Lake Terrell upland glacial resurgences and implications for late-glacial history, northwestern Washington State, U.S.A.

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Abstract: New geomorphic data from the Lake Terrell uplands along the western margin of the Fraser Lowland in Washington reveal moraines (and (or) a complex grounding zone) and raised marine terraces. A large ridge that almost encircles the upland is asymmetric, and its surface material consists of fine- to coarse-grained diamictons. These ridges are argued to have formed adjacent to an ice margin near the marine limit, where the depositional processes are variable (e.g., ice-rafted rainout, dumping, sediment gravity flow). Multiple crests and crosscutting relations suggest that at least two glacial resurgences occurred during deglaciation of this area. The presence of these features, and their probable extent and stratigraphic position, raise several questions about relative sea-level history and ice margin reconstructions for this area.

Résumé : De nouvelles données géomorphologiques des terres hautes du lac Terrell le long de la bordure ouest des basses terres du Fraser dans l'état de Washington révèlent des moraines et/ou une zone complexe d'échouement ainsi que des terrasses marines soulevées. Un vaste complexe de crêtes qui encercle presque les terres hautes est asymétrique et le matériel en surface est composé de diamictons de granulométrie fine à grossière. Ces crêtes se seraient formées dans le voisinage immédiat d'une marge glaciaire à proximité de la limite marine, là où les processus de déposition variaient, p. ex. de l'entraînement par des blocs de glace, l'immobilisation des glaces, l'écoulement gravitaire des sédiments. Les crêtes et les relations transversales multiples laissent croire qu'au moins deux résurgences glaciaires ont eu lieu durant la déglaciation. La présence de ces éléments, leur étendue possible et leur position stratigraphique soulèvent plusieurs questions sur l'historique du niveau relatif de la mer et les reconstructions des marges glaciaires de cette région.

[Traduit par la Rédaction]

Introduction

In the Fraser Lowland of southwestern British Columbia (B.C.) and northwestern Washington State (Fig. 1*a*), the Everson Interstade is represented by Everson and Fort Langley glaciomarine deposits that accumulated in coastal lowlands during retreat of ice from the last glacial maximum. At the type section in Washington, these sediments include the Kulshan (glaciomarine), Deming (fluvial), and Bellingham (glaciomarine) members and are thought to be equivalent to the Fort Langley sediments in B.C. (Fig. 1*b*). Deposits include a distinctive blue-gray fossiliferous stony mud, with till-like mixtures, marine clay, deltaic sand, and gravel, and fluvial clay, silt, sand, and gravel (18 000 km^2; Armstrong and Brown 1954; Armstrong et al. 1965; Armstrong 1981; Easterbrook 1963, 1976, 1992; Dethier et al. 1995). The sea-level history for this area is based on the interpretation of these deposits (Fig. 1*c*). The genetic classification of these types of deposits is complex and often ambiguous (e.g., Boulton 1970; Lawson 1981; Domack 1983; Goldthwait and Matsch 1989). Nevertheless, the origin of these sediments is important because the established nomenclature is related to the inferred depositional environment (Armstrong et al. 1965).

Much of the early work in this area was accomplished by examining small-scale roadside exposures where unit boundaries often were not visible and was augmented by stratigraphic sections in large gravel pits, sea-cliff exposures, and river cut-bank exposures (Fig. 2*a*). Subsequently, relative sea-level (RSL) curves were drawn based on the elevation of the Bellingham and Kulshan deposits above modern sea level that indicate two high-amplitude, marine submergences between ~13 000 and 11 000 ^{14}C years BP (Fig. 1*c*; Easterbrook 1963, 1992; Mathews et al. 1970; Armstrong 1981). In Washington, RSL is generally interpreted from the Everson Interstade stratigraphic type section (Figs. 1*c*, 2*a*). Here two massive, blue-gray, fossiliferous, stony-mud diamictons (marine) are separated by a fluvial sand (Easterbrook 1963, 1976). In B.C., Armstrong (1981) believed that the marine silt that underlies the Sumas sediments is Fort Langley marine silt, but whether these sediments correlate with the Everson type section is a question raised here. Six of the youngest radiocarbon dates from wood in the surface-mantling glaciomarine sediments between ca. 75 and 80 m elevation suggests that the area emerged after ca. 11 680 – 11 600 ^{14}C years BP (B-144097, B-144099, B-124905, GSC-5770; TO-4087, Kovanen and Easterbrook 2002*a*; also see Clague et al. 1982, 1997; James

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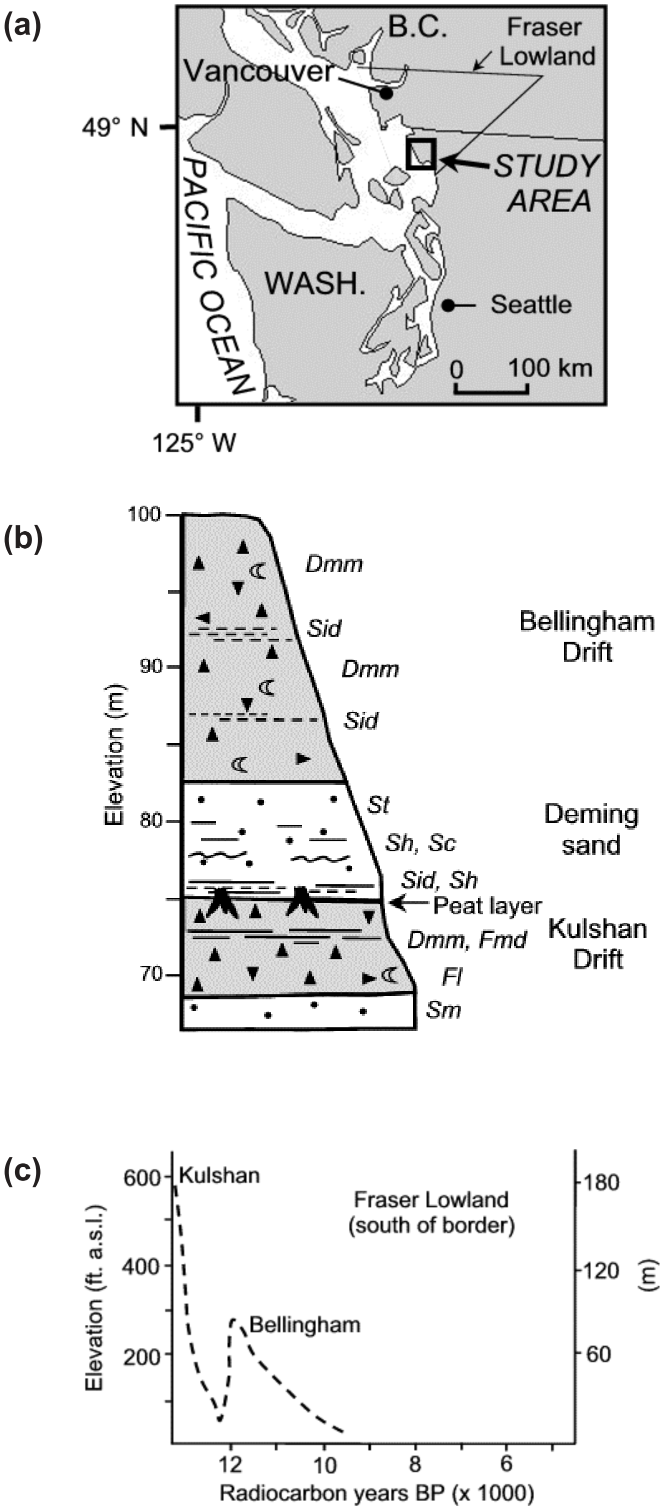
Fig. 1. (*a*) Study location. (*b*) Stratigraphy at the Everson type section (modified after Easterbrook 1963). *Dmm*, matrix-supported massive diamict; *Sm*, massive sand; *Sh* and *Sc*, horizontally and cross-stratified sand; *Sid*, laminated silt and clay with dropstones; *St*, medium to coarse and planar cross-bedding; *Fmd*, massive, fine sand; *Fl*, fine lamination. These diamictons contain articulated marine shells and sparse foraminifera, which have been used as criteria for the glaciomarine interpretation of these units. (*c*) Late-glacial relative sea-level curve (after Easterbrook 1963; Mathews et al. 1970).



et al. 2002). If the stratigraphic and genetic interpretations at the Everson type section are correct, the two transgressions of RSL are difficult to explain by glacio-isostatic adjustments of the crust alone (see Easterbrook 1963, 1992 for detailed discussion on the lithofacies; Riddihough 1979 for gravity and structure; Dyke and Peltier 2000 for RSL curves of glaciated North America).

The aim of this paper is to document a set of enigmatic features, which are probably related to ice marginal sediments that were deposited during the Everson Interstade (Armstrong et al. 1965; Armstrong 1981), and to discuss their implications for the RSL and climatic history.

Study area

The upland area around Lake Terrell (Figs. 1*a*, 2*a*, 3*a*) rises above the modern Nooksack floodplain to a maximum elevation ca. 115 m a.s.l. (above sea level). The Sumas graben (Fig. 2*a*) contains up to ca. 335 m of unlithified sediments (Armstrong 1960). The trough is not simple and splays with reentrants via Semiahmoo, Birch, Lummi, and Bellingham bays. As will be shown later in the text, this trough may have acted as an ice flow pathway and instability corridor when RSL was high, with ice terminating against topographic barriers along the margins of the Fraser Lowland in Washington.

Lake Terrell upland

No radiocarbon dates are available from the Lake Terrell upland (LTU; Fig. 2*a*; Easterbrook 1963; Kovanen 2002), therefore, we present only relative geomorphic relations.

Geomorphology

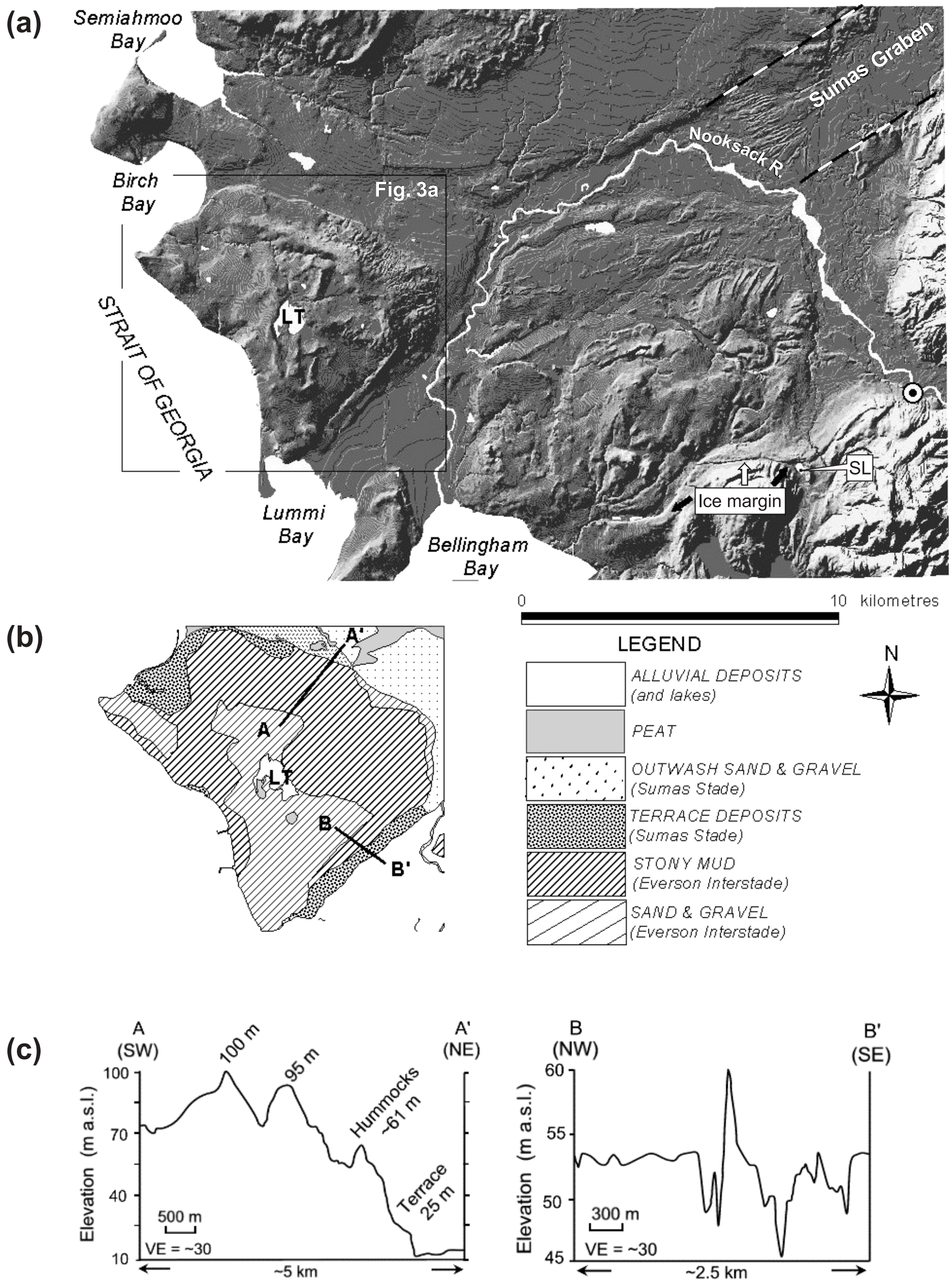
Large, subdued, crosscutting, asymmetric morainal ridges and terraces almost encircle the LTU. The ridges are broad crested, appear steeper on the distal (west) side, and taper in the down-ice direction (~8 km; Figs. 2*c*, 3*a*). The highest ridge (~115 m a.s.l.) cuts across smaller ridges. Lying conformable to the encircling ridge are several circular to elongate hummocks 2–8 m high (up to ~80 m a.s.l.). No primary structures were observed.

Uplifted coastal terraces situated in the north and southeastern parts of the upland at altitudes from 58 to 35 m a.s.l. (Easterbrook 1963, 1976) represent former sea levels. Furthermore, a tight grouping of marine strandlines between ca. 35 and 45 m a.s.l. occurs on the northwestern part of the upland.

Lithofacies

Currently, two large gravel pits are operating on the LTU and both expose a 10-m-thick surface diamicton (Figs. 3*a*, 3*b*). One pit is located in deposits between moraines (P1, Fig. 3*a*) and the other at the distal edge of a moraine (P2, Fig. 3*a*). The diamict has a muddy sand matrix that contains pebble to cobble size clasts, many of which are rounded and striated. The matrix and clast ratio varies, but is relatively high in the Lake Terrell pit (P1). Articulated and fragmented marine shells are abundant in the more sandy facies. Mud drapes and flow noses are present within the unit, which has a sharp basal contact, indicating a distinct sedimentation event. In places, the diamicton grades vertically (upward)

Fig. 2. (*a*) Shaded digital topographic model of the study area in Washington. The circle with a dot (⊙) is the location of the Everson stratigraphic type section. LT, Lake Terrell; SL, Squalicum Lake. (*b*) Surficial geology map (taken from Easterbrook 1976). (*c*) Topographic profiles A–A′ and B–B′; locations shown in (*b*). VE, vertical exaggeration; a.s.l., above sea level.



into a massive structureless unit, which makes individual lithofacies distinctions and correlations difficult. Exposures are not laterally extensive.

Underlying the diamicton are ~40 m of bedded gravel and sand, with planar cross-bedded, channel-fill structures. Wedges of sand are separated by coarse gravel and sand facies. These deposits form seaward-dipping beds (Fig. 3*b*) and show southwest bimodal paleocurrent directions. A granitic boulder (up to ~3 m in diameter) concentration forms the base of this unit.

Interpretation

This area has been mapped as Bellingham glaciomarine drift and the deposits were thought to be the product of ice-rafted rainout detritus with a wave-washed mantle (Fig. 2*b*; Easterbrook 1963, 1976). Based on the morphology shown here (Figs. 2*a*, 2*c*, 3*a*), we suggest that the small transverse ridges are moraines and that the large asymmetric ridge that almost encircles the LTU is a larger moraine (e.g., polyepisodic; Lønne 2001), possibly a grounding-line ridge. This feature may have formed when advancing ice flowing towards the

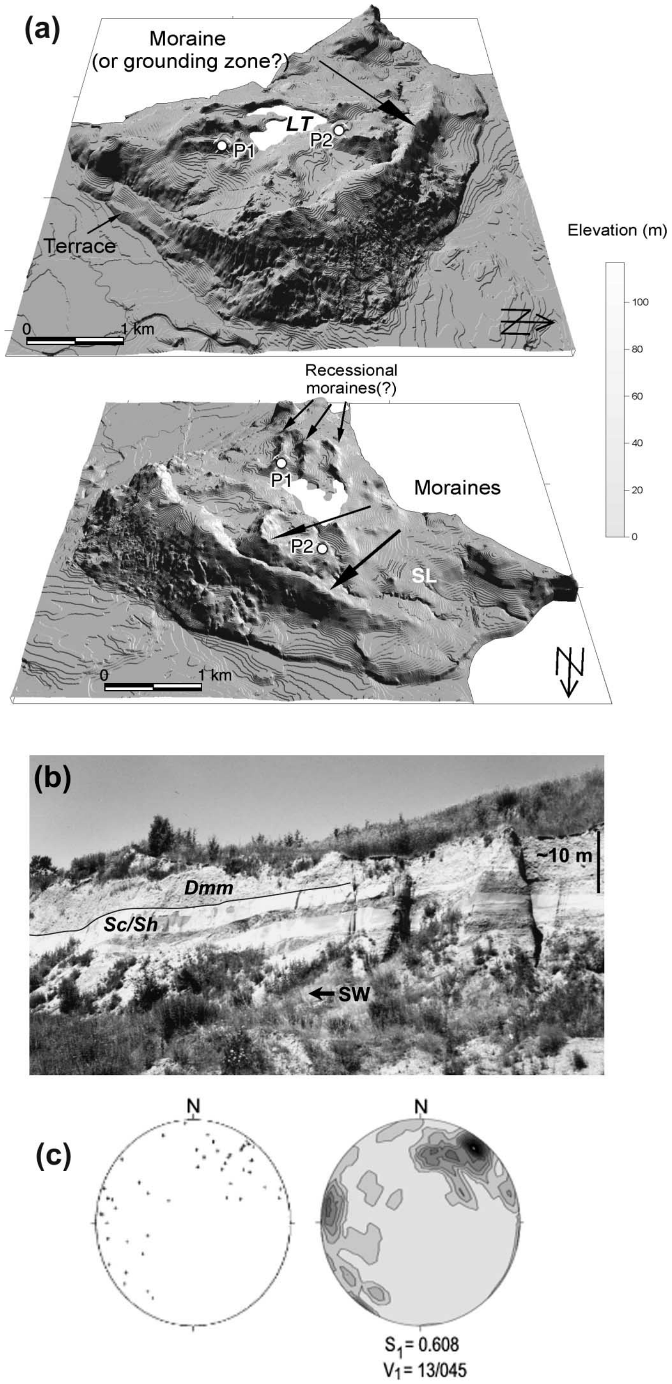


Fig. 3. (*a*) 3-D perspective projections of the Lake Terrell uplands. The topographic models (10 m horizontal resolution) are shown with different aspects to emphasize morphology. Light position angle (horizontal: –149; vertical: 39), field of view (45°), *x*- and *y*-scale (1 : 3140), *z*-scale (1 : 156), and tilt (42°) are constant. Top, rotation is 270°; bottom, rotation is 180°. Scale varies with view; ~14 km across the bottom of the images. SL, strandlines. (*b*) A gravel pit exposure where the contact between the stony mud diamicton (*Dmm*) and cross-stratified and horizontally fine sand (*Sc*/*Sh*) is seen. The basal portion of the unit contains some prominent flow structures. The underlying sand and gravel is probably related to glaciofluvial deposition during isostatic rebound of the area. (*c*) The macro-fabric of rod-shaped clast orientations (*a*-axis orientation; $n = 50$), equal-area stereonet projection and contour plot (lower hemisphere) recorded in the diamicton. The clast macrofabric displays a NE–SW orientation with a dip towards the SW. Normalized eigenvalues (S_1, S_3) are 0.608 and 0.086 and eigenvector orientations (V1, V2, V3) are 13/045, 34/306, and 53/153 (expressed as dip/azimuth).

southwest met the LTU barrier. Multiple ridge crests (Fig. 3*a*) suggest more than one glacial advance during the Everson interval. The trough-mouths (Fig. 2*a*) would have been occupied by floating ice during time of moraine construction.

The deposits within the large ridges are not well exposed, but well logs indicate 10–15 m of stony mud overlying sand and gravel. Therefore, some uncertainty exists as to what material actually forms the ridges. The ridge could be morainal with a sand and gravel core that is capped with the stony mud, or it could be a larger composite feature that was deposited near a grounding zone. The presence of channel-fill features exposed in the gravel pits suggest a (glacio)fluvial origin for the underlying sand and gravel. The various processes (sediment gravity flow, iceberg rainout, meltout) were active depending on the topography and the interaction between ice, sea level changes, and the location of meltwater sources. The textural variation of the sediments probably reflects distance from the ice, sediment supply, and source.

These observations are significant because they suggest that ice extended farther west than previously thought during the Everson interval. Because of the limited spatial coverage of suitable stratigraphic exposures and difficulties with differentiating the fine-grained diamictons, we place emphasis on the geomorphic relations, which are elaborated in the following section.

Regional geomorphic relations and implications

We have presented geomorphic evidence for constructional glacigenic landforms and deposits on the LTU at the western (distal) margin of the Fraser Lowland. The evidence suggests that at least two local ice resurgences occurred. These LTU interpretations have implications for the depositional history to the east (Fig. 2*a*). Questions concerning (*i*) the maximum extent and timing of the glacial resurgence in the central part of the lowland; (*ii*) the relation of LTU features to the double submergence in the RSL curve; (*iii*) the relation of LTU sediments to the Everson type section; and (*iv*) the classification of these sediments that were probably derived from a temperate glacier overriding marine mud (deformation till or glaciomarine in origin).

Easterbrook (1963, 1992) proposed explanations to account for a thick-stacked depositional sequence along the Nooksack River valley (in ascending order; Fig. 1*b*):

(1) Kulshan glaciomarine stony mud was at first considered to have been deposited during submergence resulting from isostatic depression and eustatic sea-level change. However, subsequent discovery of stratified silt and sand beneath the Kulshan at the type locality indicate that the area was already above sea level prior to deposition of the Kulshan. A piece of wood and an organic mat in the pre-Kulshan silt and sand were dated at 12 185 ± 80 and

12 070 ± 80 ^{14}C years BP (AA-22222 and AA-22220; Kovanen and Easterbrook 2002*b*.

(2) Fluvial Deming sand was deposited during a brief emergence. A peat layer and several rooted stumps at the base of the unit demonstrate a period of emergence between 11 810 ± 60 and 11 455 ± 125 ^{14}C years BP (B-135696 and B-1324; Easterbrook 1963; Kovanen and Easterbrook 2002*a*, 2002*b*).

(3) Bellingham stony mud was considered to have been deposited during a second submergence, which may have been caused by a combination of tectonic and isostatic movement, perhaps accompanied by eustatic sea level rise.

This depositional sequence was deposited in a relatively short time period, and the combination of causes proposed by Easterbrook (1963, 1992) has been difficult to explain because of the amplitude and very high rates of RSL changes. Mathews et al. (1970) suggested that ice loading during a readvance produced concurrent RSL changes, although the apparent extent and thickness of ice may have been too small to produce these changes.

At the Everson type section, the presence of marine fauna is an indication that marine waters were in contact with floating ice. Around the basin and glacier fringe, where there are topographic obstacles, ice may have been grounded, depositing the fine-grained debris by a variety of processes. We believe that multiple marine submergences did occur in the lowland as indicated by the many marine lithostratigraphic units throughout the Quaternary (Armstrong 1981; Easterbrook 1992; Cox and Kahle 1999), but we are uncertain about the relation of the LTU sediments to the glaciomarine sediments at the Everson type section. Kovanen and Easterbrook (2002*a*, their figs. 3, 5*b*) have shown that this area was deglaciated prior to ca. 11 113 ^{14}C years BP (AA-27066); therefore, the resurgences at LTU must be older. We also hypothesize that some of the stony mud diamictons in Washington may be younger relative to the Fort Langley sediments in B.C. and that this has confounded attempts of researchers to improve the RSL history.

Within the formal stratigraphic nomenclature, most of these fine-grained deposits would be considered Everson if it could be demonstrated that they were deposited prior to emergence of the lowland. But the interplay among the trough, ice thickness and extent, grounding line flux and sea level, and possibly local differential rates of isostatic rebound make this complicated (i.e., not a single depositional environment throughout the basin).

Temporal changes in accumulation and ablation are unlikely to cause all the rapid ice readvances noted in this area (cf. Clague et al. 1997; Kovanen and Easterbrook 2002*a*; Kovanen 2002). These must be due, in part, to the glacier flow dynamics. Significant time lags exist for surface temperature perturbations to penetrate to a critical level, so these events may not be triggered by high-frequency climate change alone. Determining which ice resurgences are due to external (sea-level changes, sediment flux) or internal (basin configuration, substrate type) factors is a challenge for future work. An integrated methodological approach involving geomorphic, stratigraphic, structural, and textural data is necessary to unravel the dynamic history of this area. Included in the dynamic history of this area is the question of the relation between the Fort Langley sediments and the Everson type section. There is a need to evaluate the timing and significance of the LTU sites in relation to RSL trends in this region.

Conclusions

This study identifies new moraine-like ridges that mark additional marginal positions of the remnant Cordilleran Ice Sheet along the western margin of the Fraser Lowland in Washington. Multiple ridge crests and crosscutting relations suggest that at least two glacial resurgences occurred during the Everson interval. The probable extent and stratigraphic position of the LTU features raises several questions about the relation of the features to the double submergence in the RSL curve, the relation of LTU sediments to the Everson type section, and the maximum extent and timing of the features to reconstructions of sea-level and ice marginal positions.

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