Pleistocene glaciation in the southern part of the North Cascade Range, Washington

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ABSTRACT

Three major Pleistocene drift sheets preserved along a transect across the southern North Cascade Range are distinguished on the basis of stratigraphic relationships and differences in morphology, weathering characteristics, and soil-profile development. The two youngest drifts have been further subdivided into members representing second-order fluctuations of glacier termini. Deposits of former southeast-flowing valley glaciers in the upper Yakima River drainage basin can be traced across a low divide at Snoqualmie Pass to the west-draining valley of the South Fork of the Snoqualmie River where alpine drift is interstratified with deposits of the Puget Lobe of the Cordilleran Ice Sheet. Preliminary paleomagnetic measurements indicate that the deeply weathered and extensively eroded oldest drift (Thorp) antedates the Brunhes-Matuyama reversal (700,000 yr). Relative-age criteria suggest that the time elapsed between deposition of Thorp drift and the intermediate drift (Kittitas) was substantially longer than that between the intermediate drift and the youngest drift (Lakedale). Soil developed on Kittitas Drift shows pronounced clay enrichment in the B horizon, in marked contrast to the weakly developed post-Lakedale soil, suggesting that the Kittitas ice advances antedate the last interglaciation of the global marine record and therefore are more than 120,000 yr old. On the basis of reconstructed ice gradients, the next-to-youngest member (Domerie) of the Lakedale Drift is believed to correlate broadly with Vashon Drift that was deposited during the last major expansion of the Puget Lobe between 15,000 and 13,500 yr ago. Two more-extensive, pre-Domerie advances of Lakedale glaciers (Bullfrog and Ronald) preceded the maximum stand of the Puget Lobe, as indicated by stratigraphic relationships and reconstructed glacier profiles. A late Lakedale readvance led to deposition of the Hyak Member prior to 11,050 yr ago in valley heads draining high-altitude source areas.
Key words: stratigraphy, glacial geology, Pleistocene.

INTRODUCTION

The rugged alpine scenery of the North Cascade Range of Washington has evolved largely through the erosional activity of former extensive glaciers. Until recently, however, few studies had been made of the glacial history of the range. The present investigation was begun with the aim of studying the glacial record in a belt from the eastern margin of the Puget Lowland across the mountains to the limit of glaciated terrain on the eastern slope. Along the transect selected for study, glacial drift in the west-draining valley of the South Fork of the Snoqualmie River can be linked directly with deposits in the southeast-draining valley of the Yakima River across a low divide at Snoqualmie Pass (Figs. 1 and 2). In this study, emphasis was placed on describing the stratigraphic succession, on developing a chronology of glacier fluctuations, on examining the relationship of valley glaciers to the Puget Lobe of the Cordilleran Ice Sheet, and on obtaining evidence of Pleistocene climatic conditions in this sector of the Cascade Range.

The upper Yakima River and the South Fork of the Snoqualmie River drain a large region of the North Cascade Range underlain by sedimentary, igneous, and metamorphic rocks, ranging in age from pre–Late Jurassic to Pliocene (Foster, 1960; Huntting and others, 1961; Stout, 1964). Dominant structures trend northwest, giving a gross northwest grain to the topography.

The Cascade Range forms a major topographic barrier to eastward flow of Pacific air and divides the state of Washington into two contrasting climatic regions, a belt of strongly maritime conditions west of the mountains and one of increasingly continental climate to the east. A striking change in climate takes place along the upper Yakima River drainage basin, which spans the transition zone between these regions. A rapid decrease in mean annual precipitation from 266 cm at Snoqualmie Pass to less than 25 cm at Ellensburg occurs through a distance of only 80 km and is accompanied by a change in vegetation from dense evergreen forest along the drainage divide to sagebrush and bunchgrass prairie near Ellensburg.

Of 756 glaciers listed in the U.S. Geological Survey's *Inventory of Glaciers in the North Cascades* (Post and others, 1970), only 14 small glaciers lie within the study area, and all are restricted to the upper Yakima River drainage basin. They lie within an altitude range of 1,420 to 2,410 m and have an average median altitude of 1,860 m. The glaciers range in size from 0.5 km^2 to only 0.025 km^2 and cover a total area of 2.3 km^2.

PREVIOUS STUDIES

The earliest references to Pleistocene glaciation in the southern North Cascade Range were in pioneer studies by Russell (1900), Smith (1904), Smith and Calkins (1906), Saunders (1914, 1916), and Campbell and others (1915). Page (1939) mapped three drift sheets in the Icicle Creek drainage basin just north of the present study area, and this succession, later modified in part by Long and Porter (1968), stood for many years as the only glacial sequence described for the Cascade Range. Glacial deposits in and near Mount Rainier National Park have been mapped and studied in detail by Crandell (1969, 1974), who traced the extent of alpine glaciers along the west side of the range and correlated certain alpine advances with advances of the Puget Lobe in the adjacent lowland. The relationship of alpine drift to Vashon Drift in the Puget Lowland along the west front of the range has been described by Cary and Carlston (1937), Mackin (1941), Crandell (1963, 1974), and Knoll (1967).

STRATIGRAPHIC USAGE

Rock-stratigraphic and soil-stratigraphic units are used in accordance with recommendations of the American Commission on Stratigraphic Nomenclature (1961) (Table 1). Sediments resulting from an ice advance were collectively mapped as *drift* (Flint, 1971, p. 147). A number of lithofacies are included within the drift

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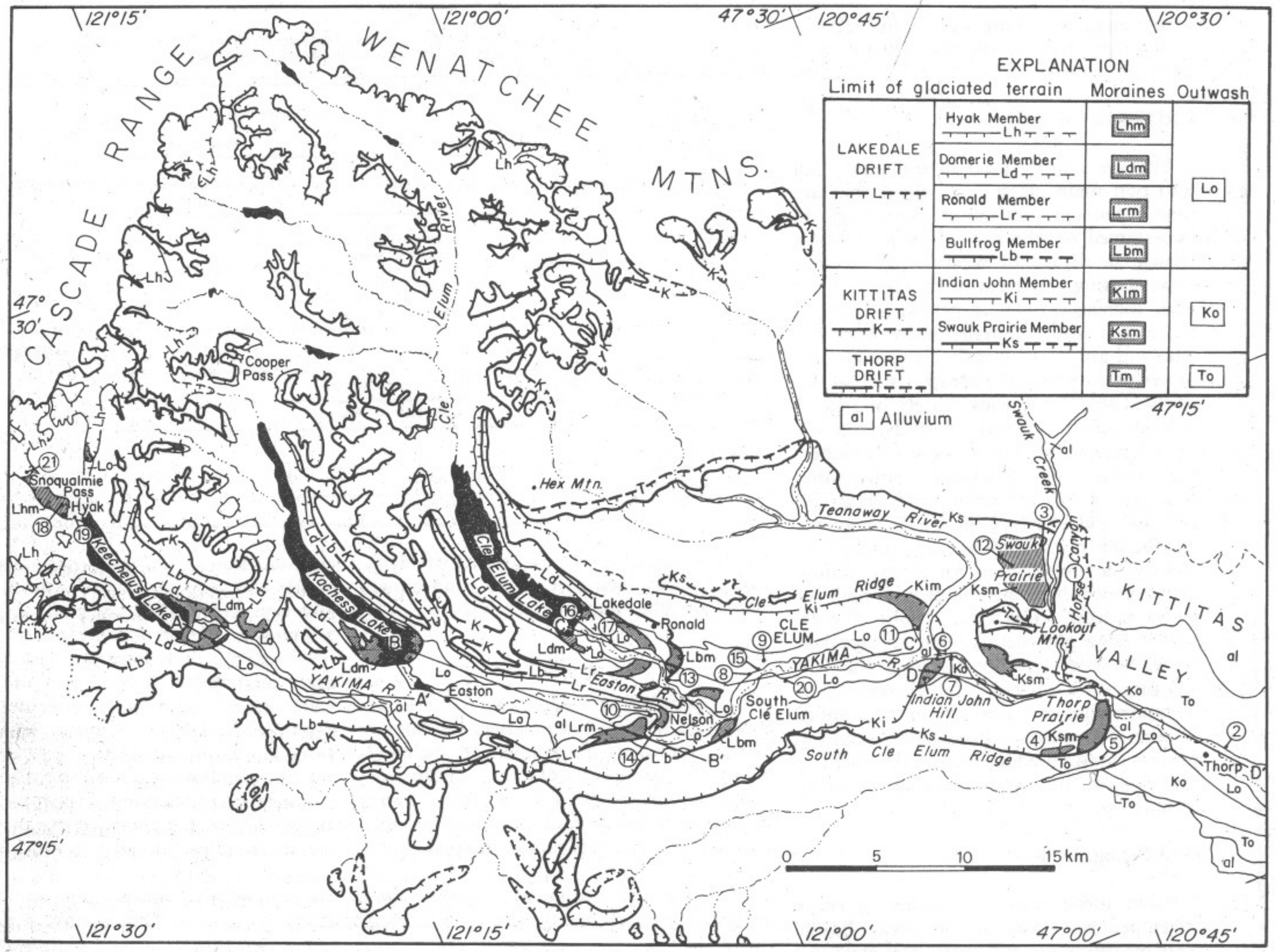

Figure 1. Glacial-geologic map of upper Yakima River drainage basin.

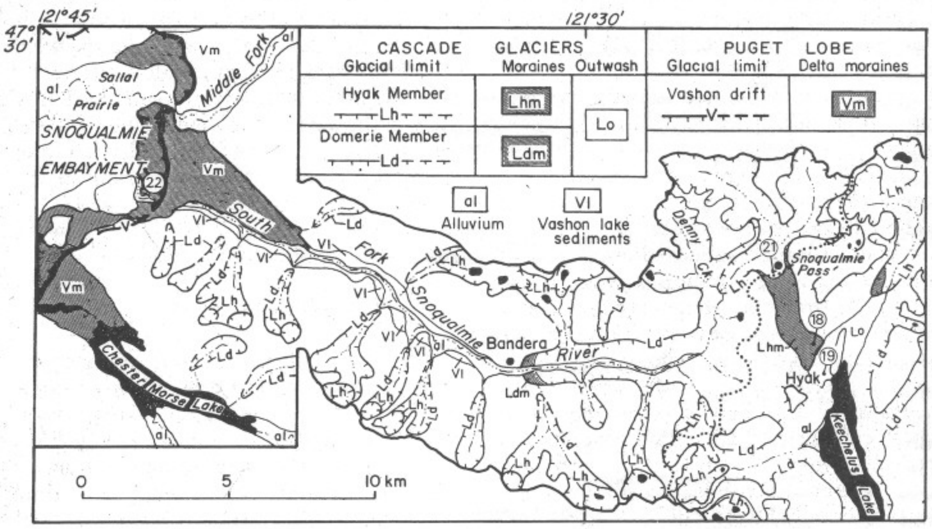

Figure 2. Glacial-geologic map of drainage basin of the South Fork of the Snoqualmie River.

sheets, among the most common of which are till, erratic stones, outwash, glacial-lacustrine sediments, and ice-contact stratified drift. Sediments originating during glaciations but not deposited directly by ice or associated meltwater are excluded from drift, as used here, and were mapped as nonglacial units. These include loess, colluvium, alluvium, and landslide sediments. The latter three also constitute the bulk of preserved interglacial deposits. Glacial-stratigraphic units (Flint, 1971, p. 373) have been used to designate the principal glacial and nonglacial episodes, as inferred from the Quaternary stratigraphic record, but rather than introduce a new set of names for the alpine region, I have adopted the Puget Lowland terminology for major first-order fluctuations (glaciations and interglaciations) of Pleistocene glaciers in the Cascades.

Stratigraphic names employed in this

paper supercede those used informally in preliminary reports (Porter, 1965, 1969, 1971).

CRITERIA OF AGE

The age criteria used in this study fall into two main classes: (1) those that are time dependent and permit relative ages to be assigned on the basis of a progressive change in degree of weathering, erosion, mass wasting, or extent of vegetation cover with increasing age of deposits; and (2) those that are essentially independent of time and are based largely on spatial relationships or physical characteristics of the drifts (Table 2). A wide variety of criteria proved useful in the field study, but the most widely applicable ones were weathering rinds, loess thickness, soil-profile characteristics, and moraine and terrace relationships. Although both granite-weathering ratios and surface-boulder frequency have been used for differentiating drifts elsewhere along the eastern flank of the Cascades (Hopkins, 1966; Porter, 1969), these parameters were not applicable in the study area because of (a) the paucity of granitic rocks in drift sheets and (b) the nonsystematic variability in the number of surface boulders on moraines, resulting from a predominance of small clasts, a thick loess mantle, and more than a century of farming.

Weathering Rinds

Mean thicknesses of weathering rinds developed on clasts of Teanaway Basalt were measured for each drift sheet, with the exception of the Hyak Member, which lacks stones with these lithological characteristics (Fig. 3; Porter, 1975). The range in error at one standard deviation for the various sampled units amounts to as much as 10 percent of the mean value. Although the ranges in rind thickness, at one standard deviation, for the Thorp, Kittitas, and Lakedale Drifts are mutually exclusive, values for the two members of the Kittitas Drift overlap, as do those of the three lower members of the Lakedale Drift. Consequently, rind measurements are inadequate to distinguish members.

Loess Thickness

Maximum thickness of loess on Kittitas and Lakedale Drifts adjacent to the Yakima River and the lower reaches of its principal tributaries appears to vary systematically with the age of the underlying drift. The mean of measurements at sites where loess is regarded as relatively thick ranges from 3.5 m on moraines and terraces of Swauk Prairie age to only 0.7 m on those of Domerie age (Fig. 4). Sediments of Hyak age generally lack a cover of wind-blown sediment other than volcanic ash.

TABLE 1. QUATERNARY GLACIAL-STRATIGRAPHIC, ROCK-STRATIGRAPHIC, AND SOIL-STRATIGRAPHIC UNITS OF THE UPPER YAKIMA RIVER DRAINAGE BASIN

Glacial-stratigraphic units	Rock-stratigraphic units			Soil-stratigraphic units
	Glacial		Nonglacial	
Holocene Interglaciation	Neoglacial drift		W tephra, Yn tephra, O tephra	Post-Lakedale soil
Fraser Glaciation	Lakedale Drift	Hyak Member	Lakedale loess	
		Domerie Member		
		Ronald Member		
		Bullfrog Member		
Olympia Interglaciation				Post-Kittitas soil
Salmon Springs Glaciation	Kittitas Drift	Indian John Member	Kittitas loess	
		Swauk Prairie Member		
Puyallup Interglaciation				
Pre-Salmon Springs glaciation(s)	Thorp Drift			
	Pre-Thorp drift (?)			

Soils

Soil profiles on each major drift sheet were sampled at 10-cm intervals. Subsequent laboratory determinations included grain-size analyses, pH, percentage of magnetic minerals, and moist color. Curves depicting the percentage of <2-μ clay and silt/clay ratios tend to emphasize pedogenic clay enrichment, but they reflect variations in silt and clay content of loessial parent materials as well. In most profiles, pH values tend to be slightly acid (pH = 5 to 7); however, the curves are not easy to interpret, making this parameter of limited value. Percentage of magnetic minerals was determined in the hope that it would provide an index of weathering, but the results are not significant. In some profiles, a decrease in magnetic minerals correlates with an increase in clay, implying weathering associated with pedogenesis. In other profiles,

TABLE 2. PRINCIPAL CRITERIA USED IN DIFFERENTIATING AND CORRELATING CASCADE ALPINE DRIFTS

Criterion	Dependent upon time	Independent of time
Postglacial modification of cirque morphology	x	
Ice-marginal features and sediments		
Upper limit of erratics		x
Altitude of crests of faceted mountain spurs		x
End moraines		
Position relative to cirques		x
Position relative to other bodies of drift		x
Size or bulk		x
Altitude		x
Postdepositional modification by eolian sedimentation	x	
Postdepositional modification by gullying	x	
Postdepositional modification by mass wasting	x	
Extent of erosion by axial or tributary stream	x	
Slope angles	x	
Outwash terraces		
Altitude above stream		x
Relationship to moraines		x
Postdepositional modification by gullying	x	
Postdepositional modification by eolian sedimentation	x	
Stratigraphic position of drift relative to:		
Other drift sheets		x
Loess		x
Tephra layers		x
Relationship of lake sediments to moraines		x
Estimated snowline position		x
Weathering and soil formation		
Thickness of weathering rinds	x	
Soil profile		
Degree of horizon development	x	
Vertical distribution of clay	x	
Vertical change in magnetic mineral content	x	
Thickness of B horizon	x	
Structure	x	
Color	x	

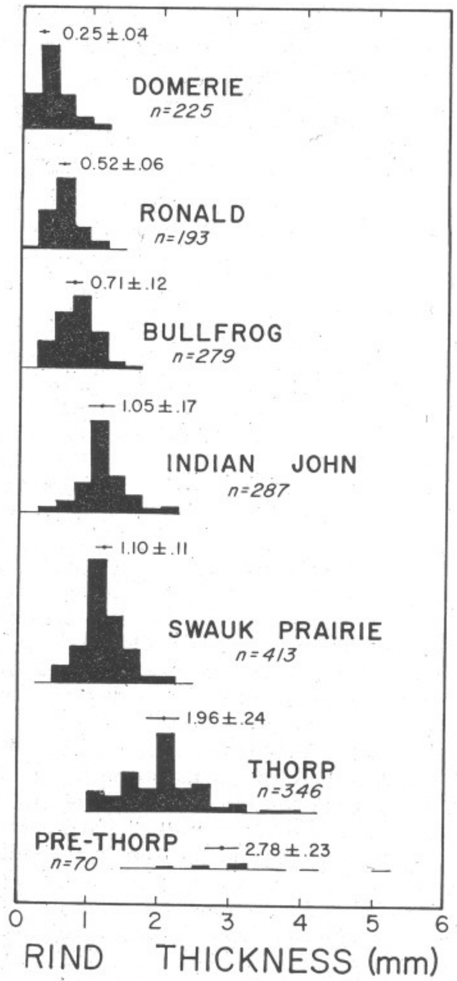

Figure 3. Size-frequency distribution and ›ean values of weathering rinds developed on ›salt clasts in principal drift sheets.

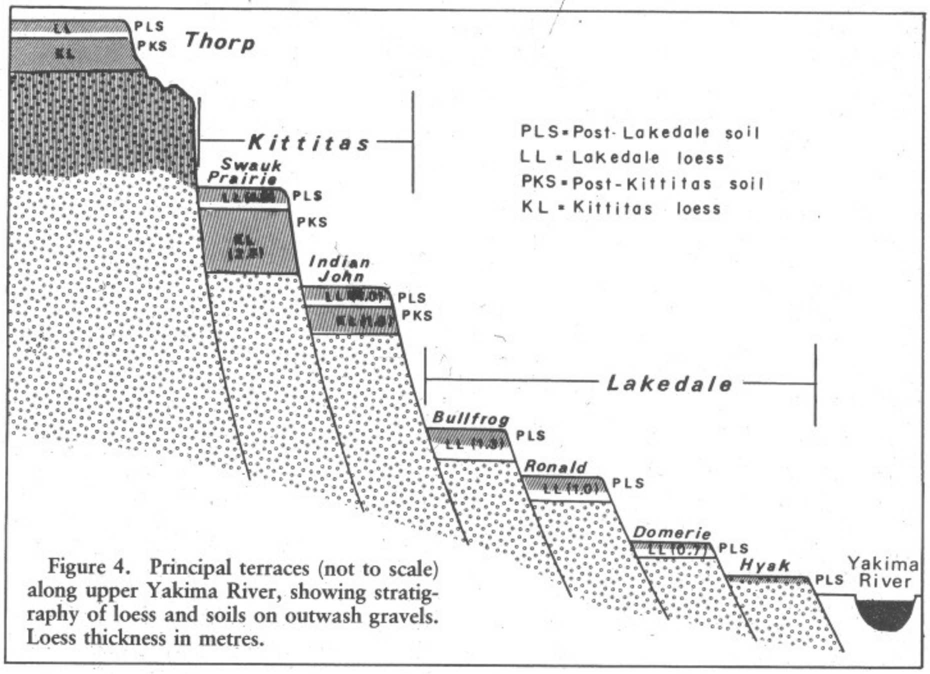

Figure 4. Principal terraces (not to scale) along upper Yakima River, showing stratigraphy of loess and soils on outwash gravels. Loess thickness in metres.

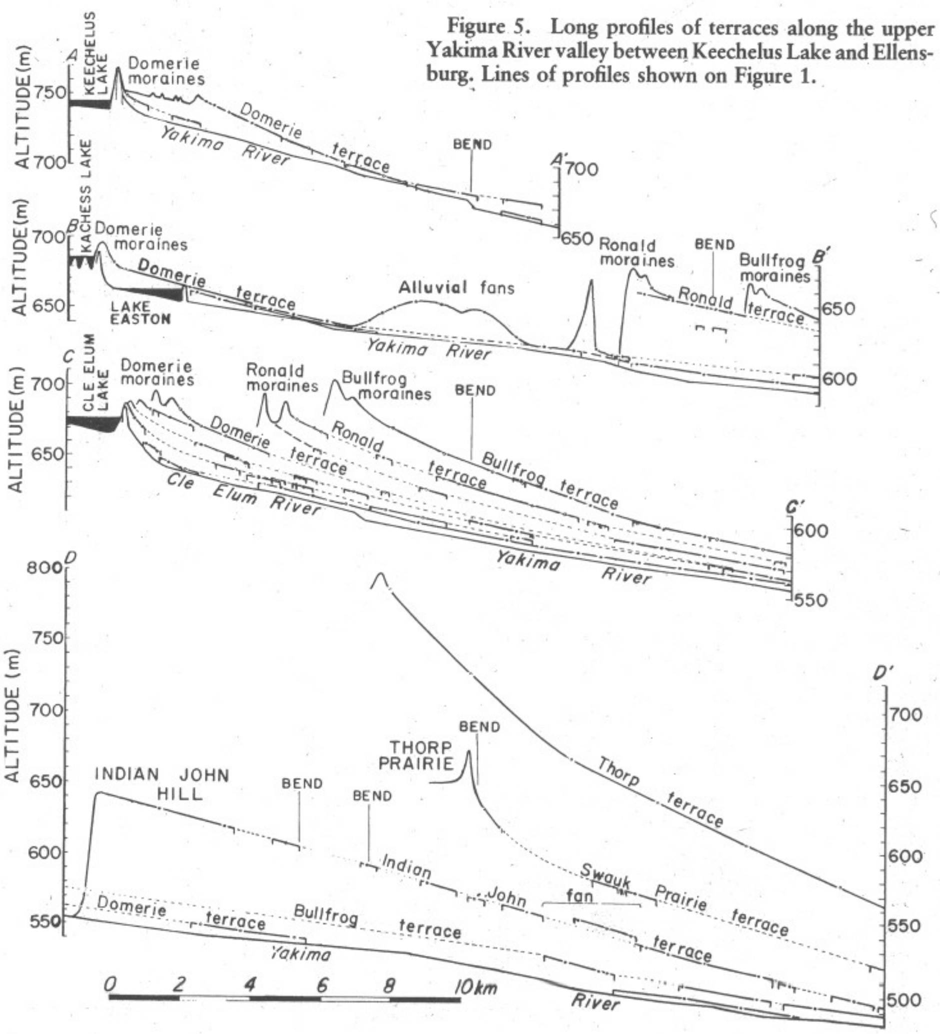

Figure 5. Long profiles of terraces along the upper Yakima River valley between Keechelus Lake and Ellensburg. Lines of profiles shown on Figure 1.

…ever, magnetic mineral variations ap… …o be more closely related to initial dif… …s in texture (and possibly composi… … parent material. Gross color differ… …were useful in distinguishing soil-stratigraphic units; the younger soils commonly have yellowish-brown hues; the older soils, reddish hues.

Moraine and Terrace Relationships

Both the relative spacing of moraines and their relative distance from cirques provide a crude basis for comparison of moraine successions in adjacent valleys, but direct correlations between valleys are possible by directly tracing outwash terraces that border the Yakima River and its principal tributaries upstream to moraines or groups of moraines belonging to each of the three major drift sheets (Fig. 1). Outwash bodies deposited during different glaciations generally were readily distinguished on the basis of degree of dissection, thickness of alluvial and colluvial cover, stratigraphy and thickness of the eolian mantle, soils, and reconstructed long profiles (Figs. 4 and 5).

UPPER YAKIMA RIVER DRAINAGE BASIN

Pleistocene glaciers of the upper Yakima River drainage basin were among the largest in the Cascades. During glacial maxima, individual valley glaciers merged to form confluent ice streams more than 40 km long and more than 400 m thick (Table 3). The stratigraphic record of their fluctuations is unusually complete, largely because the height and low gradient of the valley floor led to substantial expansion of glaciers with only a moderate lowering of snowline. Consequently, successive drift sheets, which in most other valleys lie closely spaced or nested, are spread out through many kilometers (Fig. 6).

Within 25 km of the main divide, peaks are sharp-crested, valleys commonly have parabolic cross-profiles, and most major streams head in well-formed cirques. Valley walls typically are smooth and abraded where eroded by ice, but rugged, nonglaciated crests of many interfluves show evidence of prolonged frost shattering. East of this belt, a parallel one lies, extending an additional 25 to 35 km to the limit of glaciated terrain, in which erosional modification of the landscape by ice was minimal, and the most common glacial landforms are end moraines and outwash terraces.

Possible Pre-Thorp Drift

Although neither glacial sediments nor glacial landforms of unequivocal pre-Thorp age were found during this study, some evidence points to such a possible early ice advance. Mean thickness of weathering rinds

TABLE 3. SIZE PARAMETERS OF PRESENT AND FORMER GLACIERS IN THE UPPER YAKIMA RIVER DRAINAGE BASIN

Episode	Mean length (km)	Area (km^2)	Maximum thickness (m)
Present	0.8	2.3	60
Neoglaciation	1	8.8	150
Hyak	5	140	280
Domerie	33	540	360
Ronald	46	660	410
Bullfrog	49	720	425
Indian John	64	875	500
Swauk Prairie	70	1085	635
Thorp	~68	~1000	••

on Teanaway Basalt erratics at four sites near the outer limit of Thorp Drift are 2.6, 2.6, 2.8, and 3.1 mm, resulting in a combined mean and standard deviation of 2.78 ± 0.23. These samples apparently represent a population distinct from those obtained at 20 stations on Thorp Drift which gave a mean and standard deviation of 1.96 ± 0.24. Possibly these high rind values represent incorporation of large numbers of previously weathered stones by the Thorp glacier. It is conceivable that a still older drift was sampled, however, because each of the sample localities lies at the extreme limit of mapped Thorp Drift. If that was the case, then pre-Thorp glaciers probably were shorter than those of subsequent advances, for neither till nor terraces of pre-Thorp age were found at or beyond the Thorp and Swauk Prairie terminal moraines.

Thorp Drift

The oldest unequivocal glacial sediments in the upper Yakima River drainage basin crop out near Thorp and provide evidence of an ancient advance of valley glaciers to a point at least 65 km east of the present Cascade divide. In areas not subjected to later glaciation, the original morphology of the drift has been strongly modified by erosion and mass wasting, so that many of the relative-age criteria employed to differentiate and subdivide younger drift sheets could not be applied to Thorp deposits. Except in and beyond the terminal zone, where subdued moraines and a dissected outwash train are present, the extent of Thorp ice is inferred largely from erratic stones.

Thorp till probably underlies much of the broad valley of Horse Canyon and the south slope of Lookout Mountain, but outcrops are rare. About 1.5 m of dark reddish (5YR 3/4), stony, fissile till is exposed on the south side of a subdued ridge, possibly a lateral moraine, that descends the west wall of Horse Canyon (Fig. 1, loc. 1; Table 4). Basalt clasts are decomposed and have diffuse weathering rinds as much as 2.2 mm thick, but averaging 1.8 mm. Many stones are spheroidally weathered, commonly to a depth of 2 cm or more. Although soil developed on the till has been truncated by erosion, thick clay skins are found on peds through the full depth of exposure. Some tillstones appear faceted, and many are faintly striated or grooved.

Two broad subparallel ridges of drift are traceable for about 3 km along the south slope of Lookout Mountain. Till is poorly exposed in several shallow gullies on their flanks, and erratic stones mantle their surfaces. The outer ridge, which marks the highest ice limit on Lookout Mountain, descends southeast from an altitude of 1,035 m to about 855 m with a gradient of 56 m/km, at which point it is truncated by the canyon of Swauk Creek; the inner ridge lies some 30 to 40 m lower.

Thorp erratics with weathering rinds ranging from 1.6 mm to 2.4 mm were found on the highest parts of Cle Elum Ridge to an altitude of 1,158 m and on the south side of Hex Mountain as high as 1,220 m, some 120 m above the Kittitas drift border. If these erratics closely define the former ice limit, the mean surface gradient of the Thorp glacier between Hex Mountain and Lookout Mountain must have been about 7 m/km, or some 8 times gentler than the gradient in the terminal zone.

Outwash of Thorp age has been extensively eroded since deposition. Only about 25 percent of the inferred original areal extent is still preserved in numerous small terrace remnants and in a large terrace deposit that extends southeast from Horse Canyon to a point 6 km northwest of Ellensburg. Its western limit coincides closely with the easternmost Thorp till but lies several km west of the outer limit of Kittitas till at Thorp Prairie. Each surviving remnant has been deeply gullied by ephemeral consequent streams, locally to a depth of 75 m, and almost entirely stripped of eolian man-

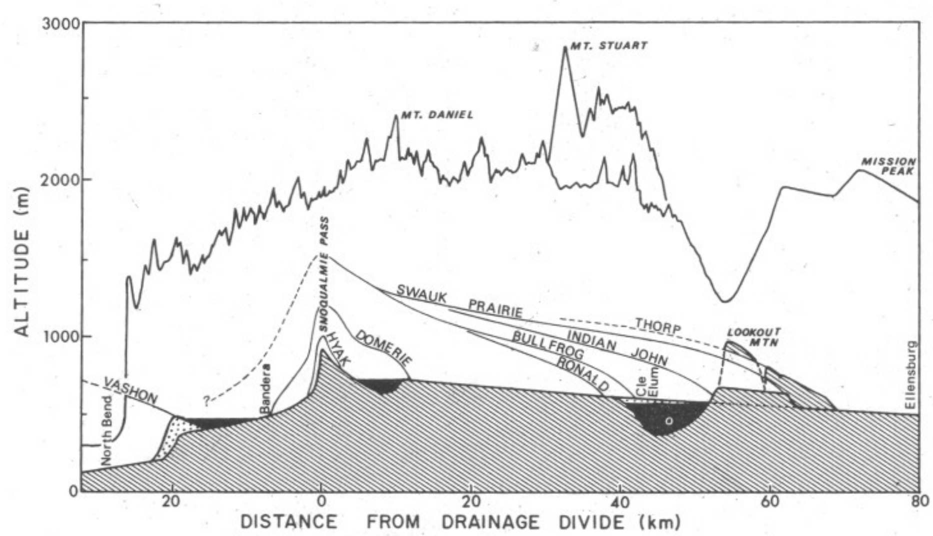

Figure 6. Long profiles of Pleistocene glaciers between North Bend and Ellensburg based on ice-limit data.

TABLE 4. TYPE LOCALITIES OF ROCK- AND SOIL-STRATIGRAPHIC UNITS IN THE UPPER YAKIMA RIVER DRAINAGE BASIN

Unit	Location of typical section	Map locality (Fig. 1)
Thorp Drift		
Till facies	Side of Horse Canyon at 790 m in NW¼ SW¼ sec. 4, T. 19 N., R. 17 E. (Thorp quadrangle)	1
Outwash facies	Landslide scarp adjacent to Yakima River in NE¼ sec. 12, T. 18 N., R. 17 E. (Thorp quadrangle)	2
Kittitas Drift		
Swauk Prairie Member		
Till facies	(a) Roadcut along U.S. 97 at northwest end of Swauk Prairie in SE¼ NW sec. 28, T. 20 N., R. 17 E. (Thorp quadrangle)	3
	(b) Canal cut on Thorp Prairie in SW¼ NE¼ sec. 30, T. 19 N., R. 17 E. (Cle Elum quadrangle)	4
Outwash facies	Roadcut near distal margin of Thorp Prairie moraine in SE¼ SW¼ sec. 32, T. 19 N., R. 17 E. (Thorp quadrangle)	5
Indian John Member		
Till facies	Side of Indian John Hill at 635 m in NW¼ SW sec. 3, T. 19 N., R. 16 E. (Cle Elum quadrangle)	6
Outwash facies	Borrow pit on north side of Indian John Hill in NW¼ SE¼ sec. 3, T. 19 N., R. 16 E. (Cle Elum quadrangle)	7
Post-Kittitas soil and Kittitas loess	Roadcut on U.S. 97 at west end of Swauk Prairie in SW¼ NW¼ sec. 29, T. 20 N., R. 17 E. (Thorp quadrangle)	12
Lakedale Drift		
Bullfrog Member		
Till and outwash facies	Borrow pit beside south bank of Cle Elum River in NE¼ SW¼ sec. 19, T. 20 N., R. 15 E. (Easton quadrangle)	13
Ronald Member		
Till facies	Cut along south bank of Yakima River east of Interstate 90 in SE¼ NW¼ sec. 36, T. 20 N., R. 14 E. (Easton quadrangle)	14
Outwash facies	Cut along north bank of Yakima River in riser of Ronald terrace in SE¼ SE¼ sec. 28, T. 20 N., R. 15 E. (Cle Elum quadrangle)	15
Domerie Member		
Till facies	Proximal face of moraine impounding Cle Elum Lake at Lakedale in NW¼ SW¼ sec. 2, T. 20 N., R. 14 E. (Kachess Lake quadrangle)	16
Outwash facies	Cut along north bank of Cle Elum River east of Domerie Flats in NW¼ SE¼ sec. 11, T. 20 N., R. 14 E. (Easton quadrangle)	17
Hyak Member		
Till facies	Roadcuts along Interstate 90 in NW¼ NW¼ sec. 15, T. 22 N., R. 11 E. (Snoqualmie Pass quadrangle)	18
Outwash facies	Cutbank along Coal Creek near Hyak in NW¼ SE¼ sec. 15, T. 22 N., R. 11 E. (Snoqualmie Pass quadrangle)	19
Post-Lakedale Soil and Lakedale loess	Cut along north bank of Yakima River in riser of Ronald terrace in SE¼ SE¼ sec. 28, T. 20 N., R. 15 E. (Cle Elum quadrangle)	15

tle. The terrace surface reaches a maximum height of about 140 m above the Yakima River just north of Thorp; the gravel is at least 50 m thick near its western limit at Thorp Prairie, where it was eroded and shaped into drumlinoid hills by ice of the Swauk Prairie advance.

In most exposures, the outwash consists of poorly sorted gravel and displays cross-stratification and cut-and-fill structures typical of braided-stream deposits. Imbricate discoidal clasts and local festooned cross-bedding indicate dominant southeastward-flowing currents. Near its upvalley limit, the bouldery outwash has a mean clast size of 10 cm; but at Ellensburg, it decreases to only 3 cm. Yakima Basalt is the dominant rock type in the gravel, commonly composing 50 percent or more of the clasts, with andesite (10 to 20 percent) and sandstone (12 to 16 percent) also being important components. Andesite is more plentiful in Thorp Drift than in younger drift sheets but is much less abundant than in gravels of the underlying Ellensburg Formation, where it constitutes 90 percent or more of the pebbles and cobbles. Chert typically forms a lag concentrate at the weathered surface of the outwash body but is rare in post-Thorp drifts (≤ 1 percent), which have a high sandstone content (30 to 65 percent). Apparently considerably less sandstone and more chert-bearing rocks were exposed in the headwaters of the basin during Thorp time than today. Cherty rocks must have been significantly reduced in area by the time of the Kittitas advances.

Thorp outwash is deeply oxidized (>10 m), and many volcanic stones near its top are weathered through. Although no exposures of uneroded relict soil were found on the terrace surface, the depth and intensity of weathering of Thorp Drift contrasts markedly with much shallower weathering profiles on the younger drift sheets, implying that a long interval of time separated the retreat of Thorp glaciers from the subsequent Kittitas ice advances.

Layers of sand, silt, and interbedded gravels crop out beneath the uppermost gravel of the Thorp terrace in steep landslide scarps east of Thorp. The silts are as much as 2 m thick and persist laterally through distances of at least 0.5 km. They resemble younger loesses in the valley but probably include some water-laid sediments. Reddish-brown soils with textural B horizons are developed at the top of some silt units. At least five major erosional unconformities are visible in the exposed section and generally coincide with the tops of the weathered silt. The gravel units rest disconformably upon the differentially truncated soils in the underlying silt. Each successive gravel unit and overlying silt possibly records an aggradational interval associated with glaciation in the headwaters of the drainage basin. If that is the case, then the geometry of the deposits suggests either that the Kittitas Valley subsided tectonically relative to the Cascade Crest during this period or that each successive ice advance was more extensive than earlier ones, resulting in progressive burial of older aggradational units and weathering profiles.

Kittitas Drift

Weathered glacial sediments postdating Thorp Drift and characterized by subdued moraines and thick dissected outwash fills underlie much of the land surface downvalley from Cle Elum. Large valley glaciers that deposited this drift terminated near the upper end of Kittitas Valley, for which the sediment is named. Weathering values fall between those of Thorp Drift and Lakedale Drift and indicate that the Kittitas ice advances occurred during a separate and distinct glacial age. Although weathering parameters in themselves do not permit subdivision of the drift sheet, landform associations clearly demonstrate at least two major terminal fluctuations of the main Yakima valley glacier.

Swauk Prairie Member. Kittitas till extends downvalley as far as Swauk Prairie and Thorp Prairie, which are broad belts of moraine, marking the terminal positions of two lobes of the Yakima valley glacier. The moraine complex at Swauk Prairie is composed of six arcuate ridges of stony till irregularly mantled with loess (Fig. 7). The surface of the moraine reaches an altitude of 750 m and has up to 35 m of relief. Most till clasts are rounded pebbles and cobbles of Teanaway Basalt and sandstones of the Roslyn and Swauk Formations, probably largely stream gravels reworked by the advancing glacier; boulders are comparatively rare. By contrast, the end moraine at Thorp Prairie, which lies south of the Yakima River, is characterized by a single prominent arcuate ridge at the outer limit of the till sheet, with more subdued undulating morainal topography behind it. The crest reaches an altitude of 680 m, some 165 m above the adjacent Yakima River. The southern lobe of the glacier overrode Yakima Basalt, the overlying pumiceous Ellensburg Formation, and Thorp Drift. Consequently, till at Thorp Prairie is very stony, has a high percentage of angular boulders of Yakima Basalt (≤2 m diam), and contains few clasts of Teanaway Basalt. The eolian mantle is thin and discontinuous, resulting in a much stonier surface. Where well exposed along irrigation canals, the fissile till is oxidized to a depth of 2 m and is discontinuously mottled to a depth of an additional 3 m (Fig. 1, loc. 4).

Four subdued arcuate moraine loops lying in a broad swale on the south slope of Lookout Mountain are correlated with the moraines at Swauk Prairie and Thorp Prairie on the basis of weathering rinds, reconstructed surface ice gradients, and gross morphology. The outermost loop rises from 785 m along its distal margin to 910 m, where it meets the western escarpment of Lookout Mountain. Where exposed in section, the moraines consist mostly of stony till.

Erratics of Teanaway Basalt were found over all but the highest parts of Cle Elum Ridge, reaching altitudes of about 975 m at its southeast end and 1,100 m near its northwest extremity. On both Hex Mountain and Easton Ridge, erratics occur to about 1,150 m. They also were found throughout the lower Teanaway River drainage basin, indicating that ice flowed into the Teanaway Valley across a saddle at the northwest end of Cle Elum Ridge. However, glacially sculptured landforms are largely lacking in this glaciated belt, and till is seldom exposed because of a thick mantle of sandy colluvium. In the few places where till was found, its upper limit is consistent with that north of the Yakima River.

Swauk Prairie outwash occurs only as scattered terrace remnants in Kittitas Valley. The largest outwash remnant, forming a high terrace adjacent to the distal slope of the moraine at Thorp Prairie, rises about 100 m above the Yakima River and is mantled with as much as 1 m of loess (Figs. 1 and 9, loc. 5). Exposed sediment is coarse cobble and boulder gravel.

Degree of weathering and erosion of Swauk Prairie deposits is substantially less than that of Thorp Drift, as shown by thinner weathering rinds, shallower weathering profiles, and less modification of depositional morphology. Although generally poorly exposed, tills apparently are oxidized to at least 2 m and gravels to even greater depths. Because moraines have been modified by mass wasting, erosion, and eolian sedimentation, no suitable exposures of relict soils were found developed directly on Swauk Prairie drift.

Indian John Member. Evidence for a significant advance of the Yakima Valley glacier following its recession from the moraines at Swauk Prairie and Thorp Prairie is found at Indian John Hill, after which drift of this advance is named. Although Indian John drift conceivably represents a separate glacial age, its weathering characteristics are nearly indistinguishable from those of the Swauk Prairie Member, suggesting that it probably formed during a major readvance after the Swauk Prairie interval but during the same glaciation.

Nearly 100 m of fluvial sediment is exposed at the type locality in a large borrow pit along the north scarp of Indian John Hill (Fig. 1, loc. 7; Table 4). The section consists largely of poorly sorted boulder-cobble gravel with interstratified layers of finer gravel and sand. The sediments are

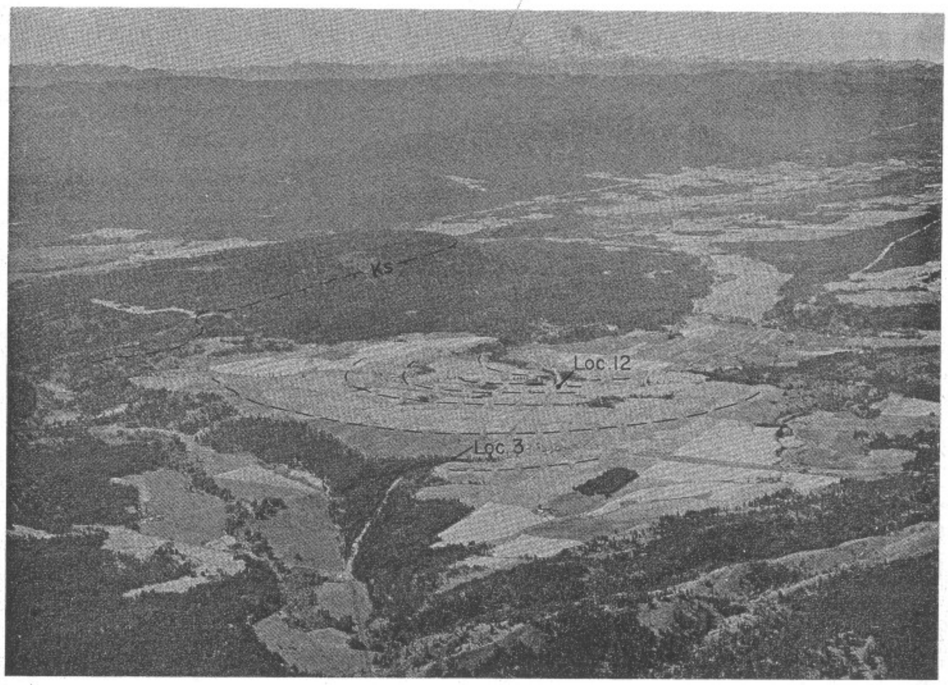

Figure 7. Swauk Prairie moraine (area of open farmland), with Swauk Creek in foreground. Dashed lines mark prominent moraine crests. Upper limit of Swauk Prairie ice (Ks) on Lookout Mountain marked by broken ticked line. View is southwest toward Mount Rainier, 85 km away (photograph by Austin S. Post).

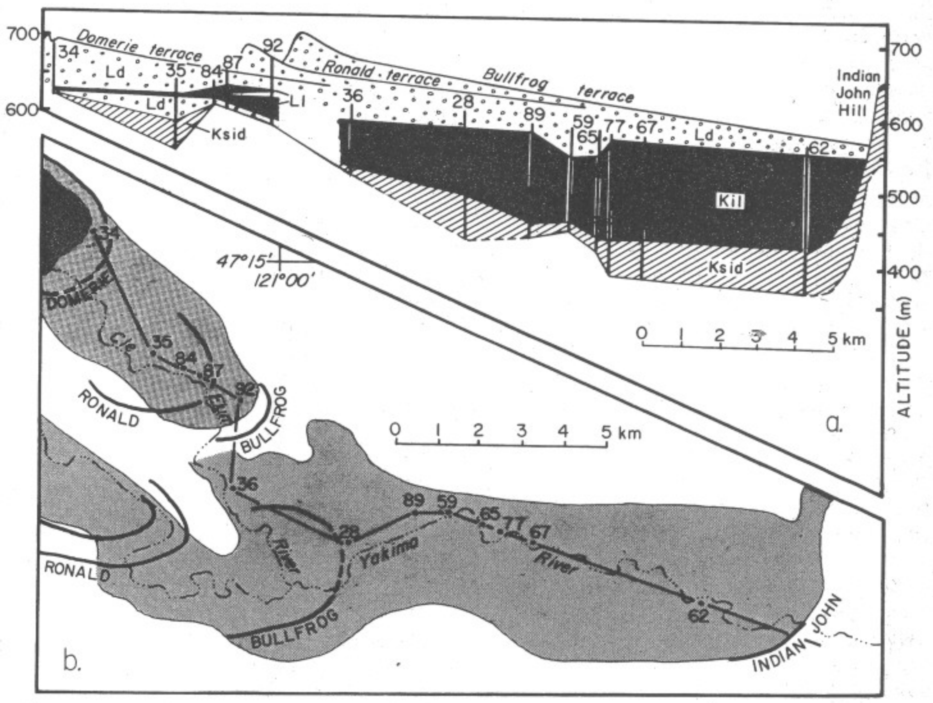

Figure 8. a. Subsurface stratigraphic section between Cle Elum Lake and Indian John Hill inferred from borehole data. Boreholes along section are indicated by numbers. b. Location of boreholes and inferred extent of former lakes (shaded pattern).

comparatively fine grained near the base but coarsen progressively toward the top, a rather common characteristic of many terrace sections in this valley; the upward coarsening probably is indicative of progressive advance of the glacier terminus during aggradation of the outwash fill.

Three low end moraines, consisting of about 2 to 3 m of stony till, are associated with the terrace gravels. Their crests, which lie at about 645 m, rise gently southwest toward South Cle Elum Ridge. Scattered exposures of till, also mapped as Indian John Member, occur along roads west of Indian John Hill. In most profiles, the till is weathered to depths of 2 to 2.4 m, and rinds average 1.0 mm thick. Some andesite clasts are thoroughly decomposed.

A group of subdued moraine ridges at the southeast end of Cle Elum Ridge trending northwest to west indicate that the terminus of the Yakima valley glacier during the Indian John advance lay in the lower Teanaway River valley opposite Lookout Mountain. Strongly deformed, rhythmically laminated lake sediments containing abundant drop stones underlie the stony till of the moraines. Axial planes of overturned folds dip west, consistent with a glacier advance from that direction.

A related lateral moraine can be traced discontinuously for nearly 10 km westward across the south slope of the Cle Elum Ridge and has a mean gradient of 29 m/km. The position of the moraine indicates that ice probably was confined to the main valley of the Yakima River and did not overtop the crest of the ridge. Corresponding moraines were not found along the west base of Lookout Mountain probably because of subsequent landsliding there.

Outwash deposited during the Indian John advance occurs as discontinuous terrace remnants in the gorge of the Yakima River downvalley from Indian John Hill and as dissected remnants along the west side of Kittitas Valley. The terrace surface descends from an altitude of 640 m at the head of the valley train to about 485 m opposite Ellensburg. Beyond Thorp Prairie, the terrace surface has been extensively mantled with basaltic fan alluvium. The edge of the terrace is less gullied than those of older and higher adjacent terraces.

More than 100 bore holes drilled by the Northern Pacific Railroad between Lakedale and the mouth of the Teanaway River indicate that the bedrock valley floor descends at least to an altitude of 365 m and that it is overlain by a sedimentary fill 200 m or more thick (Fig. 8). Basal sediments consist largely of till, gravel, and sand, most likely of Kittitas age. These are overlain in turn by a thick body of bluish lacustrine silt, clay, and sand that thickens downvalley from about 60 m to 150 m. Except through one segment 2 km wide where the top of the lake sediments has been

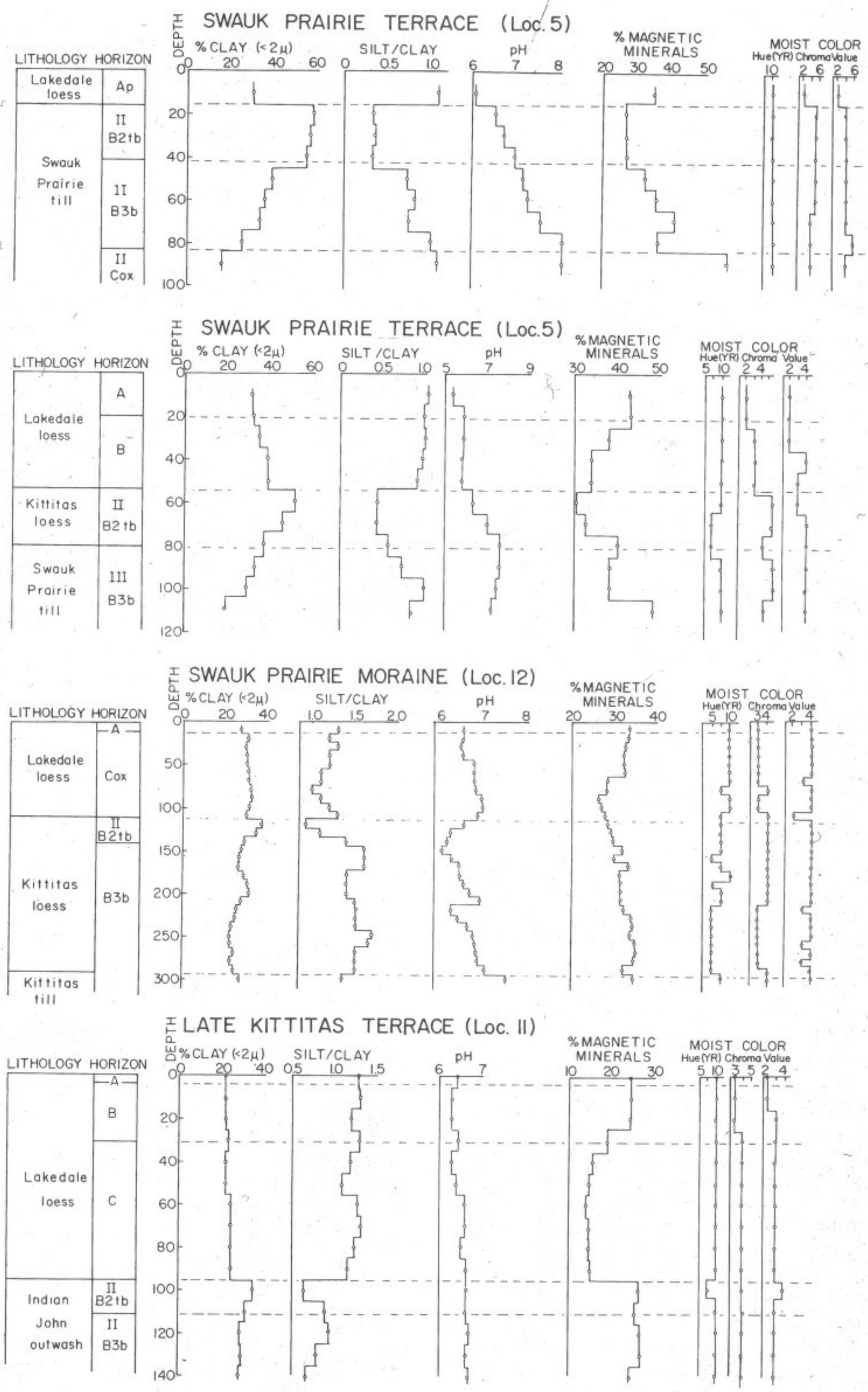

Figure 9. Profile data for post-Kittitas and post-Lakedale soils.

eroded, the upper surface of the unit is nearly planar and slopes gently downvalley. Coarse gravel and sand overlying the lake sediments are largely Lakedale outwash and postglacial alluvium. The lake in which the sediments were deposited apparently formed as the glacier retreated from the Indian John terminal moraine complex. A thick plug of till and outwash that choked the gorge of the Yakima River south of Lookout Mountain would have ponded meltwater upvalley to a depth of about 275 m until breaching of the drift dam permitted lowering and eventual drainage of the

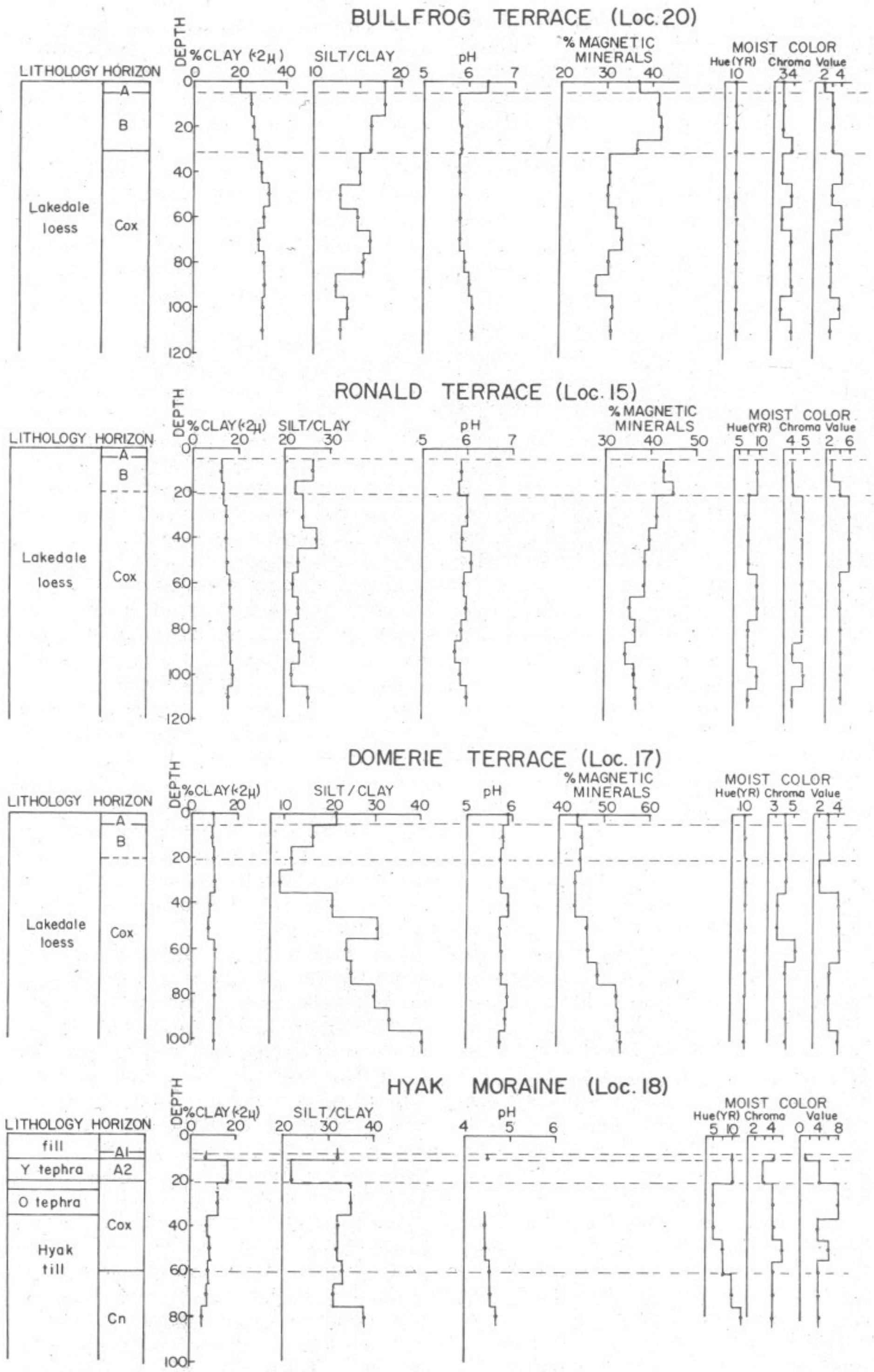

Figure 9. (*Continued*).

lake. Distribution of the lake sediments and the general topographic configuration of the valley show that the lake was 3 to 5 km wide and at least 15 km long, or somewhat larger than any of the three existing lakes in the valley.

Loess of Kittitas age mantles moraines and terraces adjacent to the Yakima River east of Teanaway. Originally it also blanketed the surrounding uplands, but it has been extensively reworked and now makes up part of a mixed colluvial layer, locally 2 m or more thick, found on most hillslopes. The post-Kittitas soil generally is developed in the top of the loess sheet; in most places it is overlain, in turn, by Lakedale loess. Kittitas loess is commonly quite sandy (40 percent by weight), with silt and clay each ranging from 20 to nearly 40 percent. In most profiles, the loess is oxidized to its base, and its moist color typically is dark brown to reddish brown. Apparent absence of Kittitas loess on late Indian John recessional sediments suggests that loess deposition in the main valley west of Lookout Mountain ceased during ice retreat. Possibly this was due to the presence of the large lake behind Indian John terminal drift, for this water body would have covered potential areas of deflation on the valley floor and greatly reduced the supply of eolian sediment.

Post-Kittitas Soil

The post-Kittitas soil is the most distinctive soil-stratigraphic unit in the upper Yakima River valley and, where recognized, constitutes the best single criterion for separating the Kittitas and Lakedale drift sheets. At a typical section at Swauk Prairie (Fig. 1, loc. 12; Table 4), the soil is developed on Kittitas loess and is buried by Lakedale loess (Fig. 9). In this and other profiles, it commonly has a well-marked textural B horizon (Bt horizon), 20 to 30 cm thick, recognizable in the field by substantial clay enrichment, a brown color (7.5YR 4/4), and by angular prismatic to blocky peds having distinctive clay skins. An A horizon generally is not recognizable. The soil contrasts with the post-Lakedale soil, which lacks clay enrichment and typically has a dark brown (10YR 4/3) color-B horizon (Bs horizon).

The interval during which the post-Kittitas soil developed apparently was marked by cessation of loess deposition and relatively stable slope conditions. No sediments dating to this interval have been identified. This interval compares closely in character with the present interglacial which, under natural conditions, is a time of dominant slope stability, soil formation, and moderate stream degradation.

Drift of Late Kittitas (?) Readvance. Five isolated exposures of oxidized drift lying stratigraphically below Lakedale outwash, at least three of which occur above Indian John lake sediments, provide evidence of a glacial advance between the Indian John and Bullfrog advances. Although possibly this drift represents a pre-Bullfrog advance of Lakedale ice, the available data favor its interpretation as a late Kittitas readvance.

Approximately 20 m of drift, oxidized to a depth of about 6 m, are exposed beneath Ronald outwash 0.2 km west of Cle Elum (Fig. 1, loc. 8). Ten meters of folded and locally faulted laminated silty sand containing drop stones and lenses of gravel are overlain by thin beds of compact and poorly sorted pebble-cobble gravel that grades upward into 6 m of very stony till containing boulders as large as 2 m. Nearby boreholes indicate that these sediments overlie recessional Indian John lake sediments; the deformed basal silty sand at this exposure possibly represents the top of the lacustrine section.

Pebble-cobble gravel at three other localities (9, 10, and 11), all close to the same altitude and occupying a similar stratigraphic position, is oxidized to a depth of at least 2 to 4 m, and many stones are weathered through. At locality 11, 95 cm of Lakedale loess overlies a Bt horizon developed in pebble-cobble gravel (Fig. 9). The buried soil appears identical to the post-Kittitas soil at Swauk Prairie, with which it tentatively is correlated.

Lakedale Drift

Valley floors throughout much of the higher parts of the Yakima River drainage basin are mantled with comparatively unweathered and little-eroded drift that retains much of its original constructional morphology. Terminal moraines of this youngest major drift sheet cross the main valley about 5 km west of Cle Elum, and outwash terraces related to them and to a succession of younger moraines upvalley can be traced discontinuously as far as Ellensburg. The formation is named for the community of Lakedale, near which the three oldest members of the drift sheet are well displayed. Although weathering rinds and other relative-age criteria can be used to distinguish subunits of the Lakedale Drift, the primary basis for subdivision was the outwash terraces that are traceable to moraines in each of the three major tributary valleys near the head of the Yakima River.

Bullfrog Member. The outermost Lakedale moraines form two arcs across the main valley, delimiting the former coalescent termini of two ice lobes (Fig. 1). The crest of one moraine (704 m) marks the downvalley limit of ice in Cle Elum valley, whereas the other (665 m) marks the ice limit in the main Yakima River valley. Each moraine is compound and consists of two distinct crests; two tills, separated by a layer of coarse gravel, are exposed in the inner of the two terminal loops of the Yakima valley ice lobe, implying two distinct advances. Outwash graded to the moraines forms a prominent terrace, as much as 75 m above the Cle Elum River but decreasing downstream to only about 25 m opposite Indian John Hill. Only about 50 percent of the inferred original surface of the valley train remains uneroded.

The Bullfrog Member is well exposed in a large borrow pit beside the Cle Elum River 2 km upstream from Bullfrog Pond (Fig. 1, loc. 13; Table 4), where more than 80 m of outwash gravel directly underlies till of the Bullfrog moraine. The basal sediments are predominantly pebble gravel with lenses of sand, and they display cut-and-fill stratification throughout. They grade upsection into coarser cobble-boulder gravel containing clasts as much as 1 m in diameter. The upward coarsening of the gravel body is similar to that which makes up the Indian John terrace; it is believed to reflect progressive aggradation along the valley floor during advance of the glacier. The gravel is capped by up to 1 m of oxidized silty sand, lacking obvious stratification and probably eolian in origin, which in turn is overlain by up to 5 m of stony light bluish-gray till oxidized to a depth of 1.5 m.

Lake sediments lying behind the outer Bullfrog moraine in the Cle Elum valley appear in several boreholes between altitudes of 595 and 635 m beneath sediments of post-Bullfrog age (Fig. 8). In two boreholes, a layer of sandy gravel separates a lower bluish-gray clay from a thinner upper one. The evenly laminated upper clay crops out beneath Ronald drift at two places along the west side of the Cle Elum valley close to river level (625 m). The basal clay unit is interpreted as the deposit of a lake dammed by the outer Bullfrog moraine. If the interstratified gravel is related to the second of the two inferred Bullfrog advances, then the upper lacustrine unit may have been deposited in a lake impounded by the inner moraine. The subsurface data indicate that the lake sediments extend upvalley at least as far as Cle Elum Lake, implying a former lake at least 6 km long.

Ronald Member. A prominent moraine loop about 1 km northwest of the Bullfrog moraine marks the position of the Cle Elum valley glacier during a subsequent halt or readvance. Drift comprising this moraine and the associated outwash train are named for the nearby town of Ronald. A comparable moraine, consisting of several nested loops, occurs in the main valley 3 km above the outermost Bullfrog moraine (Fig. 1, loc. 14). There a cutbank adjacent to the stream exposes a thick section of gravel and evenly bedded sand and silt. Till occurring at the base of the section probably dates to the Bullfrog advance.

A high outwash terrace connects the two Ronald moraines and can be traced through the Bullfrog moraines, beyond which several long terrace remnants flank the Yakima River. Through most of the valley, Ronald outwash consists largely of rounded cobble-pebble gravel and is mantled with about 1 m of loess. Only 30 percent of the original valley train has escaped postglacial erosion, but preserved depositional surfaces are only slightly gullied.

Another moraine immediately west of the Ronald moraine complex in the Yakima valley was built during a readvance of the glacier. The internal stratigraphy of the moraine was formerly displayed in a cutback along Interstate 90 at Nelson (Fig. 1, loc. 10), where laminated lake clay is strongly deformed into a series of faulted overturned folds with axial planes dipping 30° to 45° northwest upvalley (Porter, 1969, Fig. 24). The clay passes upward into complexly intermixed clay, silt, and sand as much as 5 m thick. Up to 22 m of deltaic silty sand, which grades upward into coarse sand and pebble gravel, is overlain by a fissile pebbly till, as much as 4.5 m thick. In an adjacent section next to the Chicago, Milwaukee, St. Paul, and Pacific Railroad track, the till cuts across bedded lake sediments, the contact rising from west to east. The stratigraphic sequence indicates that proglacial lake sediments were deformed by a readvance of the glacier following its retreat from the Ronald moraine. A substantial recession, probably 5 km or more, is implied by the extremely fine textured character of the lake sediment and the apparant absence of rafted stones within it.

A terrace intermediate in altitude between the Ronald and Domerie terraces is provisionally attributed to the late Ronald readvance, but remnants of it are few and discontinuous and could not be traced directly to the moraine. Near Cle Elum, the terrace stands about 12 m below the Ronald terrace and has a similar gradient.

Domerie Member. Prominent moraine systems surround the lower ends of Kachess Lake, Swamp Lake, and Keechelus Lake, indicating substantial retreat (19 to 34 km) of the Yakima valley glacier after the late Ronald readvance and its separation into several ice streams. The Cle Elum valley glacier concurrently experienced only a modest retreat of 3 km. The apparently anomalously larger retreat of the western glacier system can be explained by the geometry of the upper Cle Elum and Kachess valleys. A low divide at Cooper Pass (1,000 m) channeled early Lakedale ice as much as 150 m deep and 3.6 km wide from the upper Cle Elum drainage basin into the adjacent Kachess basin, but recession and thinning of the glacier system following the late Ronald readvance apparently reduced substantially the flow of ice through this pass. This led not only to dramatic terminal retreat of the Kachess glacier, which then was fed only from its own comparatively restricted catchment basin, but also of the Keechelus glacier, which had received a significant influx of ice through a deep valley between Keechelus Ridge and Amabilis Mountain. By Domerie time, a small lobe of ice remained in this valley, but it did not join the Keechelus glacier.

Each of the four main glacier terminal positions is marked by a moraine complex composed of as many as six distinct ridges. Most ridges do not exceed 5 m in height and are separated by broad low swales. At Kachess Lake, the inner two moraines are largely submerged except during times of maximum drawdown of the reservoir (Fig. 10). Drift comprising the moraines and associated valley trains is named for Domerie Flats, a broad outwash surface graded to moraines bordering Cle Elum Lake. The innermost of these moraines is composed of silty, stony till, in places consisting largely of deformed lake sediments (Fig. 1, loc. 16; Table 4). Fold axes parallel the lake margin, and axial planes dip upvalley (northwest). Borrow pits along the crest of the moraine west of the dam disclose large boulders (2.5 m), and comparably large stones are found in the outermost Domerie moraines at Swamp Lake.

Remnants of the Domerie valley train occur as prominent terraces below each of the major moraine complexes and can be traced at least as far as the gorge south of Lookout Mountain. Through much of its length, the terrace lies only 2 to 4 m above present river level; but close to the moraine complexes, the valley train has been entrenched to a depth of as much as 20 m. Near Cle Elum Lake, at least three terraces are discernible below the highest Domerie surface (Fig. 5). Reconstructed profiles indicate that the two higher terraces are paired; therefore, each presumably represents a constructional surface graded to a moraine of the Domerie complex, and it records an interval of readvance or terminal stability of the Cle Elum valley glacier. The lowest terrace appears to be a cut surface developed during or after ice recession.

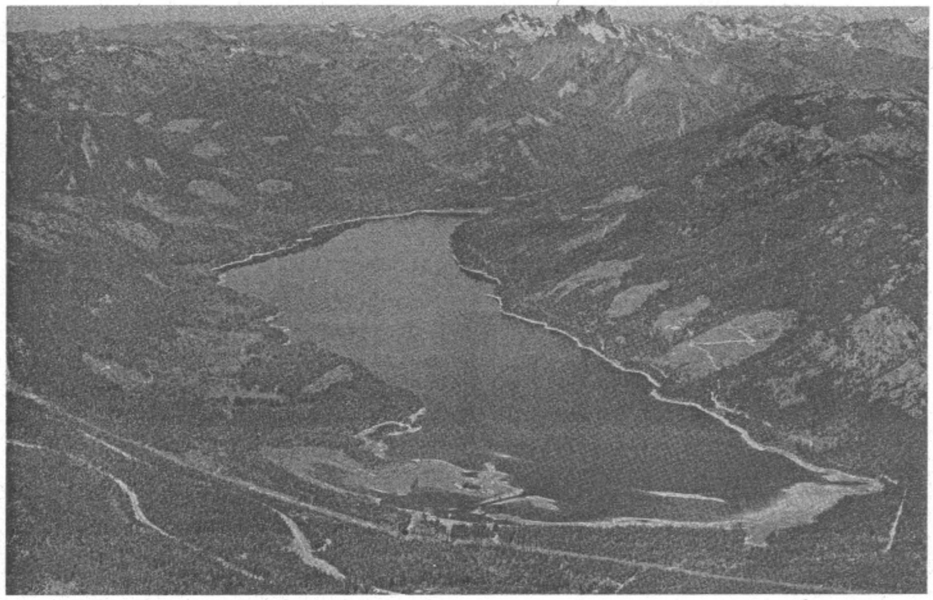

Figure 10. Domerie moraines enclosing lower end of Kachess Lake, showing partially submerged crest of inner moraine. View is north toward Cascade crest and Glacier Peak (far distance), 100 km away (photograph by Austin S. Post).

Hyak Member. The Hyak Member, named for the youngest Lakedale drift exposed near Hyak, represents a late stillstand or readvance of glaciers in the higher parts of the Cascade Range. By Hyak time, the large trunk glacier systems had disappeared, and only small residual valley and cirque glaciers remained, terminating at or above 850 m near the range crest and in tributary valley heads farther east.

Moraines of Hyak age at Snoqualmie Pass are typical of those found throughout this sector of the range. Glacier ice in the valleys of Commonwealth Creek and the headwaters of the South Fork of the Snoqualmie River coalesced near Snoqualmie Pass, then bifurcated and flowed both down the South Fork and across the divide to Hyak. Moraines occur through a distance of 3.2 km between Hyak and the pass; at their downvalley end, they grade into a low outwash terrace that slopes southeast to the shore of Keechelus Lake. Below the pass, the moraine complex consists of a series of irregular ridges separated by swales and closed depressions, many containing small ponds or bogs. Natural and artificial exposures show that moraines consist largely of crudely stratified flowtill, evenly laminated lacustrine sediments, and fluvial sand and gravel. This assemblage of sediments and morphology suggests that debris-mantled terminal ice of the Hyak glacier became stagnant and melted out differentially. By contrast, the innermost ridges of the moraine complex are sharp-crested, arcuate loops that cross the valley at the drainage divide, and they indicate that the glacier terminus remained active and fluctuating above the belt of dead-ice terrain.

The crest of the pass is a broad, flat plain underlain by bog sediments and lake silts as much as 2.2 m thick (loc. 21). Stony bluish-gray till at the base of exposed sections is overlain by laminated grayish silt, clay, and sand, and locally by gravel, deposited during the initial stages of ice recession. These sediments are overlain by peat, interstratified with which are the O, Yn, and W tephra layers (Table 5). Sections through a small arcuate moraine ridge at the west end of the pass show that stony till overlies the basal grayish lacustrine sediments, which are strongly folded. The contact between the till and lake sediments dips northwest, as do the axial planes of folds, indicating a readvance of the glacier terminus from that direction.

Many cirque basins near the Cascade crest at altitudes of 1,225 to 1,400 m formerly containing Hyak ice streams are now devoid of ice and show no indication of having regenerated glaciers during the late Holocene. Such cirques last contained glacier ice at the close of Hyak time and are floored by drift of the Hyak Member and by postglacial sediments.

Lakedale Loess. Loess related to the Lakedale ice advances mantles much of the landscape downvalley from the Domerie end moraines and is especially prominent between Swauk Prairie and Easton. Through this reach, it covers all outwash terraces of Lakedale age and forms a discontinuous mantle of variable thickness on end moraines and adjacent hillslopes. Downvalley it commonly overlies Kittitas loess and thinly mantles Thorp outwash.

Although the loess is as much as 1.6 m thick on the Bullfrog terrace, it typically is no more than 1 m thick; on surfaces of Domerie age, it averages 70 cm (Fig. 4). Thicker loess on older surfaces suggests a longer period of eolian sedimentation and

TABLE 5. PHYSICAL PROPERTIES AND AGES OF TEPHRA LAYERS IN THE UPPER YAKIMA RIVER AND SOUTH FORK SNOQUALMIE RIVER DRAINAGE BASINS

Tephra layer	Source volcano	Mean thickness (cm)*	Mean grain size (mm)*	Moist Color*	Approximate ^{14}C age†
W	Mt. St. Helens	0.5	0.1	10YR 6/4	450
Yn	Mt. St. Helens	8.0	0.5	10YR 3/4	3400
O	Mt. Mazama	7.0	0.1	5YR 4/8	6600

*Values from representative sections near Cascade Crest
†Mullineaux (1974)

implies that deflation was essentially continuous on active outwash valley trains from the time of the Bullfrog advance through the Domerie advance. This inference is supported by the apparent absence of buried soils within the loess blanket. Loess is very thin or absent on Hyak deposits, probably because valley-train surfaces below the Domerie moraines were inactive by Hyak time, and valley floors above the moraines were largely submerged beneath extensive meltwater lakes.

Like Kittitas loess, Lakedale loess is coarse textured, with sand, silt, and clay typically averaging, respectively, about 50, 30, and 20 percent by weight. Loess is finer grained southwest of the Yakima River and at increasing distances northeast of the valley center, implying that dominant winds during loess deposition were southwesterly.

Holocene Sediments

Steep, sharp-crested moraines fronting existing glaciers along the Cascade crest extend as much as 1 km beyond modern termini. Such deposits also are found in cirques and valley heads now devoid of glacier ice but lying at altitudes equal to or only slightly lower than those of nearby glaciers. Moraines reach altitudes as low as 1,250 m, some 215 m below the level of the lowest modern glacier terminus. The rubbly drift commonly bears only scattered herbaceous plants and a sparse lichen cover. Soil profiles are shallow ($\leq$ 20 cm) and immature. The youngest moraines lack tephra and therefore are less than about 450 yr old, whereas the outer ridges bear a thin discontinuous ashy mantle of tephra layer W, but no Yn tephra, and consequently are between about 450 and 3,400 yr old.

Postglacial alluvium is confined largely to modern floodplains which range in width from only a few meters to as much as 2 km, as in the case of the Yakima River. The alluvium of even the major streams is probably thin and consists mostly of point-bar and channel gravels derived by reworking of outwash sediments, and of overbank silts and lacustrine clays. Other major bodies of Holocene alluvium occur as large alluvial fans between Kachess Lake and Nelson. Profiles of the Lakedale terrace through this sector of the valley indicate that fan alluvium locally reaches a thickness of more than 25 m (Fig. 5). Although part of these sediments may have been deposited during the closing phases of the last glaciation, when glaciers had retreated to the vicinity of the Hyak moraines, the occurrence of Mazama (O) tephra deep within some exposed fans indicates that the bulk of their sediments accumulated in post-Lakedale time (Hopkins, 1966; Pavish, 1972). The presence of tephra layer Yn at or close to the surface of the fans shows that streams had changed to a predominantly degradational regime by about 3,000 yr ago.

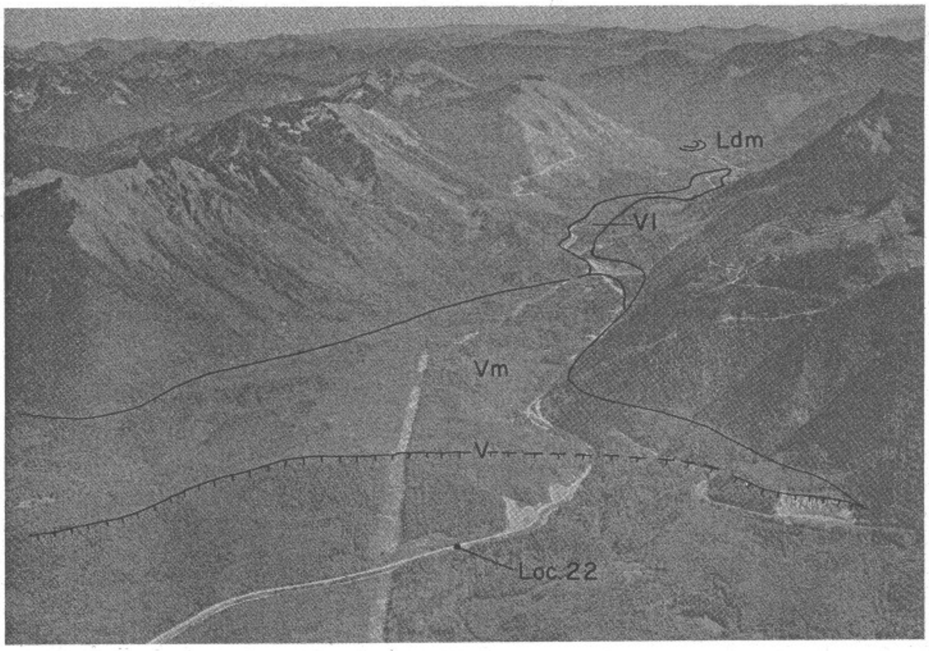

Figure 11. View east toward South Ford delta moraine (Vm) blocking lower (west) end of South Fork valley. Vashon lake sediments (Vl) extend beyond moraine toward moraine complex at Bandera (Ldm) which lies at major bend of valley (photograph by Austin S. Post).

Post-Lakedale Soil

Soils formed on Lakedale Drift are weakly developed and contrast markedly with the post-Kittitas soil (Fig. 9). None of the profiles investigated possesses a textural B horizon. Although some of the soils developed on the Bullfrog, Ronald, and Domerie Members display weak color-B horizons (10YR 4/3), those formed on Hyak surfaces have A-C profiles. West of Lake Kachess, in the region where mean annual precipitation exceeds 125 cm, podzolic soils predominate, and an A_2 horizon is present in most profiles. Through this belt, soil profiles commonly include one or more tephra layers in their upper parts, the Yn layer being the most nearly ubiquitous and most easily recognized. Not uncommonly, it coincides with the A_2 horizon developed under dense conifer forest. At Snoqualmie Pass, both the W and O tephra layers also appear in bog profiles, but the former is so thin that it usually is unrecognizable on forest floors where surface sediments are subject to disruption by plants, animals, and frost.

Weathering profiles developed in Lakedale loess on outwash terraces tend to be deeper with increasing age of terraces. This may simply reflect a longer period of soil formation on successively older terraces. However, because eolian sedimentation probably persisted on all terraces until at least the termination of the Domerie advance, the apparent deeper weathering of loess on the older Lakedale terraces may indicate progressive accretion of eolian sediment while soil was forming. This interpretation is favored because of the general similarity of soil properties for all pre-Hyak Lakedale surfaces. Although the degree of soil development on Hyak drift may be broadly comparable to that on older surfaces downvalley, strict comparison is difficult because Hyak sediments commonly lack a mantle of loess.

SNOQUALMIE RIVER DRAINAGE BASIN

Drift of Lakedale age can be traced from the upper Yakima River drainage basin across the low divide at Snoqualmie Pass and into the adjacent west-draining South Fork valley. There it can be related stratigraphically to deposits of the Puget Lobe of the Cordilleran Ice Sheet, for which a separate stratigraphic nomenclature has been developed.

Drift of the Puget Lobe

The Puget Lobe advanced southward from Canada into the Puget Lowland at least four times during the Pleistocene, depositing a succession of drift sheets that have received careful study during the past two decades (Crandell and others, 1958; Armstrong and others, 1965; Crandell, 1965). Sublobes of the glacier pushed into the lower ends of west-draining Cascade valleys, blocking streams and depositing thick drift. The Snoqualmie Embayment, a reentrant in the Cascades formed where the valleys of the South and the Middle Forks of the Snoqualmie River and the Cedar River meet the Puget Lowland, contains an array of landforms and sediments formed during at least two such incursions of northern ice. Mackin (1941) suggested that during the last glaciation, valley glaciers had retreated from their maximum stands prior to the culminating advance of the Puget Lobe. This investigation lends support to Mackin's conclusions and has generated additional data bearing on the glacial history of the embayment.

Drift of Pre-Vashon Age. Excavations in 1972–1973 along Interstate 90 near the bottom of the massive South Fork morainal embankment (Figs. 2 and 11, loc. 22) exposed evenly laminated lake sediments at an altitude of 300 m. The sediments contain peaty organic matter and wood fragments having a radiocarbon age of >50,000 yr (UW-243); they therefore antedate Vashon Drift in the adjacent lowland, which is bracketed by dates of about 15,000 and 13,500 years (Mullineaux and others, 1965). The lake sediments very likely date to pre-Fraser ponding in the Snoqualmie Embayment associated with an advance of the Puget Lobe into the southern Puget Lowland.

Vashon Drift. The position of the glacier margin during the maximum (Vashon) advance of the Fraser Glaciation in the Snoqualmie Embayment is marked by a high, massive delta moraine complex that crosses the lower ends of the principal valleys (Fig. 11). The top of the drift body in each valley stands at about 500 m, but it descends gradually both east and south. The bulk of the exposed sediment consists of coarse boulder and cobble gravel along the proximal (ice-contact) face of the morainal embankment, but it passes upvalley into well-sorted gravel and sand and finally into evenly laminated lacustrine silt and clay at least 90 m thick. The lateral continuity and upvalley slope of these deposits indicate that meltwater was ponded in each of the three valleys as the Puget Lobe advanced into the embayment and that the end moraine constructed along its margin was built into deep lakes. Because the flow of water between the succession of ice-dammed lakes ponded in the western Cascade valleys was to the south, streams entered each next lower lake on its north side. Consequently, sediments prograded both southward and eastward into the lakes, producing asymmetrical delta moraines.

A prominent linear hill (320 m) rising above the South Fork south of Sallal Prairie was interpreted by Mackin (1941) as a recessional moraine ("Sallal Moraine"). Because rock crops out at the crest of the hill and at its northern margin, the feature is here reinterpreted as a till-mantled bedrock high that has no special significance in the history of glacier recession.

Sallal Prairie is underlain by a broad fan-shaped body of coarse gravel that resulted from dissection of the Middle Fork delta moraine after recession of the glacier. A similar gravel fan opposite the mouth of the South Fork valley was deposited against residual stagnant ice following retreat of the terminus.

Lakedale Drift

Evidence for a pre-Vashon advance of a valley glacier along the South Fork of the Snoqualmie River during the last glaciation was described by Mackin (1941), who found alpine till beneath rubbly sliderock, in turn overlain by Vashon lake sediments. Although the exposure he described is no longer visible, similar sections with lake sediments overlying little-weathered alpine till were found in three places between the delta moraine and Bandera (Fig. 2). The till indicates that a valley glacier advanced to a point within at least 4 km of the Snoqualmie Embayment prior to the maximum stand of the Puget Lobe. Its exact limit is not known because terminal deposits are buried by Vashon Drift.

By the time the Puget Lobe reached its greatest extent, the terminus of the South Fork glacier must have retreated to a point 15 km or more from the crest of the delta moraine, for no evidence was found to indicate that the valley glacier terminated in the lake ponded by the lowland ice. A group of at least 5 nested moraines just upvalley from the airstrip at Bandera (510 m) is believed to mark the approximate position of the glacier front at that time. Associated lateral moraines can be traced discontinuously eastward along the south wall of the valley and rise progressively toward the drainage divide. The easternmost Vashon lake sediments that were found lie 1 km west of the moraines and are coarser than lake sediments downvalley, implying an eastern source of detritus. Although the outermost moraine loop lies only 0.5 km beyond the inferred eastern limit of the former lake, alpine drift could not be traced directly into lacustrine sediments because of extensive postglacial erosion and alluviation through this reach of the valley.

Correlation of the moraines at Bandera with Lakedale Drift east of the crest could not be based on weathering criteria because Teanaway Basalt clasts are not found in the South Fork drainage basin and because other weathering criteria are too imprecise to correlate members of a drift sheet. However, the reconstructed profile of the South Fork glacier upvalley from the Bandera moraines lies far above the limit of Hyak Drift at Snoqualmie Pass and well below the projected upper limit of Ronald and Bullfrog ice in the Keechelus valley (Fig. 6), but it coincides closely with the Domerie ice limit. On this basis, the moraines are believed to correlate broadly with the Domerie Member east of the crest. If the former are correlative with the Vashon maximum advance, as inferred, then the Domerie Member and outermost Vashon Drift in the Puget Lowland are approximately the same age.

By the time of the Hyak advance, the terminus of the South Fork glacier had retreated some 7 km farther upvalley to a point near the mouth of Denny Creek. The glacier terminus probably lay between 675 and 760 m during its fluctuating recession, or some 150 m lower than the glacier tongue that flowed southeast across the pass. In valleys tributary to the South Fork, glaciers had disappeared from all but a few of the highest and most-sheltered cirque basins where small residual ice masses, generally no more than 1 km² in area, survived.

CHRONOLOGY AND REGIONAL CORRELATIONS

Radiocarbon dates of samples collected near Seattle indicate that the Puget Lobe reached its maximum position during the Fraser Glaciation between about 15,000 and 13,500 yr ago (Mullineaux and others, 1965). Wood from the upper part of Vashon lake sediments exposed along the South Fork of the Snoqualmie River at Garcia has an age of 13,570 ± 130 yr (UW-35; Porter and Carson, 1971). Collectively, these dates indicate that the lobe probably reached its maximum extent about 14,000 yr ago and then underwent rapid terminal recession and massive loss of volume during the next 1,000 yr (Porter, 1970). If the provisional moraine correlations across the range crest are valid, then the Domerie Member dates approximately to this time (Fig. 12). This interpretation is supported by evidence suggesting substantial and rapid recession of valley glaciers following the Domerie advance, for each of the major Domerie moraine systems east of the crest borders a large, deep basin and lies 10 km or more downvalley from moraines of Hyak age, without evidence of intervening terminal halts. These relationships imply a general pattern of deglaciation similar to that in the Puget Lowland.

Hyak drift at Snoqualmie Pass is overlain by bog sediments containing tephra layer O. Basal peat below the tephra has a radiocarbon age of 7,140 ± 95 yr (UW-73), and wood at the base of the peat is 7,450 ± 70 yr old (UW-322). Wood enclosed in a late glacial gravel beneath the bog overlies till associated with a prominent arcuate moraine at the east margin of the pass and is 11,050 ± 50 yr old (UW-321). The stratigraphic relationships suggest that this is a close minimum age for Hyak till and that the Hyak advance probably culminated no more than several centuries earlier. This means that the Hyak Member may correlate with Sumas Drift in the northern Puget Lowland. Sumas till in southwestern British Columbia contains wood with ages of 11,000 ± 900 and 11,500 ± 1,100 yr (Armstrong and others, 1965) and is inferred by Armstrong (1975) to have been deposited during a readvance between about 11,800 and 11,400 yr ago. McNeeley Drift at Mount Rainier, which is overlain by a tephra layer (R) more than 8,750 ± 280 yr old (Crandell, 1974), may also correlate with Sumas Drift and repre-

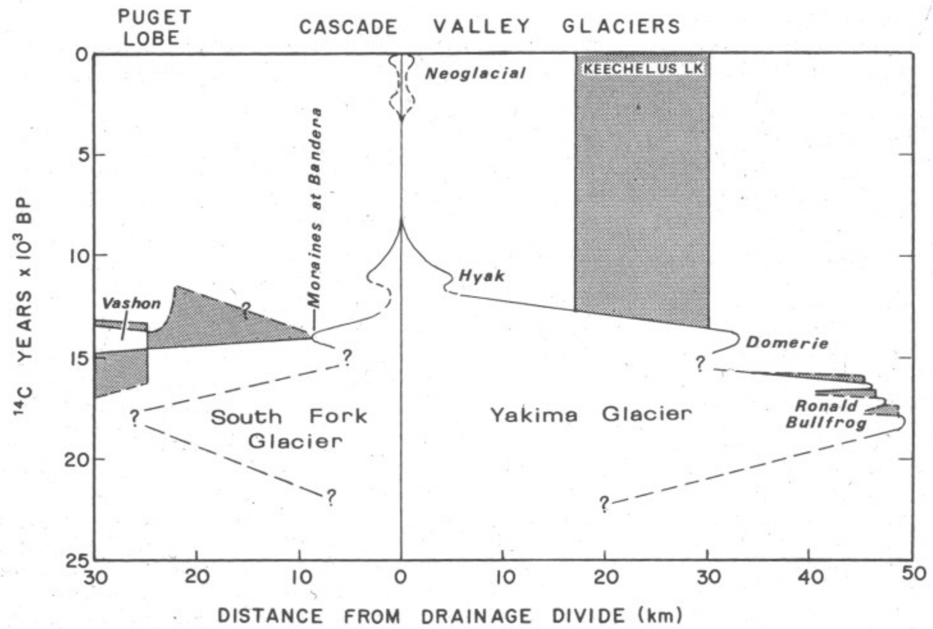

Figure 12. Time-distance curve of glacier fluctuations along transect across the southern North Cascade Range during the past 25,000 yr. Lakes are depicted by shaded pattern.

sent an advance of glaciers in the southern Cascades that was approximately contemporaneous with the Hyak advance at Snoqualmie Pass.

If the inferred correlation of the Domerie Member with Vashon Drift is correct, then the Bullfrog and Ronald Members must predate the Vashon maximum. Evans Creek Drift, which records a pre-Vashon advance of valley glaciers near Mt. Rainier (Crandell, 1963, 1974), may correlate with either or both of the pre-Domerie members of the Lakedale Drift. Although Evans Creek Drift has not been dated in its type area, its weathering characteristics are not greatly different from those of McNeeley Drift, implying that the two drifts are close in age. Deposits inferred to be equivalent to Evans Creek Drift and representing the maximum advance of valley glaciers on southeastern Vancouver Island during the Fraser Glaciation were deposited shortly after 19,150 ± 250 yr ago (GSC-210), according to Halstead (1968). Supporting data bearing on the possible age of the Evans Creek advance come from the Olympic Peninsula where Heusser (1973) has identified a pollen zone (S-7), dated between 19,000 and 18,000 yr old, which records a pre-Vashon interval of tundra vegetation implying rigorous full-glacial conditions.

Radiometric dates have not yet been obtained for pre-Lakedale drifts, but relative-age criteria provide some insight into their possible ages. I regard the Kittitas Drift as probably broadly correlative with Salmon Springs Drift in the Puget Lowland, which, like the Kittitas, is more extensive than outermost drift of Fraser age. The contrast in weathering and postglacial modification of Kittitas and Lakedale Drifts suggest that postglacial time has been substantially shorter than the length of the next earlier major nonglacial interval. Weathering profiles developed on Kittitas Drift are far deeper than those found on Lakedale Drift, and the post-Kittitas soil typically has more reddish hues than does the post-Lakedale soil; it also has a well-developed textural B horizon that is lacking in the younger soil. Comparable contrasts in post-depositional weathering and erosional modification of Salmon Springs and Fraser deposits are found along the west margin of the Puget Lowland where the two drifts are juxtaposed (Carson, 1970; W. E. Long, 1975, personal commun.). Contrasts similar to these also are found between Fraser Drift and Wingate Hill Drift in the western Cascade foothills near Mount Rainier; the latter unit was considered by Crandell (1974) as possibly early Salmon Springs in age. Consequently, I regard the interval between the maximum Kittitas advance (Swauk Prairie) and the greatest Lakedale advance (Bullfrog) as probably being equivalent to the interval between the greatest Salmon Springs advance and the Fraser Glaciation in the Puget Lowland.

In recent years, Salmon Springs Drift has rather generally been regarded as early Wisconsin in age (Easterbrook and others, 1967; Easterbrook, 1969; Birkeland and others, 1971; Porter, 1971), but the evidence for such an age assignment is not compelling. Radiocarbon dates of peat within Salmon Springs deposits in the southeastern Puget Lowland indicate an age of at least 50,000 yr, and the one finite date obtained (50,100 ± 400 yr; GrN-4116c) on an enriched sample may reflect very small amounts of contamination (Easterbrook and others, 1967). These dates, in themselves, do not exclude the possibility that all or part of Salmon Springs Drift in the type area is pre-Wisconsin. A finite radiocarbon date of 47,600 +3,300/−1,800 was obtained from peat within sediments in the northern Puget Lowland mapped as Possession Drift by Easterbrook (1969; see also Hansen and Easterbrook, 1974) and inferred to correlate with Salmon Springs Drift. This correlation rests largely on the assumption that the Whidbey Formation which underlies Possession Drift, is equivalent to the Puyallup Formation, which lies below Salmon Springs Drift. Because no finite radiocarbon dates have been obtained from either of these formations, the assumed correlations are not demonstrable. Crandell (1974) has recently argued that the Puyallup Formation may not record the last major interglaciation, as formerly thought, but rather a much earlier interval antedating intracanyon lava flows at Mount Rainier which are 320,000 to 600,000 K/Ar yr old. At present, I consider the evidence as equivocal. Although Kittitas Drift and its probable equivalent in the Puget Lowland may date to the early Wisconsin, available evidence does not exclude an alternate interpretation that these drifts are pre-Wisconsin in age. If the interval separating the Kittitas and Lakedale advances included the last interglaciation of the marine record which culminated about 120,000 yr ago (Shackleton and Opdyke, 1973; Bloom and others, 1974), then as much as 100,000 yr would have been available to develop the post-Kittitas soil, or up to ten times as long as the interval during which the post-Lakedale soil has formed. Such an interpretation is consistent with the contrasts in soil development and relative preservation of the two drift sheets. If, instead, one were to assume that the nonglacial interval was an interstadial (or "interglacial") of mid-Wisconsin age that began about 30,000 yr ago (Easterbrook, 1969; Hansen and Easterbrook, 1974), then at most only about 15,000 yr would have been available for development of the post-Kittitas soil, an interval that I regard as far too brief to produce the observed differences in weathering, soil development, and erosional modification of the Kittitas and Lakedale Drifts.

The even more striking difference in weathering and preservation between the younger drifts and the Thorp (and pre-Thorp?) deposits suggests that the oldest glacial sediments are of considerable antiquity. This inference is borne out by results of preliminary paleomagnetic measurements in the Kittitas Valley. Lowermost eolian and colluvial silts overlying Thorp gravel at Craigs Hill in Ellensburg have reversed polarity, as do silts beneath the uppermost Thorp gravel at locality 2 near Thorp (George Kukla, 1975, personal commun.). Silts higher in the Craigs Hill section are normally polarized. Consequently, the Thorp apparently lies below the level of the Brunhes-Matuyama reversal (700,000 yr) and probably was deposited largely within the Matuyama reversed epoch. Closer age assessment may ultimately be possible by dating of one or more tephra layers exposed within the thick gravel sections near Thorp.

The interval separating the Thorp and Kittitas ice advances need not have been a single lengthy interglacial age but rather a period characterized by repeated major climatic shifts that led to growth and dissipation of glaciers in Cascade valleys. The long and complex record of climatic and ice-volume fluctuations inferred from isotopic measurements of deep-sea cores indicates that during the last 800,000 yr, major glacial ages have occurred, on the average, about once every 10^5 yr (Emiliani and Shackleton, 1974). During each such interval, large glaciers may have formed in the Cascades, but if those generated between the times of the Thorp and Kittitas advances were smaller than subsequent Kittitas and Lakedale glaciers, their depositional record may have been largely obliterated or obscured by more extensive younger drifts.

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