Geotechnical Evidence for the 11 kYa glacial Lake Fraser outburst flood between Abbotsford and Pitt Meadows, B.C.

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ABSTRACT A glacier dammed lake in central British Columbia catastrophically failed about 11,000 years ago. Clague et al. (2021) presents evidence for the outburst flood using landforms and sediments with the focus upstream of Hope, B.C. This paper presents evidence for the flood between Abbotsford and Pitt Meadows. Carbon dates presented in the USGS Geomorphic Map of Western Whatcom County (2021) are used to assess the elevation range of the flood and identify possible flood features. The focus of this paper is a reinterpretation of the consolidation tests and CPT calibrations performed for the Golden Ears Bridge project. An unusual feature of the consolidation tests was a relatively constant over-consolidated difference with depth (i.e., OCD, $s'_p - s'$). The outburst flood provides a mechanism by which many meters of material could be scoured, and the OCD provides a crude means of reconstructing a possible pre-flood surface.

Introduction

Direct evidence for a large glacial outburst flood on the Fraser River has increased over the past twenty years. Blais-Stevens et al. (2003) presented evidence for two such floods based on pollen and minerology analysis of two anomalous silty-clay beds collected from the seafloor of Saanich Inlet. Clague et al. (2021) evaluated flood landforms and sediments consistent with an outburst flood upstream of Hope, B.C. and drew attention to two flood scoured surfaces at Fort Langley, B.C. and Lynden, WA which have been long known of, but not previously attributed to a particular flood event. The flood was estimated to have occurred about 11,000 years ago (11 kYa) based on radiocarbon dating in Blais-Stevens et al. (2003) and 11.1 ± 0.6 kYa based on ^{10}Be dating of relict boulders in Clague et al. (2021).

Kovanen et al. (2020) published an updated geomorphic map and interpretation of Whatcom County which is south of the Canadian border in Washington State wherein is located the Lynden scoured surface. The geomorphic map included radiocarbon dating of samples located near, and higher and lower than the Lynden scoured surface (see Figure 1). Three samples collected at Pangborn Lake to the north of the scoured surface (bog, El. +41 m) were dated to between 12.4 kYa and 11.1 kYa. One sample collected at Nolte Road to the south of the scoured surface (peat, El. +21 m) was dated to between 11.1 kYa to 10.5 kYa. In ^{14}C years the gap between the sites is 390- to 800-years.

The elevation and interpreted age of Pangborn Lake indicates that the bog predates the flood and that the flood level could not have been higher than about El. +41 m. Otherwise, the bog deposits would have been washed out by the flood. The elevation and interpreted age of the Nolte Road site indicates that the peat deposit post-dates the flood. This would be expected as there would have been at least 10 m to 20 m of water flowing over a pre-flood bog at Nolte Road, scouring it out. The potential height of water at Nolte Road is based on the elevation of the top of the ridges within the Lynden scoured area (El. +30 m) and Pangborn Lake (El. +41 m). For comparison, the minimum estimated flood depth at Ruby Creek (within the Fraser Canyon, about 12 km west of Hope) was greater than 30 m with a minimum upper flood level of El. +57 m in Clague et al. (2021); at Hope the estimated minimum flood depth was 51 m (El. +91 m).

In this paper, we identify potential flood features between Abbotsford and Pitt Meadows, B.C., and reinterpret the consolidation tests and CPT calibrations performed for the Golden Ears Bridge (GEB) project. An unusual feature of the consolidation tests and subsequent CPT calibrations was a relatively constant over-consolidated difference (i.e., OCD, $s'_p - s'$) with depth. This was noticed by third-party reviewers who pressed for a geomorphological explanation which was not forthcoming except to refer back to the consolidation tests which showed the OCD was real. The glacial outburst flood provides a mechanism by which many meters of material would be eroded, creating the observed OCD pattern.

Abbotsford Channel

Kovanen et al.'s (2020) interpretation is that westward flow of the proto-Fraser River past Mission, B.C. was prevented until the final disintegration of the Sumas glacier and that flow was established no later than 10,000 ^{14}C years ago (roughly 11.7 kYa to

11.3 kYa). This would mean that the modern Fraser River alignment was less than 1,000 years old, perhaps only a few hundred years old, when the outburst flood occurred.

The change in the alignment of the Fraser River was to the east of Sumas Mountain as the intervening terrain in Abbotsford and Langley is generally higher than El. +60 m. However, there is a channel in Abbotsford that would have provided an interconnection between the two alignments during the flood (see Figure 2 and Figure 3).

The elevation profile of the channel suggests that it was a late glacial outwash channel flowing to the south (see Figure 4). It can be inferred that water would be present in the channel during the flood as it is upstream of Lynden and lower than the tops of the scour ridges (i.e., El. +27 m compared to El. +30 m).

The direction of flow in the channel would depend on the relative water levels of the Proto and Modern Fraser River alignments. The author’s bias is towards northwards flow during the initial stages of the flood, trending towards slack water because of the relative width of the alignments at Sumas Mountain (i.e., ~4 km, modern vs. ~6 km, proto) and obstructions in the valley which would favour the Proto-Fraser alignment (e.g., Agassiz blocking ridge, Mt. Shannon, Chilliwack Mountain).

Fig. 2. Proto and Modern Fraser River with inferred connecting channel (bottom left) and significant valley hills and ridges in red (Google Earth).

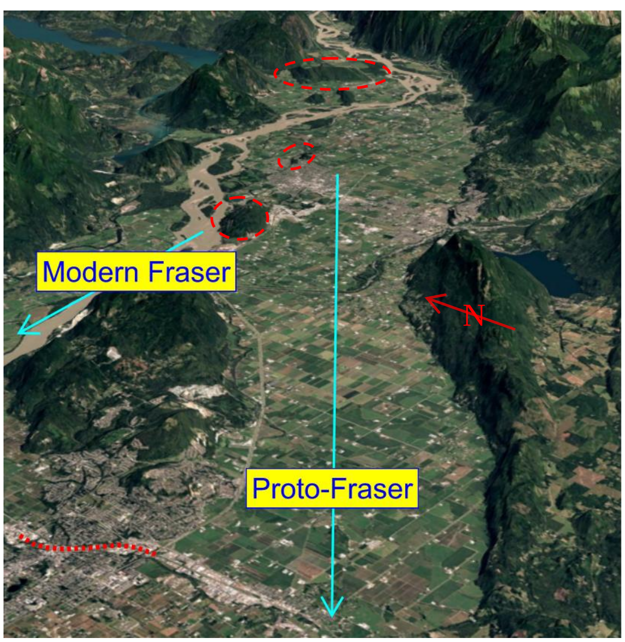


Fig. 1. Lynden scoured surface with location of radiocarbon samples from Kovanen et al. (2020).

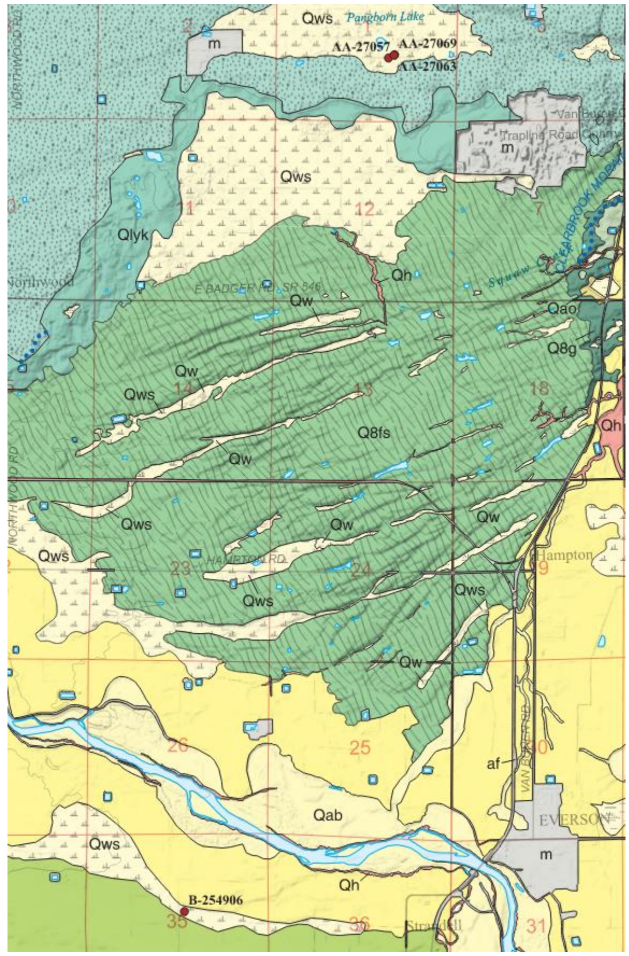


Fig. 3. LiDAR topographic map, 20 m contours with blue shading below El. +40 m, invert in red.

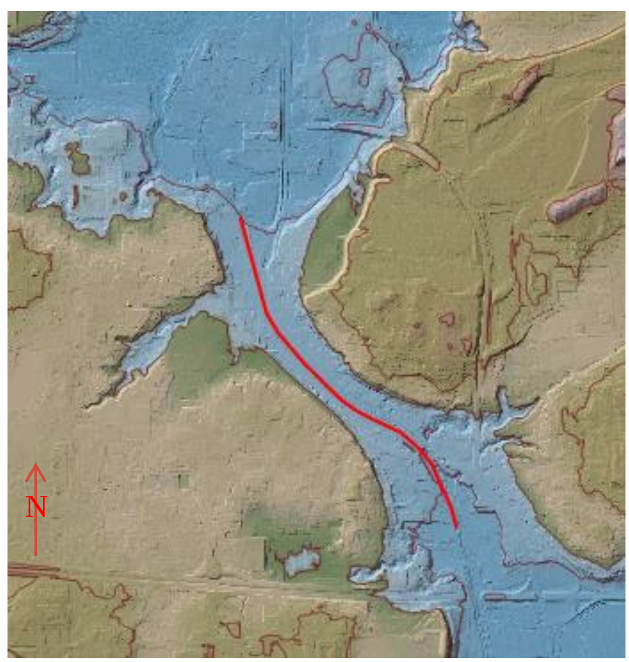
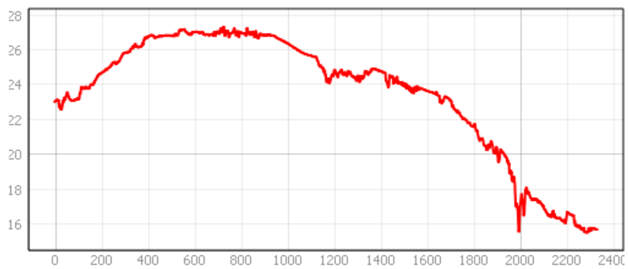


Fig. 4. Elevation profile along red line in Figure 3 with Sta. 0 at north end.

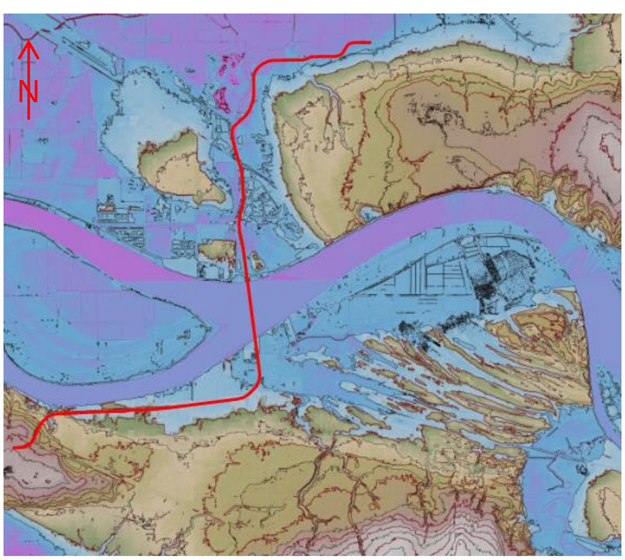


Golde Ears Bridge

Golden Ears Bridge was constructed between 2006 and 2009 to provide a crossing of the Fraser River between Highway 1 at Surrey-Coquitlam and Highway 11 at Mission-Abbotsford, which are about 50 km apart. The alignment crosses the entire width of the modern Fraser River alignment, from upland terrain in Surrey, well above the flood at El. +60 m, to lowland terrain to the north of Maple Ridge (i.e., road at El. +2 m, ridge at El. +30 m). The extent of the mainline works is shown in Figure 5.

The Fort Langley scoured surface can be seen towards the bottom right of Figure 5. The top of the streamline ridges are at about El. +15 m. The high ground at the north end of the scoured surface is at about El. +30 m and was the site of an old gravel pit which was characterised as a Gilbert-type foreset with northwest dipping beds and being about 13,000 years old (Clague et al. 2021).

Fig. 5. Approximate extents of Golden Ears Bridge mainline on LiDAR topographic map (contours: red at 10 m, black at 5 m, blue shading used below El. +9 m.)



Site Investigation

The design phase site investigation for the Golden Ears Bridge project comprised 91 CPTs (cone penetration test), 19 SCPTs (seismic cone penetration test), 76 augers holes, 54 mud rotary holes, and eight ODEX holes.

At eight locations along the alignment, deep mud rotary holes were advanced near the CPT or SCPT and many vane shear tests performed, and many piston tube samples collected for consolidation testing. The goal was to establish reliable correlation parameters for shear strength and over-consolidation which could be applied to nearby CPTs and reduce the number of mud rotary holes required. This was an important consideration as the heavily tested mud rotary holes would often take a week to complete whereas a deep CPT could often be done in a day or two.

The piston tubes used for sampling were typically standard 3” (76 mm) tubes, or standard 3.5” (89 mm) tubes if the sample was obtained below about 19 m. At BH06-43 on the north bank of the river, flush ended, thin wall tubes with a 5° cutting angle were used.

Consolidation Testing

The consolidation testing program was developed using Ladd & DeGroot (2003) as a refence. Samples were prepared by cutting the piston tube into 100 mm to 150 mm lengths using a hand portable bandsaw. A hole was drilled along the edge of the tube and a guitar string used to saw along the perimeter of the sample. The sample was then pushed out by hand (or the sample extruder if not possible by hand) and cut into the consolidation ring.

Standard lever arm machines were used with a modified loading procedure. Two load increments were placed each day, usually 8 to 10 hours apart. The load increment was x1 below the inferred pre-consolidation pressure and x2 above it (e.g., 100 kPa to 150 kPa not 200 kPa). This was done to improve the characterisation of the e-log s curve in the vicinity of the pre-consolidation pressure.

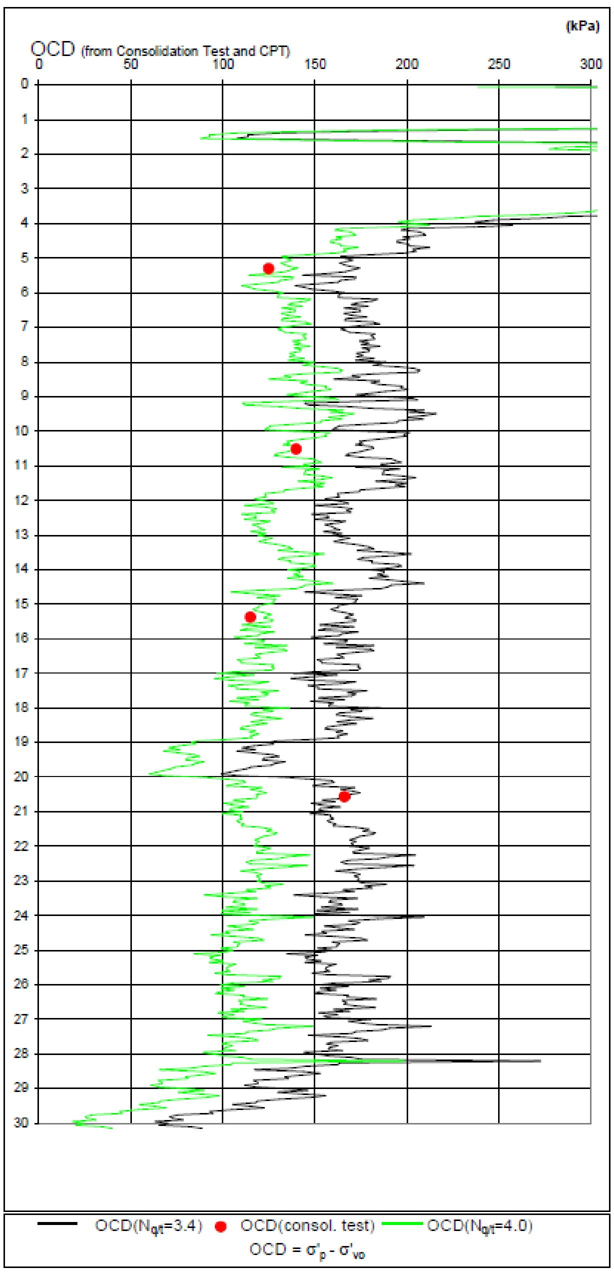
About half of the samples (25 of 52) had less than 2% strain when re-loaded to their in-situ effective stress, 20 samples were between 2% and 4% and 7 samples were between 4% and 7%.

Calibration with CPT Data

The N_{qt} correlation parameters were selected on a project-wide basis using a bounding approach. The goal being to have most of the interpreted pre-consolidation pressures fall between the two bounding lines (see Figure 7). Low deviations were reviewed and generally occurred in shallow, young, organic-rich deposits where the consolidation test had more than 4% strain at the in-situ effective stress indicating sample disturbance which would be expected to lower the interpreted pre-consolidation pressure. High deviations were less of a concern as it would result in a conservative interpretation of OCD. The N_{qt} values selected were 3.4 and 4.0.

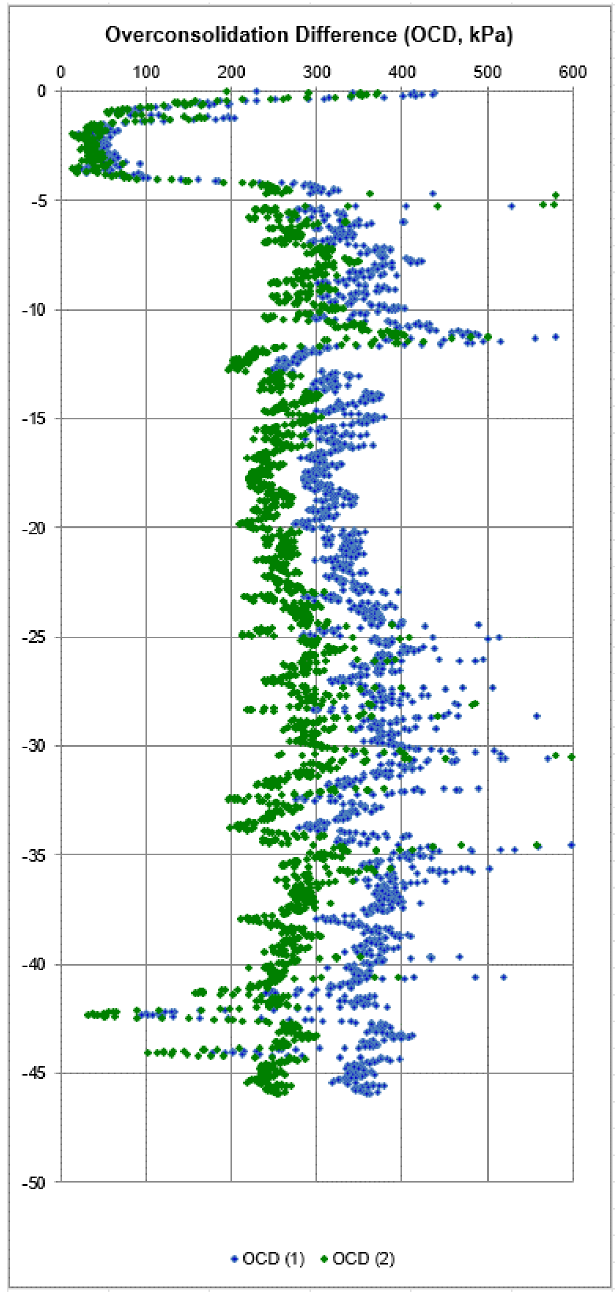
Figure 6 and Figure 7 show an OCD pattern that was consistently observed throughout the Golden Ears Project. Namely, a relatively stable magnitude of over-consolidation with depth. The magnitude of OCD varied by segment and from hole to hole, roughly as follows:

Fig. 6. OCD from CPT and consolidation tests (from GEB Factual Report, BH06-62 / SCPT06-62, Trow).



- South West – 50 kPa to 100 kPa, increasing trend moving towards Fraser River
- South Approach – 100 kPa to 200 kPa
- North Approach – 200 kPa to 300 kPa
- North of CPR – 200 kPa to < 50 kPa, decreasing trend moving to north and east

Fig. 7. Interpreted OCD from CPT04-50, N_{qt} of 3.4 (blue) and 4.0 (green).



Significance of OCD Pattern

The typical OCD profile observed in the Fraser River Delta and the Serpentine and Nicomekl lowlands is an over-consolidated crust at the surface which trends towards normally consolidated conditions with depth (i.e., OCD = 0 kPa). The over-consolidated crust is formed by aging and desiccation and does not extend much below the long-term average groundwater level. A deltaic environment also favours normally consolidated conditions as new soil is being deposited.

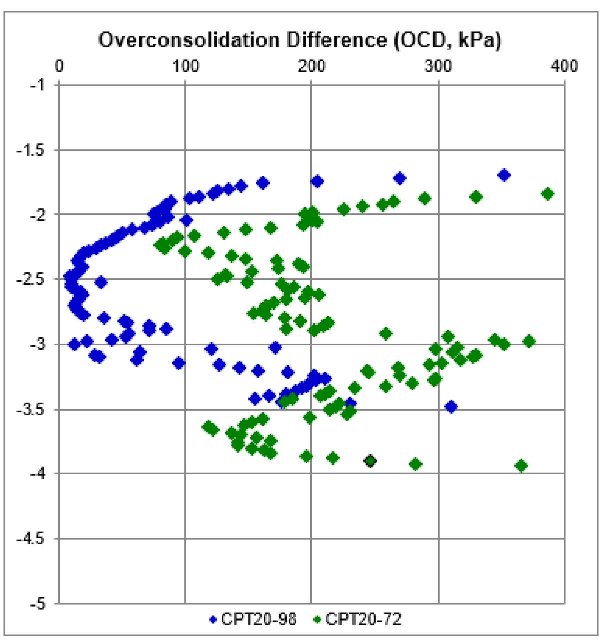
Buried over-consolidated crusts can be found on the margins of the Serpentine and Nicomekl lowlands and are evidence of the valley topography when the relative sea level was about 25 m to 12 m lower than it is today between 13 kYa and 8 kYa (James et al. 2009, and William & Roberts 1989). The normally consolidated deposits overlying the crust having been deposited during marine transgression as sea level rose.

Constant over-consolidation with depth is interpreted as the erosion of overlying material which results in the magnitude of over-consolidation observed. For example

[1] 100 kPa OCD = 5.5 m of erosion at γ = 18 kN/m^3
[2] 100 kPa OCD = 12.5 m of erosion at γ' = 8 kN/m^3

A similar situation occurs when a preload is removed. This is illustrated in Figure 8 which shows the interpreted OCD for two CPTs completed as part of the Highway 91/17 Upgrade Project in Delta, B.C. CPT20-72 was located within the footprint of a sand stockpile used for construction of Highway 91 in the 1980s. CPT20-98 was located outside of the sand stockpile. Both CPTs show a crust (i.e., higher near surface OCD), but the deeper OCD pattern of CPT20-72 suggests the removal of more than 6 m of fill, which was the old stockpile

Fig. 8. Comparison of OCD of two CPTs.



Golden Ears Bridge Interpretation

The unusual OCD patterns observed along the Golden Ears Bridge alignment are interpreted to be the result of massive erosion caused by the glacial Lake Fraser outburst flood. When the flood occurred roughly 11,000 years ago the active front of the delta was likely a short distance downstream of Golden Ears Bridge with what is now Pitt Lake being a fjord and much of Pitt Meadows being the sea (Clague et al. 1983). The outburst flood likely played a significant role in filling this basin which allowed the delta to start expanding west of New Westminster 10,000 years ago.

Figure 9 provides an annotated LiDAR map identifying significant topographic features in the vicinity of Golden Ears Bridge. Sea level at the time of the flood was roughly 25 ± 10 m lower than at present (James et al. 2009). This would imply a flood height of more than 40 m based on the difference between the 11 kYa sea level and the tops of the scour ridges.

Figure 10 provides an annotated LiDAR map with the inferred erosion along the Golden Ears Bridge alignment. For simplicity, the magnitude of erosion was calculated using a unit weight of 18 kN/m^3. The actual depth of erosion could be much greater than is implied in Figure 10. This is because the depth to the high OCD deposits are variable along the alignment, from 25 m to 35 m deep at the river banks to about 5 m deep far away from the river. Thus, the total magnitude of erosion could vary from 35 m to 40 m at the river banks to slightly more than the amount indicated in Figure 10.

There is evidence that flood induced erosion occurred along the south bank for at least 6 km downstream of the bridge. Consolidation tests performed by Trow (now exp) in 2009 as part of TetraTech's (then EBA) design work for South Fraser Perimeter Road identified over-consolidated marine clay-silts at a site where 8.5 m of mineral fill had been placed almost 20 years earlier. The 6 consolidation tests at that location had a lower-bound OCD of about 75 kPa, or 130 kPa if the weight of the fill accounted for. This implies about 7 m of erosion occurred using a unit weight of 18 kN/m^3.

The marine clay-silt at the downstream site was highly compressible (i.e., 1.2 < Cc < 2.7, LL < w%) with a well-defined break in the consolidation curve which provided a high degree of confidence in the estimation of pre-consolidation pressure. Figure 11 illustrates the characteristic shape of the e-log s curve for this series of tests. The sharp break is interpreted as evidence of structure arising from marine deposition and subsequent replacement of saline pore water with fresh water. The consolidation tests at GEB did not exhibit such sharp breaks in the e-log σ curve which suggests a more brackish depositional environment.

Fig. 9. Annotated LiDAR map identifying significant topographic features in the vicinity of GEB.

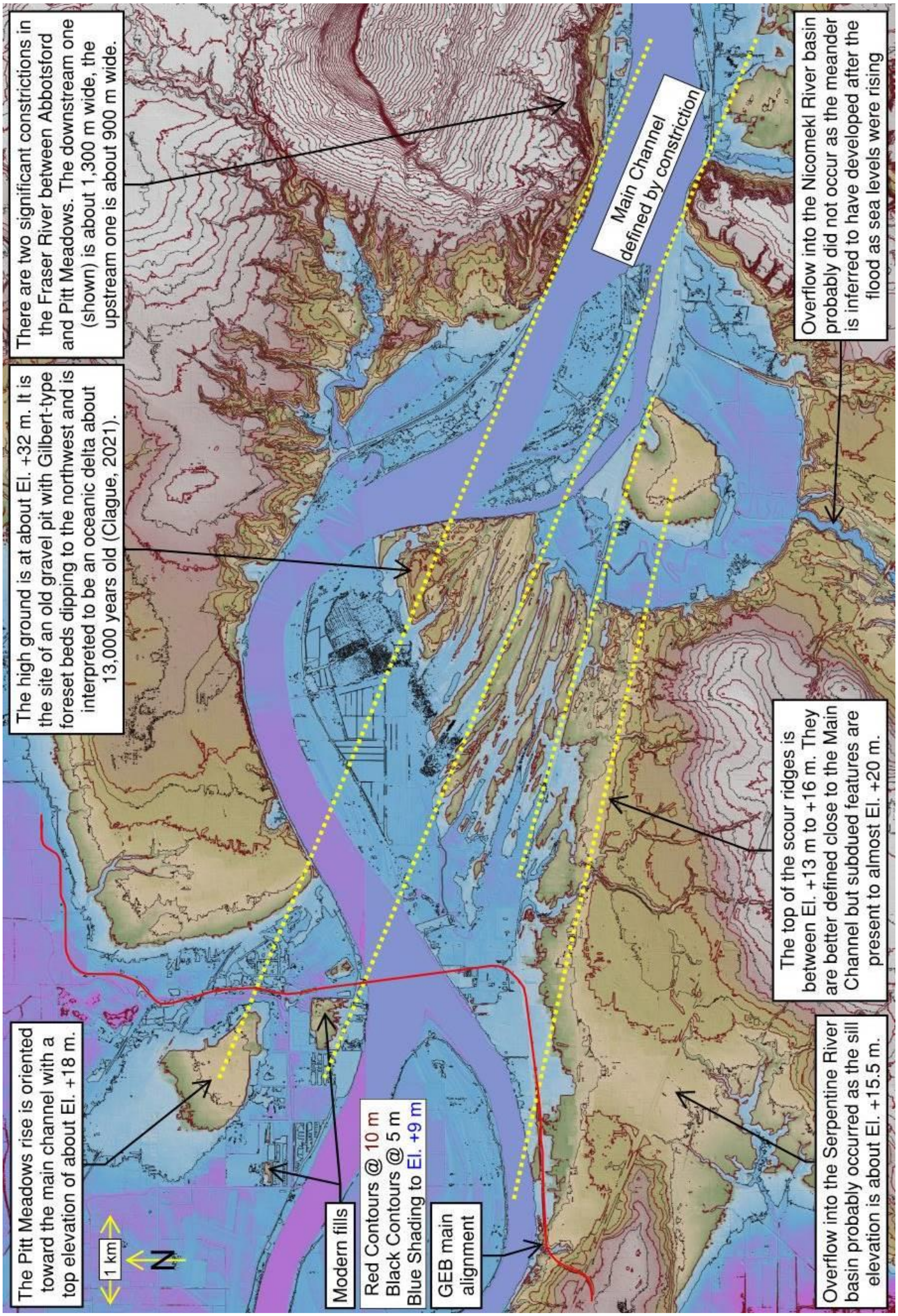


Fig. 10. Annotated LiDAR map with inferred erosion along GEB alignment.

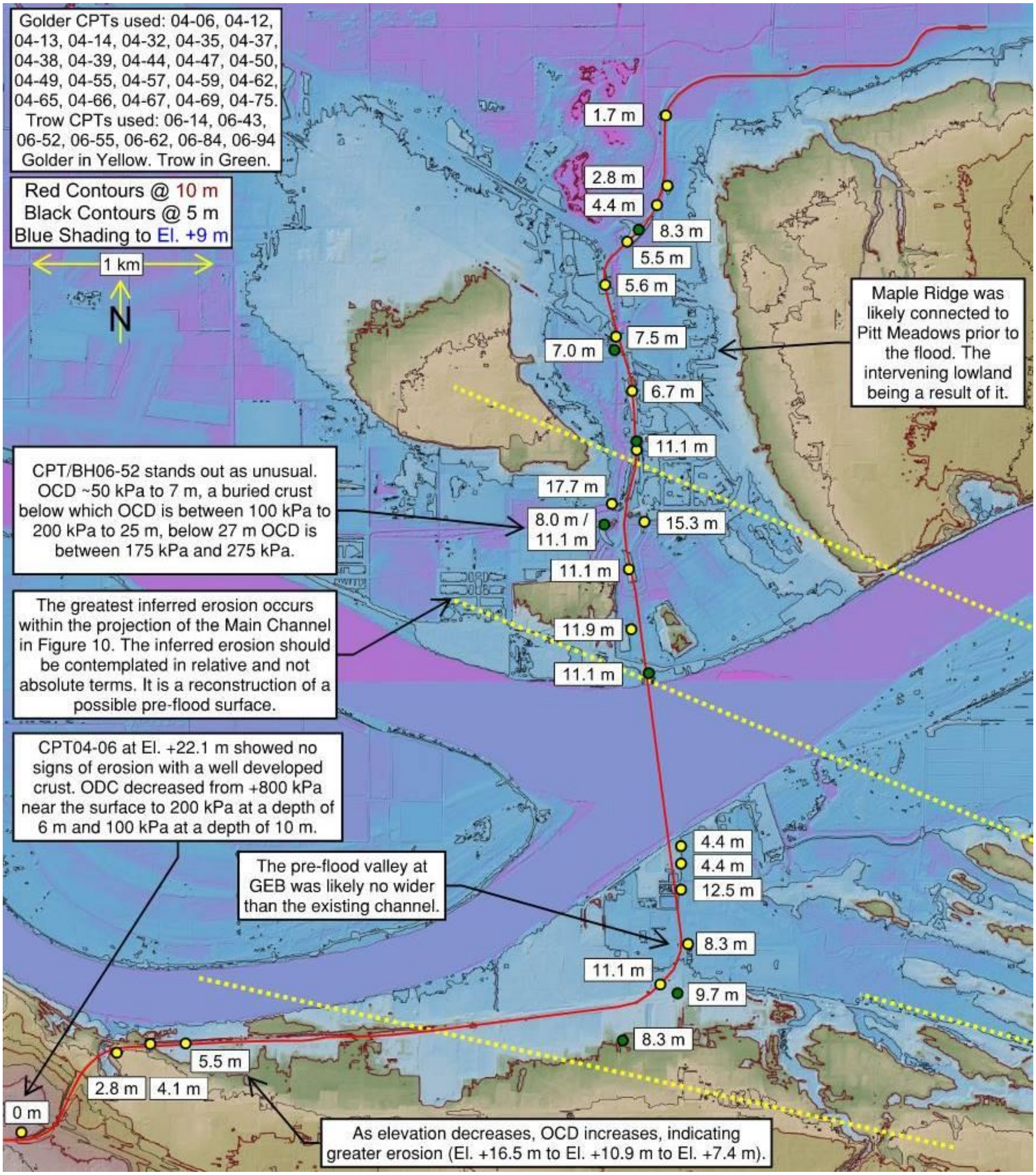
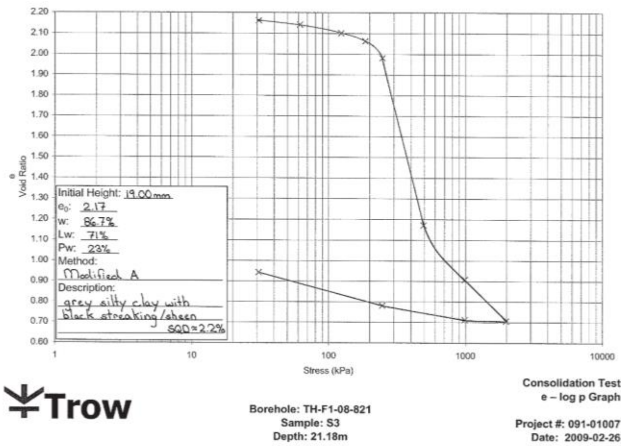


Fig. 11. Consolidation test at site 6 km downstream of Golden Ears Bridge (near 173rd Street, Surrey).



Final Thoughts

Manifestations of the glacial outburst flood are likely present throughout much of the Fraser Valley. However, they may not be recognised as such because an outburst flood is not part of the common narrative that resides within the minds of most local geo-practitioners. The same can be said for the relative rise in sea level between 11 kYa and 5 kYa. Raising awareness of the dynamism at the end of the glaciation and its relevance for geotechnical interpretation is important.

As a thought experiment, the change in sea level over the past 15,000 years should have left a detectable imprint on the interpreted OCD with depth. However, that imprint is not apparent in any of the CPTs reviewed except for CPT04-42, and it is far deeper than it should be. It may be that the though experiment is too simple in that it ignores the possibility of unusual groundwater regimes at the end of the ice age and that the entire thickness of clay-silts are consolidating as they are being raised above sea level.

The OCD pattern typical of Golden Ears Bridge should eventually disappear moving downstream to the west. With enough CPTs and consolidation tests it may be possible to determine the limits of erosion, downstream of which would have been a depositional environment

Acknowledgements

We thank Brent Case of the BC Ministry of Transportation and Infrastructure, Ujjal Chakraborty and Armando Abello of exp Services Inc. for the factual information from the GEB project, and Chris Longley and Patrick Korner of TetraTech for CPT data from the South Fraser Perimeter Road Project.

Particular thanks are given to the late Graeme Macleod (1930-2020) for involving the author in the GEB project at the start of the investigation for detailed design, and the many consolidation tests that followed.

LiDAR topographic maps were prepared by the author using information obtained from the BC LiDAR Data Portal.

2-sigma age range for ^{14}C dates determined using CALIB 8.1.0 program.

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