science for a changing world

Prepared in cooperation with Whatcom County and the Washington State Department of Natural Resources

Geomorphic Map of Western Whatcom County, Washington

By Dori J. Kovanen, Ralph A. Haugerud, and Don J. Easterbrook

Pamphlet to accompany

Scientific Investigations Map 3406

View to northeast across western Whatcom County. Lummi peninsula in foreground, Bellingham to right. Map image from Google, TerraMetrics, Landsat/Copernicus 2019.

2020

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
Kovanen, D.J., Haugerud, R.A., and Easterbrook, D.J., 2020, Geomorphic map of western Whatcom County, Washington: U.S. Geological Survey Scientific Investigations Map 3406, pamphlet 42 p., scale 1:50,000, https://doi.org/10.3133/sim3406.

ISSN 2329–132X (online)

Contents

Figures

Tables

Acknowledgments

This map was prepared for Whatcom County Council in cooperation with the Department of Natural Resources of Washington State. We thank our colleagues for their support and cooperation. They include Peter Gill, Doug Goldthorp (former Whatcom County Geologist), Mike Pelea, Linda Peterson, Paul Pittman, and J.E. “Sam” Ryan (Whatcom County Planning and Development Services); Dave Norman, Ron Teissere, and Tim Walsh (Washington State Department of Natural Resources); and Ray Wells (U.S. Geological Survey).

Geomorphic Map of Western Whatcom County, Washington

By Dori J. Kovanen[1], Ralph A. Haugerud[2], and Don J. Easterbrook[3]

Introduction

Western Whatcom County is in the northwest corner of Washington and lies at the south margin of the Fraser Lowland astride the boundary with the foothills of the northern Cascade Range. The modern landscape was largely shaped by scour and fill as the Cordilleran ice sheet advanced and retreated across the region during the last (Fraser) glaciation ~18,000 to ~11,500 years ago (fig. 1, on map sheet). Upon deglaciation, the landscape continued to evolve through the interaction of coastal, fluvial, volcanic, eolian, and hillslope processes. This report inventories and describes the landforms generated by these processes and interprets the history they record. This history will inform future investigations into the geology and hydrogeology of the area. The inventory of some landforms (for example, wetlands, alluvial flats, landslides) is also of interest because of their ecologic, economic, and (or) earth-hazards significance.

The Map Area

The map area covers approximately 1,722 square kilometers (km^2; 665 square miles, mi^2), between 123° 9′ and 122° 15′ west longitude and from the United States-Canada border at 49° to 48° 45′ north latitude. The highest elevation within the map area is 1,026 meters (m; 3,368 feet, ft), but about 70 percent of the land area is less than 152 m (500 ft) in elevation, and about 30 percent of the land area is less than 30 m (100 ft) elevation.

The southern and eastern parts of the map area are in the foothills of the northern Cascade Range, commonly called the North Cascades, which in Whatcom County includes Chuckanut, Lookout, Squalicum, and Sumas mountains, and the ridge east of Lake Whatcom, which is known locally as Stewart Mountain. Lake Whatcom and Lake Samish are large natural lakes that occupy glacier-scoured depressions between Stewart, Lookout, and Chuckanut mountains. In the foothills, bedrock is at or near the surface, and local morphology in large part reflects local differences in bedrock competence.

The remainder of the map area lies within the Fraser Lowland and San Juan Islands regions and comprises upland areas separated by lowlands. The upland surfaces consist of rolling hills of glacial drift constructed and eroded during the Quaternary. The lowlands consist largely of the Nooksack River floodplain, which extends across the map area from the North Cascades foothills to Bellingham Bay. We subdivide this area into a number of morphologic elements, which are highlighted in figures 1 and 2 (on the map sheet) and described below.

Boundary upland occupies the area immediately east of Blaine, Washington, and is part of a larger upland that extends north into British Columbia, Canada. Its surface rises to an altitude of ~158 m (520 ft).

Birch Point upland consists of the peninsula southwest of Blaine that is bounded on three sides by steep sea cliffs formed in Quaternary sediments; the surrounding water bodies are Drayton Harbor on the north, Georgia Strait on the west, and Birch Bay on the south.

Mountain View upland consists of an area of ~109 km^2 (42 mi^2) that rises to an elevation of ~117 m (385 ft) west of Ferndale, Washington. The upland is bordered on the west by sea cliffs that drop to Georgia Strait, on the north by Custer trough; and on the south by the Nooksack River and Lummi River floodplains.

Custer trough is a low-lying zone flanked by the Boundary upland to the north and Mountain View upland to the south. Dakota and California Creeks drain through the trough and discharge into Drayton Harbor.

King Mountain upland extends north from Bellingham towards the Nooksack River.

Lummi peninsula upland is an area between Lummi Bay and Bellingham Bay that rises to an altitude of ~37 m (120 ft).

Lummi Island is a northwest-southeast trending island that is ~14 km (9 mi) long and ~2.4 km (1½ mi) wide. The southern part of the island consists of a relatively rugged bedrock surface and rises to ~152 m (500 ft) above sea level. The northern part of the island is blanketed with glacial drift and averages ~46 m (150 ft) above sea level.

Point Roberts is the American portion of a ~13 km^2 (~5 mi^2) peninsula that extends across the international boundary in the northwest corner of our map area. It is ~22.5 km (~14 mi) west of Blaine. Mostly upland, it includes a small piece of the Fraser River delta that connects the Point Roberts upland to the mainland.

Sumas prairie is a low-lying area that trends northward into British Columbia. The Sumas River floodplain occupies this low-lying area and includes a portion of the historic

[1]University of British Columbia.

[2]U.S. Geological Survey.

[3]Western Washington University.

Nooksack floodplain, but is now topographically separated by levees. During flood events, the Nooksack River sometimes flows north through the Sumas prairie into Canada via the Sumas River.

Also included in the lowlands are the Wiser Lake plain and the broad Lynden-Abbotsford plain, which extend westward from Sumas prairie to the Boundary upland and southward to the Nooksack floodplain and Custer trough.

The geomorphic evolution of this landscape since the last glacial maximum is the primary subject of this report.

Previous Work

Investigations over the past 160 years have established that the geologic history—and thus physiography—of western Whatcom County includes late Cenozoic plate-boundary deformation superimposed on deformed older rocks; Pleistocene glaciation; Holocene response to deglaciation, volcanism, and rising sea level; evolving drainage networks; and ongoing tectonic deformation. We here review existing knowledge of these events, with greatest emphasis on late Pleistocene glaciation.

Late Cenozoic Plate-Boundary Deformation

The Fraser Lowland and encompassing Georgia Basin are located within the active Cascade fore-arc basin that extends from near Campbell River, British Columbia, to near Medford, Oregon, and is as much as 190 km (120 mi) wide. The North Cascades are part of the adjoining Cascade volcanic arc. Extensive exposures of plutonic and metamorphic rocks in the core of the North Cascades, on-lapping and up-warping of Miocene flood basalts on the east flank of the range (see, for example, Tabor and others, 1987), and high local relief all attest to significant late Cenozoic uplift of the North Cascades. The Fraser Lowland, a geomorphic feature, is roughly coextensive with the structural depression that Hopkins (1968) referred to as the Whatcom basin. Terrestrial Miocene strata occur at a depth of 1.3 km below sea level in two boreholes immediately north of Point Roberts and Blaine (Hopkins, 1968), which requires significant local subsidence since the Miocene. The depth of the bedrock surface beneath the top of Quaternary deposits in the lowland varies considerably. Near Ferndale (in SE¼SE ¼, sec. 35, T. 39 N., R. 2 E.) bedrock was encountered in a well at a depth of ~198 m (650 ft). Near the Canadian border, in the Sumas prairie, Pleistocene sediments as thick as 366 m (1,200 ft) (Jones, 1996) overlie as much as 3,050 m (10,000 feet) of Tertiary sedimentary rocks.

South of the Whatcom basin, the San Juan Islands and the adjoining salient of the North Cascades constitute a west-northwest trending uplift that crosses the north-south trend of the Cascade Range and Salish Lowland[4]. By analogy with the Seattle uplift and Seattle basin farther south, the San Juan uplift and Whatcom basin may be western extensions of the Yakima fold belt, which accommodates northeast-southwest shortening between the rigid Coast Range block of western Oregon and the relatively stable part of the North American Plate (Wells and others, 1998). Reidel and others (1989) indicate that deformation in the Yakima fold belt began at least as early as the Miocene. Active faulting east of the map area (discussed below) and GPS (Global Positioning System) data summarized by McCaffrey and others (2013) demonstrate that shortening continues today. Wells and others (1998) suggested that rotation of the Oregon Coast Range and shortening in the Yakima fold belt are far-field effects of northward translation along the San Andreas transform fault.

Bedrock exposed at the margins of the map area (southern Lummi Island, North Cascade foothills south of Bellingham, and Sumas Mountain) is Eocene and older (Miller and Misch, 1963; Easterbrook, 1976a; Johnson, 1984; Lapen, 2000) and has been strongly deformed (fig. 3). This is especially evident on Chuckanut and Lookout Mountains, where erosion has etched out resistant sandstone ridges in the Eocene Chuckanut Formation. The ridges outline map-scale folds that plunge to the northwest and verge to the northeast. Much of this deformation probably predates latest Eocene establishment of the Cascade arc.

Pleistocene Glaciation

Sediments preserved in coastal lowlands and adjacent valleys of the southern Salish Lowland show that the Cordilleran ice sheet covered the region at least six times during the Pleistocene, or within the past 2 million years (Crandell and others, 1958; Armstrong and others, 1965; Easterbrook, 1969, 1986, 1992; Easterbrook and others, 1967; Ryder and others, 1991; Hicock and others, 1999; also see review by Booth and others, 2004). There is minimal evidence for older glaciations in western Whatcom County because of extensive erosion and deposition during the last, Fraser, glaciation.

Fraser Glaciation and its Subdivisions

Armstrong and others (1965) divided the last (Fraser) glaciation of northwestern Washington and southwestern British Columbia into four geologic-climate units (fig. 4):

- *Evans Creek stade*.—An early alpine phase that preceded the southward advancing Cordilleran ice sheet. No record of the Evans Creek stade has been recognized in western Whatcom County.

- *Vashon stade*.—Marked by the expansion of the Cordilleran ice sheet into the lowlands and northern Cascades about 18,000 years ago. At its maximum extent shortly after 16,000 years ago (~13,000 radiocarbon years before present [^{14}C yr B.P.]; Haugerud, 2020), the Puget lobe extended across the Puget Lowland between the Cascade Range and Olympic Mountains and terminated south of Olympia, Washington (fig. 5), while the Juan de Fuca lobe of the ice sheet extended westward along the Strait of Juan de Fuca to near the continental

[4] The Salish Lowland (Haugerud, 2004) consists of the Georgia Depression, Fraser Lowland, and Puget Lowland.

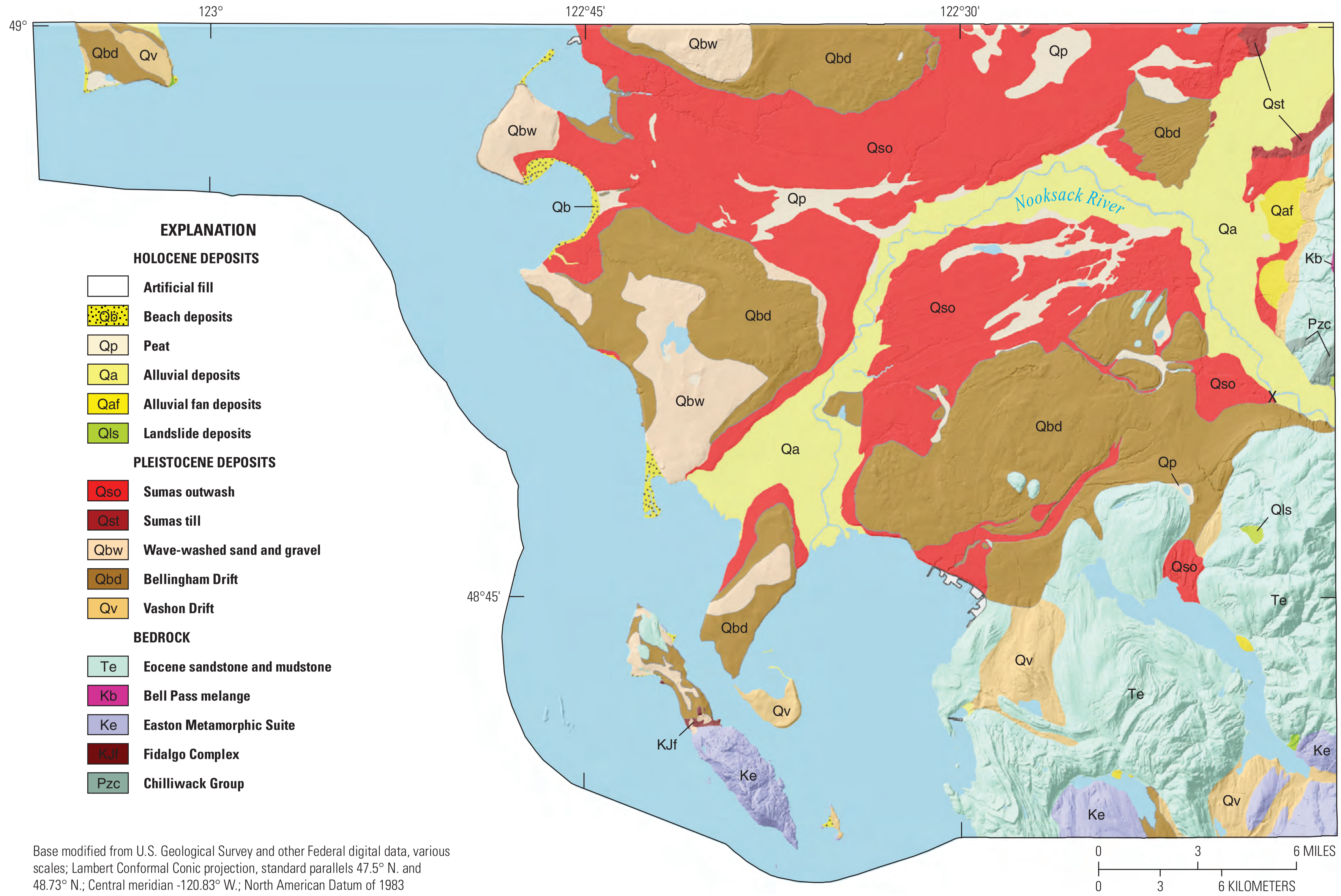

Figure 3. Geologic map of western Whatcom County, Washington. Modified from Easterbrook (1976a, as compiled by Lapin [2000]) and Logan (2003). Figure covers the same area as the geomorphic map of this report. X, at east edge of figure, marks Cedarville locality discussed in text. The distribution of Pleistocene deposits shown on this map differs from that implied by the landforms described and interpreted in this report.

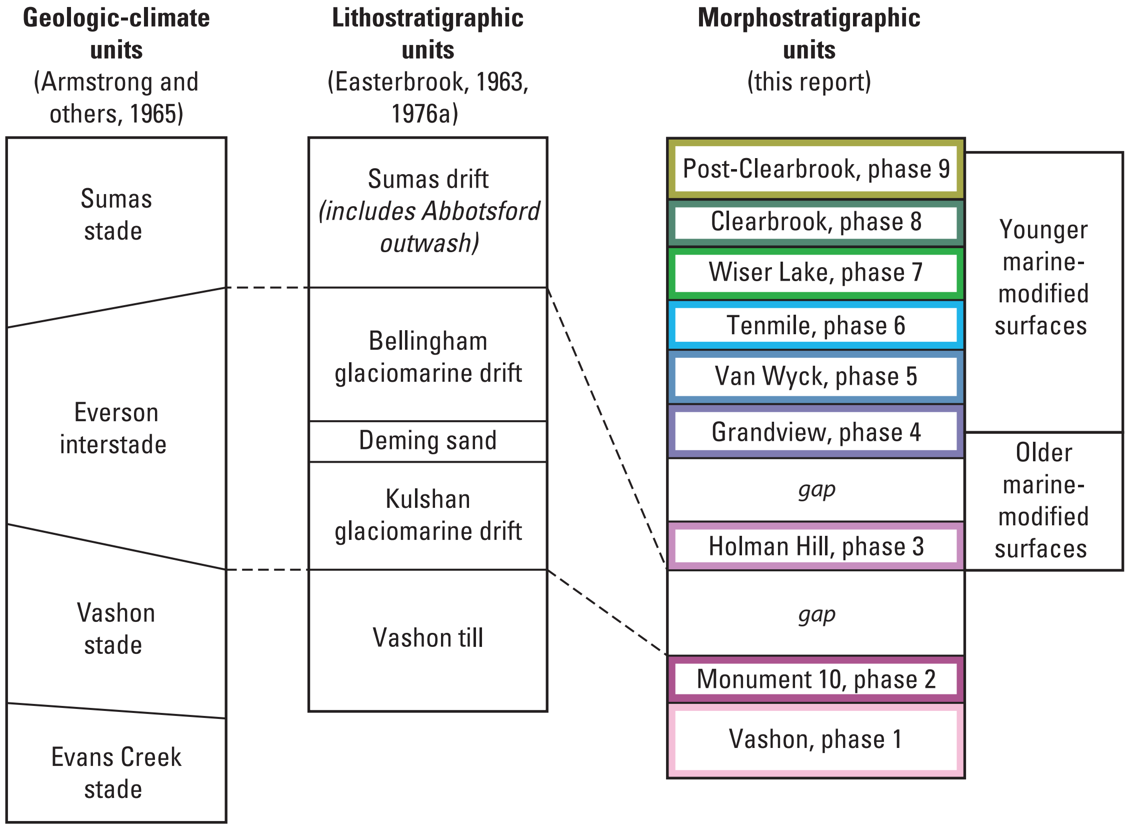

Figure 4. Stratigraphic nomenclature used by Armstrong and others (1965), Easterbrook (1963, 1976a), and in this report. Dashed lines show correlations. Neither deposits nor landforms associated with the Evans Creek stade of Armstrong and others (1965) have been recognized in western Whatcom County.

shelf edge (Bretz, 1913; Alley and Chatwin, 1979). At Bellingham, Washington, ice was at least 1,400 m thick (see also Easterbrook, 1969, 1971; Haugerud and Tabor, 2009).

- *Everson interstade*.—An interval of rapid and extensive glacier retreat that is generally associated with the onset of glaciomarine sedimentation in the Fraser Lowland and adjoining areas where land had not yet rebounded from isostatic depression. By ~12,920±65 ^{14}C yr B.P.[5] (Kelsey and others, 2004; marine reservoir correction of 800±25 years), the ice margin retreated to northern Whidbey Island and the sea inundated the glacio-isostatically depressed Puget Lowland (for example, Easterbrook, 1968, 1969; Thorson, 1980; Domack, 1983; Booth, 1987; Dethier and others, 1995; Kovanen and Slaymaker, 2004). Due to ice thinning and global sea-level rise, the retreating glacier became buoyant and deposited glaciomarine sediments in coastal areas throughout the northern and central Puget Lowland, Fraser Lowland, and parts of Vancouver Island, British Columbia (Armstrong and Brown, 1954; Armstrong, 1957, 1981; Easterbrook, 1963, 1969, 1992; Mathews and others, 1970; Armstrong and Hicock, 1980; Clague, 1981; Dethier and others, 1995; James and others, 2005). During the late stages of this interval, a dynamic outlet glacier occupied the Fraser River Valley.

- *Sumas stade*.—An interval marked by re-advance of glacial ice into the Fraser Lowland. Largely terrestrial deposits from this period formed in western Whatcom County between about 11,700 and 10,200 ^{14}C yr B.P. (Easterbrook, 1963; Armstrong and others, 1965; Armstrong, 1981; Clague and others, 1997; Kovanen and Easterbrook 2002a; Kovanen and Slaymaker, 2003).

The end of the Everson interstade of Armstrong and others (1965), defined by the cessation of glaciomarine sedimentation, must have been diachronous, as progressive uplift allowed marine inundation to persist longer at lower elevations. However, Easterbrook notes that within the accuracy of ^{14}C dating there appears to be no detectible correlation between dates on Everson deposits and elevation.

These subdivisions of the Fraser glaciation are "geologic-climate units," which were thought to be widespread climatic episodes that could be inferred from a sequence of changing depositional facies in Quaternary strata. Armstrong and others (1965) followed the recommendations of the American Commission on Stratigraphic Nomenclature (1961), which encouraged the recognition of such units, but subsequent versions of the Code of Stratigraphic Nomenclature have abandoned geologic-climate units. Despite these reservations, Vashon, Everson, and Sumas are commonly used as local stratigraphic terms and we informally follow this tradition.

[5]Unless noted otherwise, all shell ages are corrected for a marine reservoir value of 1,100 years (Kovanen and Easterbrook, 2002b). Also see section "Relative and Numerical Ages," below.

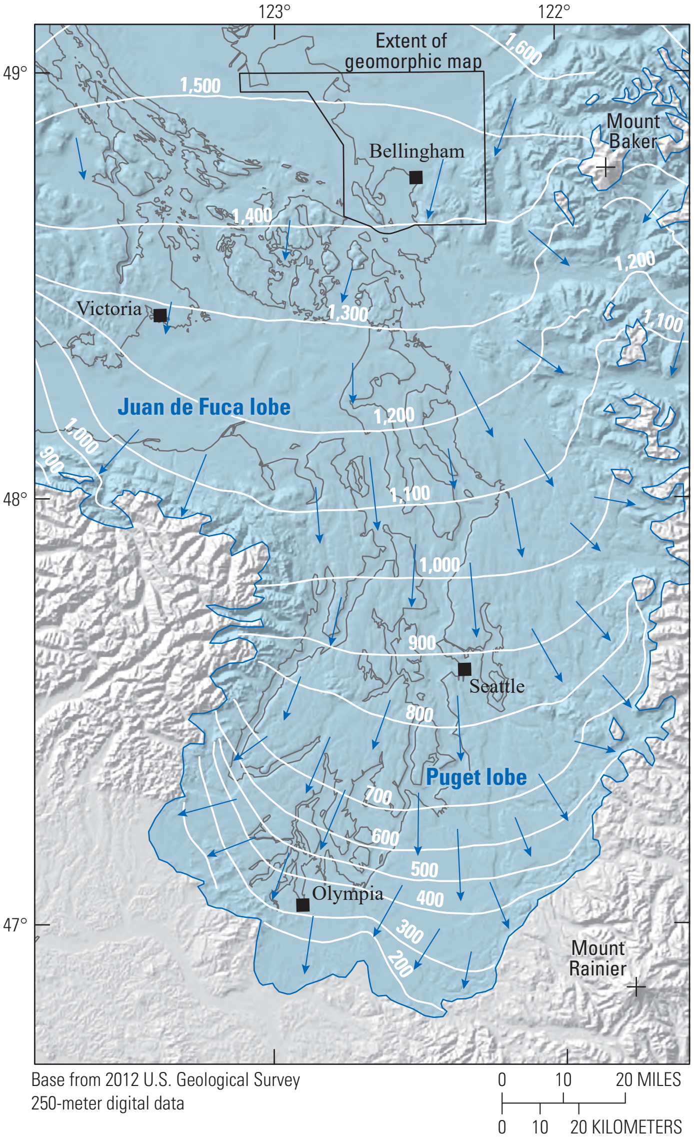

Figure 5. Map of western Washington showing the limits of the Puget lobe, the southwesternmost extension of the Cordilleran ice sheet (blue area) at its maximum extent during Fraser glaciation. Also shown are ice-flow directions (blue arrows), surface height of ice (white contours and labels denote meters above present sea level), and the extent of the geomorphic map of western Whatcom County (on map sheet).

We note, however, that glaciers, especially marine- or lake-terminating glaciers, are also affected by non-climatic factors. Floating ice tongues may respond to variations in glacier dynamics or dynamics of the terminus. For example, sedimentation or fall in relative sea level may ground an ice tongue, reduce calving rate, and lead to an ice advance that is independent of climate change.

Glaciation, Glacial-Isostatic Adjustment, and Relative Sea Level

Glaciation affects sea level via global and regional mechanisms, though this separation is a crude approximation. As illustrated by Walcott (1972), Farrell and Clark (1976), and many others, local changes in the surface load of the Earth, whether by ice-sheet growth or decay or by consequent change in sea level, have significant far-field effects. The change in Earth's shape as a response to glaciation and deglaciation is known as glacial-isostatic adjustment (GIA). GIA is commonly analyzed by forward modeling of relative sea level histories from input Earth rheology and ice-sheet history, then comparing the results with observed relative sea level histories (for example, Peltier, 2004; Mitrovica and Forte, 1997). We are far from having the understanding of Earth rheology and ice-sheet history that would be necessary to retroactively predict relative sea level histories in the Pacific Northwest.

Globally, sequestration of water in on-land ice sheets and slight cooling of marine water reduced the volume of ocean water enough that global (eustatic) mean sea level at the last glacial maximum was about 120 m (Peltier and Fairbanks, 2006) or 150 m (Lambeck and Chappell, 2001) below its present level.

Near an ice sheet, the weight of the ice causes the Earth's outer, rigid lithosphere to sink into the underlying viscous asthenosphere until the ice load is balanced by the weight of the displaced asthenosphere. Sinking takes many hundreds to thousands of years, and the time required depends, in part, on the viscosity of the asthenosphere. Where and while ice is present, sea level is hypothetical, as the sea is displaced by ice. Upon melting of the ice, the load is removed and the lithosphere slowly rises (isostatic rebound). The lag between ice sheet melting and rebound commonly leads to flooding of low elevation areas—a high relative sea level (RSL). At the north margin of the Fraser Lowland, post-Vashon marine shells are present at elevations as high as 175 m (575 ft; Armstrong, 1956), reflecting the large ice load, low asthenospheric viscosity, and consequent large amount of GIA in this area.

Asthenosphere displaced by the sinking ice sheet flows laterally and raises the surface beyond the margins of the load (a forebulge) where RSL is locally lowered. Between the forebulge and the ice load, the surface of the Earth is tilted. At the southern margin of the Cordilleran ice sheet, in the Puget Lowland around Seattle, Washington, Thorson (1989) observed that late-Vashon-age shorelines are now tilted about 1 meter per kilometer up to the north, a consequence of relaxation of down-to-the north (towards the ice sheet) tilt at the time the shorelines formed. Dethier and others (1995) found similar tilting that extends north to the 49th parallel. From these observations, James and others (2000) inferred that the region is underlain by low-viscosity (~10^{-19} Pa s) mantle and that coastal portions of the southern Cordilleran ice sheet collapsed suddenly.

The interplay between regional GIA consequent upon local ice sheet decay and rising eustatic sea levels because of global ice-sheet melting can produce a complicated RSL history. Studies in the central and northern Strait of Georgia (Hutchinson and others, 2004; James and others, 2005) and the Victoria, British Columbia, area (James and others, 2009; fig. 6*A*) have shown:

1. RSL was 90 to 150 m above present sea level about 14,000 cal (calibrated) yr B.P. Global eustatic sea level was ~90 m below present at this time, thus there was ~180 to 240 m of local glacial-isostatic depression. Note

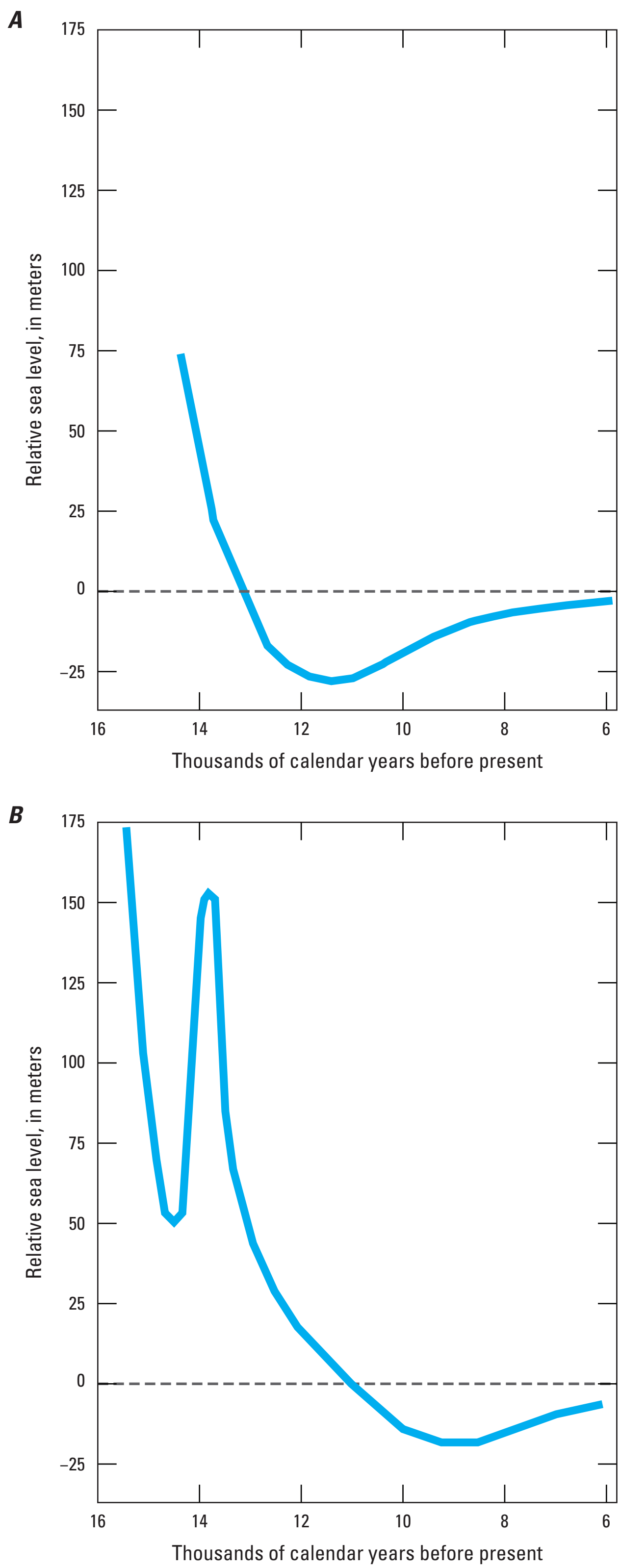

Figure 6. Relative sea-level curves for parts of the Salish Lowland, where 0 corresponds to present-day sea level. *A*, Relative sea-level curve for the Victoria, British Columbia, Canada, area, redrawn from James and others (2009). *B*, Relative sea-level curve for the Fraser Lowland, redrawn from Mathews and others (1970).

that this is not the maximum GIA, as this time is many centuries after the beginning of glacial unloading.

2. RSL fell to 10 to 40 m below present sea level at 12,000–10,000 cal yr B.P., indicating that isostatic rebound outstripped global sea level rise.
3. Rebound ceased about 8,000 cal yr B.P. After that time, local sea level tracked global sea level.
4. RSL equilibrated at near-present sea levels about 6,000 cal yr B.P.

Armstrong (1957) described a stratigraphic sequence in the eastern Fraser Lowland of late Fraser-age glaciomarine deposits succeeded by stream deposits, overlain by more glaciomarine deposits, which are in turn overlain by mostly subaerial till. This stratigraphic sequence requires an additional episode of RSL rise and fall sometime between 14,000 and 10,000 cal yr B.P. In western Whatcom County, Easterbrook (1963) described post-Vashon glaciomarine drift overlain by nonmarine and beach deposits overlain by a second glaciomarine drift unit. He noted that this stratigraphy and his mapping required at least 45 to 107 m (150 to 350 ft) of RSL rise after deposition of the nonmarine deposit, and suggested that RSL may have risen to 213 m (700 ft). Easterbrook (1963) recognized that late- and post-glacial eustatic sea-level rise and GIA together are not sufficient to explain this RSL history and suggested that some tectonic activity was required.

Mathews and others (1970) summarized these observations and published the RSL curve shown in figure 6*B*. This inference of rapid late-glacial emergence, re-submergence, and re-emergence has become known as the “yo-yo” hypothesis (Easterbrook, 1992).

Everson Stratigraphy

Easterbrook (1963) divided Everson-age sediments into a three-part sequence of Kulshan glaciomarine drift, Deming sand, and Bellingham glaciomarine drift. Following earlier usage by Armstrong (1957), he assigned overlying till, ice-contact deposits, and outwash to the Sumas drift, discussed below. Easterbrook later (1976a) mapped Everson-age sediments as Kulshan Drift, Deming Sand, and Bellingham Drift (fig. 6). He described exposures of these deposits along the south bank of the Nooksack River near Cedarville (fig. 3, at **X**; NE¼ sec. 34, T. 39 N., R. 4 E., see map sheet), in sea cliffs along Bellingham Bay (SE¼ sec. 15 and NE¼ sec. 44, T. 38 N., R. 2 E.), and near Deming (SE¼ sec. 6, T. 38 N., R. 5 E.). The outcrop extents of the Kulshan and Deming units are limited; Easterbrook (1976a) notes that they are “shown on cross-section only.”

Kulshan glaciomarine drift—The oldest Everson deposit is unstratified to weakly stratified stony mud containing marine fossils. Marine fossils in exposures along Bellingham Bay yielded reservoir-corrected ages of 12,210±80 (sample B-109852) and 12,150±210 (B-135695) ^{14}C yr B.P. Wood and an organic mat from beneath Kulshan sediments at the Cedarville locality (53 m, 175 ft elevation) yielded dates of 12,070±80 and 12,185±80 ^{14}C yr B.P. (AA-22222 and AA-22220; table 1 [on map sheet]), suggesting that the Kulshan there is younger than ~12,200 ^{14}C yr B.P.

Deming sand—About 18 m (59 ft) of stratified sand, clay, and gravel overlie the Kulshan glaciomarine drift at the Cedarville locality. At its base is a peat bed (3–15 cm, ~1–6 in thick) with fossil stumps in growth positions at an elevation of ~67 m (222 ft). Four stumps yielded radiocarbon ages ranging from 11,455±125 to 11,810±60 ^{14}C yr B.P. (B-1324, B-135696; table 1). The change in depositional environments from glaciomarine to fluvial indicated to Easterbrook that there was a significant fall in relative sea level, which he attributed to isostatic uplift. Sea level must have been below ~67 m (222 ft) near Cedarville by 11,810 ^{14}C yr B.P. in order for a forest to become established.

Easterbrook (1963) assigned sand and gravel containing wave-worn marine shells, worm tubes, and armored mudballs exposed along Bellingham Bay to his Deming sand unit. Detrital wood (log) in these sediments yielded a date of 11,660 ± 60 ^{14}C yr B.P. (B-230133). Weber (2001) and Easterbrook interpreted the sediments at Bellingham Bay as fluvial, beach, and shallow marine deposits, indicating that sea level there was ~7–13 m (23–43 ft) elevation at the time of deposition of the Deming sand.

Bellingham glaciomarine drift—Easterbrook described the youngest Everson deposit as unstratified, massive sandy clay containing sparse marine fossils. In places it is as much as 21 m (70 ft) thick and resembles a true till. According to Easterbrook (1963, 1976a, 1992), these sediments reflect a second submergence associated with a combination of local tectonism, isostatic adjustment, and eustatic sea-level rise. Radiocarbon ages of shells and detrital wood from these sediments range from ~11,680 to ~11,580 ^{14}C yr B.P. Kovanen and Easterbrook (2002a, b) provide additional radiocarbon dates.

At the Cedarville locality (described above), the top of the Deming sand is at about 76 m (250 ft) elevation and the top of overlying shell-bearing massive sandy clay is 37 m (120 ft) higher. Easterbrook observed that his Bellingham glaciomarine drift may extend up to 180 m (600 ft) elevation, and that Deming sand in the bluffs along Bellingham Bay records sea level at 12–18 m (40–60 ft) present-day elevation. This would indicate at least 167 m (550 ft) of re-submergence after Deming time, followed by rapid post-Bellingham emergence prior to deposition of Sumas drift.

Easterbrook (1963) noted that Kulshan, Deming, Bellingham, and overlying Sumas sediments are closely related in time and that radiocarbon dates cannot be used satisfactorily to distinguish them.

Armstrong (1981; see also Armstrong, 1957, 1960; Armstrong and Hicock, 1980) described Everson-equivalent marine deposits in southwest British Columbia, immediately north of our map area, as his Capilano Sediments (where marine deposits are beyond the extent of Sumas drift) and Fort Langley Formation (where marine deposits are overlain by Sumas drift). The Fort Langley Formation locally includes terrestrial deposits. Armstrong (1981) reports radiocarbon ages on wood of 11,590±280 to 10,690±180 ^{14}C yr B.P. for the Capilano sediments. The Fort Langley Formation yields radiocarbon ages of 11,800±170 ^{14}C yr B.P. (from marine shells; we have made a 1,100-year reservoir correction) to 11,680±180 ^{14}C yr B.P. (from wood).

Dethier and others (1995) studied late Fraser-age glaciomarine sediments south and southwest of western Whatcom County. They reported shell ages of 12,550 to 10,200 ^{14}C yr B.P. (these ages incorporate a 1,100 year reservoir correction) and observed that the upper limit of glaciomarine deposits rises to the north at about 0.6 m/km.

Easterbook has suggested (1963, 1992) that Everson-age glaciomarine sediments, particularly the Kulshan glaciomarine drift, were largely deposited beneath a floating ice shelf. Armstrong (1981), Domack (1983), and Dethier and others (1995) argue for deposition in mostly open water.

Sumas Stratigraphy

Easterbrook (1963, 1976a) described the Sumas drift as consisting of till, poorly stratified outwash sand and gravel, alluvial sand and gravel, and estuarine silt and clay that are younger than Bellingham glaciomarine drift and were deposited during the final occupation of the Fraser Lowland by a valley glacier.

Armstrong (1981; see also see also Armstrong, 1960; Armstrong and Hicock, 1980) defined his Sumas Drift as lodgment and flow tills, glaciofluvial deposits, and glaciolacustrine sediments that overlie Everson-age glaciomarine deposits and record the last occupation of the eastern Fraser Lowland by a glacier. He reported radiocarbon ages on wood from Sumas Drift of 11,700±150 to 10,950±200 ^{14}C yr B.P.

Interpretation of Sumas sediments and landforms led earlier workers to propose one to four advances or still-stands of the ice front during Sumas time (Armstrong, 1981; Armstrong and Hicock, 1980; Easterbrook, 1992, 1994; Clague and others, 1997; Kovanen, 2001; Kovanen, 2002; Kovanen and Easterbrook, 2002a; Kovanen and Slaymaker, 2003).

Hazards-Focused Investigations of Holocene Features

Several investigations concerned with geologic hazards have addressed the Holocene geomorphology of western Whatcom County. Of note are studies of debris torrents on alluvial fans and deltas by Easterbrook and Evans (1983), Orme (1990), Fox and others (1992), De Lachapelle (2000), Kerr and others (2004), Jakob, (2005), and Kovanen and Slaymaker (2008). Slope stability studies have been completed by Easterbrook (1973, 1976c) and Thorsen (1989), and delineations of areas with potential for enhanced seismic shaking have been reported by Easterbrook (1976b) and Palmer and others (2004). Some of these results are summarized in a map prepared by Whatcom County Planning & Development (2006).

Availability of high-resolution lidar (light detection and ranging) topography has facilitated recognition of evidence for large Holocene earthquakes in Whatcom County. Kelsey and others (2012) presented evidence suggestive of Holocene faulting within the map area. East of the map area, Sherrod and others (2013) described multiple Holocene surface-rupturing earthquakes on the Boulder Creek Fault.

Methods

Geomorphic Mapping

Geomorphology (from Greek: geo, "earth," morphe, "form," and logos, "a discourse") is the scientific study of the features of the Earth's surface. Previous studies of recent Earth history in western Whatcom County (for example, Easterbrook, 1963, 1976a; Lapen, 2000) have been primarily geologic, focused on the vertical succession of sediments in outcrops and the material properties of these sediments. In contrast, this map is geomorphic, focusing on the shape of the Earth's surface, not on the characteristics of the sediments beneath this surface, though we note that many of our surface units are diagnostic of their underlying sediments. The availability of detailed lidar topography and the use of a GIS (geographic information system) have greatly facilitated our geomorphic mapping and consequent understanding of the evolution of the landscape.

We identified different surface types on the basis of shape (for example, slope, curvature, texture) and position in the landscape. Cross-cutting relations (for example, truncation, incision, superposition) indicate relative ages of different surface patches. Surface type and relative age allow us to assign patches to distinct map units.

Our choice of map units was guided by our intent to explain the evolution of this landscape, and so our map units generally reflect a process or set of related processes operating for a defined period of time (for example, hillslope mass wasting; erosion, transport, and deposition by a river; wave action on a beach; erosion and deposition attendant upon sliding at the base of a glacier; melting of debris-rich ice). Map units must be mappable; that is, they should be chosen so that there is little ambiguity about the classification of a given patch of surface. Weaving discrete map-unit patches into a landscape history requires understanding individual landforms as parts of larger morphologic systems. This requirement also guided our choice of map units and, in some cases, our classification of surface patches. While the map is entirely derived from interpretation of detailed lidar topography, it should be evident from the discussion below that our interpretation was informed by data from other sources.

Our classification of landforms was based on examination of a variety of images derived from numerical topography and informed by our experience and judgment, with a primary emphasis on empirical delineation of process domains. This contrasts with approaches to geomorphic mapping guided by rule-based discrimination of landforms to systematically classify morphologic and process systems (Goudie and others, 1990).

Lidar Digital Elevation Model

This map reflects our interpretation of a 1.8-m (6-ft; XY resolution) digital elevation model (DEM). The DEM is a composite of four airborne lidar surveys: (1) a 2005 Puget Sound Lidar Consortium survey, at 1 pulse/m^2, funded by the Lummi Nation, that covered the Lummi Indian Reservation and adjoining areas; (2) a 2006 North Puget Sound survey, at 1 pulse/m^2, acquired under contract to the U.S. Geological Survey, that covered most of western Whatcom and Skagit Counties; (3) a 2009 Puget Sound Lidar Consortium survey, at 8 pulses/m^2, funded by the Nooksack Tribe, of the Nooksack River valley bottom upstream of Everson; and (4) a 2009 Puget Sound Lidar Consortium survey, at 8 pulses/m^2, funded in part by Washington Department of Natural Resources, that covered Lummi Island and Point Roberts. The North Puget Sound survey was acquired in leaf-on conditions. The other surveys were in leaf-off conditions. All these data are available online from the Washington Lidar Portal (https://lidarportal.dnr.wa.gov/).

Mapping from Topography

Map-unit contacts were digitized on screen in a GIS using backdrop images calculated from the DEM. These images included northwest- and northeast-illuminated hillshades (gray-scale images that simulate point-source illumination of the DEM); a vertically-illuminated hillshade calculated with a 6X vertical exaggeration; a color image in which hue corresponds to local slope; and 1-ft and 2-ft contours of some areas. Much of our interpretation was of an image with hue calculated from elevation and darkness calculated as a nonlinear function of local slope in order to enhance small variations of slope at low slopes. Digitizing scale generally was between 1:1,000 and 1:12,000.

Many map-unit boundaries are drawn at breaks in slope (for example, top of bluff, edge of alluvial flat, base of highway-fill prism). Additional contacts are drawn at textural changes (for example, lumpy melt-out terrain or wave-smoothed marine-modified surfaces, lumpy landslide surface or smooth glaciated surface). We chose geomorphic map units to emphasize both the process by which the surface was formed and the age of the surface-forming event. For the most part, we mapped our interpretation of the Earth's surface as it was prior to human modification and without the artifacts imposed by the lidar survey. In heavily modified areas, where the pre-modification surface cannot be reliably inferred, we mapped modified surfaces. We also mapped modified surfaces along some transportation corridors and wherever artificial fill is evident.

Relative and Numerical Ages

For the most part, ages of map units are known in relative terms, based on cross-cutting relations, position in an event sequence, elevation of associated fossil shorelines and (or) marine features, and degree of surface modification. Using these relative ages, we then interpreted landscape evolution and duration of processes in a time/space sequence from the assemblage of different landforms.

In several locales, previously obtained radiocarbon (^{14}C) dates constrain the ages of geomorphic units and landscape-forming processes. These dates are summarized in table 1 (on the map sheet). Only the most pertinent dates from previous studies are included. Dates mentioned in the text are conventional dates (^{14}C yr B.P., where present is 1950 C.E.) or, for marine shells, reservoir-corrected conventional dates, unless otherwise noted. Table 1 also reports calibrated ages calculated using the CALIB 6.01 program (Stuiver and Reimer, 1993). The 2-sigma calibrated age range is given in years before 1950 C.E. (cal yr B.P.).

Incomplete mixing of atmospheric carbon into the oceans and upwelling of deep-ocean water causes radiocarbon samples in marine or brackish environments to have artificially old dates (Bard, 1988). The influence of glacial meltwater and isolation from oceanic circulation due to seasonal ice variations may also lead to variation in the marine reservoir value. In western Whatcom County and the adjacent Fraser Lowland in British Columbia, marine shells older than ~11,000 ^{14}C yr B.P. have apparent ages that, on average, are 1,100 years older than contemporaneous terrestrial dates (Kovanen and Easterbrook, 2002b). Therefore, we have corrected shell dates by the above value and present them as reservoir-corrected dates in table 1. Other researchers use a marine reservoir correction of 950±50 years (Hutchinson and others, 2004) derived from a relatively bigger dataset covering a larger geographical area. We prefer the larger reservoir correction as it was derived from samples collected within the immediate vicinity of our map area. Uncertainties in marine reservoir values compound the difficulty of calibration and, hence, increase uncertainties in correlations between sites and with late-glacial sea-level histories.

Elevation

Elevations cited in the text are taken from the lidar DEM and are referenced to the North American Vertical Datum of 1988 (NAVD88) unless otherwise noted. Paleo-elevations are referenced to inferred coeval sea level.

Tilt Estimated from Fossil Shorelines and Correlation Between Uplands

Smooth, marine-modified surfaces decorated with fossil shorelines are present on the Boundary and Mountain View uplands, the southwestern edge of the King Mountain upland, Lummi peninsula, northern Lummi Island, and Point Roberts. Shorelines are truncated at various elevations on the different uplands by moraines, but they extend progressively down to the modern shoreline; the lowest mapped fossil shoreline is at ~11 m (36 ft) elevation.

The fossil shorelines present an opportunity to evaluate how much the landscape has tilted since the shorelines formed[6]. The longest of 1,575 observed fossil shoreline segments is 2.4 km in length. Most are shorter, with a mean length of 234 m. The contractor for the North Puget Sound lidar survey estimated its vertical accuracy to be ~0.17 m (root-mean-square error in the Z value, $RMSE_Z$) and there is additional error associated with determination of the shoreline position, thus it is unlikely that tilt of a single shoreline can be confidently observed. However, many shorelines may be lumped and an average tilt calculated. We did this by (1) densifying shoreline arcs to a vertex spacing of 60 m, (2) disaggregating arcs into vertex points and assigning an elevation to each vertex by intersection with the lidar DEM, (3) translating the set of vertices from each shoreline arc to the origin by subtracting the arc centroid (mean XYZ value) from each vertex, and (4) linear least-squares fitting of a plane (paleohorizontal) to the resulting point cloud.

Estimated tilt calculated from all fossil shoreline arcs is 1.26 m/km up to the northeast (N 30º E). The $RMSE_Z$ for fit of the plane to the point cloud is 0.49 m, consistent with estimated error in the DEM plus error associated with determination of the shoreline position. A jack-knife analysis suggests ±0.03 m/km uncertainty in tilt magnitude and ±11º uncertainty in tilt azimuth. Separating the fossil shoreline arcs into sub-populations and repeating the analysis suggests greater uncertainty. When we lump shorelines by age, higher, older shorelines (n=991) define an average tilt of 1.04 m/km, N 35º E, whereas lower, younger shorelines (n=584) give an average tilt of 1.15 m/km, N 25º E. This is almost certainly wrong: rebound was progressive, and older shorelines are likely to be tilted more, not less, than younger shorelines.

Correlation of shoreline features from upland to upland is essential to our interpretation of the landscape evolution of western Whatcom County. Extensive moraines bounded by younger fossil shorelines are present on the Boundary upland, Mountain View upland, Lummi peninsula, and King Mountain upland, but at different elevations. With the tilt correction outlined above, the bounding fossil shorelines are at similar elevations, thus we confidently correlate these moraines as belonging to the same, Grandview, phase.

Landscape Evolution During the Past 16,000 Years

Late Pleistocene Fraser Glaciation

We divide the evolution of the glacial landscape of western Whatcom County into nine phases that represent a sequence of events near the end of the Pleistocene (figs. 2, 4, 7). Each phase is characterized by an assemblage of related landforms. Relative chronology is derived from cross-cutting end moraines, changes in ice flow direction, meltwater landforms (channels, eskers, deltas, traces of glacial lakes), and relative sea levels. The oldest end moraines formed along the North Cascade foothills and on the Boundary upland (phases 1 and 2) and indicate the positions of temporary still stands as the ice margin retreated into western Whatcom County (fig. 7*A*). The ice margin then retreated rapidly northeastward during a time of relatively high sea level (fig. 7*B*). Subsequently, a sequence of fossil shorelines formed on recently deglaciated areas during ongoing isostatic rebound.

Ice then advanced (phases 3, 4), cutting across fossil shorelines and older moraines (fig. 7*C*); phase 4 ice diverted water flowing west from the Nooksack River valley into the Squalicum channel (figs. 2, 7*D*).

[6]Haugerud and Kovanen (2010) reported an earlier version of this analysis with somewhat different results than those presented here.

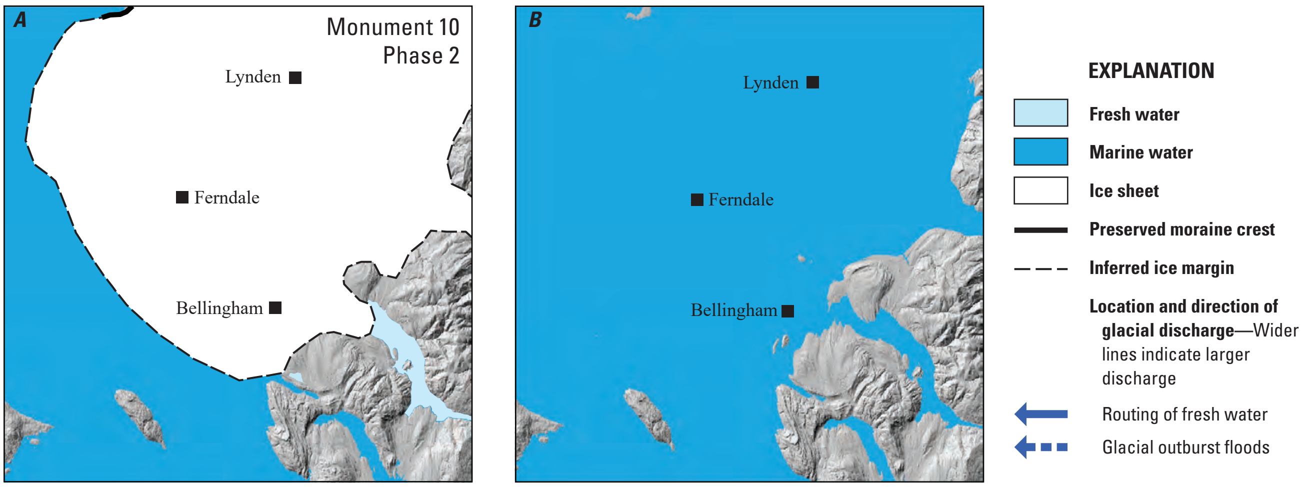

Figure 7. Inferred paleogeographies during the late Pleistocene and early Holocene in western Whatcom County, Washington. Each panel depicts the inferred extent of glacial ice, extent of marine water, locations of large lakes, and significant drainage paths. Ice flow was generally from the northeast to the west and southwest toward the periphery of the ice sheet. History summarized here; see text for more description and discussion. At the peak of the Vashon stade (phase 1, not shown), at ~17,000 calendar years before present (cal yr B.P.) (Haugerud, 2020), the area was covered by the south-flowing Cordilleran ice sheet. Ice then retreated, the ice-surface elevation lowered, and—locally—small moraines formed at high elevations late in phase 1. ***A***, Monument 10 time, phase 2: small remnant of Monument 10 moraine on Boundary upland records the ice margin when relative sea level was ~490 feet (~150 m) above modern sea level. Remnants of moraine high on Squalicum, Stewart, and Sumas mountains are likely correlative with the Monument 10 moraine. Most of western Whatcom County was covered by ice, a floating ice shelf atop seawater, or seawater. ***B***, Little geomorphic expression of ice presence in western Whatcom County: prior to phase 3, the ice margin retreated far to the northeast, as shown by occurrences of shell-bearing glaciomarine drift of the Fort Langley Formation as far east as Chilliwack, British Columbia, Canada (Armstrong, 1981, his fig. 22, site FL38 at lat. 49°6.3′ N, long. 121°55.3′ W, elevation 46 meters above sea level). The map area was entirely ice free, and low-elevation areas were inundated by marine water, which may have had abundant floating ice. Sea level at this time is not well constrained. ***C***, Holman Hill time, phase 3: ice re-advanced and stabilized to form moraines on Boundary upland, Mountain View upland, and Squalicum and Stewart mountains. Sea level is inferred from fossil shorelines that are coeval with the Holman Hill moraine, as discussed in the text. ***D***, Grandview time, phase 4: ice retreated, advanced, and stabilized to form well developed moraines on Boundary and Mountain View uplands and Lummi peninsula. Squalicum channel records a large discharge—the paleo-Fraser River—at the south margin of ice sheet, probably from the Columbia Valley (fig. 1, on map sheet) through an ice-dammed lake in the Nooksack River valley. Fossil shorelines coeval with, or slightly younger than, phase 4 moraines and the large fossil delta at the lower end of Squalicum channel establish sea level across much of the map area. ***E***, Van Wyck time, phase 5: sea level lowered and ice retreated across much of western Whatcom County. The Samish River captured the large-discharge flow from the Columbia Valley (east of area shown in this figure). With cessation of flow in Squalicum channel, the ice margin was no longer being trimmed by the paleo-Fraser River and was able to advance across the upper Squalicum channel and form moraines on Squalicum and Stewart mountains. ***F***, Tenmile Creek time, phase 6: ice retreated to open the lower-elevation Tenmile Creek flow path, which captured Columbia Valley flow that had gone to the Samish River. During Wiser Lake time, phase 7 (not shown), continued ice retreat allowed flow along the modern course of Nooksack River and the Tenmile Creek channels were abandoned. Outburst floods swept across the area southeast, south, and southwest of Lynden; apparent absence of a plausible ice dam farther up the Nooksack suggests that water came from the northeast via Sumas prairie, not through the modern Nooksack River valley. ***G***, Clearbrook time, phase 8: a still stand of retreating ice built the Clearbrook moraine around Sumas Prairie. Outburst floods from Sumas prairie continued. During post-Clearbrook time, phase 9 (not shown), another still stand of the retreating ice built the youngest known moraine in the map area near the town of Sumas. ***H***, Early Holocene: no ice was present in the Fraser lowland. As sea level continued to fall, a low ridge at Ferndale separated the Lynden low—probably occupied by a lake—from the sea. The Nooksack River flowed into the Lynden low and then, via Sumas prairie and the Fraser River, to the sea. See text for discussion of the development of the modern Nooksack River and its delta. The landforms described in this report are consistent with, and in places require, a history of progressive glacio-isostatic adjustment that includes untilting and relative sea level fall. This history is here approximated as follows: from Monument 10 time through Grandview time (phases 2 through 4, panels *A*-*D*), 1.2 meters per kilometer down to N 23° E tilt of the land surface and relative sea levels at Bellingham of 122 m (Monument 10, panel *A*), to 116 m (panel *B*), 39 m (Holman Hill, panel *C*) and 23 m (Grandview, panel *D*). During phase 5 (Van Wyck, panel *E*) tilt is 0.6 meters per kilometer and relative sea level at Bellingham is 21 m. During phases 6–9 (panels *F*, *G*), tilt is 0.3 meters per kilometer and relative sea levels at Bellingham are 13 m (Tenmile Creek, panel *F*) and 12 m (Clearbrook, panel *G*). During the early Holocene (panel *H*) we assume no tilt and that relative sea level is the same as present-day sea level.

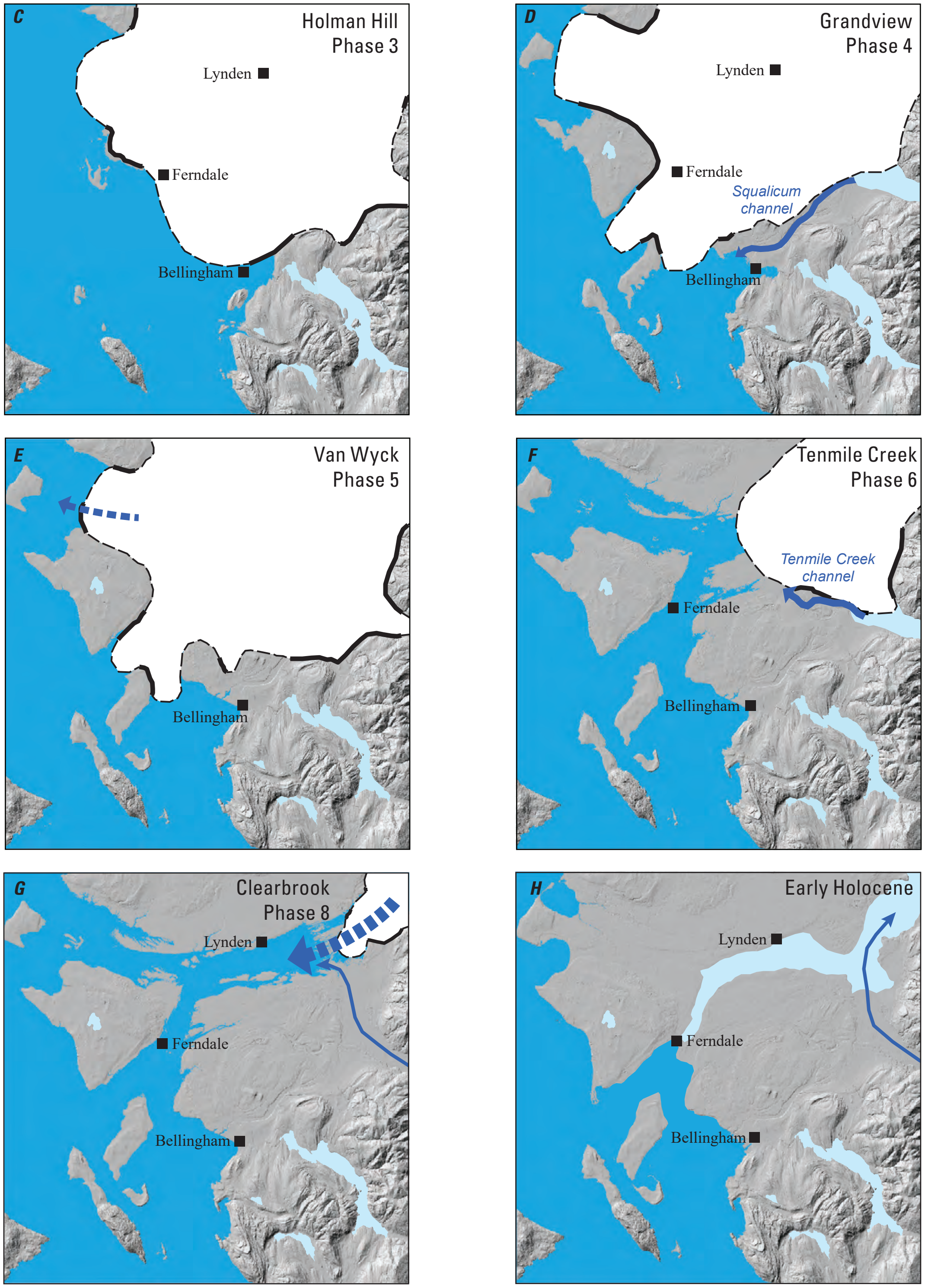

Figure 7.—Continued

Phase 5 was marked by the progressive retreat of the ice front across much of the map area, accompanied by advance of the ice front across the Squalicum channel (fig. 7*E*). Meltwater from the Nooksack drainage appears to have drained south to the Samish River (fig. 1) at this time. During phase 5, outburst floods scoured and entrenched some surfaces in low-lying areas. Northeastward retreat from phase 5 is marked by still stands of the ice front characterized by progressively more subdued moraines (phase 6, fig. 7*F*) and also development of an outwash plain. Continued retreat allowed water from the Nooksack drainage to incise channels in the landscape, deepen old channels, and deposit additional sediment on the outwash plain (phase 7). Glacial still stands and (or) oscillations of the ice margin during continued retreat formed end moraines that define phases 8 (fig. 7*G*) and 9; the associated outwash flats are of limited extent. Other events, such as outburst floods possibly originating from glacial lakes in British Columbia, scoured local surfaces.

Below we describe the characteristic landforms associated with this sequence of events. This description is an oversimplification as geomorphic processes are highly variable in place, time, and magnitude. Absolute ages are provided based generally on published stratigraphic data and seven radiocarbon dates obtained during this study.

Terrestrial Surfaces Formed Prior to the Sumas Stade

Phase 1, Vashon

Phase 1, Vashon, is represented by subglacial features that formed during the Vashon stade and ice-marginal features that formed when the ice-sheet margin thinned and retreated into western Whatcom County.

Much of the Vashon-age surface consists of smooth, north-south trending streamlined ridges up to 1.3 km (0.9 mi) long with local relief up to ~36 m (118 ft). The north-south trend of the ridges demonstrates that the ice sheet was flowing south when they formed, which suggests that (1) the ice sheet was thick enough that local topography (for example, Chuckanut Mountain) did not significantly influence the ice-flow direction, and (2) flow was not from the eastern Fraser Lowland southwest towards a calving ice margin (as it probably was during the Everson Interstade) but from the Coast Mountains of British Columbia south towards the Puget Lowland.

Lake Padden moraine consists of discontinuous ridges that extend from west of Lake Padden, across Lookout Mountain toward Lake Whatcom. Squalicum Mountain moraine (table 2) consists of segments on the western and northeastern flanks of Squalicum Mountain. The moraine segments range in elevation from 405 to 149 m (1,329 to 490 ft) elevation. These remnant moraines are the outermost in extent and highest in the map area, which suggests that they are the oldest. Collectively, they represent the first moraines constructed during deglaciation in western Whatcom County. Based on their elevation, most of the map area was covered with ice when they formed. Whether or not these moraines represent short-lived still stands of ice during recession or a readvance is not clear.

Phase 2, Monument 10

On the western portion of Boundary upland, the Monument 10 moraine is a subequant patch of subaerial meltout topography that rises as high as ~164 m (540 ft) elevation (fig. 8; table 2). Faint northeast-southwest ridges within this patch suggest that it is a remnant of a lateral moraine. This is the oldest terrestrial surface on the upland and is trimmed by fossil shorelines; the highest is at ~150 m (~490 ft) elevation. Shorelines at this elevation formed as the landscape was undergoing rapid isostatic rebound (see, for example, Hutchinson and others, 2004; James and others, 2009).

The Anderson Creek moraine fills part of the valley south of Squalicum Lake and extends ~5 km (3 mi) eastward along the north slope of Stewart Mountain up to an elevation of ~214 m (705 ft; fig. 9; table 2). Its elevation indicates that the Nooksack drainage was blocked by ice. Meltwater at that time was probably diverted southward along the South Fork of the Nooksack River and then through the Samish River valley (fig. 1). The age of the Anderson Creek moraine relative to the Monument 10 moraine is uncertain; its higher elevation could reflect older, more extensive ice or a more proximal position. For convenience we include the Anderson Creek moraine in phase 2.

Figure 7*A* presents a tentative configuration of the ice margin and relative sea level during phase 2.

Marine-Modified Surfaces

Collapse of the thinning Vashon-age ice sheet and its replacement by marine water exposed ice-modified surfaces, which were then mantled by glaciomarine and marine sediments. Ongoing isostatic rebound moved these surfaces through the surf zone, where wave action further modified submarine depositional surfaces and created fossil shorelines characterized by constructional bars, spits and deltas, erosional wave-cut notches, and down-slope truncation of subaerial gullies. We describe the products of this history as “marine-modified surfaces.”

We establish the relative age of a marine-modified surface on the basis of its tilt-corrected elevation: higher surfaces must be older. We are not here asserting that RSL did, in fact, fall monotonically. Instead, we recognize that any re-submergence would not be evident in the landscape: the process that created and preserved marine-modified surfaces was emergence.

The oldest marine-modified surface is at and below ~150 m (490 ft) elevation on the Boundary upland, where cross-cutting relations establish it as younger than the phase 2 Monument 10 moraine. The high elevation, even after a tilt correction, establishes the marine modified surface as older than the phase 3 Holman Hill moraine, located 11 to 16 km farther south, which is subaerial down to ~90–70 m elevation.

We map all marine-modified surfaces at elevations higher than the fossil shoreline that appears to be coeval with moraines of the Grandview phase (phase 4) as older marine-modified surface (unit Qmo). Interpretation of the landscape provides little detail about the northeastern extent of marine inundation before phase 4. Armstrong (1981) reports shell-bearing glaciomarine

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
	SURFACES OLDER THAN SUMAS STADE	
Phase 1, Vashon	**Features formed by sub-ice and ice-marginal processes during and after the Vashon ice maximum and before the ice-sheet margin had retreated as far northeast as the present shoreline of western Whatcom County.**	**Oldest moraines in western Whatcom County. Area to northwest of moraines was covered with ice. Older than all relict shorelines.**
Lake Padden moraine	Extends across Lookout Mountain from Lake Padden toward Lake Whatcom (secs. 3, 4, 7, 8, T. 37 N., R, 3 E.; sec. 34, T. 38 N., R. 3 E.)—discontinuous, narrow (20–50 m, 100–160 ft wide) ridge, up to 4 m (12 ft) high, at elevations ranging from ~325 to 149 m (1,066 to 490 ft).	
Squalicum Mountain moraine	Squalicum Mountain (secs. 11, 12, 13, 14, 23, T. 39 N., R. 3E.)—conspicuous, narrow (~30 m, 98 ft wide), discontinuous ridges, (as long as 1.3 km, 0.9 mi), locally 5 m (16 ft) high; range from ~405 to 265 m (1,329 to 869 ft) elevation.	
Phase 2, Monument 10	**High-elevation moraines with melt-out topography.**	
Monument 10 moraine	Boundary upland (W½ sec. 35, T. 41 N., R. 1 E.)—a 0.7-km-wide (0.4 mi) patch of subaerial melt-out topography (for example, undulating); up to ~164 m (540 ft) elevation; local relief as much as ~14 m (46 ft); trimmed by shorelines, the highest ~155 m (508 ft) elevation.	Formed early during Everson time before the ice margin retreated to a position farther northeast up the Fraser valley, or at a time when the western edge of the Everson-age ice shelf was grounded on the Boundary upland. Older than all relict shorelines.
Anderson Creek moraine	Valley south of Squalicum Lake (NE¼ sec. 18, T. 39 N., R. 3 E.)—narrow (65 m wide), arcuate, sharply crested ridge; as high as ~180 m (590 ft) elevation and local relief of ~15 m (49 ft); moraine extends ~5 km (3.1 mi) eastward along north slope of Stewart Mountain and has segments as high as ~300 m (984 ft) elevation.	Age of this moraine relative to the Monument 10 moraine is uncertain. Altitude and position against Stewart Mountain suggest that the glacier which formed this moraine extended east into the Nooksack River valley.
	SURFACES FORMED DURING SUMAS STADE	
Phase 3, Holman Hill	**Moraines with melt-out topography cut by high-elevation shorelines.**	**Crossing-cutting relations indicate a readvance of ice margin.** **Coeval marine surfaces included in map unit Qmo.**
Holman Hill moraine	Mountain View upland (secs. 15, 14, T. 40 N., R. 1 E.)—broad, undulating ridge west of Ferndale; as much as 106 m (348 ft) elevation, 2.6 km (1.6 mi) wide, local relief of ~39 m (130 ft) distally, and ~23 m (75 ft) proximally; digitate margin truncates some marine features at ~90–70 m (295–230 ft) elevation and shorelines lap over some lobes of the moraine between ~73 and 65 m (240–214 ft) elevation.	Associated with a range of sea levels. Its formation was contemporaneous with local relative sea levels that ranged from ~73 to 65 m (240 to 215 ft) present-day elevation. Down-slope extension of moraine into unit Qmo suggests that ice extended into marine water. Outermost Sumas moraine.

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.—Continued

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
Monument 11 moraine	Boundary upland (W½ sec. 36, T. 41 N., R. 1 E.)—consists of two closely-spaced ridge crests that converge at an apex and are up to ~130 m (427 ft) elevation, ~250 m (820 ft) wide, with local relief up to 12 m (39 ft); distally the moraine truncates fossil shorelines from ~123 to 105 m (403–344 ft) elevation; proximally it is buried by the younger Haynie Creek moraine.	Truncation of shorelines indicates readvance of the ice. Relict shorelines at relatively lower elevation are obscured by younger Haynie Creek moraine
Sunset moraine	East of Squalicum Lake (sec. 20, T. 37 N., R. 2 E.)—moraine fills valley and extends 5 km eastward along Stewart Mountain to ~215 m (705 ft) elevation. West of Squalicum Lake (sec. 20, T. 37 N., R. 2 E.)–moraine extends along the north side of Squalicum Mountain, then slopes and broadens to ~21 m (69 ft) elevation within the Bellingham city limits; modified by marine processes below ~55 m elevation.	Altitude and position against Stewart Mountain suggest that the glacier expanded east into the Nooksack valley.
Alderwood moraine	South of Bellingham airport and north of Marine Drive (sec. 14, T. 39 N., R. 2 E.)—moraine crest as high as 43 m (174 ft). To west, overlapped by younger Airport moraine. Modified by marine processes below ~40 m elevation.	Younger than other phase 3 moraines.
Phase 4, Grandview	**Post-Holman Hill, syn-Squalicum channel, pre-100 ft shoreline (~26 m or 85 ft at Bellingham, ~41 m or 135 ft south side Boundary upland).**	**Younger than Holman Hill, as coeval shorelines are significantly lower; downslope extension of ridges below shorelines may indicate that the ice margin extended into marine water.** **Crossing-cutting relations indicate readvance of ice.** **Older marine surfaces mapped as Qmo. Coeval and younger marine surfaces mapped as Qmy.**
Grandview moraine	Mountain View upland (secs. 11, 13, T. 40 N., R. 1 E.)—distinctive, broad ridge wraps around upland up to ~117 m (384 ft) elevation and ~1.2 km (0.7 mi) wide with local relief of ~30 m (98 ft); moraine limbs on the north and southeast side of the upland slope to ~23 m (75 ft) elevation and narrow to 0.4–1 km wide; moraine truncates shorelines to ~38 m (124 ft) elevation; younger shorelines superimposed on moraine limbs up to ~35 m (115 ft) elevation.	Truncation of shorelines and the older Holman Hill moraine indicates re-advance of the ice.
Haynie Creek moraine	Boundary upland (sec. 1, T. 41 N., R. 1 E.)—distinctive, sharply crested ridge wraps around easternmost part of upland; crest is as high as ~122 m (400 ft) elevation and 0.5 km (0.3 mi) wide with local relief to ~50 m (164 ft); slopes/tapers along south side of upland to ~43 m (141 ft) elevation where it is 170 m wide with local relief of ~9 m (30 ft); truncates shorelines to ~77 m (253 ft) elevation; associated with streamlined surface to the east.	Older than 11,413±80 ^{14}C yr B.P. Truncation of shorelines and the older Monument 11 moraine indicates a readvance of the ice margin. Sea level was probably lower than ~41 m (134 ft) and at least as high as ~36 m (118 ft).

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.—Continued

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
Lummi moraine	Lummi peninsula (N½ sec. 13, T. 38 N., R. 1 E.)—sharp-crested ridge wraps around northern end of the Lummi peninsula; up to ~50 m (164 ft) elevation, ~640 m (2,100 ft) wide with relief ~20-5 m (65–16 ft); slopes to ~13 m (43 ft) elevation on both sides of the upland; moraine truncates shorelines ~36-26 m (118–85 ft) elevation and other shorelines lap over the moraine, as high as ~23 m (75 ft) elevation.	Truncations of shorelines indicate a re-advance of the ice margin.
Airport moraine	Southwestern part of King Mountain upland (secs. 11, 14, 15, T. 38 N., R. 3 E.)—broad (~3 km N-S, 5.8 km W-E), arc-shaped, hummocky surface with numerous closed depressions; up to ~70 m (230 ft) elevation with a local relief up of ~42 m (138 ft); distally, surface is delineated by a distinct, irregular-shaped digitate margin at ~25 m (~80 ft) elevation; along its south, west, and northwestern margin shorelines cut into the moraine.	Younger than 12,090±350 ^{14}C yr B.P.
Phase 5, Van Wyck	**South of the Nooksack River, the transition from Grandview (phase 4) to Van Wyck (phase 5) is defined by advance of ice to block the upper Squalicum Creek meltwater channel. North of the Nooksack River, the transition is marked by retreat of ice from phase 4 termini and construction of moraine surfaces that are truncated by fossil shorelines that are slightly lower (in tilt-corrected framework) than the immediately post-phase-4 shorelines.**	**Overriding of Squalicum Creek meltwater channel indicates local ice readvance.**
Squalicum Lake moraine	Immediately north of Squalicum Lake (sec. 7, T. 38 N.. R. 4 E.)—hummocky ridge banked against Squalicum and Stewart mountains; up to ~163 m (535 ft) elevation and 400 m (1,000 ft) wide; multiple ridge crests in vicinity of Squalicum Lake; local relief that varies from ~15 m (50 ft) distally to ~50 m (160 ft) proximally; moraine extends eastward ~7.5 km (4.6 mi) and is as high as ~161 m (530 ft) elevation; west of Squalicum Lake, moraine extends 4.6 km (2.9 mi) along Squalicum Mountain and drapes into Squalicum channel, then extends another 3.9 km (2.4 mi) west to a point north of King Mountain. King Mountain upland (secs. 3, 4, 5, 6, T. 38 N., R. 3 E.)—moraine forms a broad (~3.8 km N-S, 5.1 km W-E), strongly undulating surface between 113 and 72 m (370 and 235 ft) elevation with local relief up ~15 m (50 ft); distal, southwestward facing slope forms a distinct, irregular-shaped, digitate margin at ~72 m (236 ft) elevation.	Altitude and position against Stewart Mtn suggests that the glacier extended east up the Nooksack valley.
Northwest Drive moraine	King Mountain upland, east of I-5 and north of Bakerview Road (secs. 11, 12, 13, T. 38 N., R. 2 E.)—northwest-trending, 1.7 km (1.05 mi) long hummocky ridge with crest elevation of 45 to 60 m (145 to 190 ft). Cross-cuts east end of Airport moraine.	Younger than Airport moraine.

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.—Continued

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
Lummi Shore Road moraine	Lummi peninsula (sec. 12, T. 38 N., R. 1 E., secs. 7, 18, 19, T. 38 N., R. 2 E.)–discontinuous, sinuous narrow ridge 30–16 m (98-52 ft) elevation, up to 10 m (33 ft) high; situated on a terrace that is ~14 m (46 ft) elevation; truncates fossil shorelines.	Interpretation as moraine is debatable.
Birch Point moraine	Birch Point upland (SE¼ sec. 20, T. 40 N., R. 1 E.)–irregular-shaped ridge, 300 m (980 ft) wide, 1.4 km (0.9 mi) long, and up to ~27 m (89 ft) elevation; distal side is defined by semi-circular erosional features interpreted as scoured cataracts; isolated linear ridges with local relief of up to 5 m (16 ft) and ~1.5 km (0.9 mi) long and ~200 m (650 ft) wide.	Associated with erosional features that are best explained by the breaching of the moraine by meltwater outburst floods (for example, jökulhlaups).
Dakota Creek moraine	Boundary upland (N½ sec. 11, T. 40 N., R. 1 E.)—discontinuous, narrow ridges ~60–49 m (197–160 ft) elevation.	
Lampman Road moraine	Southwest of Ferndale (SE¼ sec. 25, T. 39 N., R. 1 E.)—narrow (60 m, 210 ft), discontinuous ridge on a terrace at 18–12 m (60-39 ft) with relief up to 9 m (30 ft).	
Wahl moraines	Along Mount Baker Highway northeast of Squalicum Lake (sec. 32, T. 39 N., R. 4 E.), thence southwest, west, and north to town of Wahl—multiple closely spaced, indistinct ridges as much as ~50 m (164 ft) wide and 0.8 km long; they range in altitude from ~103 to 79 m (338 to 259 ft) with local relief of ~3 m.	Obliterated upper part of earlier-formed Squalicum Creek meltwater channel.
Phase 6, Tenmile	**Defined by water drainage via the Tenmile Creek channels.**	**South of the Nooksack River.**
Tenmile moraine	North of Tenmile Creek (S½ sec. 14, T. 38 N., R. 3 E.)—2.3 km (1.4 mi) wide belt of ridge segments drape obliquely across NE-SW trending streamlined features; as high as ~63 m (207 ft) elevation with local relief of ~6 m; southeastern margin truncated by multiple E-W scoured channels associated with former spillway of a lake that was impounded in the Nooksack Valley.	Older than 11,113±77 14C yr B.P.
Cedarville moraine	Near Cedarville (N½ sec. 5, T. 39 N., R. 3 E.)—subtle, 1.6-km-long (260 m, 850 ft wide) surface at ~70 m (230 ft) elevation, with isolated mounds; truncated by fluvial erosion; proximally bounded by a terrace (~49 m, 162 ft elevation) and distally by a small tributary of the Nooksack River at ~61–52 m (200–170 ft) elevation, producing a variable local relief (~16–8 m, 52–26 ft).	May be a continuation of the Tenmile moraine.

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.—Continued

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
Goshen moraine	Near Goshen (sec. 12, T. 40 N., R. 3 E.)—narrow, subtle, arcuate ridge, 300 m (980 ft) wide, nestled between bedrock ridges at ~45 m (148 ft) elevation; 2 km northeastward of Tenmile Creek moraine; retreat of ice left small transverse ridges and eskers superimposed on bedrock ridges.	
Phase 7, Wiser Lake	**Defined by abandonment of Tenmile Creek channel; formed before stabilization of ice margin at Clearbrook moraine**	
Wiser Lake outwash plain	South of the Nooksack floodplain—extensive outwash surface (a sandur); ~16 km (10 mi) long, 6.2 km (3.8 mi) wide in the distal zone and 2.8 km (1.7 mi) wide in the proximal zone, oriented NE-SW, at ~34–18 m (111–59 ft) elevation; flat (slope of 42 ft in 6 mi), as much as ~18 m (59 ft) above the Nooksack River's modern floodplain.	Younger than Tenmile Creek channel; 11,113±77 (AA-27066) and 11,080±100 ^{14}C yr B.P. (AA-27056) and older than peat in a depression along the fringe of the floodplain; 9,460±50 ^{14}C yr B.P. (B-254906).
Phase 8, Clearbrook	**Defined by moraines and outburst flood features that nearly extend across the full width of the Sumas prairie near Sumas.**	**North of the Nooksack River.** **Retreat of ice to this position allowed unimpeded westward flow of the Nooksack River.**
Clearbrook moraine	A complex, breached, arcuate moraine with outwash apron partially surrounds Sumas prairie (~5.4 km, 3.3 mi across), mostly in NE ¼ of T 40 N., R. 4 E. Northeast of Everson (secs. 14, 15, 21, 22, T. 40 N., R. 4 E.)—scraps of moraine crest at elevations of ~36–60 m (120–200 ft) rise up to ~40 m (131 ft) above the Sumas River floodplain; along its southeast margin, nested against Sumas Mountain, as high as ~65 m (213 ft) elevation, is a ~0.7–2.9-km-wide (1.8-0.4 mi), ~4-km-long (2.5 mi), southwest-sloping (0.3°) surface that rises abruptly (~40 m, 131 ft) above the modern Sumas River floodplain (~20 m, 66 ft elevation). Distal limits of this surface are scarps cut into outwash by the Nooksack and Sumas Rivers. Proximally, the surface consists of segmented (~230 m, 750 ft long), narrow (~60 m, 200 ft wide) ridges (local relief up to ~26 m, 85 ft), separated by kettles or breached by meltwater channels. The western margin of the original surface has been removed by subsequent meltwater erosion that breached the moraine, producing a 2.4-km-wide (1.5 mi) gap. North of Everson (secs. 7, 18, 19, T. 40 N., R. 4 E.)—moraine crest is present only in northern part of this sector. To the west, long (~2.5 km, 1.5 mi) parallel to subparallel ridges and furrows form a broad (~4.3-1.6 km wide and ~5 km long) surface at ~30 m (98 ft) elevation, with relief up to 7 m (23 ft); distal end of the surface is graded to slightly above the altitude of the modern Nooksack River floodplain at ~20 m (65 ft) elevation.	Older(?) than 10,250 ^{14}C yr B.P. (AA-27063 and AA-27057). Collectively, landform assemblages provide an outline of the former glacier margin. Furrowed surface north and west of Everson is in appropriate position for an outwash apron and appears to have been formed and (or) modified by one or more outburst floods.

Table 2. Descriptions of glacial phases and moraines in western Whatcom County.—Continued

[ft, feet; m, meters; mi, miles; RSL, relative sea level]

Phases and moraine names[1]	Definitions and descriptions[2]	Comments
Phase 9, post-Clearbrook	**Not well-defined but represented by ridges and an outwash surface which are at most ~6.7 km (4.2 mi) inside of the Clearbrook moraine.**	
Post-Clearbrook moraine	West of Sumas (W½ sec. 33, T. 41 N., R. 4 E.)—two narrow, arcuate ridges as high as ~29-18 m (94–59 ft) elevation rise to ~11 m (35 ft) above the Sumas prairie; southeast of Sumas (SE¼ sec. 11, T. 40 N., R. 4 E.) an outwash surface as high as ~47 m (155 ft) elevation rises to ~30 m (100 ft) above the Sumas prairie.	Two ridges inset or banked against older and topographically higher undulating surface associated with the Clearbrook moraine indicate that they are younger than the Clearbrook phase. The southwestern margin of outwash surface appears to fill in older kame-kettle topography associated with the Clearbrook moraine and is therefore younger than the Clearbrook phase.

[1] All phase and moraine names are informal. Named moraines are located on map and figure 2.

[2] All elevations are based on high-resolution lidar data and are present-day elevations unless otherwise noted. Many features were formed at lower absolute elevations due to isostatic response to ice loading. Please see the discussions in sections "Glaciation, Glacial-Isostatic Adjustment, and Relative Sea Level" and "Tilt Estimated from Fossil Shorelines and Correlation Between Uplands" for an analysis of the magnitudes of isostatic rebound and associated tilting.

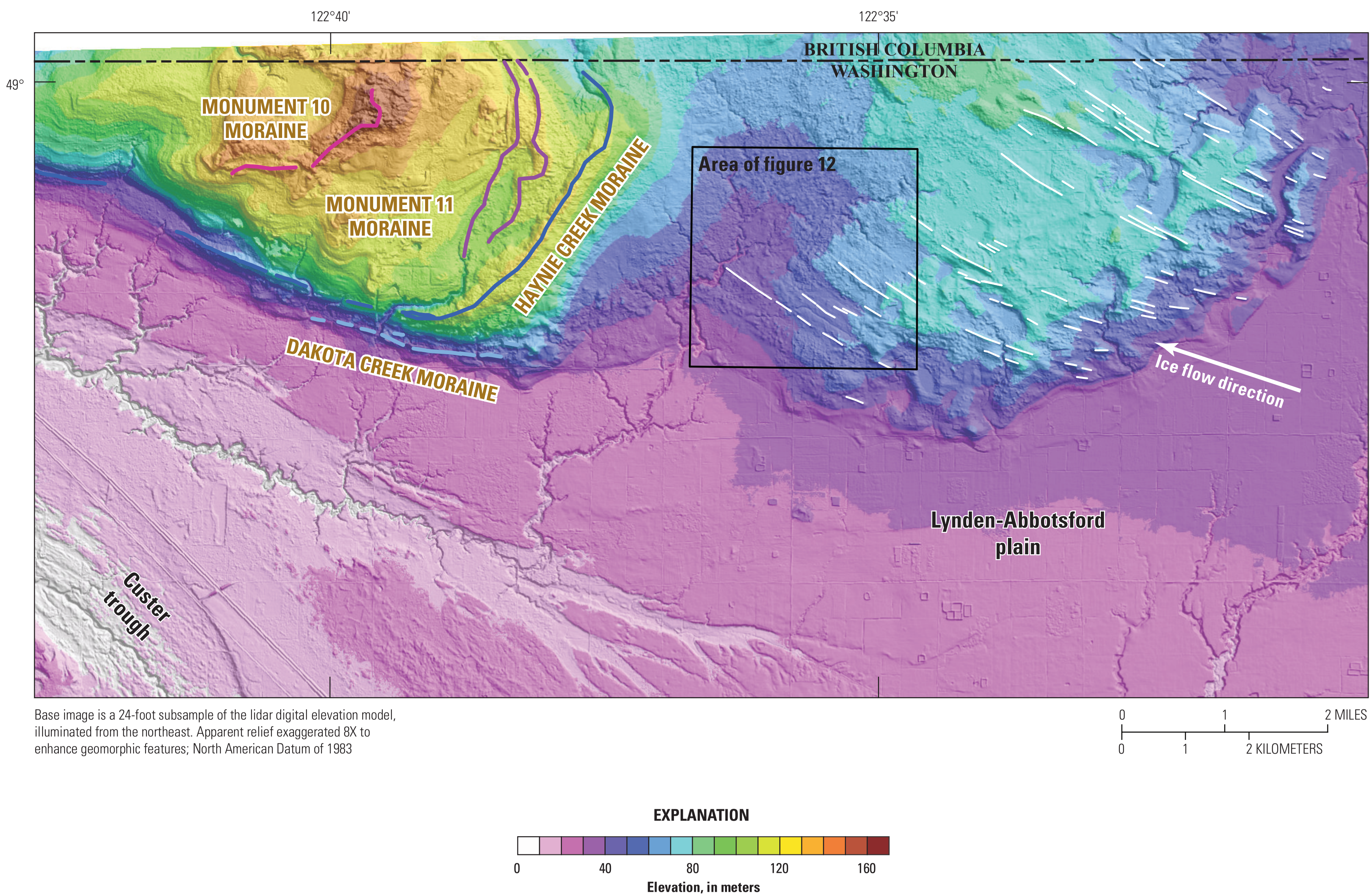

Figure 8. Colored-relief map of Boundary upland showing moraine crests of Monument 10 age (phase 2; magenta line), Holman Hill age (phase 3, Monument 11 moraine, purple lines), Grandview age (phase 4, Haynie Creek moraine, dark blue line), and Van Wyck age (phase 5, Dakota Creek moraine; light blue lines) and superimposed glacial lineations (white lines).

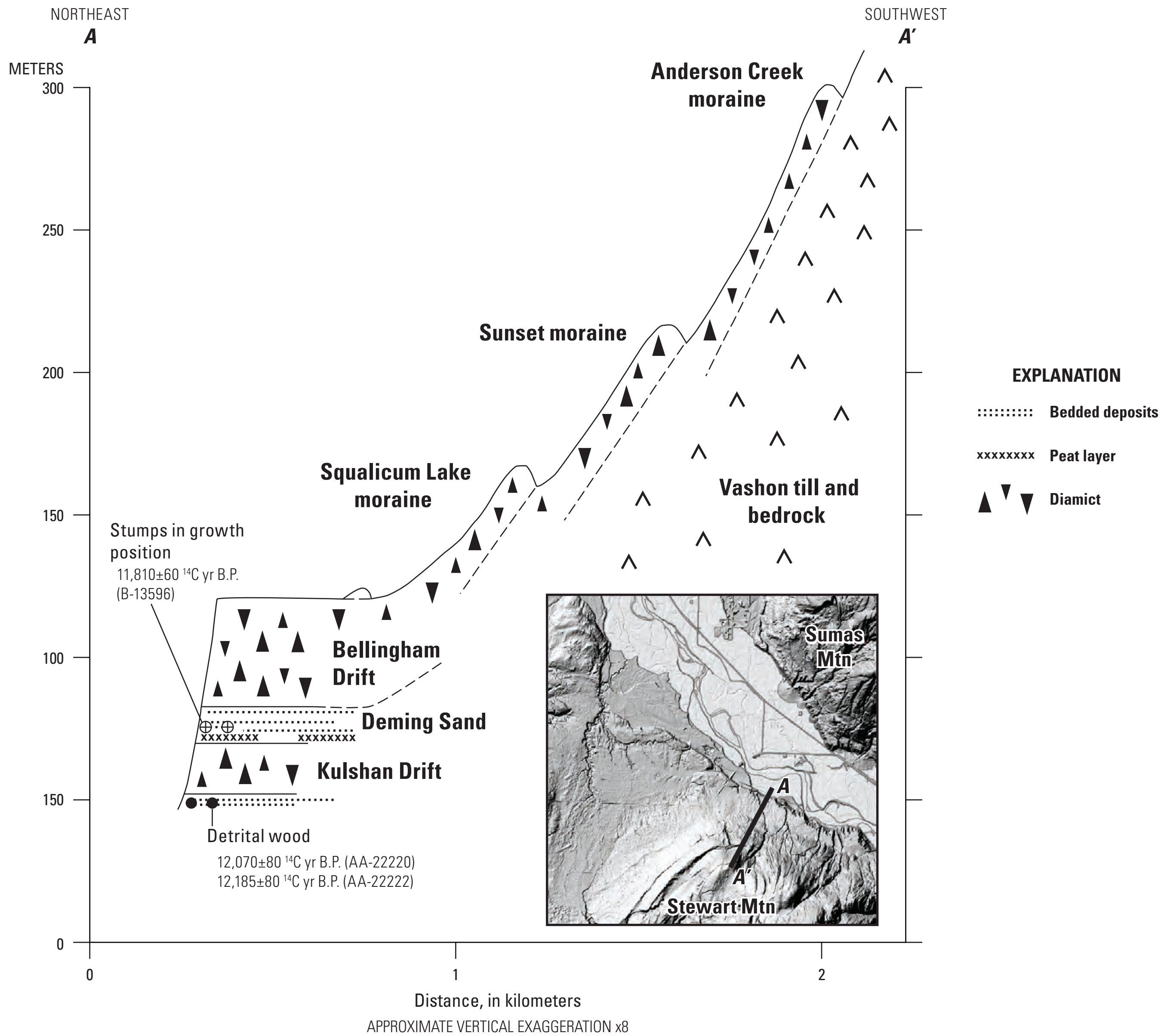

Figure 9. Simplified topographic profile through the Cedarville locality on the northern flank of Stewart Mountain (X on fig. 3), showing elevations of moraine crests and their relations to dated samples and Easterbrook's (1976a) type section for his Kulshan Drift, Deming Sand, and Bellingham Drift. Inset shows location of profile.

drift of the Fort Langley Formation north of Chilliwack, British Columbia (site FL38 at lat 49º6.3′ N, long 121º55.3′ W, his fig. 22), approximately 49 km (31 mi) northeast of our map area. This observation indicates ~90 km (55 mi) of ice margin retreat after formation of the Monument 10 moraine (phase 2) and before formation of Grandview (phase 4) moraines. Whether this retreat occurred before or after formation of the Holman Hill moraine (phase 3) is unclear, though we think it slightly more likely that the most extensive marine inundation (fig. 7*B*) preceded phase 3.

Marine-modified surfaces at lower elevations than the phase 4 fossil shoreline are younger (post-Grandview) and we map them as unit Qmy. These younger surfaces formed during the Sumas stade.

Terrestrial Surfaces Formed During the Sumas Stade

The Sumas stade of Armstrong and others (1965) is defined as the period in which ice advanced across the emergent Fraser Lowland, blanketing (and locally eroding) previously deposited glaciomarine drift. The lidar surveys we interpret in this study demonstrate that Sumas ice extended at least as far southwest as the modern coastline and that there were as many as six distinct Sumas ice-margin readvances or still stands in western Whatcom County. Our phases 3–9 are episodes within the Sumas stade.

Phase 3, Holman Hill

In the central part of the Mountain View upland, west of Ferndale, the Holman Hill end moraine is of relatively low local relief and consists of small, irregular mounds (fig. 10; table 2; Kovanen and Slaymaker, 2003; Haugerud and Maudlin, 2005). Maximum elevation is ~106 m (348 ft) and most of the moraine crest is above 90 m (295 ft) elevation. The western edge of the moraine is defined locally by digitate lobes. These lobes crosscut some marine features at ~90–70 m (295–230 ft) elevation, although fossil shorelines also trim some lobes of the moraine from 73 to 65 m (239 to 214 ft) elevation. Together, these observations suggest that formation of the Holman Hill moraine was contemporaneous with local RSLs that ranged

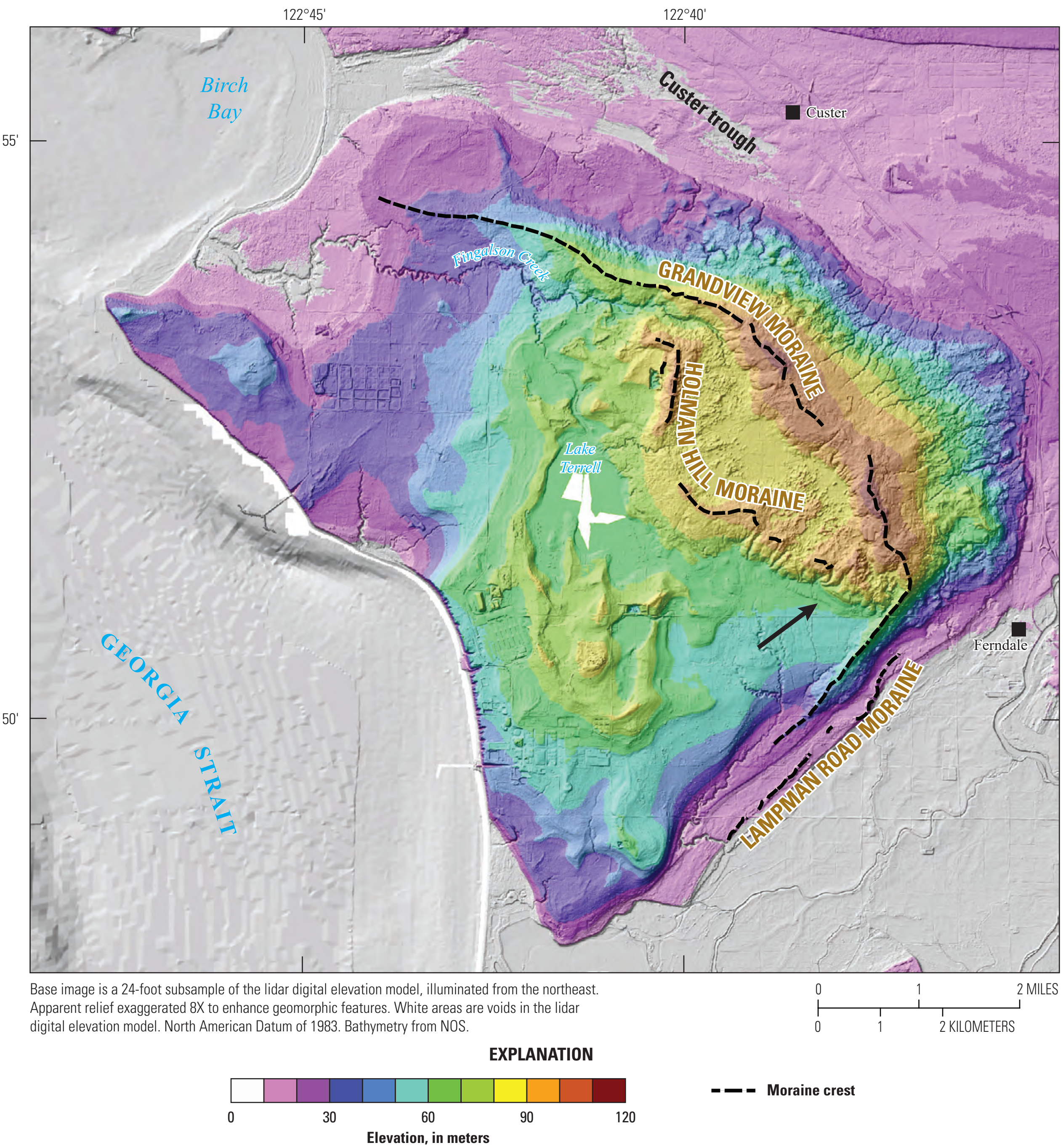

Figure 10. Colored-relief map of Mountain View upland showing moraine crests of Holman Hill age (phase 4), Grandview age (phase 4), and Van Wyck age (phase 5, Lampman Road moraine). Arrow points to fossil shorelines eroded into Holman Hill moraine at ~73 m (~240 ft) elevation 3 to 4 km southeast of Lake Terrell. To the northwest and southeast these shorelines were overrun by the moraine, establishing penecontemporaneity of moraine and shorelines. Lower-elevation, thus younger, fossil shorelines are conspicuous south of Lake Terrell. Along Fingalson Creek, fossil shorelines at elevations of ~35–65 m (115–215 ft) are truncated by the Grandview moraine. To the northwest, at elevations of 25–35 m (80–115 ft), younger fossil shorelines overprint the Grandview moraine.

from ~73 to 65 m (239 to 215 ft) elevation. Fingalson Creek has cut down along the northwest margin of the moraine and an unnamed creek that flows into Lake Terrell breaches its western margin. The moraine is the outermost and therefore the oldest on the Mountain View upland.

The Holman Hill moraine is more distal, relative to a Fraser River or Coast Mountains ice source, than the Monument 10 moraine. Holman Hill moraine is also at a lower elevation (both present-day and tilt-restored late Pleistocene elevation). Thus, we infer that, at the time of formation of the shorelines that trim the Monument 10 moraine, the Holman Hill moraine location was ice-free and covered by marine water. Because the Holman Hill moraine cross-cuts fossil shorelines, we infer an advance of the ice margin, and we consider it to be the oldest Sumas feature.

On the Boundary upland, the Monument 11 moraine consists of two closely spaced ridge crests at elevations up to ~130 m (427 ft; fig. 8; table 2). On the northern side of the upland, the moraine extends northwestward into British Columbia, while on the south side it narrows, slopes downward (104 m, 340 ft elevation), and is nestled against the older wave-washed surface. The distal part of the moraine truncates shorelines from 123 to 105 m (403–344 ft) elevation. The proximal side of the moraine is buried by the younger Haynie Creek moraine. The Monument 11 moraine may have extended to lower elevations and truncated lower-elevation shorelines. Cross-cutting relations show that the Monument 11 moraine formed as ice advanced over an emergent area. We include it in the phase 3 with the Holman Hill moraine.

The Sunset moraine (fig. 11, table 2) extends west along the north side of Squalicum Mountain, then slopes and broadens to ~55 m (~180 ft) elevation within the Bellingham city limits, below which we infer it to be modified by marine processes. In the area between Squalicum Creek and King Mountain, interior to the Sunset moraine, older marine-modified surface (unit Qmo) must be younger than the Sunset moraine. This surface is as high as 60 m (197 ft) elevation. Relative sea level during construction of the Sunset moraine was thus at least this high, and on this basis we assign the Sunset moraine to phase 3. East of Squalicum Lake, a moraine extends 5 km eastward along Stewart Mountain to ~215 m (705 ft) elevation and is probably correlative. The elevation of this moraine crest indicates that phase 3 ice extended into the Nooksack River valley east of the map area.

The Alderwood moraine, southeast of the Bellingham airport, extends down to a fossil shoreline at ~40 m (130 ft) elevation, thus is younger than other moraines included in phase 3. If the Alderwood moraine were as old as the Sunset moraine, it would be wave-washed to higher elevations.

Figure 7*C* shows the ice configuration and relative sea level during phase 3. Phase 3 ice northeast of the map area was probably thick enough to divert water flowing along the south margin of the ice sheet (for example, from the Chilliwack valley) into the Columbia Valley via the Cultus Lake basin, whence it flowed south, joined by water from the upper Nooksack drainage, via the lower South Fork of the Nooksack, to the Samish River valley (fig. 1; Easterbrook, 1992; Armstrong, 1981; Saunders, 1985; Kovanen and Easterbrook, 1997; Dragovich and others, 1998; Haugerud, 2007). The width and meander radius of fossil channels in the Columbia Valley and the lower Samish River valley suggest that discharge along this flow path was similar to that of the modern Fraser River.

Our interpretation of the landscape provides little information on the earliest history of the Sumas stade. Specifically, we cannot discern how far northeast the ice margin retreated between formation of the Holman Hill and correlative moraines of phase 3 and re-advance to form Grandview and correlative moraines of phase 4.

Phase 4, Grandview

The Grandview phase is characterized by prominent end moraines that fringe the Boundary and Mountain View uplands and the Lummi peninsula. Cross-cutting relations demonstrate that the Grandview moraines represent a re-advance of the ice margin. The moraines are onlapped by prominent fossil shorelines. Applying the tilt correction discussed above to these shorelines indicates a fairly consistent paleo-elevation and consequently we correlate the shorelines and infer that the moraines they onlap belong to the same phase. The onlap relations of the shorelines and the moraines indicate that (1) shorelines on the distal faces of the moraines could have formed at the same time as the moraines; (2) all parts of the shorelines could have formed shortly after retreating ice abandoned the moraines; (3) the shorelines could have formed upon later re-submergence of the local area; or (4) some combination of the above.

The Grandview moraine wraps around the Mountain View upland (fig. 10; table 2; Kovanen and Slaymaker, 2003; Haugerud and Maudlin, 2005) and truncates both the Holman Hill moraine and well preserved fossil shorelines higher than ~38 m (124 ft) elevation. The southern limb of the moraine (at secs. 26, 35, T. 39 N., R. 1 E.) narrows as it descends to 23 m (75 ft) elevation and the northern limb descends to 26 m (84 ft) elevation. Lower-elevation fossil shorelines lap onto the moraine limbs, showing that, in part, the moraine was formed in, or later covered by, seawater. The highest shoreline, at an elevation of ~35 m (115 ft), is especially well developed and may reflect slowing, local cessation, or even minor reversal of relative sea level fall due to isostatic rebound at or shortly after the time of maximum phase 4 ice extent.

The Haynie Creek moraine wraps around the western, higher-elevation part of Boundary upland and truncates the Monument 11 moraine (fig. 8; table 2). The southern limb of the Haynie Creek moraine ends at a flat surface that we interpret as a marine terrace (a shoreline feature) at ~41 m (135 ft) elevation (secs. 3, 4, T. 40 N., R. 1 E.). The relation of the moraine to the marine terrace suggests that either (1) the moraine formed when sea level was at ~41 m; or (2) the shoreline terrace at ~41 m formed prior to moraine construction. The Haynie Creek moraine is older than basal peat recovered from a meltwater channel ~9 km to the east of (interior to) the Haynie Creek moraine. The peat yielded a radiocarbon age of 11,413 ± 80 ^{14}C yr B.P. (sample AA-27072).

The Lummi moraine wraps around the northern end of the Lummi peninsula (table 2) and truncates a sequence of shorelines at ~36–26 m (118–85 ft) elevation, while other shorelines—the highest at ~23 m (75 ft) elevation—onlap the moraine. Similar to the Grandview and Haynie Creek moraines, this moraine truncates fossil shorelines and thus formed during a re-advance of the ice margin. Sea level was no higher than ~26 m (85 ft), the elevation of the lowest shoreline truncated by the Lummi moraine.

The broad, kettled Airport moraine, in the vicinity of Bellingham International Airport between Marietta and King Mountain, is bounded by, and thus the same age as or older than, fossil shorelines at elevations of 30 to 25 m. When rebound-related tilt is restored, these shorelines are at similar elevation to the shorelines that bound the Haynie Creek, Grandview, and Lummi moraines, thus we consider the Airport moraine to be phase 4 in age.

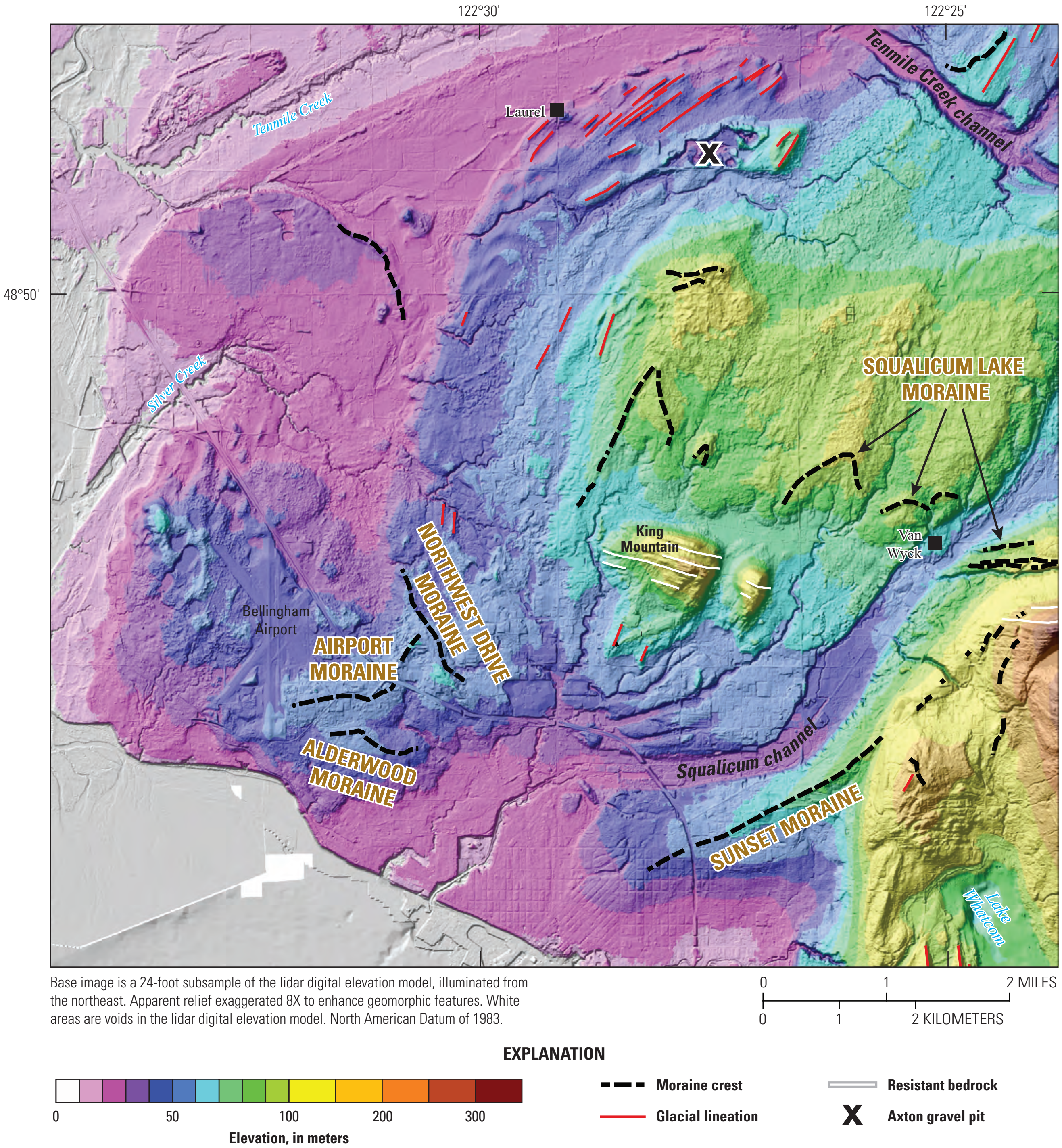

Figure 11. Colored-relief map of King Mountain upland and adjoining areas showing moraine crests (dashed black lines), Tenmile Creek and Squalicum meltwater channels, glacial lineations (red lines; ice flow was from northeast to southwest), and traces of resistant beds in the steeply dipping Chuckanut Formation bedrock (thin white lines on King Mountain and farther east). Squalicum channel expands southwest into a large fossil delta—now trimmed by Holocene shoreline erosion and historic development, with superimposed street grid and abandoned gravel pit—that records sea level at the time the channel was active. X marks location of Axton gravel pit.

The Squalicum meltwater channel is deeply incised (as much as ~35 m, 115 ft), is aligned roughly parallel to the main ice-flow direction, and is up to ~9.3 km (5.7 mi) long and 700–350 m (2,300–1,150 ft) wide (fig. 11). The elevation of the floor of the channel presently ranges from ~23 m (75 ft) to ~60 m (197 ft). The surface of the fossil delta at the mouth of Squalicum Creek is at a similar tilt-restored paleo-elevation as the shorelines that trim the Airport moraine and the distal ends of the Lummi, Grandview, and Haynie Creek moraines. We thus interpret the Squalicum channel and delta to have formed during phase 4 and map them as unit Q4o. The channel is essentially headless: it peters out into minor channels and a shallow depression south and west of the community of Wahl (near sec. 26, T. 39 N., R. 3 E.). We infer that it was later filled by deposition of phase 5 moraine.

The 350–700 m (1,150–2,300 ft) width of Squalicum channel is similar to that of abandoned channels in Columbia Valley, which suggests that Squalicum channel received Columbia Valley (fig. 1) drainage; no other plausible sources of similar magnitude are evident. The dimensions of Squalicum and Columbia Valley channels are similar to that of the modern Fraser River. Perhaps during phase 4 much of the Fraser basin drained through the Columbia Valley and Squalicum channel.

Fig. 7*D* shows the inferred ice margin, marine inundation, and large-discharge flow paths during phase 4.

Phase 5, Van Wyck

Post-Grandview surfaces on the King Mountain upland and adjoining areas cannot be definitely correlated with post-Grandview surfaces north of the Nooksack River. South of the Nooksack River, we divide a sequence of recessional moraines into the Van Wyck phase (5; fig. 7*E*) and Tenmile Creek phase (6; fig. 7*F*). The Wiser Lake phase (7; not shown in fig. 7) reflects the development of an outwash plain associated with a change in the pathway of meltwater and also glacial outburst floods. North of the Nooksack River, we tentatively assign some features to phase 5, but the majority of post-Grandview terrestrial surfaces are assigned to the Lynden-Abbotsford plain and the Wiser Lake phase (7).

South of Nooksack River

South of the Nooksack River, the transition from Grandview (phase 4) to Van Wyck (phase 5) is defined by advance of ice to block the upper Squalicum meltwater channel. Perhaps abandonment of the Squalicum channel was a consequence of on-going isostatic rebound that lowered the divide between the South Fork Nooksack River and the Samish River relative to the head of the Squalicum channel. Such lowering would have allowed meltwater from the Columbia Valley flowpath and from the upper Nooksack drainage to flow south into the Samish River. Without active fluvial erosion of the Sumas ice front in the region between Van Wyck and Cedarville, the ice then advanced south to the slopes of Stewart Mountain, obliterating the upper reaches of the Squalicum Creek meltwater channel.

On the north side of Stewart and Squalicum mountains and on the King Mountain upland there are several subtle moraine crests that record progressive retreat of Van Wyck-age ice (figs. 9 and 11; table 2). The Squalicum Lake moraine, banked against Squalicum and Stewart mountains up to an elevation of ~161 m (530 ft), extends eastward toward the Nooksack valley. Its altitude and position along Stewart Mountain demonstrates that the Nooksack valley in the vicinity of Deming was occupied by phase 5 ice. West of Squalicum Lake, the moraine extends 4.6 km along Squalicum Mountain before it drapes into Squalicum channel. The moraine is separated from the older Sunset moraine by a narrow ravine. On the King Mountain upland the Squalicum Lake moraine forms a broad (~3.8 km north-south, 5.1 km west-east), strongly undulating surface between 113 and 72 m (370 and 236 ft) elevation. The moraine surface is a complex of irregular hummocks, ridges, enclosed depressions, and steep slopes. Some of the hummocks appear to be part of an integrated system of small transverse ridges indicative of active ice recession. The surface as a whole appears to be a complex assemblage of cross-cutting and discontinuous end moraines that formed during intermittent stillstands as the active ice front receded. To the west and northwest are regions of well-developed glacial flow lineations (fig. 11) that were not obliterated by such end-moraine deposition. Marine shells recovered from sediments that underlie the flow lineations yielded a radiocarbon age of 11,620 ± 70 ^{14}C yr B.P. (B-254905). Six other dates from the Axton Pit quarry (fig. 11, table 1) yielded similar results. These dates represent a maximum age for the Van Wyck phase. Unless there was significant ice retreat and then re-advance between Grandview and Van Wyck time, for which we see no evidence in this area, these are also pre-Grandview ages.

The subtle Northwest Drive moraine, which lies west of King Mountain, truncates the crest of the phase 4 Airport moraine and marks the limit of phase 5 ice at this point (fig. 11).

The Wahl moraine is a series of closely spaced, parallel, narrow ridges distributed over the surface of a knob near the present head of Squalicum Creek (table 2). They range from 103 to 79 m (338–259 ft) in elevation. An ice margin at this position blocked the Nooksack paleo-drainage, which during phase 4 had flowed west through this region to Squalicum channel.

The Lummi Shore Road moraine is a discontinuous, narrow ridge 30–16 m (98–52 ft) elevation, up to 10 m (33 ft) high, which wraps around the northern end of the Lummi peninsula. It is sinuous, truncates fossil shorelines, is parallel to inferred ice-flow direction, and rests on a nearly flat surface at ~14 m (46 ft) elevation. Several kettles lie immediately to the west and north of the ridge, and at some locations the ridge gives the appearance of having been pushed by glacial ice. Although we are uncertain about the origin of this landform, we consider it to mark a former ice boundary. Perhaps it formed by ice-marginal squeezing (Benn and Evans, 1998).

East of Ferndale, an isolated, gently south-sloping surface (mostly in sec. 27, T. 39 N., R. 2 E.) rises ~12 m (40 ft) above the Wiser Lake outwash plain to the north. Relict bar-and-swale topography and kettles on the north part of the surface lead us to interpret it as an outwash fan, formed by meltwater discharging from the glacier. Shorelines are cut into the surface at 26–23 m (85–75 ft) elevation. Along the northeast and eastern margin of the surface are erosional pedestals with up to ~7 m (23 ft) in local relief that we interpret as relict terminal moraine. These features lie inboard of, and thus must be younger than, the Airport moraine, and are higher than and thus older than outwash flats associated with the Tenmile Creek meltwater channel. We therefore assign these erosional pedestals and the outwash fan surface to phase 5.

North of Nooksack River

North of the Nooksack River, the transition to phase 5 is marked by retreat of ice from phase 4 termini and construction of morainal surfaces truncated by fossil shorelines that are slightly lower (in tilt-corrected framework) than the immediately post-phase-4 shorelines.

On the Birch Point upland, the Birch point moraine (table 2) consists of a 300-m-wide, 1.4-km-long (0.9 mi) ridge at an elevation as high as ~27 m (89 ft) and is ~21 m (70 ft) above the floor of the Custer trough north of the upland. Extending west from the moraine are sub-parallel ridges as long as ~2.4 km (1.5 mi) and as wide as ~200 m (656 ft) that have local relief of as much as ~5 m (16 ft). We tentatively interpret these ridges as erosional features produced by an outburst flood. Flat areas between the ridges where they meet the moraine appear to be filled former plunge pools, formed where a cataract spilled over the moraine. The distal end of the ridged surface is of relatively low relief, and is bisected by a subtle broad gap that may have once allowed water to flow across the surface. Though we interpret these ridges, plunge pools, and eroded moraine to have been made by an outburst flood[7], we do not know the source. If a proglacial outburst flood originated from an ice-dam failure upvalley and produced the scoured features by overtopping the upland, such a flood would have substantially inundated sites upstream, but we see no evidence of this. The flood must predate unit Q7fd at the northeastern margin of the Mountain View upland, because there is no record of a large flood on this surface at similar elevations as the Birch Point upland, ~16–27 m (54–89 ft). We tentatively classify all of these features as phase 5.

On the Boundary upland, the Dakota Creek moraine (fig. 8) lies inboard of the Haynie Creek (phase 4) moraine and is trimmed by a fossil shoreline at slightly lower elevation than the fossil shoreline that trims the Haynie Creek moraine, thus we tentatively classify it, and the extensively glaciated ground to the east and northeast, as phase 5. The glaciated ground to the east and northeast appears to be polygenetic: older, hummocky (kettled?), glacial terrain is overprinted by subparallel, northwest-trending glacial flow lineations; superimposed on the flow lineations are low-amplitude transverse ridges (fig. 12).

[7] The sudden release of water from a glacier or glacier-dammed lake sometimes results in a catastrophic flood and causes rapid landscape change. These are widely referred to by the Icelandic term "jökulhlaup." Jökulhlaups may be triggered by: (1) the sudden drainage of an ice-dammed lake, below or through the ice dam; (2) overflow of a periglacial lake and rapid fluvial incision of ice, bedrock or sediment barriers; or (c) collapse of a subglacial water reservoir. The type of landform produced during a jökulhlaup depends on the nature of the flood flow, its sediment load, and the topography of the flood pathway. Flood physics related to the ice surface height, position, and flood pathways are not discussed here, but we have considered them in a preliminary manner.

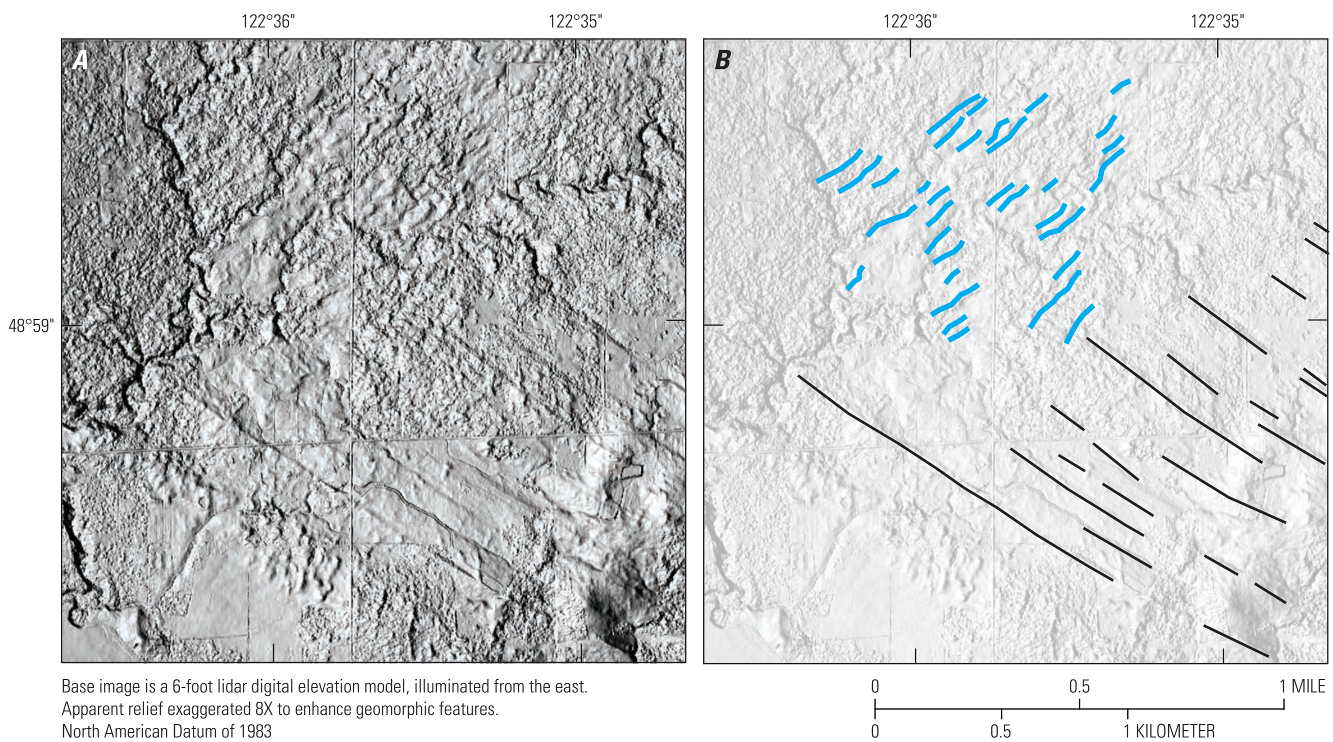

Figure 12. *A*, Detailed view of eastern Boundary upland showing glacial lineations in lower right part of image and transverse ridges ("washboard moraine") in upper left part of image. These transverse ridges may be relict crevasse fillings. *B*, Line drawing of same area showing glacial lineations (narrow black lines) and washboard (thick blue lines). Not all features identified. Area of image shown in figure 8.

These transverse ridges resemble "washboard moraine" (Cline and others, 2011) that are probably melted-out crevasse fillings. Flow to the northwest of phase 5 ice produced the lineations. Preservation of crevasse fillings require that the ice then stagnated and melted in place. The absence of a well-defined terminal moraine associated with the lineations might suggest that the lineations formed during phase 4, at the same time as the Haynie Creek moraine, but in that case the formation of the Dakota Creek moraine is unexplained.

Southwest of Ferndale (fig. 10; N½ sec. 29, T. 39 N., R. 1 E.), at ~18–12 m (60–39 ft) elevation, a terrace extends ~4.5 km (2.8 mi) and is as high as ~5 m (16 ft) above the modern floodplain. A distinct discontinuous ridge rises to ~9 m (30 ft) above the terrace surface. We interpret the ridge as a moraine (unit Q5g), and refer to it as the Lampman Road moraine. On its northwest side the moraine is bordered by a narrow outwash flat (unit Q5o).

Extent of Phase 5 Ice

Ice of the Sumas stade retreated significantly during phase 5. The maximum ice extent can be inferred from the Squalicum Lake, Lummi Shore Road, Lampman Road, Birch Point, and Dakota Creek moraines, which are truncated by fossil shorelines that are slightly lower (in the tilt-corrected framework) than the immediately post-phase-4 shorelines. Figure 7*E* shows inferred maximum extent of phase 5 ice and associated marine inundation. The minimum extent of phase 5 ice can be inferred from the position of the Wahl moraine.

Phase 6, Tenmile Creek

We define the transition from Van Wyck (phase 5) to Tenmile Creek (phase 6) as the initiation of water flow through the Tenmile Creek meltwater channel. The northward-retreating ice front lingered long enough to construct the Cedarville, Tenmile, and Goshen moraines (fig. 13). West-flowing Nooksack drainage ponded against the ice margin before being routed into the Tenmile Creek meltwater channel. The size of the Tenmile Creek channel suggests that at this time, as during phase 4, the Nooksack carried flow from the Columbia Valley. Apparently at this time the inlet of the Tenmile channel was lower than the path into the Samish River (fig. 1).

Remnants of a lake bottom (mapped as unit Q6l) occupy an area (secs. 19, 28, 29, and 30, T. 39 N., R. 4 E.) southwest of the Cedarville moraine. When the ice front was at the Cedarville moraine, or shortly thereafter at the Tenmile moraine, water overflowed a bedrock ridge that extends from Wahl to Goshen and eroded a spillway (scoured surface, unit Q6s) into the Tenmile Creek meltwater channel. The elevation of the lake was limited by the elevation of the ridge; scour features are present on the ridge at an elevation of ~75 m (245 ft), so the lake surface was at least that high. Erosion by westward flow of water lowered the spillway elevation to ~58 m (190 ft) elevation. Erosion of the spillway was sufficient to drain the lake as the Cedarville moraine is now fronted by a late-phase 6 outwash flat (unit Q6o).

The Tenmile Creek meltwater channel is ~5.8 km (3.6 mi) long, ~ 0.5 km (0.3 mi) wide, and 25 m (82 ft) deep. The channel is not at the bottom of a local valley, separates glaciated areas with differing textures, and splits to enclose a prominent remnant of the adjoining upland, all of which suggest that the channel formed at an ice margin. The floor of the channel ranges in elevation from ~43 to 27 m (141–88 ft) and contains terraces and bars. Peat from within the channel has yielded ages of 11,113±77 (AA-27066) and 11,080±100 (AA-27056) ^{14}C yr B.P. (Kovanen and Easterbrook, 2002a). These are younger limiting ages for the lake and spillway.

The Tenmile moraine, immediately north of the Tenmile Creek meltwater channel, drapes obliquely across glacially streamlined hills that trend northeast-southwest (fig. 13). The moraine is discontinuous; some gaps (for example, NE¼ of NE¼ of sec. 23, T. 39 N., R. 3 E.) appear to have been eroded by water exiting the ice front in this area, and other gaps (secs. 19 and 24, T. 39 N., R. 3 E.) were eroded by water flowing west from the Nooksack valley. Continued retreat of ice led to construction of the Goshen moraine, which comprises two narrow, subtle arcuate ridges between bedrock ridges (fig. 13).

A relatively smooth outwash flat as much as ~1 km wide extends 7 km west from the mouth of the Tenmile channel (unit Q6o). The distal part of this surface banks against an isolated fan-shaped surface (mentioned above) that rises ~12 m (40 ft) above it. The proximal part of this surface is onlapped by younger outburst-flood landforms (unit Q7fd, described and interpreted below) and buried beneath dunes (unit Qd) at the mouth of the Tenmile Creek meltwater channel.

Northeast of the Nooksack River, discontinuous outwash flats situated above hillside ice-moulded ground (kame terraces) are assigned to phase 6 on the basis of their elevation. Elevations of the outwash flats decrease to the south, reflecting southward flow of ice-marginal drainage along the west flank of Sumas Mountain. The paleogeography we infer for phase 6 is shown in figure 7*F*.

Phase 7, Wiser Lake

Abandonment of the Tenmile Creek channel and its truncation by younger surfaces in sec. 16, T. 39 N., R. 3 E. lead us to infer that retreat of the ice front opened a new, lower drainage pathway north of Goshen, several kilometers south of Everson. This change in drainage routing marked the transition from phase 6 to phase 7 and led to the development of the Wiser Lake outwash plain. We include in phase 7 depositional surfaces north and northwest of the Nooksack River that have elevations and surface textures similar to those of the Wiser Lake outwash plain.

The Wiser Lake outwash plain (fig. 2) is ~16 km (10 mi) long, 6.2 km (3.8 mi) wide in the distal zone and 2.8 km (1.7 mi) wide in the proximal zone, oriented northeast-southwest, at ~34–18 m (111–59 ft) elevation, and is as much as ~18 m (59 ft) above the modern Nooksack floodplain.

In general, the main part of the outwash plain is characterized by channels (unit Q7fc) and fluvial bedform (unit Q7fd) networks. The bedforms are large; they include compound, longitudinal and transverse bars with wavelengths as large as 430–850 m (1,400–2,100 ft) and heights ~1–3.5 m (3–11 ft). Two channels entrench the surface. They are as much as

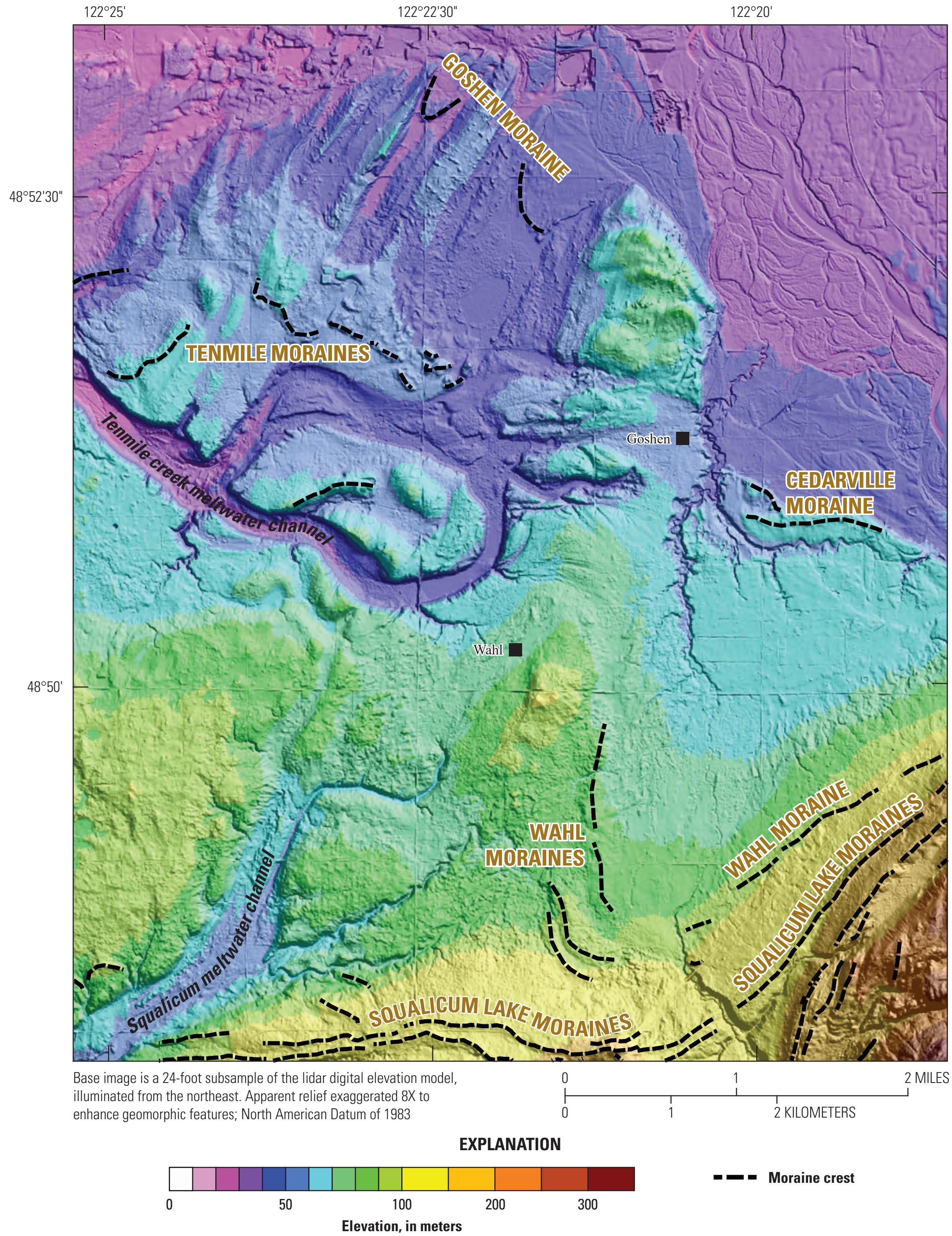

Figure 13. Colored-relief map of Goshen-Wahl area showing Tenmile Creek and upper Squalicum meltwater channels. Note broad, flat former lake floor 1.5–4 km east of Wahl. Three well-defined spillways from this lake into Tenmile channel system are preserved west of Goshen, with elevations of 58–62 m (190–204 ft). Faint scouring at 75 m (245 ft) elevation 0.75 km northeast of Wahl indicates that at initiation of drainage, the lake elevation was at least that high. Similar features at head of Squalicum channel must have been obliterated by deposition associated with the Wahl (phase 5) moraines. Note pronounced northeast-southwest ridges in northwest part of map, indicating ice-flow direction, locally with superimposed washboard moraine. Wiser Lake outwash plain (northernmost part of map) is here pockmarked by gravel pits. Between the pits, relict bedforms at elevations of 30–40 m (100–130 ft) show water flow from the east-southeast.

8 km long (5 mi), ~200–600 m (650–2,000 ft) wide, and ~2–8 m (6–26 ft) deep. They may have been deeper, as in places they are partly filled with younger material. The channels are less well defined down the outwash plain as they are progressively infilled. These channels merge in the proximal part of the plain and presently contain lake-filled depressions (Wiser, Fountain, and Green lakes). Peat associated with the northern channel has been found as deep as 10 m (35 ft) below ground surface on the margin of Wiser Lake (Riggs, 1958; Easterbrook, 1976a).

North of the Nooksack floodplain, northwest of Fishtrap Creek, an impressive, long (5.6 km, 3.5 mi), fluvial bedform complex with large bars rises ~14 m (46 ft) above the modern floodplain (fig. 14). The complex is inset relative to the Lynden-Abbotsford plain and consists of at least eight individual bars (migrating bedload sheets?) with downstream avalanche faces and minor channels or splays on their surfaces. The southern margin of the complex drapes into the valley, which presently confines the Nooksack River. No notable lateral scouring of the Nooksack River is observed along its southern margin. These bars diminish downstream to ~10 m (33 ft) height. The large size of these features compared to those associated with modern drainage and discharge regimes suggests to us that these features are indicators of great floods that once flowed through the area. Immediately to the north is a prominent, ~12.4 km (7.7 mi) long, west-tending straight scarp that rises up to 6 m (20 ft) above the lowest part of the bar complex. The scarp may have been scoured by the floods that formed the bar complex, or the bar complex could be younger. The scarp could be an erosional remnant of the outburst flood(s) that scoured much of the Custer trough (the topographic low that extends southeast from Blaine).

The distal end of the Wiser Lake outwash plain consists of a ~4.3 km (2.7 mi) long, nearly north-south trending, straight scarp that rises ~12 m (39 ft) above the modern floodplain. The floodplain is ~1.6 km (1 mi) across in this reach. Because the scarp is so straight, we infer that it was eroded by an outburst flood(s) that must postdate deposition of the Wiser Lake outwash plain. (step A4 below). Scouring by this later outburst flood event may have created the ~2 km (1.3 mi) wide topographic low between Ferndale and the Fishtrap Creek area that the Nooksack River presently occupies.

The Wiser Lake outwash plain is older than peat in a depression that fringes the modern floodplain west of Everson, which yielded a date of 9,460 ± 50 ^{14}C yr B.P. (sample B-254906).

Surfaces of the Lynden-Abbotsford Plain

North of the Nooksack River, formation of moraines that we tentatively assign to phase 5 (Van Wyck) was followed by ice retreat and concomitant marine flooding and development of a marine shoreline, then development of the Lynden-Abbotsford

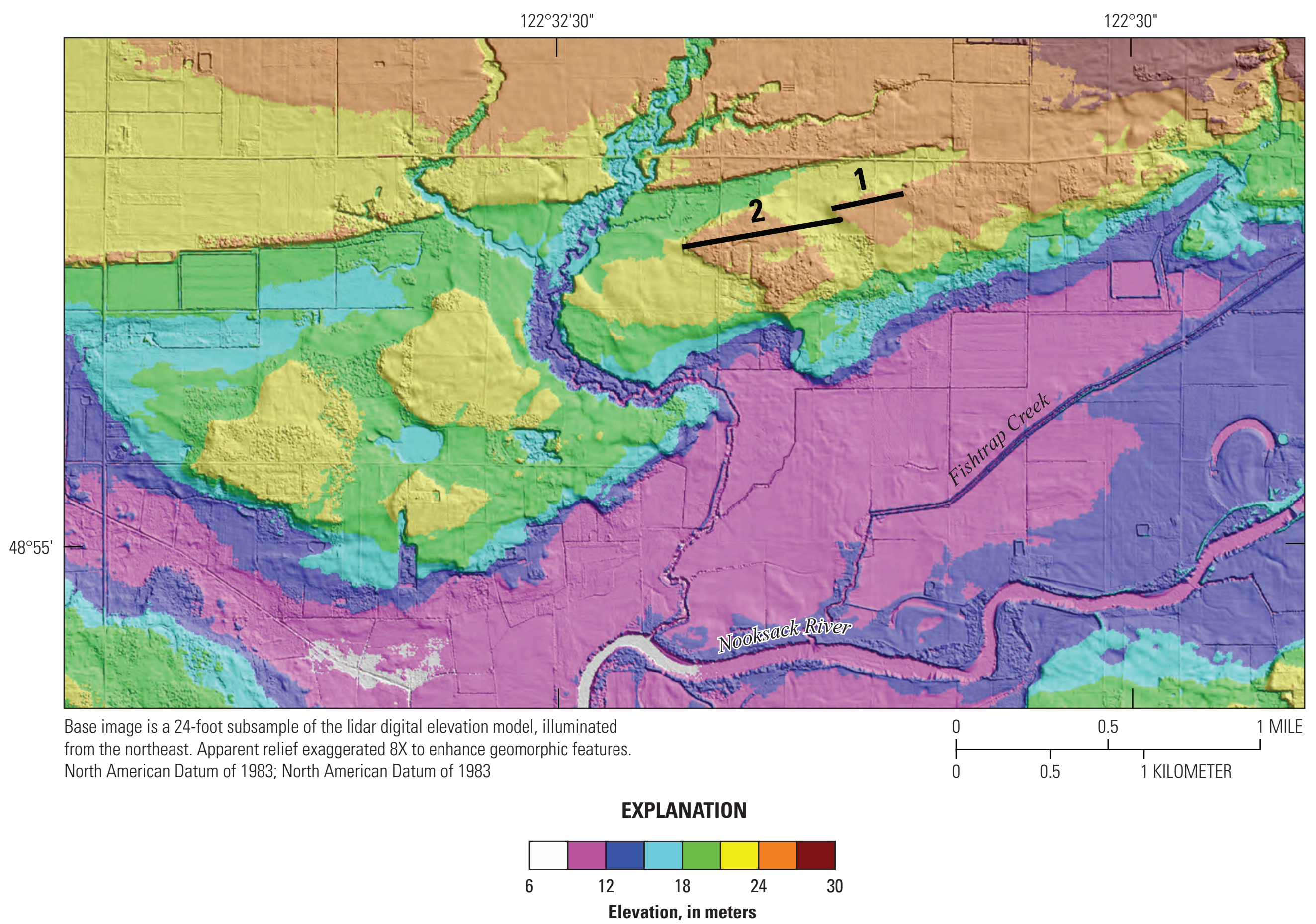

Figure 14. Colored-relief map of fluvial bedform complex north of Nooksack River. Crest-to-crest distances: 1, about 360 meters (1,200 feet); 2, about 850 meters (2,800 feet).

plain. Collectively, the surfaces of this plain may be coeval with Van Wyck, Tenmile Creek, and early Wiser Lake phases south of the Nooksack River.

The Lynden-Abbotsford plain is a broad (as wide as 15 km) smooth surface and has a gentle southwest slope (~62 ft over 7 mi; 4 m/km). Though now incised by younger streams, it was clearly once continuous. Throughout much of its extent the dominant relief is anthropogenic: drainage ditches and manure lagoons. It ranges in elevation from ~48 to 23 m (158 to 75 ft) and rises ~10–35 m (35–115 ft) above the modern Nooksack floodplain. The slope of the plain, the distribution of kettles, subtle bar-and-swale topography, and relations to nearby moraines indicate that the eastern part of the plain was formed by meltwater flowing south (from British Columbia) and west from the post-Van Wyck Sumas ice sheet. Lower slope, greater smoothness, and low elevation suggest that the western part of the plain may have been smoothed by shallow marine (tidal?) deposition and erosion. Subtle erosional scarps divide it into higher and older (Qlo), intermediate (Qli), and lower and younger (Qly) segments that step down to the south towards the Nooksack River.

At its eastern, proximal, end, unit Qlo (~36-21 m, 118–69 ft, elevation) is discontinuous, largely truncated by the younger Qli surface. But it appears to have graded into outwash flats that surround upper Bertrand Creek at and north of the United States-Canada border.

Unit Qli (~48–21 m, 157–70 ft elevation) extends north into British Columbia. At the border, Qli includes kettled outwash fans (Qlip). Peat from the base of a bog inset into Qlip yielded a radiocarbon age of 11,413±75 ^{14}C yr B.P. (sample AA-27072), which is a minimum age for the fan and the Qli surface.

The youngest part of the Lynden-Abbotsford plain (unit Qly) is inset into Qli along a northeast-trending erosional scarp. Along upper Bertrand Creek (sections 1, 2, 11, 12, T. 40 N., R. 2 E.), remnants of a proto-Bertrand Creek channel are incised into Qli. We infer that these are coeval with the younger part of the plain to the south, and map them as Qly also.

The eastern, proximal portion of Qly comprises broad outwash fans (unit Qlyp) with numerous relict channels that extend west from the vicinity of Clearbrook. At the eastern end of the easternmost fan, in sec. 5, T. 40 N., R. 4 E. and sec. 32, T. 41 N., R. 4 E., the fan abuts a fragment of Clearbrook (phase 8) moraine, demonstrating that this youngest part of the Lynden-Abbotsford plain is of (early) Clearbrook age. The proximal parts of these fans include the large kettles of Pangborn bog and Judson Lake, the unnamed kettle that occupies much of sections 11 and 12, T. 40 N., R. 3. E., and the surrounding pitted terrain that we map as unit Qlyk (kettled surface). Presence of kettles demonstrates that the fans were, in part, deposited over stagnant ice. Northeast of Lynden, in sec. 9, T. 40 N., R. 3 E., small channels incised into the Qly plain are mapped as unit Qlyc. These channels may be essentially coeval with the youngest phase of the Lynden-Abbotsford plain, or may reflect initial stage of incision in response to later (latest Pleistocene or Holocene) lowering of base level.

Fishtrap Creek incises the distal end of a subtle ridge that occupies the margin of the Lynden-Abbotsford plain at Lynden. The ridge rises as much as ~18 m (60 ft) above the modern Nooksack River floodplain, and the crest descends to the southwest, downstream. We interpret this ridge as a natural levee at the margin of the Wiser Lake outwash plain, formed during catastrophic flooding associated with outburst events (phase 7). We thus mapped the ridge as unit Q7fd (depositional landforms associated with outburst floods), Qlyp (proximal fan), and Qlyk (kettled surface, where the levee engulfed ice blocks that later melted).

Peat from basal sediments in a remnant meltwater channel within unit Qlyk yielded a radiocarbon age of 10,980±72 ^{14}C yr B.P. (sample AA-27062), which is a minimum age for the Qly surface. Peat recovered from basal sediments in Pangborn Lake, ~3 mi (5 km) to the east of AA-27062 within Qlyp, yielded radiocarbon ages of 10,265±65 (AA-27063) and 10,245±90 ^{14}C yr B.P. (AA-27066; Kovanen and Easterbrook, 2002).

Phase 8, Clearbrook

By phase 8, Sumas ice had retreated into the Sumas prairie region and the ice front stabilized at the Clearbrook moraine that bounds the prairie on the west, south, and southeast. We map as Clearbrook-age surface most of the area that Easterbrook (1976a) showed as Sumas till (his unit Qs).

To the southeast, in sections 14, 15, 21, and 22, T40N R4E, discontinuous fragments of the crest of the Clearbrook moraine extend from the foot of Sumas Mountain west to the Sumas River (table 2). An outwash apron that extends south from the moraine has locally been mined for aggregate. On the west, there are fragments of moraine crest south of Clearbrook; to the northwest, the former ice margin is recorded by ice-marginal meltwater channels that form the eastern margin of the Lynden-Abbotsford plain and adjacent kame-kettle surfaces that record melting of debris-covered Clearbrook-age ice.

An extensive low-relief conical apron extends as much as 3½ miles southwest from the western Clearbrook ice margin. This apron is decorated with a series of long (2.5 km, 1.5 mi) parallel to subparallel ridges, scarps and furrows with as much as 7 m (23 ft) of relief. The ridges and furrows are insufficiently parallel to have formed by ice scour and they lack the subtle asymmetry of longitudinal dunes. We interpret this ridged terrain (map unit Q8fs) to have been scoured by an outburst flood(s). The distal end of the surface is onlapped by the modern Nooksack River floodplain at an elevation of ~20 m (65 ft). Figure 7*G* shows the inferred ice configuration during the Clearbrook phase.

Farther southwest near Ferndale, low, nearly flat terrace surfaces that border the modern Nooksack floodplain are set into the Wiser Lake plain. They are thus younger than phase 7, yet predate the modern Nooksack. After phase 6 this area was marine (fig. 7*F*, 7*G*), probably with a relatively small tidal prism and thus with modest currents unlikely to form extensive flats. We thus infer that these flats formed during Clearbrook-age outburst floods and map them as unit Q8f. South of Ferndale, where the inferred floods tumbled over a phase 5 moraine, these surfaces have longitudinal scours that reinforce their interpretation as flood features (unit Q8fs).

Phase 9, Post-Clearbrook

Outwash flats inside the Clearbrook moraine, kame-kettle terrain associated with outwash flats that are incised into Clearbrook-age outwash flats, two narrow, arcuate morainal ridges 2 km west-southwest of Sumas, and a small fragment of end moraine astride the United States-Canada border in the town of Sumas are all evidence for the presence of younger, post-Clearbrook ice.

Evolution of the Wiser Lake Outwash Plain

The Wiser Lake outwash plain appears to have developed by processes similar to those described for outwash plains associated with glacial outburst floods in New England and Iceland (Koteff and Pessl, 1981; Gomez and others, 2000). We here adapt this model and present two contrasting interpretations to explain how the Wiser Lake plain developed over time. Limiting radiocarbon ages (samples AA-27056 and B-254906) indicate the plain developed in 1,600 years or less—perhaps much less. Interpretation A, which is illustrated on the map and in figure 15, proposes multiple outburst floods:

A1. The Wiser Lake outwash plain is a composite feature that was built progressively as the ice margin retreated northeast from its phase 6 position and southwest-flowing water distributed sediment, forming the outwash plain (fig. 15*A*). When the ice front was near the head of the outwash plain (near Strandell and Everson; fig. 2), an outburst flood entrenched the deep channels (unit Q7fc). Shortly thereafter, north-flowing water from the Nooksack drainage was routed westward onto the outwash plain, parallel to the ice front, and constructed a complex of aggradational bedforms. These bedforms bury the head of the entrenched channel and their northernmost margins drape into a glacial trough or depression. Water that flowed parallel to the ice front west of Everson and meltwater that emerged through tunnels at the ice front was routed southwest and dissected some of the bedforms, forming chutes.

A2. The ice front retreated from the head of the outwash plain and the consequent topographic discontinuity prevented water from flowing onto the surface (fig. 15*B*). The ancestral Nooksack River abandoned the outwash plain in favor of the newly exposed lower-elevation flow path.

A3. Following progressive lowering and retreat of the ice front, the glacier stabilized at the Clearbrook moraine (phase 8, discussed above) and constructed an outwash surface (fig. 15*C*). Subsequently, an outburst flood scoured the adjacent outwash surface and also breached the central part of the moraine. While the ice front was at this position, the ancestral Nooksack River must have flowed west.

A4. Alternatively or in addition to A3, as glaciation continued to wane and the ice margin retreated northward, further outburst floods scoured the outwash surface associated with the Clearbrook moraine and also dissected the central part of the moraine (fig. 15*D*). The Nooksack River eventually assumed a course on the scoured surface between Lynden and the Wiser Lake outwash plain (also see the discussion on fluvial adjustment below).

Phase 7 saw the transition from stable large flows from the southeast (down the path of the modern Nooksack River from Deming to Everson) to unstable large flows (outburst floods) from the northeast (out of Sumas prairie to Everson) and thence to the west. This transition was likely coincident with thinning of the ice surface in the Cultus Lake basin, northeast of the map area, to the point where ice was no longer thick enough to force drainage from the Fraser valley east of Chilliwack into the Columbia Valley. The discharge of the Nooksack River at Deming was thus substantially reduced. If the thinned ice at Cultus Lake was part of a glacier that, farther northeast, sloped down to the east (flowed up the Fraser Valley), the outburst floods of phase 7 and phase 8 may have been sourced from a temporary glacial impoundment in the Fraser valley. Alternatively, some of the outburst floods may have been sourced by sudden draining of ice-dammed lakes farther northeast (for example, Blais-Stevens and others, 2003; Johnsen and Brennand, 2004) or from the Chilliwack Valley (Saunders, 1985; Saunders and others, 1987).

Easterbrook prefers interpretation B (fig. 16) in which the Wiser Lake outwash plain was continuous between Lynden and Strandell and was subsequently scoured by a single large glacial outburst flood:

B1. The Wiser Lake outwash plain is a composite feature that was built progressively as the ice margin retreated northeastward from phase 6 ice marginal positions and as southwest-flowing water distributed sediment (fig. 16*A*).

B2. As the ice margin retreated to the position of the Clearbrook moraine (phase 8, discussed above), younger outwash was added to the northeasternmost portion of the Wiser Lake outwash plain and the Nooksack could extend its course northward to join the head of the outwash plain near Everson (fig. 16*B*). While ice was forming the Clearbrook moraine, it built an outwash terrace (Q8o), a remnant of which still persists on the east side of Sumas valley. Because there was no place else for this outwash to go, it must have flowed across the Wiser Lake outwash plain.

B3. Sometime following the retreat of ice from the Clearbrook moraine, a large outburst flood probably caused by the sudden draining of an ice-dammed lake in British Columbia (i) breached the central part of the moraine (fig. 16*C*); (ii) scoured the outwash plain and produced the entrenched channels; (iii) scoured the valley that the Nooksack floodplain now occupies (from Everson to Ferndale); (iv) scoured the Custer trough, producing an avulsion channel and overtopping the Birch Point upland; (v) scoured surfaces southwest of Ferndale by spilling over low divides; and (vi) deposited the stacked bedforms north of the Wiser Lake outwash plain. Essentially, this outburst flood was both erosional and depositional: erosional during the early stages of the flood and depositional during the waning stages. A proglacial lake

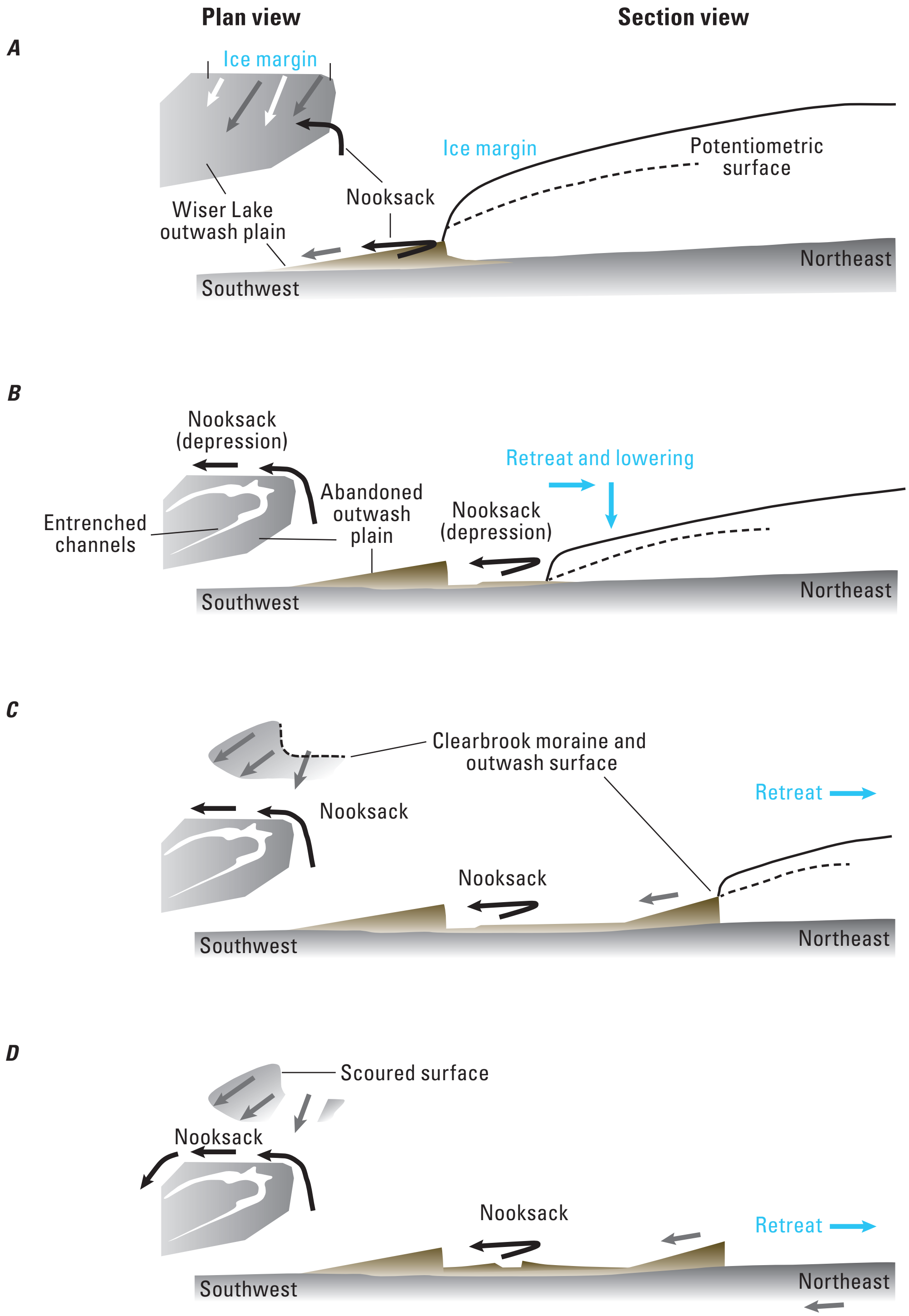

Figure 15. Schematic conceptual model for development of the Wiser Lake outwash plain and ancestral Nooksack River associated with the retreating ice margin (see text for details). Arrows represent water flow. *A*, Ice front is adjacent to the Wiser Lake outwash plain and meltwater is routed directly onto the plain. Orientations of fossil bedforms on the eastern end of the Wiser Lake plain (see fig. 13) indicate flow from the east-southeast, that is, water draining the Nooksack basin. No moraine crests from this stage, or the next stage, are preserved. *B*, The ice margin retreats from the head of the outwash plain and the resulting step at the margin of the Nooksack depression prevents water from flowing onto the outwash plain; the ancestral Nooksack River abandons the outwash plain in favor of a lower elevation path. The abandoned outwash surface displays deeply entrenched flood channels. During continued retreat, the ice margin occupied the lower elevation terrain. *C*, After further retreat, the ice margin stabilized for a short time and constructed the Clearbrook moraine (dashed line on plan view) and associated outwash surface. *D*, Subsequent outburst floods scoured the outwash surface and dissected the central part of the Clearbrook moraine.

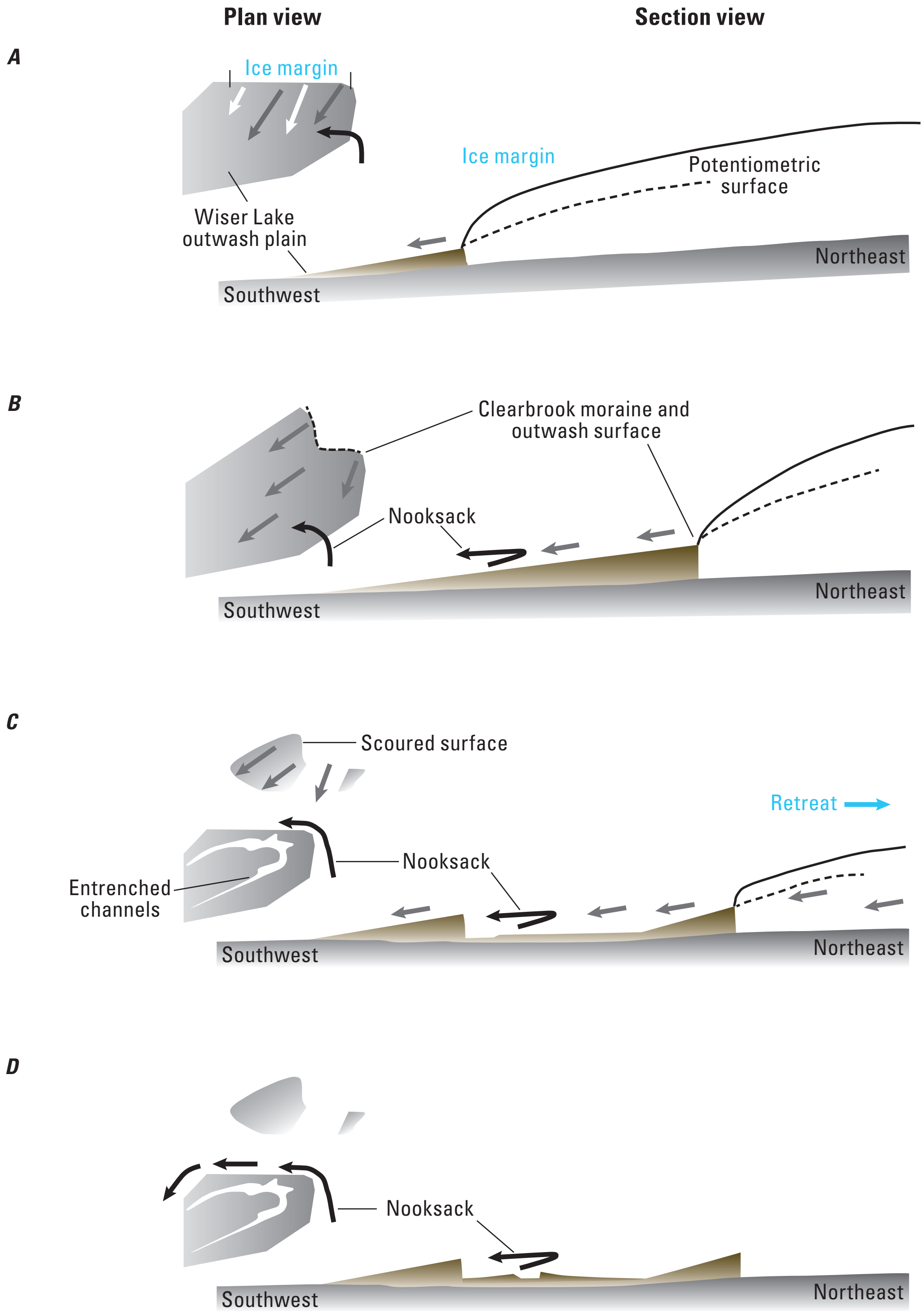

Figure 16. Alternate schematic conceptual model for the development of the Wiser Lake outwash plain and ancestral Nooksack River associated with the retreating ice margin (see text for details). Arrows signify meltwater flow. *A*, Ice front is coupled to the outwash surface and meltwater is routed directly onto the surface. *B*, The outwash plain continues to develop as the ice front retreats, stabilizes, and the Clearbrook moraine (dashed line on plan view) is constructed. During this time, meltwater exiting the Clearbrook ice front is confluent with water flowing north from the Nooksack basin. *C*, After ice retreats from the Clearbrook moraine, an outburst flood(s) entrenches channels on the Wiser Lake outwash plain, erodes through a portion of the Clearbrook moraine, scours the Custer trough (figs. 1, 10), and perhaps scours the valley that presently confines the Nooksack River. *D*, The Nooksack River eventually assumes a course on the scoured surface between Lynden and the Wiser Lake outwash plain.

in the Chilliwack Valley (Saunders, 1985; Saunders and others, 1987), which persisted until late in Sumas time, was likely the source of floodwater.

B4. The Nooksack River assumed a course on the scoured surface between Lynden and the Wiser Lake outwash plain (fig. 16*D*; also see discussion on fluvial adjustment below).

The geomorphic map could be modified to reflect interpretation B by showing all outburst-flood surfaces and most outwash surfaces to be of the same relative age. Recast in this manner, the Wiser Lake outwash plain, Clearbrook moraine and associated outwash, Custer trough area, Birch Point upland, and scoured marine surfaces southwest of Ferndale would be shown as the same age, phase 8 or younger.

Latest Pleistocene and (or) Holocene Events

Since the retreat of Vashon and Sumas ice about 15,000 years ago, hillslopes have been adjusting to ice-free conditions and streams have eroded and filled their valleys as they approximate equilibrium between gradient, discharge, and sediment supply. In many places, especially on hillslopes, map relations and our knowledge of local geologic history are insufficient to date the resulting surfaces as conclusively Pleistocene or Holocene, thus we identify them as latest Pleistocene and (or) Holocene.

Stream incision, shoreline erosion, and collapse of glacially oversteepened slopes have led to the formation of hillslopes (unit Qh) where the dominant surface-forming processes are varieties of mass wasting. Typically bounded above and below by sharp breaks of slope, hillslopes could be subdivided based on the age of incision at the toe of the slope, though we have chosen not to do so. Active geomorphic processes on these slopes include creep and shallow debris flows. In general, hillslopes are near their failure limit. Note that we have mapped small stream gullies as hillslopes, as typically the gully walls are the majority of the map area and the gullies are too small to divide into alluvial flat and bounding hillslopes.

Locally, the upper parts of some hillslopes are less steep and are bounded by upper and lower slope breaks. We mapped these areas as older hillslope (unit Qho), as they are older than the steeper hillslopes that undercut them, though their exact age is uncertain. On the southwest side of Lummi Island there are talus slopes of mappable extent, some wooded and some not. We mapped these hillslopes as unit Qht.

On the glaciated hills southeast of Bellingham, there are a few patches of steep slope cut by shallow, subparallel, adjacent gullies. We have mapped these as gullied hillslope (Qhg).

In several locales there are smoothly sloping, conical surfaces at the toes of gullies, the toes of slopes, or confined within valleys. These appear to have been alluvial fans that are now abandoned as continued drainage has incised into them. These surfaces are mapped as older alluvial fans (Qfo) of uncertain latest Pleistocene or Holocene age.

Some alluvial flats are of uncertain Holocene or latest Pleistocene age. These we have mapped as unit Qao. In general, these are either (1) perched above the modern valley bottom but in settings where they are not easily assigned a late-glacial age, or (2) on the local valley bottom in settings where modern discharge does not appear to be sufficient to construct the observed alluvial flat.

We have mapped sand dunes (Qd) northwest of the Nooksack River in the Custer trough. Southeast of the Nooksack River, elongate ridges of similar texture ornament the distal end of the Wiser Lake outwash plain.

Holocene Changes to the Landscape of Whatcom County

Landslides and Fans

Landslides in western Whatcom County are mostly on steep glaciated slopes of the North Cascade foothills, along the Nooksack River, or along coastal bluffs. Mapped slides are largely deep-seated translational slides and are recognized by uphill scarps, bulbous toes, position in hillslope hollows and (locally) irregular surfaces. Many small slumps and debris flows are too small to be resolved with the 6-ft DEM we use in this study. Many slides are currently active; others probably have not moved in thousands of years. We have not attempted to differentiate landslides on the basis of their age of movement.

Smoothly sloping, conical fans ornament the lower slopes of many hillsides. Material within the fans was probably deposited by both streamflow and debris flow. The bulk of the material is probably paraglacial, mobilized and deposited immediately following glaciation (see, for example, Church and Slaymaker, 1989). The fans remain active, most conspicuously along Swift Creek (east of Everson), where stream- and debris-flows are depositing asbestos-bearing debris from a large landslide just east of the map, and Smith Creek (east of Lake Whatcom), where a 1983 debris flow destroyed homes.

Changing Course of the Nooksack River

The Nooksack River has a rich Holocene history. Here we summarize and extend a story that has, in large part, been told by Cameron (1989), Pittman and others (2003), Linneman and others (2007) and Hutchings and others (2007).

Present Morphology

At present there is a pronounced transition in the river's patterns a few kilometers upstream of Everson (fig. 17). Upriver from the transition, the valley is narrower, the channel occupies a fluvially incised valley, the river is anastomosing, and overall the channel is steeper (~20 ft/mi). Terraces border the eastern and western side of the valley. Incision of fans on the eastern side of the valley demonstrates that incision is postglacial.

Downriver from the transition, the river is a single, meandering channel with a lower gradient (~7 ft/mi). The channel is mostly confined by natural levees several meters higher than the surrounding floodplain, which laps onto older Pleistocene surfaces. Early (~1880) maps showed freshwater

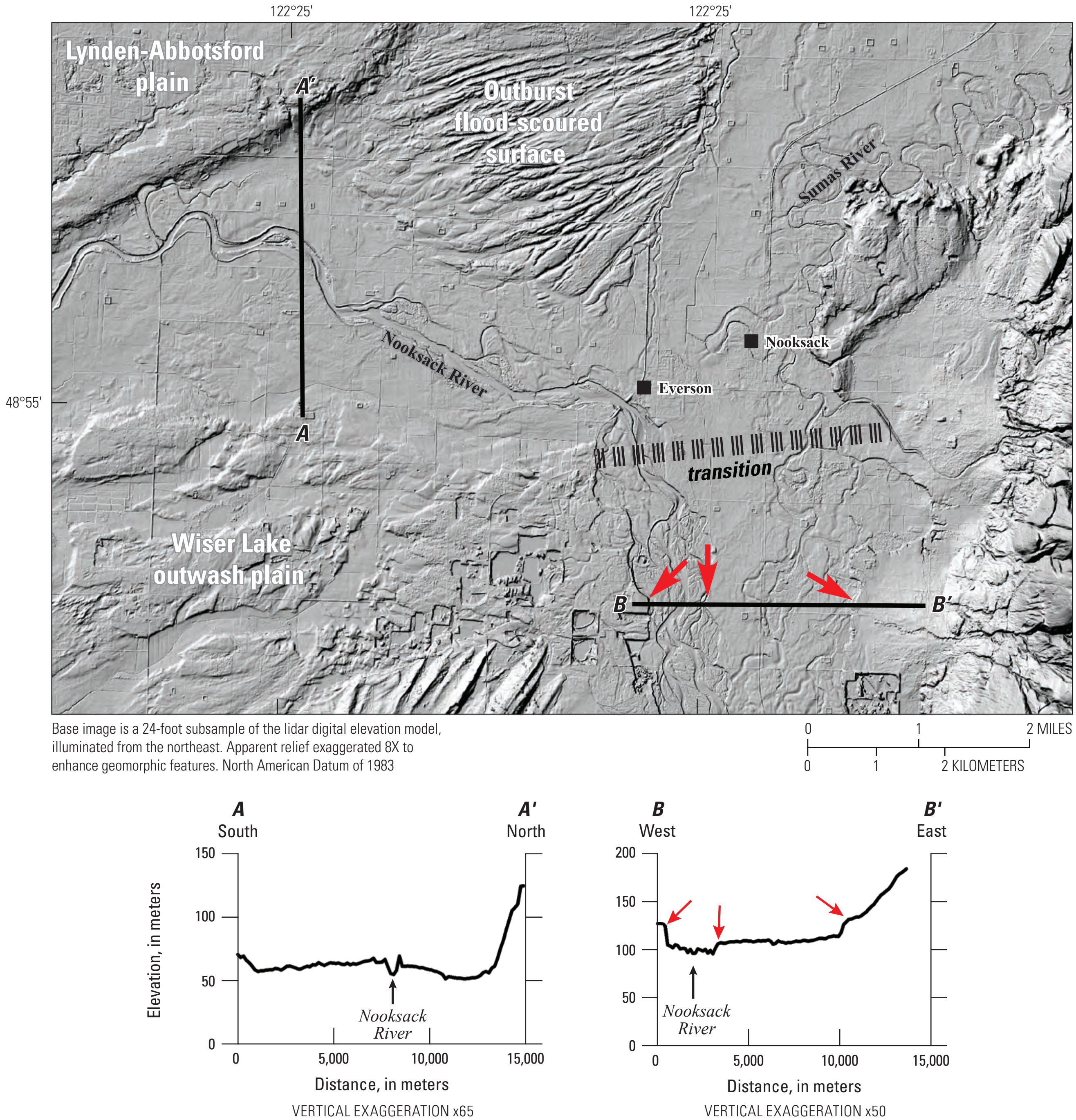

Figure 17. Shaded-relief image of Everson area showing the transition zone and topographic profiles discussed in the text. The transition zone marks a change in the modern Nooksack River channel type, valley slope, and overall valley form. Red arrows associated with profile *B*-*B′* point to terraces formed by normal fluvial incision of the channel.

wetland and lakes in topographic depressions adjacent to the valley wall between Everson and Ferndale. The valley margins lack river terrace remnants and erosional scarps, which would be expected to have developed if the river had eroded its present valley. We conclude that downstream of the transition the modern Nooksack River occupies a pre-existing glacial trough or valley that extended almost to Ferndale, which we call the "Lynden low."

At Ferndale, the Nooksack River is incised into a gently rumpled surface that we interpet as a late Pleistocene flood surface. Minimum elevation of the surface is about 10 m (33 ft). The fluvial valley is essentially the active channel; there is no sign of past lateral migration of the channel, or of past deeper incision and subsequent aggradation. The narrowness of the valley here is remarkable, as numerous studies have noted that at the end of the Pleistocene (12,000–10,000 cal yr B.P.), local relative sea level was at least 15 m (49 ft) lower than present (see, for example, Mathews and others, 1970; Clague and others, 1982; Hutchinson and others, 2004; James and others, 2009). If the Nooksack had flowed past Ferndale 10,000 years ago, it should have incised below its present level and subsequently aggraded, creating a broader fluvial valley.

Stratigraphic Evidence

Deposit-based studies provide some insight into the Holocene history of the Nooksack River. Basal peat at a depth of 3–4 m (~10–12 ft), on the flank of the Lynden low west of Everson, yielded a date of 9,460±50 ^{14}C yr B.P. (sample B-254906). The surface of the peat bed here is at ~21 m (69 ft) elevation. At this locale the valley existed by ~9,500 ^{14}C yr B.P. (~11,066 cal yr B.P.).

Cameron (1989), in a study focused on the subsurface stratigraphy of Sumas Valley, described a buried wedge of gravel, locally >20 m (65 ft) thick, that thins and pinches out northward. The top surface of the wedge is north-sloping, clasts become smaller to the north, and clasts are overwhelmingly red and dark gray andesite with andesine phenocrysts (likely debris from Mount Baker). The wedge was deposited by the Nooksack River flowing north into Sumas Valley. Cameron observed that the distal end of the wedge (her Unit 3) overlies Mount Mazama tephra (6,800 yr B.P.). The Middle Fork lahar (volcanic mudflow) from Mount Baker flowed down the Nooksack River and reached at least as far as Cedarville (Dragovich and others, 1997) at ~5,650 ^{14}C yr B.P. (Hyde and Crandell, 1978; Kovanen, 1996; Easterbrook and Kovanen, 1996; Kovanen and others, 2001). The gravel wedge described by Cameron (1989) likely formed by subsequent down-valley reworking of the lahar deposit.

Hutchings (2003, 2004) studied materials collected from an archaeological site in Ferndale. Earliest occupation of the site was about 5,000 ^{14}C yr B.P. and inhabitants consumed shellfish collected from a rocky beach. Hutchings concluded that the coastline was then at Ferndale.

Inferred History

At the end of phase 9, meltwater must have issued from the snout of the Sumas glacier at Sumas prairie. The amount of meltwater is unknown, but perhaps this was the proto-Fraser River. Lack of an obvious channel farther downstream suggests that relative sea level was significantly higher than the ~10 m elevation ridge across the Nooksack valley at Ferndale. Upon disintegration of the Sumas glacier, the Fraser River flowed west past Mission (fig. 1).

By the end of the Pleistocene at 10,000 ^{14}C yr B.P., relative sea level was lower than present. Lack of any plausible channel in western Whatcom County requires that, at that time, both the Fraser and Nooksack Rivers reached the sea along the route of the modern Fraser. The Nooksack was tributary to the Fraser River via Sumas valley (fig. 7*H*). Part of the Lynden low, extending from just north of Ferndale to Lynden and then Everson, may have been a lake that drained east into the north-flowing Nooksack.

During mid-Holocene time, the north-flowing Nooksack River constructed an alluvial fan near Everson. Construction of the fan likely was a consequence of, or was accelerated by, increased sediment supply following the Middle Fork lahar. As this fan aggraded into the Sumas valley and the Lynden low, it would have bisected the Lynden low, forming a lake to the west if one was not already present. Further aggradation of the fan raised the lake level, causing the lake to overtop the low ridge at Ferndale, incise a new outlet, and thus facilitate avulsion to form the present westward course of the Nooksack. Evidence for a middle Holocene rocky marine shoreline at Ferndale indicates that avulsion happened after 5,000 ^{14}C yr B.P., or that a remnant of the lake in the Lynden low persisted until that time and was an effective sediment trap that prevented growth of the Nooksack delta at Ferndale.

Note that at times the Nooksack still flows to the north. At Everson, a low divide separates the Nooksack and Sumas basins. During large floods, water flows over this divide to Johnson Creek (fig. 17), thence north to Sumas, the Sumas River, and further north to the Fraser River.

Growth of the Nooksack Delta

Between 1897 and 1967, the Nooksack River delta prograded more than a mile into Bellingham Bay (Sternberg, 1967; Easterbrook, 1975); the mean frontal advance rate was ~25 m/yr. Extrapolation of this rate along the 10 km length of the delta leads to the inference that the delta is about 400 years old! Maudlin and Stark (2007) estimated the sediment accumulation rate between 1855 and 1992 to be 90,000 m^3/yr. They thought this rate too large to have been sustained throughout the Holocene and suggested that within the past several centuries the Nooksack shifted from a course northward through Sumas valley to the Fraser River to its present course past Lynden and Ferndale to Bellingham Bay.

Limited borehole data suggest the deltaic deposits are thin: for example, Well Report ID 305498 from the Washington Department of Ecology Well Reports database (https://fortress.wa.gov/ecy/waterresources/map/WCLSWebMap/), for a well in SE¼ sec. 7, T. 38 N., R. 2 E. , reports hardpan at a depth of 2 m (6 ft) and gravel clay at 6 m (19 ft). Borehole ID 91087 in the Subsurface Data layer of the Washington Geologic Information Portal (https://geologyportal.dnr.wa.gov/), for a geotechnical boring in NE¼ sec. 5, T. 38 N., R. 3 E. , has the top of glaciomarine drift at a depth of 2½ m (8½ ft). The area of the delta, including the Lummi River branch and submerged areas above the -3 m (NAVD) isobath, is about 68 km^2. If the average thickness of deltaic deposits is estimated at 3 m (10 ft) and sediment accumulated at the rate estimated by Maudlin and Stark (2007), the delta represents 2,200 years of deposition.

Despite likely late 19th century increase in sedimentation rate associated with major diking and straightening of the river, as well as with agricultural clearing and logging in the watershed (for example, Linneman and others, 2007; Collins, 2008), we think the discordance between the high modern growth rate of the delta and its moderate size is consistent with the delta being significantly younger than 5,000 years old, in accord with the archaeological evidence (Hutchings, 2003, 2004).

Shoreline Development

Late Holocene wave erosion has notched nearshore slopes to produce the nearshore profile typical of the Salish Lowland, with bluff (mapped as hillslope, unit Qh), shoreline angle (base of bluff) at an elevation near mean higher high water (MHHW), and a relatively steeply-sloping beach face (unit Qbf) underlain by gravel or sand that extends from the shoreline angle downwards to relatively low-angle tidal flat commonly underlain by finer grained sand and silt, at elevations near mean lower low water (MLLW). Our mapping extends to the beach-face–tidal-flat boundary or the limit of terrestrial lidar data, whichever is higher. Areas seawards of the beach-face–tidal-flat boundary (or the limit of terrestrial lidar data) are shown on our map as open water. In some locales the beach has prograded, leaving a flat back-beach surface (unit Qbb) at near-MHHW elevation that extends from the fossil shoreline angle out to a berm crest at the upper edge of the beach face. In some places, longshore drift has built extensive spits (for example, Semiahmoo Spit that separates Drayton Harbor from Boundary Bay) and the axial flats of these spits, if wide enough, are mapped as back beach. In a few locales, the back beach contains a lagoon.

Possible Tectonic Deformation

The advent of lidar topography has resulted in recognition of widespread Holocene tectonic deformation in northwest Washington (for example, Barnett and others, 2010), including the Kendall scarp 10 km east of the map area (Sherrod and others, 2013), where the Boulder Creek Fault, with several kilometers of Tertiary down-to-the-south normal displacement, is now active as a north-verging reverse fault.

Geomorphic evidence at some locales within western Whatcom County suggests local Quaternary tectonic deformation.

Uplifted Holocene beaches.—The regional history of rising relative sea level during the early Holocene, followed by stabilization in the middle Holocene, dictates that accreted back-beach surfaces in equilibrium with modern tidal conditions—typically at an elevation near MHHW (in this region roughly 2.2 m [7 ft] above the NAVD88 datum used for the lidar data and throughout this report)—are no older than middle Holocene and older beach surfaces should be submerged. However, higher-elevation fossil beach surfaces are preserved on the north end of Sandy Point (Neptune Beach, where the too-high region is mostly fossil accreted back beach) at 6.7 m (22 ft), along the Birch Bay shoreline at 3.6–4.5 m (12–15 ft) (where the too-high surface was probably formed as beach face), and possibly at the northwest corner of Lummi peninsula (sec. 14, T. 38 N., R. 1 E.). Kelsey and others (2012) present additional data on the Sandy Point and Birch Bay locales. In contrast to our interpretation of probable tectonic uplift, Engels and Roberts (2005) interpret the beach-ridge complex at Maple Beach on the east side of Point Roberts, at an elevation of ~4 m (13 ft), to have largely formed since 2,250 yr B.P. in equilibrium with modern sea level.

Scarp near Marietta.—A linear north-northeast-trending scarp in secs. 8, 9, and 17, T. 38 N., R. 2 E. separates younger marine-modified surface (unit Qmy) to the east from flood-shaped surface (unit Q7f) to the west. The 1.5–2.4-m-high (5 to 8 ft) west-facing scarp appears to have formed by fluvial scour. Elevation of the top of the scarp is 9 m (~31 ft) on the south end, 16 m (~54 ft) in the middle, and 13 m (~44 ft) at its north end. In the central portion of the scarp (W½ sec. 9), the toe of the scarp is higher than the top of the scarp at its northern end. This geometry is unlikely to have formed by fluvial scour alone. It may have formed by a combination of fluvial scour and (unrecognized) subsequent deposition. But it is most simply explained by subsequent gentle warping of the scarp and adjoining surfaces.

Warped latest Pleistocene shoreline.—Fossil shorelines that bound the proximal sides of the Haney Creek, Grandview, and Lummi peninsula moraines define a best-fit plane with an up-to-the-northeast slope, similar to that defined by fitting all fossil shorelines in the map area. Elevations of points along the post-Grandview fossil shoreline that extends north and west from Ferndale are as much as 5 m higher than this best-fit plane, suggesting the possibility of gentle folding after latest Pleistocene formation of this shoreline. This conclusion is tenuous, as much of the fossil shoreline is poorly defined. Furthermore, non-planarity of this shoreline may be primary, a consequence of progressive retreat of the post-Grandview ice sheet that resulted in the shoreline being younger to the northeast, coupled with progressive glacio-isostatic rebound.

Stewart Mountain scarp.—A diffuse scarp, shown as queried on the geomorphic map, that extends across the west face of Stewart Mountain may be a composite Quaternary fault scarp (that is, formed by fault offset) and fault-line scarp (that is, formed by differential erosion across an older fault). The northern part of the scarp coincides with a fault contact between the lower member of the Chuckanut Formation to the east and the upper member to the west (Haugerud, unpublished geologic mapping). This fault could be the southwards extension of the Boulder Creek Fault. The area east of the scarp is more extensively dissected than the area to the west, consistent with recent uplift of the hanging wall.

Vedder and Sumas faults.—We have recognized no geomorphic evidence for post-glacial slip on the Vedder and Sumas faults that many (for example, Easterbrook and others, 2001) have hypothesized to trend northeast-southwest across the northeast corner of the map area.

Anthropogenic Changes to the Landscape of Whatcom County

Over the past 150 years there has been extensive grading in and around Bellingham, as well as cutting and filling along road and railroad corridors. There are extensive bank hardening and levees along all reaches of the Nooksack River. Several reaches of the Nooksack are 80–100 percent leveed and (or) armored. Anthropogenic modifications along the lower mainstem Nooksack River include several water-supply diversions.

Perhaps the most extensive anthropogenic change, though, is that associated with diking of the Nooksack River and draining of associated wetlands to create unit Qws. This is especially obvious in the Nooksack delta, where diked areas are on average 60 cm (~2 ft) lower than adjacent undiked areas. Some of this elevation difference reflects regional sea-level rise (~20 cm over the last century; Miller and Douglas, 2007). Haugerud (2008) inferred that the remainder of the elevation difference between the diked and undiked areas records compaction-related subsidence not balanced by ongoing sedimentation. The diking and draining of the Nooksack delta has increased the area of productive agricultural land at the cost of increased risk from flooding, damaged fish and wildlife resources, and foregone sequestration of carbon in wetland sediments. Overall, the extent of unit Qws (starved wetland) shows that over the past 160 years, western Whatcom County has lost at least ~40 km^2 (15 mi^2) of wetland, at least 70 percent of the wetlands present prior to first Euro-American settlement in 1854.

Geomorphic Evidence Regarding the Yo-Yo Hypothesis

As noted above, Easterbrook (1963, 1969, 1992) has explained deposition of subaerial Deming sand and its subsequent burial by marine-shell-bearing diamict (the Bellingham glaciomarine drift of Easterbrook, 1963, 1976a) at the Cedarville locality (NE¼ sec. 34, T. 39 N., R. 4 E.) as recording a short-lived reversal in post-Vashon relative sea level fall, at least 37 m (121 ft) and perhaps as much as 107 m (350 ft) up and down in several hundred years, caused by a combination of local tectonic, glacio-isostatic, and global eustatic movements. This is Easterbrook's (1992) hypothesized "yo-yo effect" in post-Vashon vertical tectonics. We failed to develop conclusive geomorphic evidence for or against the yo-yo hypothesis.

Shoreline benches that developed near where Grandview-age (phase 4) moraines entered salt water may record a period of RSL stability or even rise of RSL during postglacial isostatic rebound. This would be appropriate, as Grandview-age moraines mark the greatest lateral extent of Sumas ice and, most likely, the maximum Sumas ice load—thus this is the most likely time to see an isostatically driven reversal (or slower rebound) in the late-glacial RSL curve. The predicted elevation of RSL at the Cedarville locality during Grandview time depends on the value one uses to compensate for rebound-related tilting, but unless there was (highly improbable) down-to-the-east tilting of >2 m/km, RSL was too low for Grandview-age isostatic subsidence to explain burial of the Deming sand by glaciomarine deposition.

Easterbrook favors the interpretation that the Deming sand and the subsequent marine transgression inferred from strata at the Cedarville locality are older than all of the marine-modified surfaces in western Whatcom County; that is, that there is no preserved geomorphic evidence (for example, a marine terrace) for earlier (post-Kulshan glaciomarine drift, pre-Deming sand) emergence that would be expected at the Cedarville locality, which is at ~67 m (222 ft) elevation. The fact that we cannot recognize remains of a marine terrace at this elevation means little, given that these elevations are found mostly on the erosion-resistant bedrock slopes of Sehome Hill, Lookout Mountain, Squalicum Mountain, Stewart Mountain, and Sumas Mountain, or have been significantly modified by subsequent Sumas glaciations (phases 3–5). Easterbrook's interpretation appears to be permitted by our observations of surface features.

Haugerud suggests that Bellingham glaciomarine drift of Easterbrook (1963, 1976a) in western Whatcom County, which overlies terrestrial deposits, was subaerially redeposited by Sumas ice. This interpretation implies that shells contained within such drift are reworked and their ages are thus maxima for final deposition of the containing diamict.

More work to explore sedimentology and structure of diamictons mapped by Easterbrook (1976a) as Bellingham glaciomarine drift, with the aim of elucidating depositional processes (for example, marine fallout, soft-bed deformation, or debris flow consequent upon ice melt-out), might help decide between these conflicting interpretations. Dating and paleo-ecological studies of cores obtained from small basins located beyond the extent of Sumas ice and at elevations predicted to be marine, then subaerial, then marine during the hypothesized yo-yo could be even more informative regarding the existence and magnitude of reversals in post-Vashon RSL fall.

Potential Changes to Stratigraphic Nomenclature

Armstrong and others (1965) proposed the term "Everson Interstade" as a geologic-climatic unit, the majority of which was younger than their Vashon Stade and older than their Sumas Stade, though the unit had time-transgressive boundaries (fig. 4). Since then, "Everson" has been widely applied to post-Vashon glaciomarine deposits in northwest Washington. Studies in areas to the southwest (Dethier and others, 1995; Kovanen and Slaymaker, 2004; Polenz and others, 2005) strongly suggest that glaciomarine deposition in those locales was contemporaneous with late Vashon ice in Whatcom County. We show in this report that glaciomarine conditions, limited to progressively lower elevations, were clearly contemporaneous with almost all of Sumas-age deposition. A reevaluation of the term "Everson" and its application is in order.

Our work shows that the sequence of events during the Sumas part of Fraser glaciation is more complex than previously thought. Sumas glaciation includes at least two significant ice advances (phases 3 and 4), which were likely separated by a significant retreat, followed by stillstands during retreat and (or) changes in ice-margin dynamics (phases 5–9) and multiple outburst floods that modified the landscape. Future field work may show that corresponding changes to recognized lithostratigraphy may be in order.

References Cited

Alley, N.F., and Chatwin, S.C., 1979, Late Pleistocene history and geomorphology, southwestern Vancouver Island, British Columbia: Canadian Journal of Earth Sciences, v. 16, p. 1645–1657.

American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Bulletin of the American Association of Petroleum Geologists, v. 45, p. 645–660.

Armstrong, J.E., 1956, Surficial geology of Vancouver area, British Columbia: Geological Survey of Canada Paper 55–40.

Armstrong, J.E., 1957, Surficial geology of New Westminster map-area, British Columbia: Geological Survey of Canada Map 57–5, 25 p.

Armstrong, J.E., 1981, Post-Vashon Wisconsin glaciation, Fraser Lowland, British Columbia: Geological Survey of Canada Bulletin 322, 34 p.

Armstrong, J.E., and Brown, W.L., 1954, Late Wisconsin marine drift and associated sediments of the lower Fraser Valley, British Columbia, Canada: Geological Society of America Bulletin, v. 65, p. 349–364.

Armstrong, J.E., and Hicock, S.R., 1980, Surficial geology of New Westminster map-area, British Columbia: Geological Survey of Canada Map 1484A.

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble, J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321–330.

Bard, E., 1988, Correction of accelerator mass spectrometry 14C ages measured in planktonic foraminifera: paleooceanographic implications: Paleoceanography, v. 3, p. 635–645.

Barnett, E.A., Haugerud, R.A., Sherrod, B.L., Weaver, C.S., Pratt, T.L., and Blakely, R.J., 2010, Preliminary atlas of active shallow tectonic deformation in the Puget Lowland, Washington: U.S. Geological Survey Open-File Report 2010–1149, accessed March 15, 2018, at https://pubs.usgs.gov/of/2010/1149/.

Benn, D.I., and Evans, D.J.A., 1998, Glaciers and Glaciation: London, Arnold, 734 p.

Blais-Stevens, A., Clague, J.J., Mathewes, R.W., Hebda, R.J., Bornhold, B.D., 2003, Record of large, Late Pleistocene outburst floods preserved in Saanich Inlet sediments, Vancouver Island, Canada: Quaternary Science Reviews, v. 22, p. 2327–2334.

Booth, D.B., 1987, Timing and processes of deglaciation along the southern margin of the Cordilleran ice sheet, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, Geology of North America, v. K-3, p. 71–90.

Booth, D.B., Troost, K.G., Clague, J.J., and Waitt, R.B., 2004, The Cordilleran Ice Sheet, *in* Gillespie, A.R., Porter, S.C., Atwater, B.F., eds., Developments in Quaternary Sciences Volume 1, The Quaternary Period in the United States: International Union for Quaternary Research, Elsevier International, p. 17–43.

Bretz, J H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin No. 8, 244 p.

Cameron, V., 1989, The late Quaternary geomorphic history of the Sumas Valley: Burnaby, British Columbia, Canada, Simon Fraser University, M.A. thesis, ,154 p.

Church, M., and Slaymaker O., 1989, Disequilibrium of Holocene sediment yield in glaciated British Columbia: Nature, v. 337, p. 452–454.

Clague, J.J., 1981, Late Quaternary geology and geochronology of British Columbia, Part 2: Geological Survey of Canada Paper 80–35, 41 p.

Clague, J.J., Harper, J.R., Hebda, R.J., and Howes, D.E., 1982, Late Quaternary sea levels and crustal movements, coastal British Columbia: Canadian Journal of Earth Sciences, v. 19, 597–618.

Clague, J.J., Mathewes, R.W., Guilbault, J.P., Hutchinson, I., and Rickets, B.D., 1997, Pre-Younger Dryas resurgence of the southwestern margin of the Cordilleran Ice Sheet, British Columbia, Canada: Boreas, v. 26, p. 261–277.

Cline, M.D., Iverson, N.R., and Harding, C., 2011, Spatial analysis of Des Moines Lobe washboard moraines using LiDAR data [abs.]: Geological Society of America Abstracts with Programs, v. 43, p. 216.

Collins, B.D., 2008, Source descriptions for features in a geodatabase of Puget Sound's pre-settlement river valley, estuary and nearshore habitats (September 14, 2008 version): Puget Sound River History Project, Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, accessed March 2018, at http://riverhistory.ess.washington.edu/ims/source_narrative.pdf.

Crandell, D.R., Mullineaux, D.R., and Waldron, H.H., 1958, Pleistocene sequence in the southeastern part of the Puget Sound Lowland, Washington: American Journal of Science, v. 256, 384–397.

De Lachapelle, J., 2000, Late Holocene aggradation processes and rates for three alluvial fans, Cascade Foothills, Washington: Bellingham, Washington, Western Washington University, M.S. thesis.

Dethier, D.P., Pessel, F., Jr., Keuler, R.F., Balzarini, M.A., and Pevear, D.R., 1995, Late Wisconsinan glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington: Geological Society of America Bulletin, v. 107, p. 1288–1303.

Domack, E.W., 1983. Facies of late Pleistocene glacial-marine sediments on Whidbey Island, Washington—An isostatic glacial marine sequence, in Molnia, B.F., ed., Glacial-Marine Sedimentation: New York, Plenum, p. 335–570.

Dragovich, J.D., Dunn, A., Parkinson, K.T., Kahle, S.C., Pringle, P.T., 1997, Quaternary stratigraphy and cross sections, Nooksack, Columbia, and Saar Creek Valleys, Kendall and Deming 7.5-minute quadrangles, western Whatcom County, Washington: Washington Division of Geology and Earth Resources Open File Report 97–4, 13 p., 8 plates.

Dragovich, J.D., Norman, D.K., Grisamer, C.L., Logan, R.L., and Anderson, G., 1998, Geologic map and interpreted geologic history of the Bow and Alger 7.5-minute quadrangles, western Skagit County, Washington: Washington Division of Geology and Earth Resources Open File Report 98–5, scale 1:24,000, 3 pl., 80 p.

Easterbrook, D.J., 1963, Late Pleistocene glacial events and relative sea-level changes in the northern Puget Lowland, Washington: Geological Society of America Bulletin, v. 74, p. 1465–1484.

Easterbrook, D.J., 1968, Pleistocene stratigraphy of Island County, Washington: Washington Division of Water Resources Bulletin 25, 34 p.

Easterbrook, D.J., 1969, Pleistocene chronology of the Puget Lowland and San Juan Islands, Washington: Geological Society of America Bulletin, v. 80, p. 2273–2286.

Easterbrook, D.J., 1971, Geology and geomorphology of western Whatcom County, Washington: Bellingham, Washington, Western Washington State College Press, 68 p.

Easterbrook, D.J., 1973, Environmental geology of western Whatcom County, Washington: Report to Whatcom County, 78 p.

Easterbrook, D.J., 1975, Mt. Baker eruptions: Geology, v. 3, p. 679–682.

Easterbrook, D.J., 1976a, Geologic map of western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-854-B, scale 1:62,500.

Easterbrook, D.J., 1976b, Map showing engineering characteristics of geologic materials, western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-854-D, scale 1:62,500.

Easterbrook, D.J., 1976c, Map showing slope stability, western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-854-C, scale 1:62,500.

Easterbrook, D.J., 1986, Stratigraphy and chronology of Quaternary deposits of the Puget Lowland and Olympic Mountains of Washington and the Cascade Mountains of Washington and Oregon: Quaternary Science Reviews, v. 5, p. 145–159.

Easterbrook, D.J., 1992, Advance and retreat of Cordilleran ice sheets in Washington, USA: Géographie Physique et Quaternaire, v. 46, p. 51–68.

Easterbrook, D.J., 1994, Stratigraphy and chronology of early to late Pleistocene glacial and interglacial sediments in the Puget Lowland, Washington, *in* Swanson, D.A., and Haugerud, R.A., eds., Geologic field trips in the Pacific Northwest, Volume 1, Chapter 1J: Department of Geological Sciences, University of Washington, p. 1–38.

Easterbrook, D.J., and Kovanen, D.J., 1996, Far-reaching mid-Holocene lahar from Mt. Baker in the Nooksack valley of the Cascades, Washington [abs.]: Geological Society of America Abstracts with Programs, v. 28, p. 64.

Easterbrook, D.J., Crandell, D.R., and Leopold, E.B., 1967, Pre-Olympia stratigraphy and chronology in the central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, p. 13–20.

Easterbrook, D.J., and Evans, B., 1983, Alluvial fans and deltas flood hazard areas: Weden and Associates, report prepared for Whatcom County, 98 p.

Easterbrook, D.J., Engebretson, D., and Kovanen, D.J., 2001, Potential seismic hazards of the Sumas and Vedder Mt. Faults: Washington State Energy Facility Site Evaluation Council, 10 p., accessed March 2018 at http://www.efsec.wa.gov/Sumas2/adj2001/whatcomcoprefiled/dje-2.pdf.

Engels, S., and Roberts, M.C., 2005, The architecture of prograding sandy-gravel beach ridges formed during the last Holocene highstand, southwestern British Columbia, Canada: Journal of Sedimentary Research, v. 75, p. 1052–1064.

Farrell, W.E., and Clark, J.A., 1976, On postglacial sea level: Geophysical Journal of the Royal Astronomical Society, v. 46, p. 647–667.

Fox, S., De Chant, J., and Raines, M., 1992, Alluvial fan hazard areas: Whatcom County [Washington] Planning Department, Whatcom County Environmental Resources Report Series, 39 p. plus appendixes.

Gomez, B., Smith, L.C., Magilligan, F.J., Mertes, L.A.K., and Smith, N.D., 2000, Glacier outburst floods and outwash plain development, Skeiðarársandur, Iceland: Terra Nova, v. 12, p. 126–131.

Goudie, A.S., Lewin, J., Richards, K., Anderson, M., Burt, T., Whalley, B., and Worsley, P., 1990, Geomorphological techniques, 2d ed: Routledge New York, 592 p..

Haugerud, R.A., 2004, Cascadia—Physiography: U.S. Geological Survey Geological Investigation Series I-2689, scale: 1:2,000,000, accessed March 2018 at https://pubs.usgs.gov/imap/i2689.

Haugerud, R.A., 2007, A speculative history of the Sumas ice advance, Fraser Lowland, southwestern British Columbia and northwest Washington [abs.]: Geological Society of America Cordilleran Section, 103rd Annual Meeting, Paper 6-7, accessed March 2018 at https://gsa.confex.com/gsa/2007CD/finalprogram/abstract_121297.htm.

Haugerud, R.A., 2008, Delta subsidence in northwest Washington [abs.]: Geological Society of America Annual Meeting, Paper 53-10, accessed March 2018 at https://gsa.confex.com/gsa/2008AM/finalprogram/abstract_151718.htm.

Haugerud, R.A., 2020, Deglaciation of the Puget Lowland, Washington, *in* Waitt, R.B., Thackray, G.D., and Gillespie, A.R., eds., Untangling the Quaternary period—A legacy of Stephen C. Porter: Geological Society of America Special Paper 548, https://doi.org/10.1130/2020.2548(14).

Haugerud, R.A., and Kovanen, D.J., 2010, Direct observation of tilt associated with glacio-isostatic rebound, western Whatcom County, Washington [abs.]: Geological Society of America Cordilleran Section, 106th Annual Meeting, Paper 43-3, accessed March 2018 at https://gsa.confex.com/gsa/2010CD/finalprogram/abstract_172996.htm.

Haugerud, R.A., and Maudlin, M., 2005, Latest Pleistocene landforms near Ferndale, Whatcom County, Washington, imaged by high-resolution LiDAR survey [abs.]: Geological Society of America Abstracts with Programs, v. 37, p. 430, accessed April 2018 at https://gsa.confex.com/gsa/2005AM/webprogram/Paper97709.html.

Haugerud, R.A., and Tabor, R.W., 2009, Geologic map of the North Cascade Range, Washington: U.S. Geological Survey Scientific Investigations Map I-2940, 2 pamphlets, 29 p. and 23 p., 2 sheets, scale 1:200,000. [Also available at https://pubs.usgs.gov/sim/2940/.]

Hicock, S.R., Lian, O.B., and Mathewes, R.W., 1999, Bond cycles recorded in terrestrial Pleistocene sediments of southwestern British Columbia: Journal of Quaternary Research, v. 14, p. 443–449.

Hopkins, W.S., Jr., 1968, Subsurface Miocene rocks, British Columbia-Washington, a palynological investigation: Geological Society of America Bulletin, v. 79, p. 763–767.

Hutchings, R.M., 2003, Geoarchaeological and paleoecological investigations at the Ferndale site (45WH34); delta development and human adaptive strategies on the southern Pacific northwestern coast [abs.]: Geological Society of America Abstracts with Programs, v. 35, p. 228, accessed April 2018 at https://gsa.confex.com/gsa/2003AM/webprogram/Paper67789.html.

Hutchings, R.M., 2004, Mid-Holocene river development and south-central Pacific Northwest coast Prehistory: Geoarcheology of the Ferndale Site (45WH34), Nooksack River: Bellingham, Washington, Western Washington University, M.S. thesis, 165 p.

Hutchings, R.M., Pittman, P., Campbell, S., and Maudlin, M.R., 2007, Avulsion-initiated, late Holocene sociocultural reorganization in the southeastern Fraser/Nooksack Lowland; an hypothesis [abs.]: Geological Society of America, Cordilleran Section, 103rd annual meeting, Paper 24-4, accessed March 2018 at https://gsa.confex.com/gsa/2007CD/finalprogram/abstract_120930.htm.

Hutchinson, I., James, T.S., Clague, J.J., Barrie, J.V., and Conway, K.W., 2004, Reconstruction of late Quaternary sea-level change in southwestern British Columbia from sediments in isolation basins: Boreas, v. 33, p. 183–194.

Hyde, J.H., and Crandell, D.R., 1978, Postglacial volcanic deposits at Mount Baker, Washington, and potential hazards from future eruptions: U.S. Geological Survey Professional Paper 1022-C, 17 p., 1 plate.

Jakob, M., 2005, Debris-flow hazard analysis, *in* Jakob, M., and Hungr, O., eds., Debris-flow hazards and related phenomena: New York, Springer-Verlag, p. 411–443.

James, T.S., Clague, J.J., Wang, K., and Hutchinson, I., 2000, Postglacial rebound at the northern Cascadia subduction zone: Quaternary Science Reviews, v. 19, p. 1527–1541.

James, T.S., Hutchinson, I., Barrie, J.V., Conway, K.W., and Mathews, D., 2005, Relative sea-level change in the northern Strait of Georgia, British Columbia: Géographie physique et Quaternaire, v. 59, p. 113–127.

James, T., Gowan, E.J., Hutchinson, I., Clague, J.J., Barrie, J.V., and Conway, K.W., 2009, Sea-level change and paleogeographic reconstructions, southern Vancouver Island, British Columbia, Canada: Quaternary Science Reviews, v. 28, p. 1200–1216.

Johnsen, T.F., and Brennand, T.A., 2004, Late-glacial lakes in the Thompson Basin, British Columbia: paleogeography and evolution: Canadian Journal of Earth Sciences, v. 41, p. 1367–1383.

Johnson, S.Y., 1984, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, p. 92–106.

Jones, M.A., 1996, Thickness of unconsolidated deposits in the Puget Sound Lowland, Washington and British Columbia: U.S. Geological Survey Water-Resources Investigation Report 94-4133, 1 plate, scale 1:450,000. [Also available online at https://pubs.er.usgs.gov/publication/wri944133.]

Kelsey, H.M., Sherrod, B.L., Johnson, S.Y., and Dadisman, S.V., 2004, Land-level changes from a late Holocene earthquake in the northern Puget Lowland, Washington: Geology, v. 32, p. 469–472.

Kelsey, H.M., Sherrod, B.L., Blakely, R.J., and Haugerud, R.A., 2012, Holocene faulting in the Bellingham forearc basin—Upper-plate deformation at the northern end of the Cascadia subduction zone: Journal of Geophysical Research, v. 117, B03409, accessed March 2018 at https://doi.org/10.1029/2011JB008816.

Kerr Wood Leidal Associates Limited, 2004, Jones Creek debris flow study, final report: Whatcom County Public Works Department, Washington, Whatcom County Flood Control Zone Dristrict, accessed March 2018 at https://www.whatcomcounty.us/DocumentCenter/View/11552.

Koteff, C., and Pessl, F., Jr., 1981, Systematic ice retreat in New England: U.S. Geological Survey Professional Paper 1179, 20 p.

Kovanen, D.J., 1996, Extensive late-Pleistocene alpine glaciation in the Nooksack River valley, North Cascades, Washington: Bellingham, Washington, Western Washington University, M.S. thesis, 172 p.

Kovanen, D.J., 2001, Late glacial ice margin fluctuations (~12.5–10.0 ^{14}C kyr BP) in the Fraser Lowland and adjacent Nooksack Valley, southwestern British Columbia and northwestern Washington: Vancouver, University of British Columbia, Canada, Ph.D. dissertation.

Kovanen, D.J., 2002, Morphologic and stratigraphic evidence for Allerød and Younger Dryas age glacier fluctuations of the Cordilleran Ice Sheet, British Columbia, Canada and northwestern Washington, U.S.A.: Boreas, v. 31, p. 163–184.

Kovanen, D.J., and Easterbrook, D.J., 1997, Major drainage changes of the Chilliwack and Nooksack rivers of SW British Columbia, Canada and NW Washington [abs.]: Geological Society of America Abstracts with Programs, v. 29, p. 23.

Kovanen, D.J., and Easterbrook, D.J., 2002a, Timing and extent of Allerød and younger Dryas age (~12,500-10,000 ^{14}C yr B.P.) oscillation of the Cordilleran Ice Sheet in the Fraser Lowland, western North America: Quaternary Research, v. 57, p. 208–224.

Kovanen, D.J., and Easterbrook, D.J., 2002b, Paleodeviations of radiocarbon marine reservoir values for the NE Pacific: Geology, v. 30, p. 243–246.

Kovanen, D.J., and Slaymaker, O., 2003, Lake Terrell upland glacial resurgences and implications for late-glacial history, Northwestern Washington State, U.S.A.: Canadian Journal of Earth Sciences, v. 40, p. 1767–1772.

Kovanen, D.J., and Slaymaker, O., 2004, Relict shorelines and ice-flow patterns of the northern Puget Lowland from lidar data and digital terrain modelling: Geografiska Annaler, v. 86A, p. 385–400.

Kovanen, D.J., and Slaymaker, O., 2008, The morphometric and stratigraphic framework for estimates of debris flow incidence in the North Cascades foothills, Washington State, USA: Geomorphology, v. 99, p. 224–245.

Kovanen, D.J., Easterbrook, D.J., and Thomas, T., 2001, Holocene eruptive history of Mount Baker, Washington: Canadian Journal of Earth Sciences, v. 38, p. 1355–1366.

Lambeck, K., and Chappell, J., 2001, Sea level change through the last glacial cycle: Science, v. 292, p. 679–686.

Lapen, T.J., 2000, Geologic map of the Bellingham 1:100,000-scale quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File-Report 2000-5, 35 p., 2 plates, scale 1:100,000.

Linneman, S., Pittman, P., and Vaugeois, L., 2007, Lively landscapes—major Holocene geomorphic events in the Nooksack-Sumas Valley, *in* Stelling, P., and Tucker, D.S., eds., Floods, faults, and fire—Geological field trips in Washington State and Southwest British Columbia: Geological Society of America Field Guide 9, p. 99–119.

Logan, R.L., 2003, Geologic map of the Washington portion of the Roche Harbor 1:100,000 quadrangle: Washington Division of Geology and Earth Resources, Open File Report 2003-17, scale 1:100,000. [Also available online at http://www.dnr.wa.gov/Publications/ger_ofr2003-17_geol_map_rocheharbor_100k.pdf.]

Mathews, W.H., Fyles, J.G., and Nasmith, H.W., 1970, Postglacial crustal movements in southwestern British Columbia and adjacent Washington State: Canadian Journal of Earth Sciences, v. 7, p. 690–702.

Maudlin, M.R., and Stark, A.M., 2007, Analysis of Nooksack River delta progradation into Bellingham Bay, Washington using archival data sources [abs.]: Geological Society of America, Cordilleran Section, 103rd Annual Meeting, Paper 16-2, accessed March 2018 at http://gsa.confex.com/gsa/2007CD/finalprogram/abstract_120577.htm.

McCaffrey, R., King, R.W., Payne, S.J., and Lancaster, M., 2013, Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities: Journal of Geophysical Research, v, 118, p. 709–723.

Miller, L., and Douglas, B.C., 2007, Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise: Geophysical Research Letters, v. 34, L16602, accessed March 2018 at https://doi.org/10.1029/2007GL030862.

Miller, G.M., and Misch, P., 1963, Early Eocene angular unconformity at western front of northern Cascades, Whatcom County, Washington: American Association of Petroleum Geologists Bulletin, v. 47, p. 163–174.

Mitrovica, J.X., and Forte, A.M., 1997, Radial profile of mantle viscosity: Results from the joint inversion of convection and postglacial rebound observables: Journal of Geophysical Research, v. 102, p. 2751–2769.

Orme, A.R., 1990, Recurrence of debris production under coniferous forest, Cascade foothills, Northwest United States, *in* Thornes J., ed., Vegetation and erosion—Processes and environments: Chichester, U.K., John Wiley and Sons, p. 67–84.

Palmer, S.P., Magsino, S.L., Bilderback, E.L., Poelstra, J.L., Folger, D.S., and Niggemann, R.A., 2004, Liquefaction susceptibility map of Whatcom County Map, Washington: Washington Division of Geology and Earth Resources Open File Report 04–20, scale 1:175,000.

Peltier, W.R., 2004, Global glacial isostasy and the surface of the ice-age Earth—The ICE-5G (VM2) model and GRACE: Annual Reviews of Earth and Planetary Science, v. 32, p. 111–149.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and last glacial maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3322–3337.

Pittman, P.D., Maudlin, M.R., and Collins, B.D., 2003, Evidence of a major late Holocene river avulsion [abs.]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 334. [Also available at https://gsa.confex.com/gsa/2003AM/finalprogram/abstract_66728.htm.]

Polenz, M., Slaughter, S.L., and Thorsen, G.W., 2005, Geologic map of the Coupeville and part of the Port Townsend North 7.5-minute quadrangles, Island County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-58, scale 1:24,000.

Porter, S.C., and Swanson, T.W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, p. 205–213.

Reidel, S., Fecht, K., Hagood, M.C., and Tolan T.L., 1989, The geologic evolution of the central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geologic Society of America Special Paper 239, p. 247–264.

Riggs, G.B., 1958, Peat resources of Washington: Washington State Division of Mines and Geology Bulletin No. 44, 272 p.

Ryder, J.M., Fulton, R.J., and Clague, J.J., 1991, The Cordilleran ice sheet and the glacial geomorphology of the southern and central British Columbia: Gèographie Physique et Quaternaire, v. 45, p. 365–377.

Saunders, I.R., 1985, Late Quaternary geology and geomorphology of the Chilliwack River valley, British Columbia: Burnaby, British Columbia, Canada, Simon Fraser University, M.S. thesis 140 p.

Saunders, I.R., Clague, J.J., and Roberts, M.C., 1987, Deglaciation of Chilliwack River valley, British Columbia: Canadian Journal of Earth Sciences, v. 24, p. 915–923.

Sherrod, B.L., Barnett, E., Schermer, E., Kelsey, H.M., Hughes, J., Foit, F.F., Jr., Weaver, C.S, Haugerud, R., and Hyatt, T., 2013, Holocene tectonics and fault reactivation in the foothills of the north Cascade Mountains, Washington: Geosphere, v. 9, p. 827–852.

Sternberg, R.W., 1967 Recent sediments in Bellingham Bay, Washington: Northwest Science, v. 41, p. 63–79.

Stuiver, M., and Reimer, P.J. 1993, Extended ^{14}C data base and revised CALIB 3.0 14C age calibration program: Radiocarbon, v. 35, p. 215–230.

Tabor, R.W., Frizzell, V.A., Jr., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Zartman, R.E., 1987, Geologic map of the Chelan 30 x 60 minute quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series I-1661, 56 p., scale 1:100,000. [Also available at https://pubs.usgs.gov/imap/i1661/.]

Thorsen, G.W., 1989, Splitting and sagging mountains: Washington Geologic Newsletter, v. 17, no. 4, p. 3–13.

Thorson, R.M., 1980, Ice-sheet glaciation in the Puget Lowland, Washington, during the Vashon Stade (late Pleistocene): Quaternary Research, v. 13, p. 303–321.

Thorson, R.M., 1989, Glacio-isostatic response of the Puget Sound area, Washington: Geological Society of America Bulletin, v. 101, p. 1163–1174.

U.S. Coast and Geodetic Survey, 1855, Reconnaissance of Bellingham Bay, Washington: U.S. Coast and Geodetic Survey Chart No. 6376, scale 1:20,000.

U.S. Coast and Geodetic Survey, 1887, Sheet no. 10, Topography of Rosario Strait, WT, Nooksachk River, scale 1:10,000, surveyor J.J. Gilbert: U.S. Coast and Geodetic Survey Topographic Sheet t1799, accessed March 2018 at http://riverhistory.ess.washington.edu/tsheets/.

U.S. Coast and Geodetic Survey, 1906, Navigation Chart of Bellingham Bay, Washington: U.S. Coast and Geodetic Survey Chart No. 6378, scale 1:40,000.

Walcott, R.I., 1972, Past sea levels, eustasy, and deformation of the Earth: Quaternary Research, v. 2, p. 1–14.

Weber, S., 2001, Late Pleistocene littoral deposits in the Deming sand at Bellingham Bay, Washington, and their implications for relative sea level changes: Bellingham, Washington, Western Washington University, M.A. thesis, 157 p.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore arc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759–762.

Whatcom County Planning & Development Services, 2006, Whatcom critical areas—geologically hazardous areas: Whatcom County, Washington, Whatcom County Planning & Development Services, scale 1:83,000, accessed March, 2018 at https://www.whatcomcounty.us/DocumentCenter/View/1837.