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Sand dykes in late Pleistocene deltaic sediments, Fraser Lowland, British Columbia

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Abstract: Sand dykes and deformation structures occur in late Pleistocene deltaic sediments of the Fort Langley Formation near Maple Ridge, British Columbia. One 5 m wide, vertical-sided sand dyke intruded stratified sands and gravels and an overlying 4 m thick layer of fossiliferous clay. The source of the injected material is a sand stratum located at 8 m depth. A smaller, 35 cm wide sand dyke intruded 70 cm of horizontally stratified sands to vent onto a subaqueous depositional surface on a sandy delta front. Normal faulting and tilting and folding in strata 20 m away from the dykes suggest that lateral spreading may have accompanied dyke emplacement. Possible causes for liquefaction at the study site are nonseismic landslides or an earthquake that occurred 12 500–11 500 ^{14}C years ago.

Résumé : Des dykes de sable et des structures de déformation se rencontrent dans les sédiments deltaïques du Pléistocène supérieur de la Formation de Fort Langley, près de Maple Ridge (Colombie-Britannique). Un dyke de sable de 5 m de largeur, aux parois verticales, recoupe des graviers et sables stratifiés et une couche d'argile fossilifère sus-jacente de 4 m d'épaisseur. Le sable du dyke provient d'une strate de sable située à 8 m de profondeur. Un dyke de sable plus petit (35 cm de largeur) recoupe 70 cm de sables stratifiés horizontalement et débouche sur une surface de sédimentation subaquatique dans un front deltaïque sableux. La formation de failles normales, le basculement et le plissement de strates à 20 m des dykes laissent supposer que la mise en place des dykes peut avoir été accompagnée par un étalement latéral. Les causes de liquéfaction au site à l'étude pourraient être des glissements de terrain d'origine non séismique ou un séisme survenu il y a entre 12 500 et 11 500 ans (âge ^{14}C).

INTRODUCTION

Exposures of the late Pleistocene Fort Langley Formation at a borrow pit in the Fraser Lowland, British Columbia (Fig. 1) were described by Armstrong (1977, 1981) as proglacial, deltaic sediments with ice-collapse structures. We examined the exposures and agree with Armstrong (1977, 1981) that the sediments are deltaic, however we find little evidence to indicate a paleoenvironment in close proximity to wasting glaciers, calling into question the ice-collapse origin invoked for the strata. We observed sand dykes, normal faulting, and associated folding that appear to have been formed by liquefaction. In this paper we describe the stratigraphic evidence bearing on the origin of the sand dykes and deformation and discuss possible triggering mechanisms.

BACKGROUND AND SETTING

The Fraser Lowland is a region of low relief bounded by the Coast Mountains to the north, the Cascade Mountains to the east and southeast, and the Strait of Georgia to the west (Fig. 1). The Fort Langley Formation occurs widely in the central Fraser Lowland and consists of up to 100 m of stratified sands; silts, and gravels; minor clay; and till that were deposited 12 900–11 680 BP (^{14}C years ago), during the late stage of the Fraser Glaciation (Fig. 2; Armstrong, 1981; Clague, 1981).

During the Fraser Glaciation maximum approximately 18 000–15 000 ^{14}C years ago, Vashon till was deposited throughout the Fraser Lowland. As the ice sheet retreated, relative sea level rose to a maximum of 200 m above the present datum by 12 900 BP. At this time the Fort Langley Formation was deposited on the transgressed lowland in ice-marginal and proglacial settings (Clague and Luternauer, 1982). Subsequent limited readvances of ice during the Sumas event (Clague et al., 1997) were followed by the final disappearance of the Cordilleran Ice Sheet about 10 500–11 000 BP. Relative sea level dropped to 30 m above the present datum some time at about 11 300 BP and approached its present position about 11 000 BP (J. Clague, pers. comm., 2000).

The study site is the Kirkpatrick sand and gravel pit (Fig. 3) located at the north margin of the Fraser Lowland near Maple Ridge, British Columbia (Fig. 1). The pit has been excavated in a prominent bench of glacial sediments with an upper surface at 155 m elevation. The bench exposes part of a delta constructed during deglaciation approximately 13 000–12 000 BP (Armstrong, 1981; Clague et al., 1982).

METHODOLOGY

Photomosaics of the extensive lateral exposures at the study site were used to record lithofacies, sedimentary structures and paleocurrent measurements. Trenching of outcrops and a ground-penetrating radar survey provided information on the three-dimensional geometry of the deposits (Tribe, 1994; J. Rae, pers. comm., 1995). Numbered outcrops examined for this study are shown in Figure 4 and stratigraphic sections are shown in Figure 5.

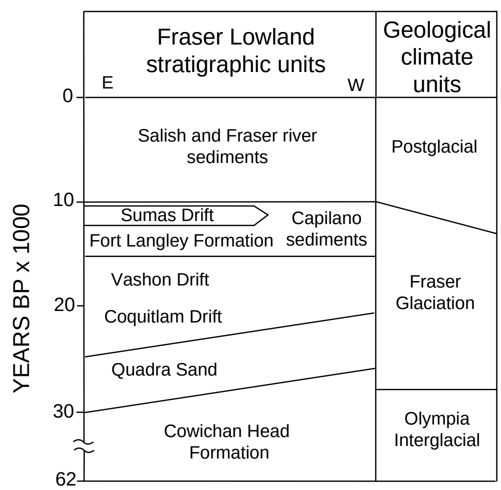

Figure 2. *Quaternary stratigraphy of the Fraser Lowland and corresponding geological climate units (*from *Clague, 1981).*

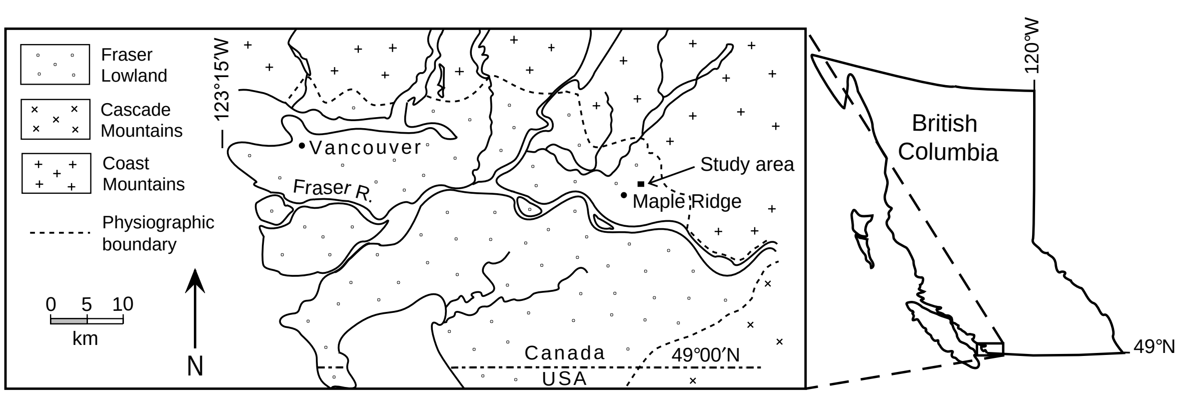

Figure 1. *Location map of study area.*

Figure 3.

Southeast-view of the study site showing the locations of the large (long arrow) and small (short arrow) sand dykes.

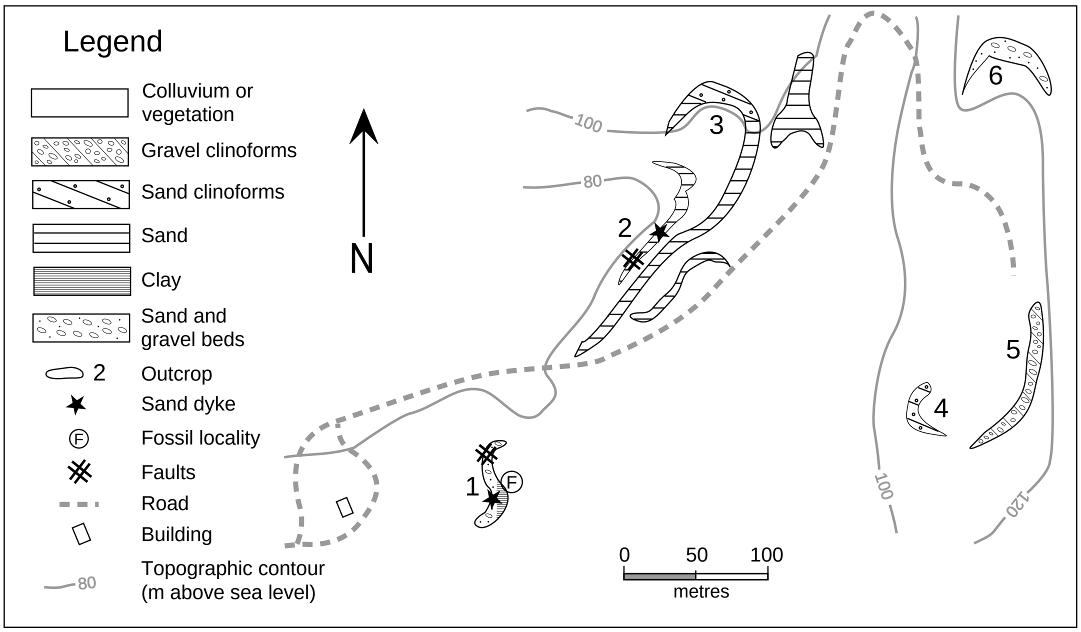

Figure 4. *Map of outcrops.*

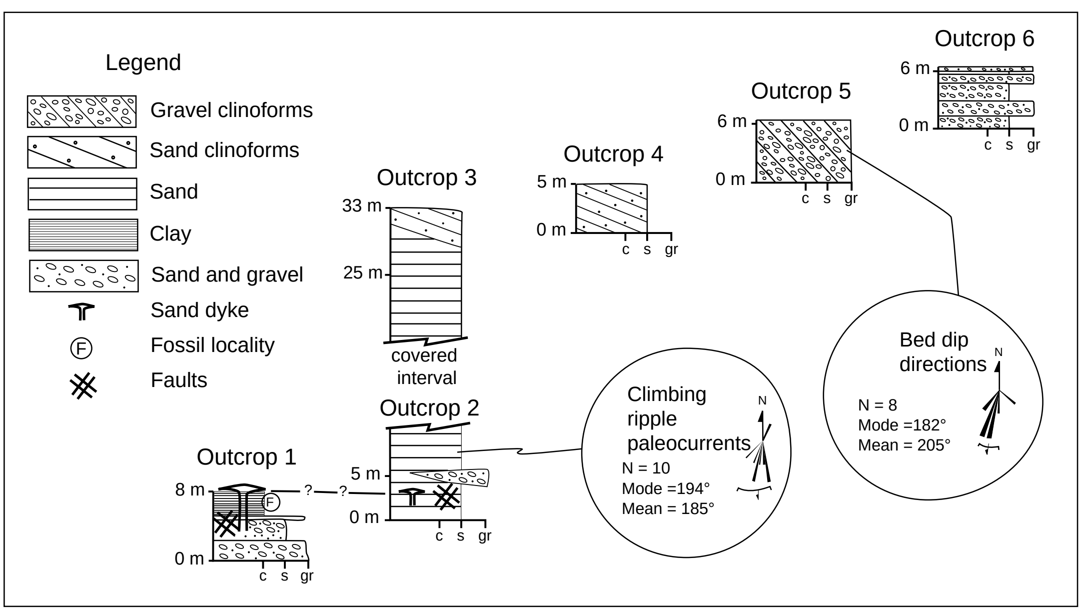

Figure 5. *Stratigraphic logs shown in relative vertical position.*

STRATIGRAPHY

The lowest exposure (outcrop 1) consists of 5 m of subhorizontal, 10 cm to 1 m thick, interbedded gravel and sand, and 4 m of overlying laminated to massive clay. The clay contains up to 10% silt, scattered stones, and marine bivalve shells in growth position. Bivalves include *Tresus*, *Macoma*, *Saxicava arctica* and/or *Saxicava rugosa*, and possible *Clinocardium* (G. Johanessen, pers. comm., 1994). Deformation structures at outcrop 1 include a large sand dyke (*see* next section) and steeply tilted beds of sand and gravel.

The next highest exposures (outcrops 2 and 3) consist of subhorizontally stratified sand that outcrops through a vertical range of 33 m. Individual sand beds are 10–80 cm thick and consist of 2–10 cm of normally graded sand that grades into 1–5 cm of climbing ripple cross-stratified sand, which, in turn, is overlain by silt and mud. Gravel occurs within the sand in the southern part of outcrop 2. Ripples indicate paleoflow toward the south. Centimetre-scale flame-and-pillow dewatering structures are visible in some places where basal fine sand laminae are sharply overlain by coarser grained sand. The southern half of outcrop 2 is topped by a diamicton unit up to 3 m thick that erosively overlies and contains rip-up clasts of the underlying sands (Fig. 6). Deformation is confined to the base of outcrop 2 and includes a small sand dyke and extensively deformed host strata.

Subhorizontal sand of outcrops 2 and 3 grade upward into approximately 5 m of gently dipping (5–15º) sand clinoforms exposed at outcrops 3 and 4. The dipping sand beds are normally graded, parallel, and ripple cross-stratified. They are coarser than the underlying sand at outcrop 2. Bedding dips, ripple cross-stratification, and pebble imbrication indicate a southward flow direction. No deformation was observed in this outcrop.

The dipping sand beds grade upward into south-dipping (15–35º) downlapping gravel clinoforms at outcrop 5. Gravel beds themselves grade upward from pebbles and cobbles into normally graded, massive, or parallel-stratified coarse sand. No deformation was observed in this outcrop.

The highest stratigraphic exposure (outcrop 6) consists of 2–3 m of thick-bedded, poorly sorted gravel, sand, and minor silt showing abrupt lateral changes in lithology and bedding attitude. In some areas the bedding is deformed into folds with amplitudes on order of a metre.

LARGE SAND DYKE

The large sand dyke exposed at outcrop 1 is vertical, straight-sided, over 5 m wide, and intrudes up to 4 m of gravel and sand and 4 m of overlying fossiliferous clay (Fig. 7). Sand and gravel beds adjacent to the dyke are tilted up along the margins of the dyke. Clay beds truncated by the dyke are tilted subvertically (A in Fig. 7) and exhibit a weak vertical foliation. Five metres to the right (when facing the outcrop) of the dyke, steep dyke-ward dipping faults in the clay beds record a dyke-side-up apparent slip. Two ground penetrating radar profiles taken along the crest of outcrop 1 and 2 m back from the crest indicate that the dyke is at least 2 m wide in the plane perpendicular to the outcrop face (J. Rae, pers. comm., 1995).

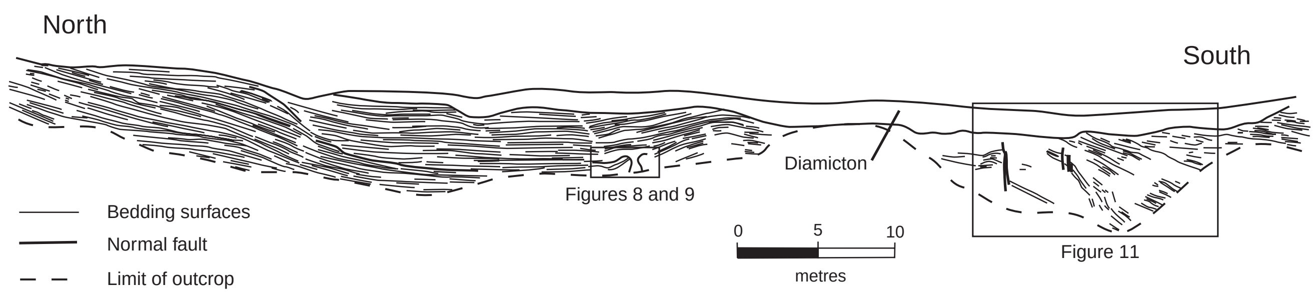

Figure 6. *Sketch of beds observed at outcrop 2.*

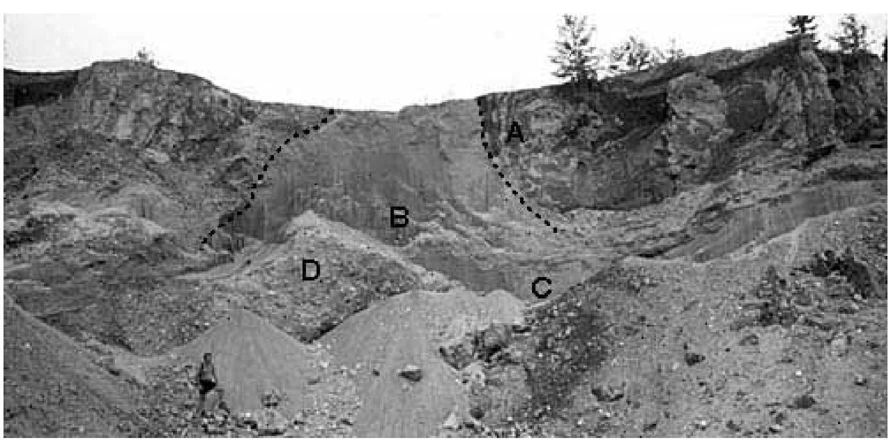

Figure 7.

Large sand dyke (dotted lines) at outcrop 1. Labelled features are steeply tilted clay beds (A), pebble stringers (B), the probable source bed for the liquefied sand (C) and a tilted and truncated gravel stratum below the source bed (D). Person is 1.6 m tall.

The dyke consists of well sorted, coarse sand with no visible internal stratification. Pebble stringers drawn into the body of the dyke can be traced laterally to gravel beds truncated at the right dyke margin (B in Fig. 7). At 8 m depth, the dyke widens and merges laterally with a subhorizontal, 2 m thick, coarse sand bed (C in Fig. 7). Beneath this sand bed, a thick gravel bed is tilted up toward the centre of the dyke where it appears to be truncated (D in Fig. 7).

SMALL SAND DYKE

The small sand dyke (Fig. 8, 9) is exposed near the bottom of outcrop 2. It has a width of 25–35 cm and extends vertically through 70 cm of subhorizontally bedded, fine- to coarse-grained sand. Strata enclosing the dyke are deformed into an antiform by pervasive, steeply dipping faults. Immediately adjacent to the dyke, the faults are predominantly dyke-side-down (A in Fig. 8), whereas 30 cm away from the dyke the faults are predominantly dyke-side-up (B in Fig. 8). An inclined, concave-upward shear surface at approximately 0.5 m below the top of the dyke may record normal fault displacement (C in Fig. 8).

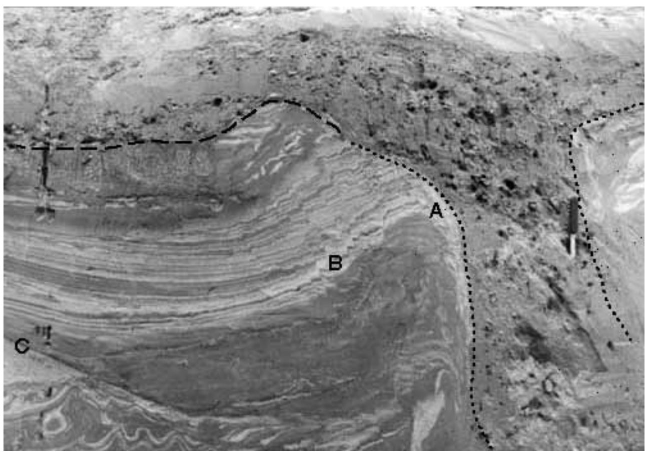

Figure 8. *Close-up of small sand dyke (dotted line) and the surface on which the sand was vented (dashed line) at outcrop 2. Dyke-side-down faults (A), dyke-side-up faults (B), and a concave-upward shear surface (C) are labelled. Pocket knife with extended blade is 15 cm long.*

The top of the dyke merges with a wedge-like, silty, pebbly sand that is in angular unconformity with the underlying sandy sediments. The silty, pebbly sand wedge grades laterally away from the dyke into a normally graded, coarse sand bed (A in Fig. 9) overlain by a weakly laminated, fine and silty, fine sand (B in Fig. 9; Mak, 1995). These strata attain a maximum thickness of 0.15 m directly above the dyke and pinch out within 3 m of the dyke. The strata are overlain by undeformed, subhorizontally bedded sands characteristic of most of outcrop 2.

The dyke consists of massive silt and fine sand with about 10% well rounded pebbles up to 3 cm in diameter. The pebbles occur in stringers parallel to the dyke margins. The dyke becomes coarser grained with depth, increases to almost 1 m wide, then pinches out 2 m below the dyke top. Strata adjacent to and immediately below the lower termination of the dyke contain gravelly coarse sand. Silty, fine sand similar to that within the dyke was not observed in the exposure (Mak, 1995).

OTHER DEFORMATION

Steeply tilted sand and gravel dip away from the large sand dyke 20 m to the north at outcrop 1 (Fig. 10). At outcrop 2, numerous normal and some reverse faults disrupt strata about 20 m south of the small sand dyke (Fig. 6, 11). Here, the faults

Figure 9. *Small sand dyke (dotted lines) at outcrop 2. The surface on which the sand was vented (dashed line) is overlain by a basal pebbly stratum (A) and a graded sand bed (B). Shovel handle is 50 cm long.*

***Figure 10.** Steeply tilted sand and gravel strata 20 m north of the large sand dyke, which is out of view in the right background. Outcrop height is 6 m.*

***Figure 11.** Normal faults and folds deforming sand strata at the south end of outcrop 2. Outcrop is 6 m high.*

are spaced 2–20 cm apart and most show 0.5–50 cm of apparent slip. The largest observed apparent slip is more than 1.5 m along a normal fault. The strata are rotated and displaced down toward the south. In some places strata are folded over fault terminations and show small-scale fluid deformation structures.

ORIGIN OF SEDIMENTS AND STRUCTURES

The stratigraphy at the study site consists dominantly of a coarsening-upward sequence of strata that exhibit progressively steeper foreset bounding surfaces. The subhorizontally bedded sand of outcrops 2 and 3 are characterized by normal grading, cross-stratification, climbing ripple structures and centimetre-scale water escape structures. These sediments were probably deposited by sediment gravity flows and turbidity currents that flowed across the lower slope of a delta. The dipping, normally graded, massive, and stratified sand and gravel beds of outcrops 3, 4, and 5 were deposited on the foreset slope of a prograding delta. The thick fossiliferous clay beds of outcrop 1 were deposited in a low-energy, shallow glaciomarine environment that supported infaunal bivalves. The underlying sand and gravel at outcrop 1 are older deltaic facies of the Fort Langley Formation. Outcrop 6 may represent shoreline or beach deposits of a ca. 155 m sea-level stand. The inferred depositional environment is a delta formed where a south-flowing stream flowed into the sea at the northern margin of the Fraser Lowland. Within this setting, sand dykes were emplaced on the lower delta slope.

The large sand dyke formed in a sequence of sands and gravels underlying thick clay beds. The clay beds formed an impermeable capping layer that required fracturing in order to relieve excess pore pressures in the underlying sandy sediments. During liquefaction pebble stringers derived from adjacent gravel beds were drawn into the dyke. Overlying strata were ruptured and folded parallel to the dyke margins, indicating shear drag during emplacement. The top of the large sand dyke has been eroded, but the surface on which the liquefied sediment was vented was probably close to the modern ground surface. The source of the material within the large sand dyke appears to be a sand stratum located 4 m below the clay beds.

The small sand dyke formed in subhorizontally bedded sandy strata. Abundant mud laminae in injected strata below the top of the dyke may have acted as a low permeability capping layer. Truncated strata were faulted and steeply tilted. Faults adjacent to the dyke indicate that the walls subsided into a depression created by the collapse of grain structure and by settlement during venting of the liquefied material on the delta surface. The source of material in the dyke is interpreted to be an unsampled stratum lying more than 2 m below the top of the dyke (Mak, 1995).

Originally subhorizontally bedded strata at outcrops 1 and 2 were deformed by normal faults, rotated, and steeply tilted. The character of the faulting at the southern end of outcrop 2 indicates that slope failure occurred here, with the failed mass moving downslope to the south possibly as a lateral spread. Fluid and plastic deformation structures, such as folds and fluid escape structures, indicate that strata were saturated during deformation.

DISCUSSION

Stratigraphy at the study site suggests that the sand dykes did not form by ice-collapse mechanisms, as suggested by Armstrong (1977, 1981). The inferred paleoenvironment is a deltaic-shallow marine setting. No evidence for a high-energy, ice-proximal depositional environment was observed at the study site. Evidence for abrupt vertical emplacement of the sand dykes by upward-directed hydraulic forces during one or possibly two liquefaction events is found in the tight folding and intense faulting of strata adjacent to the dykes, the presence of pebble stringers drawn into the dykes, and, in the case of the small sand dyke, well preserved vented material.

A variety of triggering mechanisms can produce liquefaction features in many different sedimentary environments. Glacial or permafrost-induced liquefaction events (Clague et al., 1992) are unlikely explanations for the study area for the same reasons that the sand dykes are not considered to be ice-collapse in origin, namely, stratigraphic evidence does not suggest depositional environments in close proximity to active or wasting glaciers. Furthermore, the liquefaction occurred on the slope of a prograding delta. Marine mechanisms, such as the sudden lowering of sea level or wave pounding (Clague et al., 1992) or excess pore pressures generated by tidal fluctuations (Mayall, 1983) are also unlikely. Syndepositional deformation (Clague et al., 1992) is ruled out because 4 m of clay, in the case of the large sand dyke, and a minimum of 2 m of thinly bedded, stratified sand, in the case of the small sand dyke, indicate that time passed between deposition of the liquefiable sediments and their venting onto the seafloor.

Nonseismic landsliding is a plausible mechanism to produce the sand dykes at the study site. Liquefaction is known to occur on deltas due to slope failure of delta-front sediments (Miall, 1986). The marine-deltaic paleoenvironment inferred for the study area thus favours the development of saturated sediments, slope instability, and liquefaction. Lateral-spread slope failures can accompany liquefaction in saturated sediments with very gentle gradients (Obermeier, 1996). The great width and straight, parallel sides of the large sand dyke also favour a lateral-spread type of slope failure (Obermeier, 1996). The inferred slope failure at outcrop 2 may have ran out to the south and loaded sediments in the vicinity of outcrop 1 causing liquefaction and eruption of the large sand dyke; however, the inferred slope failure did not cause liquefaction of the small sand dyke as the failure occurred downslope of this feature. No evidence for slope failure and faulting was observed in regions upslope of the small sand dyke despite the extensive lateral and vertical exposure.

Earthquake ground shaking is another plausible explanation for liquefaction at the study site. Earthquakes have produced sand dykes and liquefaction-related slope failures throughout the world (Obermeier, 1996), including the Fraser Lowland (Clague et al., 1998). Crucial to the paleoseismicity argument is documentation of isochronous liquefaction features that are restricted to single stratigraphic layers separated by undeformed beds, and that can be correlated over distances greater than a few kilometres (Sims, 1973). Only then can local intrabasin liquefaction triggers, such as nonseismic landsliding, be ruled out.

At the study site, the stratigraphy suggests stable deposition and aggradation of over 30 m of sediment interrupted by at least one sudden liquefaction and fault-inducing event. With the exception of the folds observed at outcrop 6, which have a markedly different character and a presumably unrelated origin to the sediments stratigraphically below, the sand dykes and faults are the only deformation observed at the study site, and all occur near a similar stratigraphic position at the bottom of the exposure. The age relationship between the sand dykes and the faulted areas is uncertain due to the lack of outcrop. Even if liquefaction and faulting at outcrops 1 and 2 were simultaneous, the sand dykes are not far apart enough from each other to satisfy the criterion of regional isochronous deformation necessary to infer a paleoseismic origin. Liquefaction structures have not been documented elsewhere in the Fort Langley Formation except possibly as ice-collapse structures (Armstrong, 1981).

Bivalves collected from the clay beds were not dated as part of this study, but Armstrong (1981) reported a radiocarbon date of 12 900 ± 170 BP (GSC-2193) from the marine bivalves *Macoma calcarea* and *Nuculana fossa* that he collected from the study site. We assume this age, reduced by 400 ^{14}C years to adjust for the marine reservoir effect (J. Clague, pers. comm., 2000), for the fossils we observed in the clay strata. The event responsible for the large sand dyke thus must postdate 12 500 BP yet predate the fall of relative sea level to a point where the water table was too far below the ground surface to ensure saturated sediments. Therefore, a tentative time frame inferred for the emplacement of the large sand dyke is 12 500 BP to about 11 500 BP, the latter date being the approximate time that relative sea level fell below 95 m a.s.l. (i.e. the elevation of the top of outcrop 1).

SUMMARY AND CONCLUSIONS

Sand dykes, extensional faulting, and complex stratal deformation were observed in deltaic sands and gravels of the Fort Langley Formation. The large sand dyke is a vertical, straight-sided dyke over 5 m wide consisting of massive, well sorted, coarse sand that intruded 4 m of sand and gravel and 4 m of fossiliferous clay. The source of the liquefied sand appears to be a sand bed located 8 m below the top of the dyke. Tilting of strata 20 m north of the large sand dyke may have been contemporaneous with dyke emplacement.

The small sand dyke is 25–35 cm wide and consists of silty, pebbly sand that intruded 70 cm of sand to vent onto the delta slope. Normal faulting, block rotation, and folding of saturated sediments 20 m south of the small sand dyke suggest that lateral spreading may have accompanied dyke emplacement.

Although originally described as ice-collapse features, stratigraphic evidence supports a nonglacial origin for the sand dykes. Plausible liquefaction-inducing mechanisms are nonseismic landsliding and earthquake shaking. Due to limited outcrop we were unable to resolve whether the sand dykes and nearby deformation are synchronous. We hope that documentation of these liquefaction features will stimulate search for similar structures to test the hypothesis of a late Pleistocene earthquake in the interval 12 500–11 500 BP.

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