clasts from the southern Puget Lowland of 0.5 mm or less, typical oxidation depths of 0.5 m, and no significant alteration of matrix.

Distribution and Topographic Expression

Vashon till mantles most of the rolling uplands above the Skykomish and Snoqualmie River valleys. Later recessional deposits are largely confined to channels through this topography and so do not obscure it. Scattered exposures of pre-Vashon deposits and bedrock, however, indicate that Vashon till largely blanketed a preexisting topography that was not greatly altered by the passage of the ice. The till is significantly thinner on the upglacier side of hills having at least a few tens of meters of relief than on the downglacier side, 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. A similar pattern of till deposition to the south and to the west of the map area was shown by Mullineaux (1970, p. 44–45) and by an analysis (Nancy Brown, written commun., 1983) of well data recorded in Liesch and others (1963).

The till surface is marked by numerous linear depressions and elongate ridges that 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, approximately 10 m (30 ft) wide, and traverse the countryside for as far as several kilometers. They are generally 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, bedrock, or a till mantle over bedrock.

Toward the margin of the former ice sheet, patchy till exposures give way to a scattering of rounded pebbles that thins upslope, commonly through a rise in altitude of about 30 m (100 ft). Benches, changes in slope, and uncommon moraines also define the most probable limit of the Vashon ice sheet.

Intratill Stratified Sedimentary Deposits

In some exposures, Vashon till includes tough, compact, crudely to well-bedded clast-supported deposits with widely varying proportions of silty matrix. Such deposits typically lie close to or interstratified with more characteristic lodgment till and are 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, representing 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 "lodgment till complex." Examples 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 upland channels east of Lake Joy.

Engineering Properties

Vashon till is the "hardpan" of local experience and terminology. It drains poorly, has a low permeability (10^{-6} cm/sec (Olmstead, 1969)), is relatively stable on moderate slopes where not immediately underlain by less competent deposits, and has good bearing strength for roads and foundations if undisturbed. Because it is generally thin, however, the ground stability in the proximity of long steep slopes merely capped by the till will be more dependent upon the underlying geologic material (Tubbs, 1974). Management of the runoff from the nearly impervious till surface there may be important in maintaining that stability

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 material and meltwater to the ice margin. The morphology of the sedimentary material deposited in this environment depends largely upon the topography and drainage system adjacent to the ice margin (Flint, 1971). Where an ice tongue extends up a river valley or blocks its mouth, sediment will aggrade into that valley. The ensuing deposits will range from waterlain ice-contact sedimentary material to fluvial or lacustrine deposits far from the ice margin that are indistinguishable from those derived from non-ice-contact sources. Despite their different morphologies, these deposits are 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 during deglaciation. Additional smaller deposits are present where active ice lobes were stable long enough for debris to accumulate. The best example is in the Bengston Lake area north of the Tolt River, where two nested moraines that loop across the upland plain mark the location of a near-maximum recessional stand.

Great embankments of ice-contact deposits fill the mouths of west-draining alpine valleys along the former margin of the Vashon ice sheet. Clast lithologies and rare foreset beds indicate that these materials originated outside the local drainage basins and were deposited by ice and water flowing upvalley (Macklin, 1941; Booth, 1986a). 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 partly 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 exposed material is exclusively well sorted fluvial sand and gravel (see the section "Vashon-age Recessional History"). The surface altitudes of the embankments vary unsystematically between 760 and 510 m (2,500 to 1,700 ft) with local drift limits 30 to 640 m (100 to 2,100 ft) higher.

Sedimentary and Morphological Characteristics

The ice-contact deposits show wide variation in sedimentary materials and morphology. They include predominantly well sorted gravel and sand, commonly with local foreset bedding. Lenses and thick layers of diamicton, probably flowtill and lodgment till, are also found in many exposures, particularly in the valley-filling embankments. Lenses of diamicton are exposed in the valley walls of the Hancock and Calligan Lake outlets. Thicker layers of pebble-silt diamicton are exposed 2.5 km (1.5 mi) west-southwest of Index, south of U.S. Route 2, and are the primary sedimentary deposits encountered in test borings through the embankment just west of Spada Lake (Converse Ward Davis Dixon, 1979) and just 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 to at least 560 m (1840 ft) altitude. Excavations through the middle of this embankment reveal a layer 1 to 2 m (3 to 6 ft) thick 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 lodgment till exposed throughout the area with a slightly 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 studies of glacial sedimentation into lacustrine environments (Eyles and Eyles, 1983) suggest that subglacial meltout is the source of this deposit (Booth, 1986a). Water-transported sedimentary material is also common in these embankments, typically forming a planar deposit at the top of these features.

Engineering Properties

The ice-contact sedimentary materials were deposited by multiple processes; therefore, their engineering properties can vary considerably over short distances. Moderately well sorted fluvial gravel and sand may be expected where deposited far from former ice margins and show many of the engineering properties of the recessional outwash. Deposits near the ice-contact surface, however, commonly show abrupt and unpredictable grain-size variations. Boulders larger than a meter in diameter are common. Lenses and thicker layers of till may also be encountered. The two major reservoirs in the area demonstrate the relative impermeability of the embankments behind which they are impounded, but detailed subsurface exploration of each has demonstrated the internal variations as well (Shannon and Wilson, 1959; Converse Ward Davis Dixon, 1979).

Recessional Outwash Deposits

Description

Much of the terrain is mantled by sedimentary deposits typically comprising an interbedded mixture of sand and subrounded to well-rounded gravel with clasts as much as 30 cm (12 in.) in diameter. The deposits range in thickness from less than 1 m (3 ft) to more than 100 m (330 ft) in large deltas, such as those along the east side of the Snoqualmie River valley. A light-orange oxidation color on otherwise fresh clasts is present through the full depth of exposure. Except where locally cemented by iron oxide, the sedimentary deposits are easily excavated with a shovel. Clast lithologies are characteristic of the Vashon Drift as a whole; although they consist mainly of local types, they generally have an exotic component as well. Fining upward of the sedimentary material, which would plausibly reflect retreat of the ice margin, is uncommon. Neither crossbedding nor very fine sand and silt are as common in these recessional deposits, probably deposited by proglacial streams, as they are in equivalent fluvial deposits of the advance outwash.

Maximum and mean grain sizes vary considerably between exposures. Although the largest clasts typically reach 30 cm (12 in.), extremely large boulders (2–3 m (7–10 ft) 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 material deposited during ice recession is generally composed of massive to thinly laminated silt to very fine sand. Rare dropstones are present in many exposures. In the North Fork of the Snoqualmie River valley, lacustrine sedimentary material is distinctly coarser than in the other alpine valleys. Medium sand is common here and silt is uncommon, which suggests that the depositional environment was a rapidly aggrading valley in which deposition kept pace with rising base level. These conditions probably reflect the relatively large area, high altitudes, and steep tributary-valley gradients characteristic of the North Fork Snoqualmie drainage basin and unique to this map area.

Distribution

The greatest volumes of recessional outwash sand and gravel are in deltas built into a recessional lake formed in the Snoqualmie River valley. Such 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 gravel and sand deposits to a corresponding series of deltas built into the Snoqualmie River 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 (see the section "Vashon-age Recessional History").

Marginal Lacustrine Deposits

The Vashon-age ice sheet impounded lakes in many of the alpine valleys. The maximum altitude of the resulting lake deposits, commonly well correlated with the altitude of the corresponding valley-mouth embankment, and the paucity of ice-rafted pebbles suggest that some of these embankments dammed their valleys well into the postglacial period. Exposures of Vashon till beneath the marginal lacustrine deposits in the Sultan Basin and in the South Fork of the Skykomish River valley confirm that parts of these marginal 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 (Booth, 1986 a).

Engineering Properties

The recessional outwash deposits provide most of the sand and gravel used for construction, which according to Livington (1971) has proven the most valuable mineral resource of western Washington. In the Snoqualmie and Skykomish River valleys, most of the large deltas and many small ones are actively mined. Grain sizes commonly range from medium sand to 20-cm- (8-in.-) diameter cobbles. Fine-grained materials are rare in the main body of the deltas. Upstream channel deposits, however, can be much more variable in grain size. Many of these channel deposits are merely thin covers over subglacially deposited material, which renders commercial evaluation difficult.

With these granular deposits, permeability is high, stability is good, and settlement should be negligible. Areas underlain by thick accumulations of the recessional outwash should be well drained, but because the deposit is typically underlain by lodgment till or impermeable bedrock, perched ground water is possible. Shallow wells in the recessional outwash deposits are prone to seasonal fluctuations and contamination. Nevertheless, they are an important ground water source throughout the area (Newcomb, 1952).

In contrast, recessional lacustrine deposits are both weak and impermeable. Poor surface drainage, low slope stability, and low bearing strength make such areas particularly ill suited for most types of development.

Alpine Drifts and Related Deposits

Older alpine drift, undivided

Deposits above the limit of the former Vashon ice sheet on the interfluves between west-draining alpine valleys, particularly south of the North Fork of the Tolt River, were left by Cascade glaciers. They form low-relief surfaces above roughly 1,000 m (3,300 ft) altitude. Weathering rinds on fine grained clasts are 1–8 mm thick, and granitic clasts are decomposed to grus. Oxidation effects vary but they are always more intense than in either ice-sheet or alpine deposits of the last glaciation. Clast lithologies typically specify an alpine source, with granitics common even in those deposits found far west of any granitic bedrock exposures. Similar deposits are also well exposed 16 km (10 mi) east of the map area along roads above the Foss River (P. Thompson Davis, unpublished data).

Alpine drift of Mt Stickney

West of Mt. Stickney, till and stratified drift mantle the bedrock ridges, forming a broad gently sloping surface with a pronounced morainal crest. The lithology of the drift, 80 to 90 percent granitic clasts, indicates transport by alpine ice from granitic source areas east of Mt. Stickney. This drift is largely above the former limit of Puget-lobe ice, although locally above Wallace Lake some of this material has been reworked by the Vashon-age ice sheet. Modern U-shaped alpine valley floors, cut hundreds of meters into the upland surface, were occupied by younger valley glaciers. Thus the glacier responsible for this deposit must have formed as a widespread icecap, covering all but the highest peaks and ridges. Evidence for the extent of this ice north and west of the Cascade rangefront has been completely obscured by younger deposits. Enigmatically, no other plausibly correlative deposits have been found in the map area.

Weathering rinds on fine-grained volcanic clasts at the depositional surface of the deposit measure 1–3 mm thick, and granitic clasts show a wide range of decomposition with slightly grusified stones dominant. Sedimentary material exposed and reworked by the

Vashon-age ice sheet is generally less weathered, which indicates its long isolation from weathering while it lay deep beneath the original depositional surface.

Alpine till

Deposits mapped as alpine till are loose to compact diamictons having angular to subrounded clasts less than 30 cm (12 in.) diameter supported by a silt- or sand-rich matrix. Clasts are generally fresh and unoxidized. Counts of clast lithologies indicate upvalley sources. This unit includes only those few deposits sufficiently continuous and well exposed to map.

Alpine glacial deposits, undivided

Dense vegetation cover, sporadic exposures, and poor access up most of the alpine valleys render the identification, subdivision, and delineation of alpine glacial deposits difficult. The distribution of such deposits is inferred mainly from aerial photographs and sporadic field exposures. As mapped, they also include significant amounts of colluvium, alluvial fans, recent valley-bottom alluvium, and bedrock. Contacts between this unit and bedrock upslope may be gradational and are only approximately located. The weathering characteristics and topographic position of such deposits are similar to those mapped more specifically as the alpine till.

Glacial and talus deposits

Some sliderock observed on aerial photographs show ridged lobate lower boundaries, suggesting either deposition at the base of small glaciers or permanent snowfields, or the presence of active rock glaciers. All are apparently unvegetated and are typically found only on north-facing slopes in areas above 1,200 m (4,000 ft) altitude. Their distinct morphology and absence of extensive 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 ice sheet advances, such evidence is sparse in the map area. Moderately weathered ice-sheet drift (unit *Qpf*), however, is sporadically exposed up to 50 m (160 ft) altitude above the maximum Vashon-age ice limit in this area. These deposits imply a slightly more voluminous pre-Vashon ice sheet advance, which correlates well with the pre-Vashon advance reported by Carson (1970) and Lea (1984) in the southern Puget Lowland, where an older drift terminus lies 10 km (6 mi) beyond the Vashon terminus. From the reconstructed Vashon ice-surface slope in this map area (fig. 4), a corresponding surface-altitude increase of 50–60 m (160–200 ft) for the older ice sheet is expected. The weathering characteristics of this older, more extensive ice-sheet drift in the map area are also consistent with deposits studied in detail by Colman and Pierce (1981) and Lea (1984) farther south. Carson (1970) correlated this maximum-extent ice sheet advance with the Salmon Springs glaciation of Crandell and others (1958). This correlation, however, is implausible given observed weathering thicknesses and the age of the type Salmon Springs Drift (greater than 600,000 yr B.P.; Easterbrook and others, 1981). Colman and Pierce (1981) favored a 140,000 yr B.P. age for this drift, consistent with its weathering characteristics relative to the Vashon Drift. This suggests a possible correlation with the Bull Lake Drift in the Rocky Mountains region (Pierce, 1979) and the interval of 195,000–130,000 yr B.P. covered by oxygen-isotope stage 6 (Shakelton and Opdyke, 1973).

Alpine Glacial Advances

The current stratigraphic framework for alpine glacial deposits on the western slopes of the Cascade Range is given by Crandell and Miller (1974) (table 1). Although speculative, correlation between deposits found near Mount Rainer and those in this map area 110 km (70 mi) farther north are suggested by certain topographic and weathering characteristics. The undivided older alpine drift (unit *Qaod*) is clearly of a pre-Evans Creek age, given its degree of weathering and absence of constructional morphology. More specifically, this unit includes deposits that share weathering and morphologic characteristics described by Crandell and Miller (1974, p. 19) for the Wingate Hill Drift. Weathering rinds on clasts in the alpine drift of Mt. Stickney (unit *Qams*) also indicate a pre-Evans Creek age (Colman and Pierce, 1981). However, its weathering is less intense and its constructional morphology is more pronounced than in most of the deposits mapped here as undivided older alpine drift. These characteristics invite comparison with the Hayden Creek Drift (Crandell and Miller, 1974, p. 21–22).

The remainder of alpine drift found in this area (units *Qaag* and *Qaat*) comprise less weathered deposits. One deposit in particular, damming a bog 2 km (1 mi) south of Lake Hancock and showing a distinct morainal form, permits estimation of the equilibrium-line altitude (ELA) of the glacier that formed it. The areal extent of this glacier can be reconstructed by making reasonable assumptions about its surface gradient and source area. Applying the methods of ELA estimation described in Porter (1975) and Pierce (1979) yields an ELA of slightly above 1,000 m (3,300 ft) and a median glacier altitude about 60 m (200 ft) higher. This is within 100 m (300 ft) of 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.

No evidence for the merging of alpine and Puget-lobe glaciers was found in this area. The presence of marginal lacustrine deposits in the alpine valleys confirms only a retreat of alpine glaciers from their Fraser-age maximum prior to the final retreat of the Vashon-age ice sheet (Porter, 1976) 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 fieldwork for this report in that area disclosed only abundant Holocene alluvial-fan deposits along the steep valley walls. Just north of the map area, however, exposures in the South Fork of the Stilliguamish River valley show ice-sheet till (unit *Qvt*) overlying unweathered alpine till (unit *Qaat*) but separated by a 1-m (3 ft) layer of fluvially deposited sand and gravel (unit *Qva*) (Booth, 1988). This sequence indicates that alpine and Puget-lobe glaciers never merged during the Fraser glaciation in this valley. Because the thickness of the ice sheet decreased to the south, a similar relationship probably existed in all valleys within this map area.

NON-GLACIAL DEPOSITS

Older Alluvium

A few deposits of fluvial gravel and sand that form terraces above the level of the modern floodplains cannot be readily assigned to a recessional interval during the last ice retreat because their surfaces project downstream to levels well below those produced during deglaciation. For example, a series of three such broad terraces are located along the Skykomish River near Gold Bar. In this valley the terraces are numbered on the map sheet from 1 through 3, indicating successively younger intervals of deposition.

Younger Alluvium

Recently transported sand and gravel are present along all of the major streams and rivers in the area. This sediment generally underlies a surface devoid of mature vegetation. Although the age of these surfaces is inferred from vegetation and morphology to be on the order of years or decades, this unit includes some deposits equivalent in age to the mapped older alluvium unit but lacking any observed topographic demarcation.

Bog Deposits

Poorly drained depressions are common throughout much of this area, particularly on surfaces underlain by lodgment till. Identification of bog deposits is based on 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 into the younger alluvium. In many such places, the form and gradient of the channel have been inherited from glacial activity, with the modern 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 enter 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. Although gradational with talus and 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

Subangular to very angular blocks of local bedrock mantle hillslopes below steep rock cliffs. They are most pronounced above 1,000 m (3,300 ft) altitude 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

Surface material on hillslopes moves downhill sporadically by various processes dependent on local failures in the soil or underlying rocks, expansion and contraction, or biological activity. I mapped mass-wastage deposits that are sufficiently thick and continuous to obscure both the underlying material and characteristic topographic features that might otherwise serve to identify it.

Landslide Deposits

I identified landslide deposits by characteristic hummocky topography, distinct scarps, or anomalous closed depressions that are not associated with collapsed ice-contact deposits. These landslide deposits 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. Nonhorizontal 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 where adjacent to actively downcutting streams. Instability is indicated not only by the surficial form and presence of discrete scarps and fissures, but also by the character of the vegetation, which for recent slides may include trees canted irregularly downslope.

Modified Land

Modified land mapped in this area includes two major dams, 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 alluvium of the Skykomish and Snoqualmie Rivers are shown only where their width is easily represented at this scale of mapping.

CHANNELWAYS

Numerous troughs and valleys incise the till and bedrock landscape, particularly in the uplands east of the Snoqualmie River valley. Although some were probably formed from the scouring action of ice or from erosion by subaerial recessional meltwater, other valleys discussed here as "channelways" instead reflect erosion by subglacial meltwater. In map view, channelways appear as narrow, sinuous to linear valleys occupied by lakes, bogs, or underfit streams. Valley bottoms have low gradients and commonly trivial drainage areas. Their sidewalls are steep, with relief of 10 to over 100 m (30–330 ft). They are isolated features in some areas but generally form either anastomosing or dendritic networks across the landscape. These characteristics suggest their similarity to tunnel valleys described in central and northern Europe (Ehlers, 1981) and central North America (Wright, 1973). Bog deposits, modern alluvium, till, and recessional outwash deposits are commonly exposed in the channelways. Only rarely, however, can they be differentiated at this map scale.

Although the channelways are similar topographically to "overflow channels" and "sluiceways" (Coates and Kirkland, 1974), features attributed primarily to subaerial fluvial erosion, several characteristics are particularly inconsistent with this process here (Mannerfelt, 1949; Peel, 1956; Sissions, 1958; Derbyshire, 1961; Young, 1980; Ehlers, 1981). They include: (1) "humped" or "up-and-down" longitudinal profiles; (2) abrupt channel termini without deltas or fans; (3) multiple intakes and outflows; (4) till, eskers, or other ice-contact sedimentary deposits sporadically exposed in the troughs; and (5) perched topographic position without significant drainage area.

Excavation by sliding ice may have played an active role but appears insufficient for the formation of most channelways. They commonly lie oblique to independent indicators of the ice-flow direction. Their sinuosity is not reflected by any changing orientation of the ice-flow pattern. Because they are characteristically deep, narrow, and steep-walled, they offer higher resistance to ice flow than the unincised topography around them (Weertman, 1979). Deepening of such channels by direct glacier erosion therefore appears unlikely. Finally, the bedrock knobs associated with areas of best developed channelways are commonly non-streamlined, a characteristic that intuitively precludes the dominance of active erosion by ice (Linton, 1963).

Despite the obvious unimportance of subaerial river erosion, many of the morphogological features of channelways are suggestive of a fluvial origin. Marginal and proglacial drainage is an appealing and oft-cited explanation for these and similar features (Mackin, 1941; Knoll, 1967). During ice recession some water could have been diverted subaerially through such valleys, but rates of ice retreat would allow only trivial occupation times by this means. Only catastrophic drainage from ice-dammed lakes might yield substantial subaerial discharges, but their paths can be predicted and prove to be quite restricted (Booth, 1984b, c).

Erosion by subglacial water, however, is a plausible mechanism compatible with the observed characteristics and distribution of the channelways. In particular, channelways are usually aligned subparallel to ice-surface gradients, which correspond to the expected average flow direction of subglacial water (Shreve, 1972). The map shows this relationship by a general parallelism between channelways and ice-flow indicators, which are used to infer the probable direction of the ice-surface gradient. Where channelways are used as directional indicators (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. Channelways and ice-flow directions most commonly diverge on the downglacier side of bedrock hills, where a low-pressure shadow should favor subglacial water flow oblique to the ice flow. A detailed reconstruction of the theoretical flow paths for subglacial water in the map area (Booth, 1984b, p. 91) demonstrates that the enigmatic "up-and-down" profile of the channelways with respect to the present topography merely reflects the hydraulically favored route for water flowing under any substantial thickness of sloping ice.

Channelways 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 a bizarre topography of isolated bedrock knobs separated by single or anastomosing steep-sided flat-floored valleys. Any sufficiently extensive ice-sheet advance would have covered this channelway system; therefore, they owe their present form to multiple glaciations and a far longer period of erosion than just the duration of the Vashon-age glaciation. They display a progressive development that reflects relative subglacial drainage areas, local bedrock resistance, and expansion to a point that active ice scour has taken a significant role in their continued shaping (the "through valley" stage of Coates and Kirkland (1974)).

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 (Bretz, 1913) character and sequence of these features. Thorson (1981), however, provides a far more complete framework of the deglaciation sequence in which to define more detailed, localized stratigraphy.

Postglacial topography divides the map area into three distinct areas: (1) the upland valleys and channels east of the Snoqualmie River, (2) the Skykomish River valley and its northern tributary valleys, and (3) the Snoqualmie River valley. Throughout most of the recessional period, meltwater activity followed a simple and consistent pattern. Water draining beneath the ice-sheet margin from the north was impounded in a lake occupying the upper Skykomish River valley. It spilled southward first through the broad trough southeast of Gold Bar and subsequently through the Elwell Creek valley southwest of Sultan. This water thus entered the upland channel system, combined with additional water derived from the gradually retreating ice margin in that area, and flowed south and southwest into the Snoqualmie River valley. The ice sheet blocked the

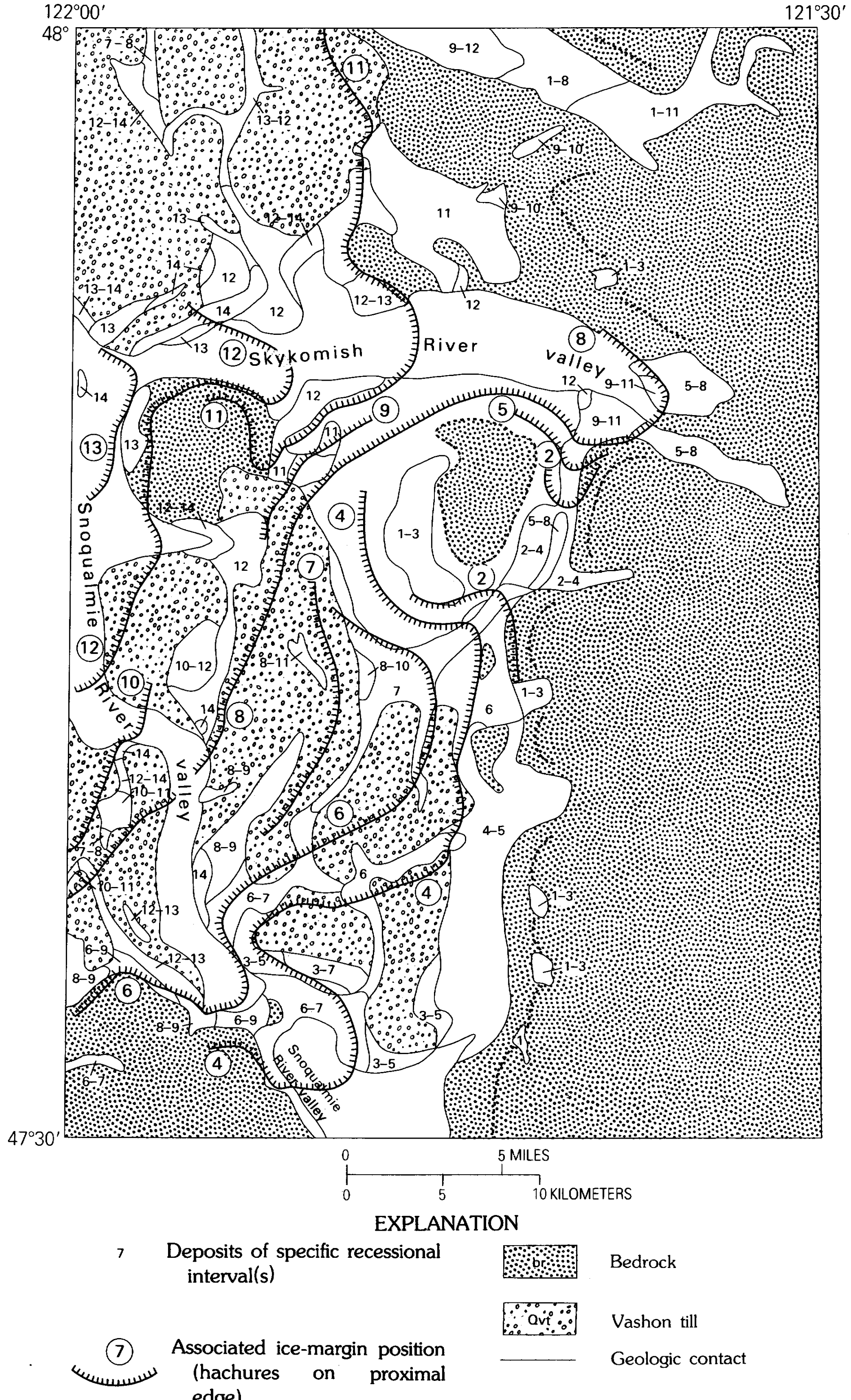

Figure 5. Distribution of the recessional outwash deposits of the Vashon stade of Armstrong and others (1965). Numerals refer to deposits and associated ice-margin positions of specific recessional intervals from 1 (oldest) to 14 (youngest).

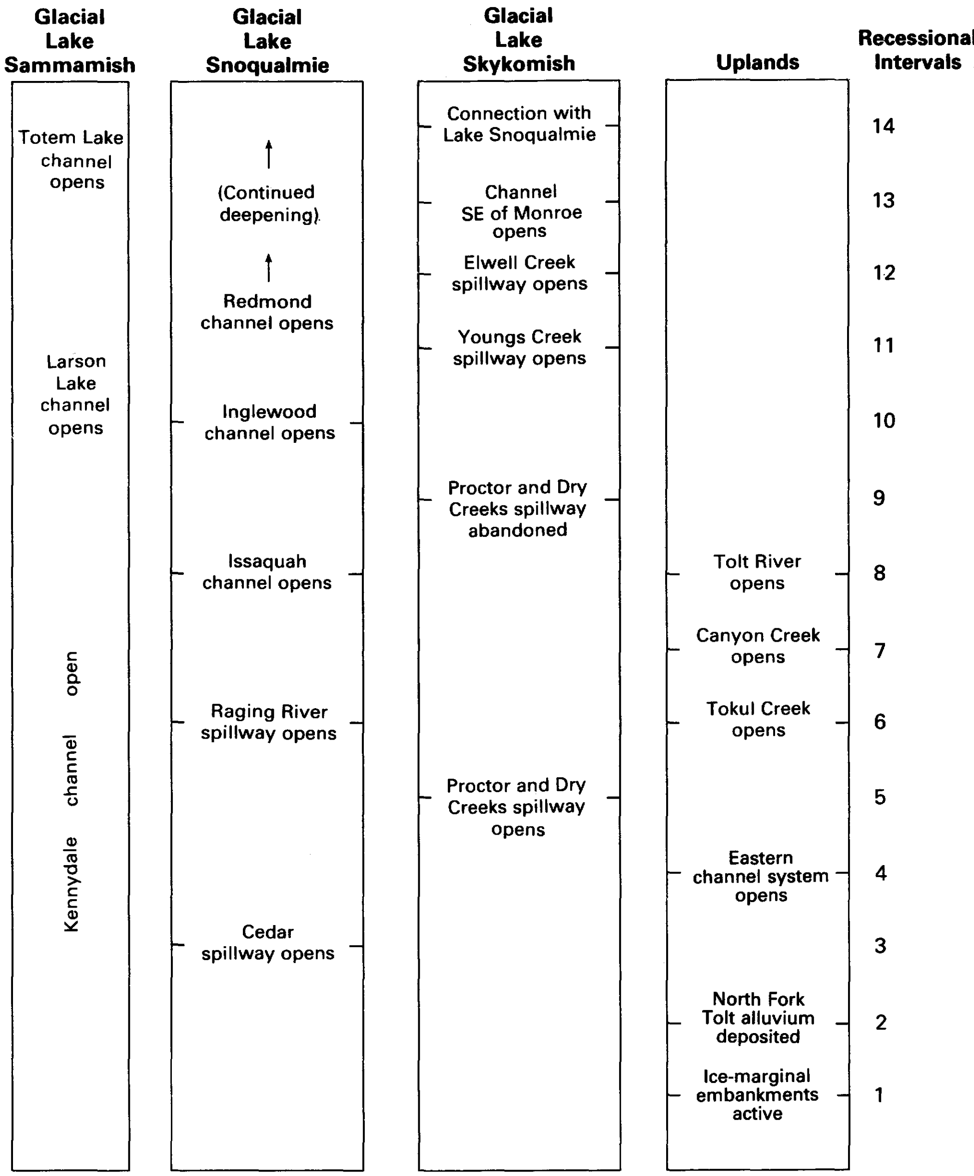

Figure 6. Correlation of recessional intervals and spillway activity in the east-central Puget Lowland during the Vashon stade of Armstrong and others (1965).

northerly drainage of this valley, creating a series of lakes that drained into lower bodies of water to the south and west beyond the limits of the map area. Spillways that controlled the level of such lakes in both the Snoqualmie River and Skykomish River valleys can be identified. Stream deposits, deltas, and lake bottom deposits associated with these lake levels provide the basis for the time-stratigraphic assignment and correlation of the mapped recessional deposits.

To elucidate these relations, time intervals within the recession are numbered sequentially and given in parentheses in the following discussion. 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 (figs. 5 and 6). 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 map area. Thus individual recessional deposits and active meltwater routes commonly include more than one time interval. In particular, recessional deposits in the Sultan Basin, near the northeast corner of the map area, can be only weakly associated with intervals defined to the south and west. In the following discussion, numerals in parentheses refer to the time-stratigraphic assignments (1 being the oldest) whose relation with particular events can be seen more concisely on the chart of recessional intervals (fig. 6). Where correlating spatially separated features, we can compensate for the systematic increase in present-day altitudes northward due to isostatic rebound following deglaciation by using Thorson's (1979, figs. 17 and 23) gradient of 0.9 m/km (5 ft/mi) along a 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 portions of the embankments blocking alpine valleys (intervals 1–3). Their upper surfaces lie at various altitudes below their local ice-maximum limits, which requires that they did not form simultaneously (Booth,1986a). Their formation, however, must have preceded the deglaciation of all channels farther west.

In a study focused just south of the map 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 at maximum stage that carried the water from each of the blocked drainages southward, dumping sediment into each valley in turn on its north side and draining off to the south. Yet neither coarse-grained fluvial deposits nor deeply scoured continuous channels, plausible remnants of such a hypothesized torrent, can be found at or near the level of these embankments along this more northern portion of the ice margin.

Such fluvial features, however, are found roughly 200 m (660 ft) below the level of these 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 (Booth, 1984b, c) confirms that instead of draining subaerially at the ice margin or across the ice-sheet surface, water would tend to occupy this lower, subglacial position during ice-maximum stage and for as long during the recession as ice still covered the area (subglacial fluvial erosion by this water probably accounts for the steep scarp north of Mt. Si.). This suggests that any water transport of sedimentary material in the embankments was typically local off the ice surface.

Emergence of subaerial channels in the upland region followed the formation of these embankments as the ice margin began retreating from the mountain front. The highest and easternmost of these channels (intervals 4–5) 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 River valley (interval 3; see below). The bedrock and till that emerged from beneath the ice in this area is now largely submerged by these deposits.

Farther north, an alluvial deposit chokes the valley of Dry Creek and the North Fork of the Tolt River with associated lake deposits present farther up the North Fork valley (intervals 2–4). The surface altitude 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 (intervals 4–5), 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 for any standstill of the ice margin during this time is absent, the presence of spillways permits discrete intervals to be assigned within this period. The subaerial emergence of Tokul Creek, Canyon Creek, and the Tolt River define three such intervals (6, 7, and 8). Terraces and channels found near Beaver Creek suggest an early connection (interval 6) between the older eastern channels and Tokul Creek. These three main stream channels lie approximately 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, westernmost 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 associated ice-contact deposits. During their respective occupation by recessional meltwater, the basins upstream of each outlet channel aggraded with fluvial sedimentary materials to concordant altitudes. Their thicknesses, 30–60 m (100–200 ft), and the likely rates of ice retreat required by the maximum 1,500-year occupation time of Puget-lobe ice (Rigg and Gould, 1957; Mullineaux and others, 1965) testify to a remarkably high influx 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, below 150 m (500 ft) altitude, 4 km (2.5 mi) downstream of a plausible spillway out of the Tolt basin, and shows no major accumulation of sediment within the channel. As only minor sediment transport could have occurred in the low-gradient segment, significant meltwater occupation of Griffin Creek must have been very short lived (during interval 7).

SKYKOMISH RIVER VALLEY

The high bedrock divide just south of the Skykomish River permitted relatively few drainage routes across it. The highest, most eastern, and longest occupied route is the broad south-trending trough south of Gold Bar, now occupied by Proctor and Dry Creeks (intervals 5–8). Its location is structurally controlled by a fault-line scarp between resistant Tertiary volcanic rocks and a region of easily eroded argillite-rich melange. This passageway formed the only drainage route for the entire upper Skykomish River valley during most of the Vashon-age glaciation. It would have been favored as a subglacial drainage route both at ice maximum and during retreat so long as ice was sufficiently thick to prevent subglacial drainage farther west (for example, through the Elwell Creek valley south of Sultan). All water at the east ice margin, and at the glacier bed within several tens of kilometers from it, collected from west-flowing alpine valleys and submarginal drainage farther north and would thus have been channeled through here. As a subsequent subaerial drainage route, the Proctor-Dry Creek trough provided much of the water and sediment for those southern channels closer to the maximum ice margin (interval 5) and for the water and sediment that later entered the Tolt basin (intervals 6–8). The top of the Skykomish River embankment and the upper limit of lake deposits found farther upstream (intervals 5–8), east of the map area, are roughly graded to the subaerial altitude of this trough (490 m (1,600 ft)) (Cary and Carlston, 1937; W. T. Laprade, oral commun., 1982).

Continued ice thinning eventually would have allowed subglacial drainage farther west (intervals 9–10) under a lower hydraulic potential than the now-subaerial Proctor-Dry Creek trough. Base level of the ice-dammed lake (glacial Lake Skykomish) then fell continuously as the ice thinned; therefore, no discrete intermediate intervals can be defined. Once the spillway at Youngs Creek (interval 11) south of Sultan was free of ice, however, the lake level again stabilized, and a set of identifiable lacustrine deposits, terraces, and outwash plains graded to 180 m (600 ft) developed. Water that flowed over Olney Pass from an ice-dammed lake (glacial Lake Sultan) 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. The relatively short distance of ice-margin retreat required to open a lower drainage path, as contrasted with the apparently large volume of sedimentary material graded to the Youngs Creek spillway, is enigmatic. Exposure of the lower spillway at Elwell Creek (130 m (430 ft)) (interval 12) brought about another drop in lake altitude. The location of deposits graded to this base level attests to the ice margin's continued westward retreat out of the Skykomish River valley. Final retreat from this valley created a penultimate level of water and deposits (interval 13) before the valley merged with the regional lake system, glacial Lake Bretz (Waitt and Thorson, 1983).

SNOQUALMIE RIVER VALLEY

Five distinct spillways link the Snoqualmie River valley with the rest of the lowland to the south and west (fig. 7). Continuous ice retreat created a discrete sequence of lakes whose levels were controlled by the then lowest and most northern of these spillways, successively exposed by the retreating ice margin. Lake levels are particularly well marked by the altitudes of alluvium and deltas deposited during simultaneous drainage from the upland channel system. Because the Snoqualmie River valley trends north-south, features distributed along the valley associated with a single recessional water plane altitude now stand at higher altitudes to the north, because thicker overriding ice resulted in greater amounts of postglacial rebound to the north (Thorson, 1980). To facilitate comparisons, altitudes are given with both their 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 approximately equal to that of the entire Skykomish River valley, and because it coincidentally matches the rebound of the last regional-lake spillway of the entire Puget Sound area (the Leland Creek spillway of Thorson, 1980, discussed below). Estimates of the correction can be made for unspecified features from Thorson (1979, plate 1) or more approximately 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 area at the foot of a broad trough (the Cedar spillway, fig. 7) between Rattlesnake Mountain and the Cascade rangefront. This trough probably acted first as a subglacial meltwater passage. As the ice margin retreated north, it became a subaerial spillway with an altitude of 280/+45 m (920/+150 ft), impounding a proglacial lake between it and the ice (intervals 3–5). Bretz (1910) named this body Lake Snohomish. Fluvial deposits in the lower North Fork of the Snoqualmie River valley, associated with the upland channel sequence (intervals 4–5), must have in part aggraded into this lake.

The opening of a spillway southwest of Fall City (Anderson, 1965; Curran, 1965) over the divide between the Raging River and the East Fork of Issaquah Creek (158/+36 m (520/+120 ft)) appears to have been almost synchronous with the opening of Tokul Creek as the primary upland drainage path. Evidence includes the absence of the 280-m- (920-ft-) level deposits upstream along Tokul Creek or the 158-m- (520-ft-) level deposits along the lower North Fork of the Snoqualmie River (intervals 6–7). Drainage to the west during this time was into glacial Lake Sammamish, the altitude of which was then controlled by the Kenneydale channel (91/+37 m (300/+120 ft)), situated southwest of the map area. An early diversion of south-flowing water east of Snoqualmie Falls reflects a nearby ice-margin position, whereas the multiple levels of the delta at Tokul Creek show subsequent downcutting of the Raging River spillway. Voluminous ice-contact fluvial deposits just north of Snoqulamie Falls along the east wall of the Snoqualmie valley show that a tongue of ice extended down the late-glacial precursor of the modern valley both before and during drainage via the Raging River. The 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 River valley to the large Griffin Creek bogs.

Continued marginal 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 during this time, and deposits of the

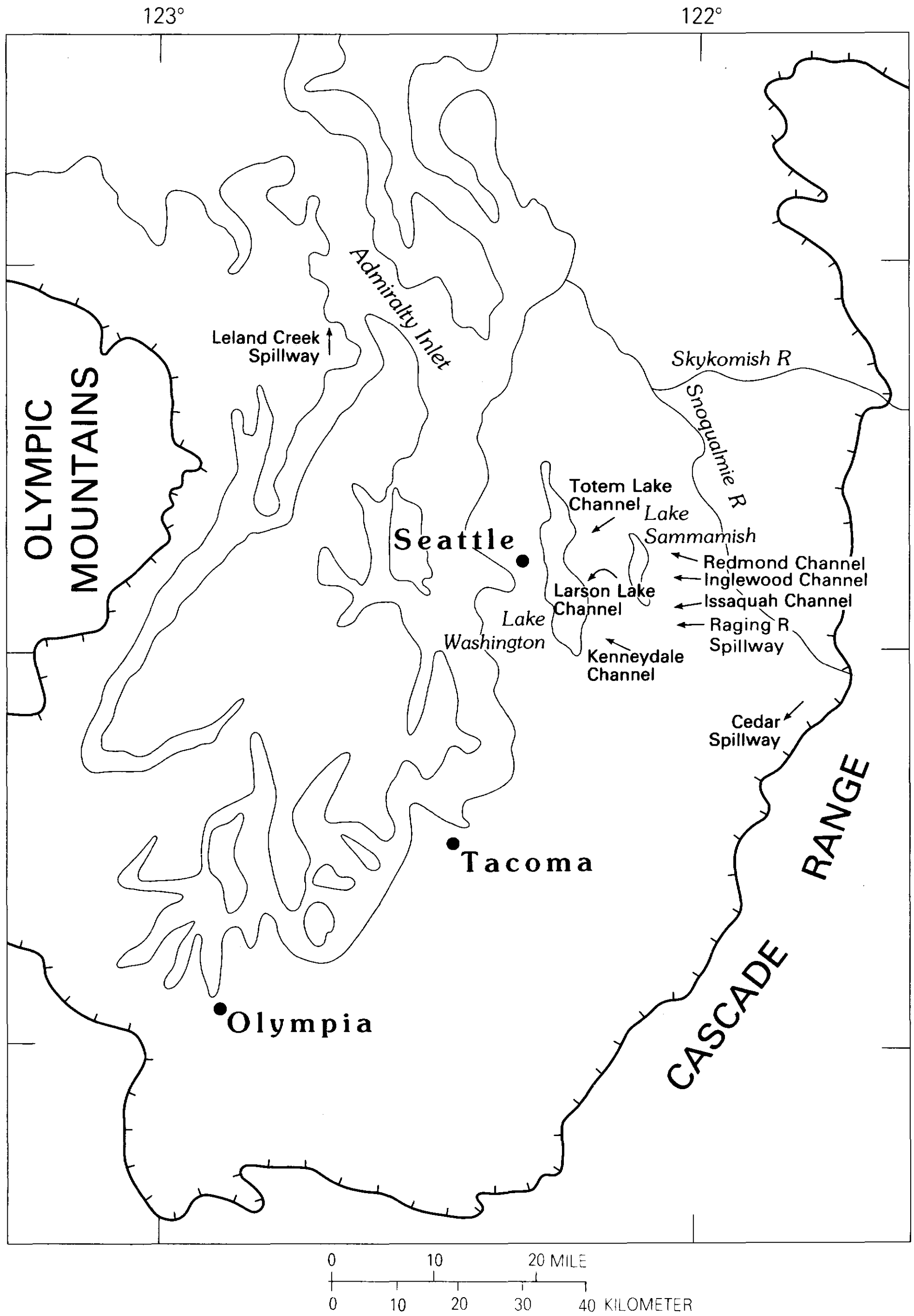

Figure 7. Spillways and channels linking Vashon-age recessional lakes in the eastern and central Puget Lowland (Thorson, 1980). The Cedar, Raging River, Issaquah, Inglewood, and Redmond channels were the five drainage routes for water impounded in the Snoqualmie River valley. Hachured line indicates position of Puget lobe-ice limit (from Thorson, 1980) during the Vashon stade of Armstrong and others (1965).

Tolt River delta, including its southern end where fluvial material buried the stagnant tip of the Snoqualmie River valley ice tongue (intervals 8–9). Occupation of the Inglewood channel (107/+31 m, 350/+100 ft) was briefer (intervals 10–11), as only a minor shift of the ice-margin position just west of the map area 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 River valley spillways. The level of deposits in the main valley indicates that their altitudes were 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 Lake channel of glacial Lake Sammamish (76/+33 m (250/+110 ft)), west of the map area (fig. 7), was active at this time (interals 12–13). Consequently, continued retreat of the ice in the map area affected only the location of sedimentation in the lake; the lake altitude itself was controlled by the retreat much farther west. Lake-bottom silt that underlies constructional terraces along the sides of the Redmond channel are below the level of this stage (intervals 12–13) but above that of the subsequent stage (interval 14). These relationships require deposition of the silt during this time as well. Although the Redmond channel itself must have deepened as water from the Snoqualmie River valley flowed through it, its early recessional existence and exploitation are required by the recessional deposits found within it. Because till caps the surface on either side of the channel and does not appear to drape down into it, the channel was probably not a primary preglacial or subglacial feature. Thus its formation must have been relatively rapid, undoubtedly aided by the great thickness of easily eroded advance outwash deposits present beneath a relatively thin resistant cover of till.

Opening of the next lowest channel (Totem Lake) to drain glacial Lake Sammamish allowed the lake to merge with Lake Bretz (interval 14), identified by Thorson (1981) as the last and largest glacial lake to occupy central Puget Sound. Its altitude was fixed by the Leland Creek spillway (68/+0 m (225/+0 ft)) on the northeast corner of the Olympic Peninsula (fig. 7). Deposits within the map area whose altitudes indicate deposition contemporaneous with this interval of recession include deltas located at Monroe, east of Stillwater (3 km (2 mi) north of Carnation), and near Griffin Creek (3 km (2 mi) south of Carnation). The lake persisted until ice-margin retreat permitted final drainage through Admiralty Inlet and connection of Puget Sound to the open ocean.

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