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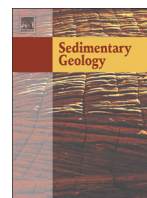
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Sensitive clay landslide detection and characterization in and around Lakelse Lake, British Columbia, Canada

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ABSTRACT

The Lakelse Lake area in northwestern British Columbia, Canada, has a long history, and prehistory, of rapid sensitive clay landslides moving on very low gradients. However, until now, many landslides have gone undetected. We use an array of modern tools to identify hitherto unknown or poorly known landslide deposits, including acoustic subbottom profiles, multibeam sonar, and LiDAR. The combination of these methods reveals not only landslide deposits, but also geomorphic and sedimentologic structures that give clues about landslide type and mode of emplacement. LiDAR and bathymetric data reveal the areal extent of landslide deposits as well as the orientation of ridges that differentiate between spreading and flowing kinematics. The subbottom profiles show two-dimensional structures of disturbed landslide deposits, including horst and grabens indicative of landslides classified as spreads. A preliminary computer tomography (CT) scan of a sediment core confirms the structures of one subbottom profile. We also use archival data from the Ministry of Transportation and Infrastructure and resident interviews to better characterize historic landslides.

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1. Introduction

Sensitive clays are largely restricted to uplifted glaciomarine sediments in a few areas of the globe, but they are most common in Canada, Alaska, and Norway (Torrance, 1983). Clays may be described as sensitive when the undisturbed strength is greater than the disturbed (remoulded) strength, where the remoulded material can behave as a fluid (Geertsema and Torrance, 2005). Sensitivity is defined as the ratio of the undisturbed shear strength and the disturbed shear strength. When remoulded shear strength is <0.5 kPa and sensitivity exceeds 30, the deposits are called quick clays and sensitivity develops due to the removal of salt from the porewater (Torrance, 1983).

Landslides involving sensitive clays typically occur as spreads or flows (flowslides) depending in part on the degree of remoulding of the displaced material (Demers et al., 2014; Geertsema et al., 2017). Spreads display both extensional ridges and depressions, typically referred to as horsts and grabens, oriented perpendicular to movement direction (Fig. 1) (Carson, 1977, 1979; Geertsema, 2004; Geertsema

et al., 2006b; Demers et al., 2014, 2017). Spreads often involve movement along and remoulding of thinner sensitive zones. Flows may have ridges parallel to movement direction and lobate forms (Geertsema, 2004). Mobile flows often evacuate more material from the zone of depletion (Cruden and Varnes, 1996; Locat et al., 2017), involve a greater percentage (or thickness) of remoulding, retain less undisturbed sediment with preserved bedding, and have greater travel distances. Composite landslides (Cruden and Varnes, 1996) may occur that display both spreading and flowing behaviour (Geertsema et al., 2006b). The landslides may be triggered by bank erosion and move retrogressively, or by external loads and display progressive movement (Locat et al., 2013, 2017). Whether these sensitive clay landslides initiate at a break in the valley slope, or are triggered some distance behind the break in slope, the scarps usually migrate landward. As the landslide retrogresses into the slope in one direction, the mobilized debris travels in the opposite direction downslope.

The Lakelse Lake area in northwestern British Columbia (Fig. 2) is subject to sensitive clay landslides that suddenly and rapidly travel on extremely low gradients, sometimes less than one degree, often with trees rafting in the upright position. Although the landslides can cover many hectares of ground, because of their low gradients they are difficult to detect in forested landscapes. The primary objective of this

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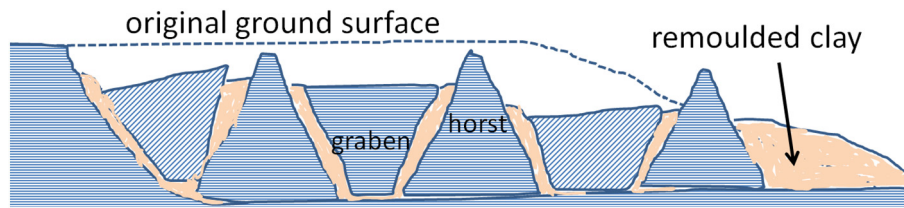


Fig. 1. Schematic representation of a spread in sensitive clays (Carson, 1977; Locat et al., 2017). The horsts, also referred to as ridges or hummocks, are often between 4 and 5 m high and preserve the bedding of the source area. Landslide rupture surfaces tend to occur along bedding.

paper is to use a suite of methods, including historic interviews, government archives, LiDAR from around Lakelse Lake and multibeam bathymetry, acoustic subbottom profiling, and preliminary coring of Lakelse Lake sediments to detect and characterize landslides that occur in sensitive clay. Evidence for historic and pre-historic landslides comes from mapping (Clague, 1978; Geertsema and Schwab, 1997; Geertsema et al., 2017) and from oral reports (Geertsema et al., 2017). Large historic landslides in the area include two on the east side of Lakelse Lake that occurred in 1962 and another at Mink Creek around December 1993 or January 1994 (Geertsema et al., 2017) (Fig. 2).

2. Setting

Lakelse Lake is located in the Kitimat–Kitsumkalum trough within the northwest-southeast trending Kitimat Ranges of the Coast Mountains in northwestern British Columbia, Canada (Holland, 1976; Clague, 1984). Mountain peaks rise to some 1500 m above sea level (m asl). Local bedrock consists of granodioritic intrusions of Cretaceous to Eocene age (Duffel and Souther, 1964).

The conifer forest-covered Kitimat–Kitsumkalum trough is characterized by rolling to flat terrain, composed of gullied glacial and post-glacial sediments and isolated bedrock hills. Valley fill consists of thick

glaciomarine mud, glaciofluvial gravel and till, while postglacial deposits include alluvium, bogs and fens, and slopes mantled with colluvium (Clague, 1984).

During the latest Pleistocene, ice flowing down the Skeena River valley bifurcated near the city of Terrace with one lobe flowing southward towards the town of Kitimat and the other westward down Skeena valley (Fig. 2). Isostatic depression allowed the sea to transgress landward with retreating ice. The terminus of the south-flowing glacier retreated from the present location of Kitimat towards Terrace about 12,500 years ago. Isostatic rebound continued for about another 2000 years following deglaciation. Local sea level fell from its highest level at about 200 m asl to at or below present sea level by 9000–8500 years ago (Clague, 1984).

3. Methods

We obtained archival data from the British Columbia Ministry of Transportation and Infrastructure (MOTI) and from interview records from the Terrace Museum. Data from MOTI include reports, drill logs, photographs and letters from the two 1962 Lakelse landslides including a Department of Highways report (Brawner, 1962). We also use the recorded interviews conducted by the Terrace Museum staff in 1979

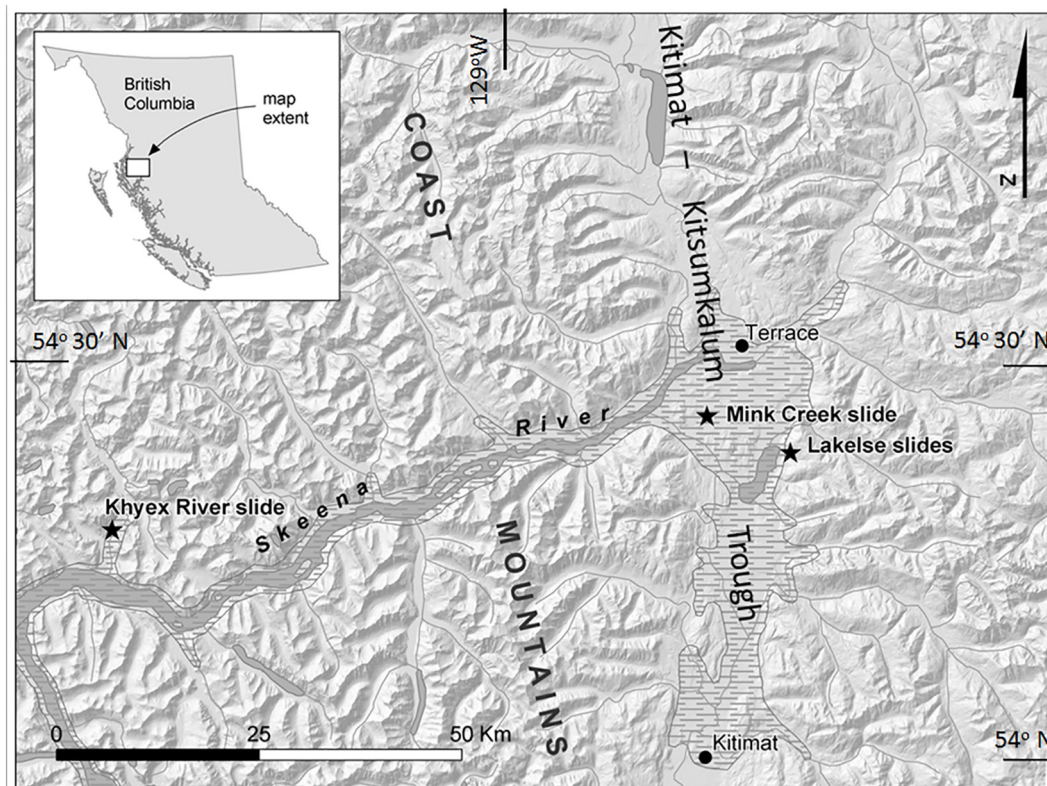


Fig. 2. Sensitive clay landslides (black stars) near Lakelse Lake, British Columbia. Stippled pattern indicates maximum sea level elevation (200 m asl) during deglaciation.

with a long-time Lakelse Lake area resident, David Bowen-Colthurst, to obtain information on the northernmost 1962 landslide.

In December 2016, we performed an aerial LiDAR survey of nearly 450 km² of terrain surrounding Lakelse Lake. We acquired data with a Riegl Q780 full waveform scanner with dedicated Applanix PosAV Inertial Measurement Unit (IMU). With only a minor dusting of snow and leafless deciduous vegetation, conditions were excellent for LiDAR collection. LiDAR and flight trajectory were processed with vertical and horizontal positional uncertainties that are less than ± 10 cm (1σ). Average point density for the LiDAR survey was 17 laser shots m⁻². We classified all of the LiDAR data into ground and non-ground laser returns, with the latter ones being subsequently gridded into 1 m bare earth Geotiffs.

We collected bathymetric data with a 400 kHz Reson® 7125 multibeam sonar, which uses 512 beams in a single ping to illuminate an across-track swath with an angle of 165°, with a maximum ping rate of 50 Hz. A patch test on the lake prior to the survey determined physical offsets of the system components, and we continuously measured sound velocity at the sonar head. We periodically launched a sound velocity probe to correct for the variation in sound velocity with depth. We georeferenced and corrected the bathymetric data for vessel motion using an Applanix PosMV V5 consisting of an IMU and Trimble GNSS receivers. A GNSS Azimuth Measurement Subsystem calibration increased the accuracy of our GNSS-based heading. We used WAAS corrected GPS with horizontal and vertical resolutions respectively of <1 m and 0.006 m and adjusted the data for changes in the lake's water level throughout the survey by using repeated measurements of lake water level at a shore-based reference location. We gridded the processed soundings to a horizontal resolution of 0.5 × 0.5 m.

We collected over 50 subbottom acoustic profiles of Lakelse sediments using a Knudsen Pinger SBPTM system coupled with a 15 KHz transducer over four days in 2015 and 2016 (Blais-Stevens et al., 2016). We interpreted morphometric characteristics of the deposits using Kingdom Suite software (v. 8.8) and estimated thicknesses of landslide deposits using Surfer software. We collected an exploratory 1.23 m long sediment core using a Livingston piston corer and scanned the core with a Siemens™ SOMATOM Definition AS + 128 CT-Scanner at INRS in Québec City.

4. Results and discussion

4.1. Archival data, interviews, and previously published work

We used a range of published and non-published materials to gather information about landslides. Stories of vertically oriented trees moving into waterbodies have been recounted in oral traditions of local First Nations and provide context and evidence of translational landslides in general (Geertsema et al., 2017). Unpublished archival data provided information for the 1962 Lakelse landslides, whereas the nearby Mink Creek landslide was previously described by Geertsema et al. (2006b and references therein), but a brief summary is given below. Both Lakelse landslides damaged large sections of highway, severed hydro transmission lines and damaged a provincial campground. Heavy equipment and vehicles were lost, but there were no fatalities. Both landslides were thought to be the result of construction of an earth-fill berm beside the highway (Brawner, 1962).

4.1.1. Southern Lakelse landslide

On 25 May 1962, a large section of highway collapsed and became entrained in a landslide. In an internal Department of Highways report, Brawner (1962) writes: “Shortly after 6 P.M. Friday, operators of several motor vehicles, one logging truck and construction equipment felt major ground movement and observed tilting and falling trees in the area involved in the slide. Several of the operators who were in the area during movement gave eyewitness reports. They observed sudden alternate rising

and falling and undulation of the ground accompanied by large cracks opening and closing and trees falling and becoming uprooted.” The landslide destroyed >1.1 km of new highway construction and severed the hydro transmission line between Terrace and Kitimat, but did not enter the lake. Brawner (1962) estimated the volume between 9 and 11.5 Mm³, based, in part, on an assumed slide depth of 7–9 m.

4.1.2. Northern Lakelse landslide

While authorities were still dealing with the aftermath of the 25 May landslide, a second landslide occurred on 7 June 1962. In contrast to the earlier event, this second landslide entered Lakelse Lake, but there is scant evidence of a landslide-generated displacement wave. Although we found no mention of this in the Ministry of Highways archives, there is mention of a “tidal wave” in an interview of David Bowen-Colthurst conducted by Neil Weber and Judy Dimmer on 22 January 1979 (on file at the Heritage Park Museum in Terrace – accession number 78–12). Colthurst recounts that his wife told him that the debris built up to “the tops of those trees ... and then all of a sudden it just went. That caused a bit of a tidal wave out there.” He further describes how another resident, Roger Walsh, experienced the wave. “Now Roger – he was out there with his boat and he was putting some lumber in it. He said one minute, well one second, he was on dry land – the water had gone down, and the next second it was way over the top of his hipwaders.” After this Mr. Walsh escaped to dry land. There is no description of subsequent waves, or of wave-related damage. From the description, we can assume this wave was between 1 and 2 m in height. Fig. 3 shows a photo of the northern Lakelse landslide shortly after it happened, with trees still in the upright position.

4.1.3. Mink Creek

Three decades after the Lakelse landslides occurred, another took place on Mink Creek, a tributary of Lakelse River (Geertsema and Torrance, 2005; Geertsema et al., 2006b). About late 1993, a 43 ha landslide involving some 2.5 Mm³, flowed into Mink Creek. The landslide retrogressed 600 m into the valley slope with a total travel distance of 1.6 km over a 1.7° travel angle (Geertsema and Cruden, 2008) and was likely triggered by bank erosion. The composite landslide involved successive movements along a variety of rupture surfaces exhibiting both spreading (horst and grabens) and more fluid flowing behaviour (Geertsema, 2004; Geertsema et al., 2006b). In some instances, material first spread, then collapsed and flowed. This is the only known landslide in the area with exposed rupture surfaces. The landslide dam on Mink Creek remains in place.



Fig. 3. Trees upright in the water following the June 1962 landslide in Lakelse Lake. Yellow dashed line outlines the subaerial portion of the landslide. Photo courtesy Heritage Park Museum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

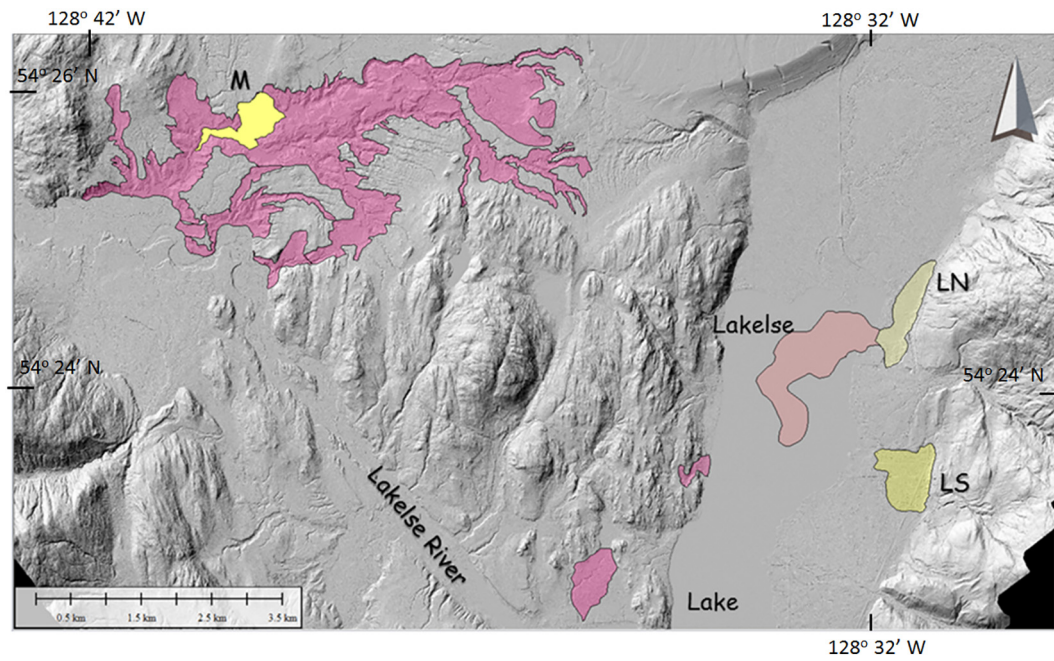


Fig. 4. LiDAR image showing three historic (yellow) and many more as yet largely undated prehistoric (purple) sensitive clay landslides. The Lakelse South (LS), Lakelse North (LN), and Mink Creek (M) landslides happened in May and June 1962, and December or January 1993/1994, respectively. The rose portion of the Lakelse Lake North landslide is underwater. There may be many more landslide deposits covered with alluvium that are not apparent on LiDAR imagery. Non-sensitive clay landslides are not mapped. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. LiDAR evidence of landslides

The area around Lakelse Lake is heavily forested. Sensitive clay landslides tend to have scarps much lower than tree height and are thus difficult to identify on aerial photographs. Even the two historic landslides on the east side of the lake are difficult to delimit without LiDAR.

Geertsema and Schwab (1997) used stereo aerial photographs to map area landslides, but they primarily captured landslides with wetlands in their zones of depletion and landslides in recently deforested

areas. Mature forests in the areas masked landslides, preventing their detection, and therefore the extensive landslide complex between Lakelse Lake and the Mink Creek landslides remained undiscovered until we interpreted the 2016 LiDAR data (Fig. 4).

In addition to mapping previously undiscovered sensitive clay landslides, our LiDAR data were detailed enough to characterize morphologically-based styles of movement. Many of the landslide deposits we mapped (Fig. 4) have transverse ridges, characteristic of spreads (evident in Figs. 5, 6) Indeed, most of the mapped landslides

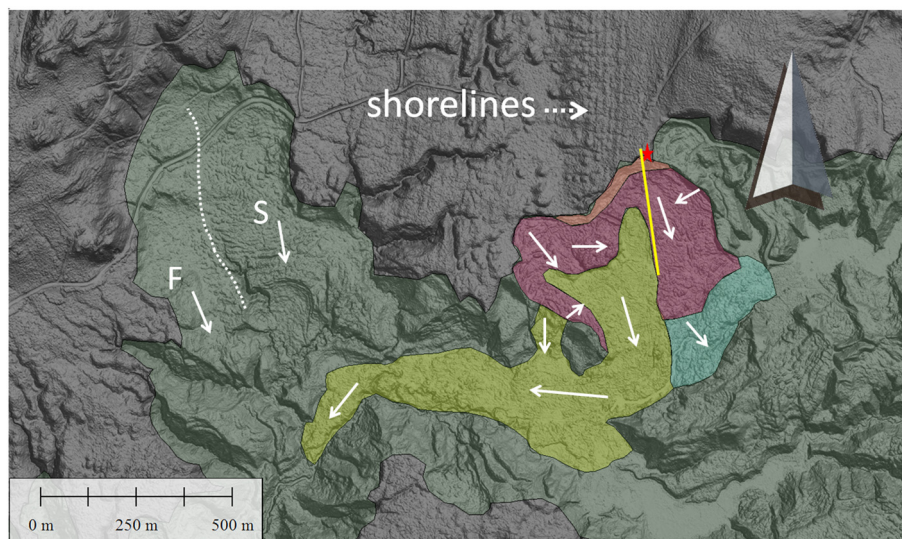


Fig. 5. LiDAR image of the 1993 Mink Creek landslide (multi-coloured feature and yellow feature (M) in Fig. 4) is shown with different stages of movement. This is a complex landslide involving spreading and flowing along a south sloping rupture surface. Purple colour represents spreading with ridges oriented transverse to movement direction (white arrows). The blue area shows a zone of compression. The yellow zone depicts flow where ridges are less prominent, and hummocks are more chaotic. The pink zone, at the main scarp, represents the final stage of rotational movement. The shaded green area outside of the landslide shows older sensitive clay landslides, most characterized by ridges, typical of spreads. The Mink Creek landslide intersected paleo shorelines and remobilized a 5000 year old landslide (red star). Yellow line represents the cross-section in Fig. 7. Note the demarcation (white dotted line) between spread (S) and flow (F) in the undated landslide to the west. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

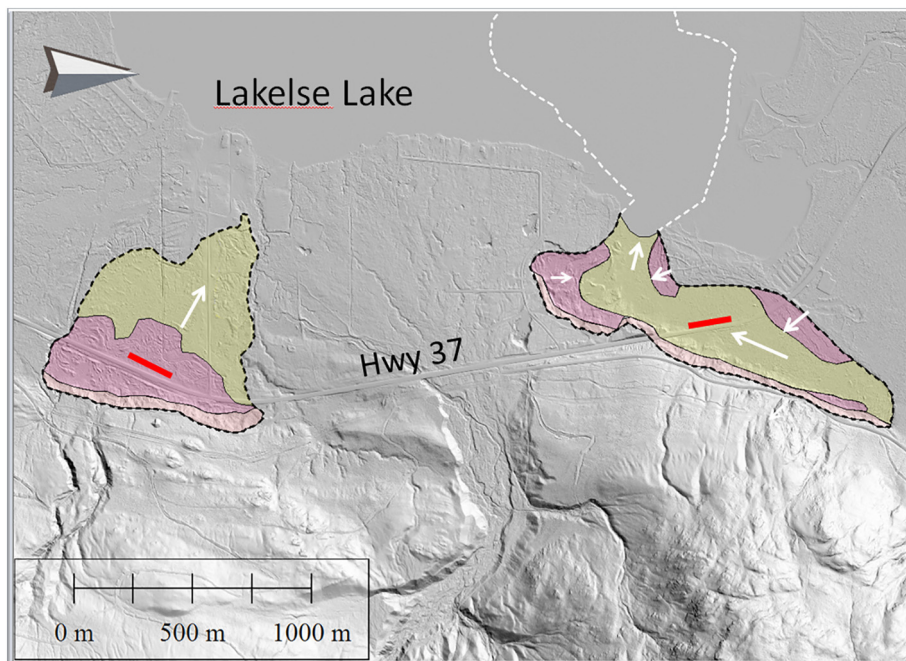


Fig. 6. LiDAR image of the 1962 Lakelse landslides showing zones of spreading (purple) with transverse ridges, flow (yellow) with few ridges and hummocks, and late stage rotation (pink). White arrows indicate movement directions. Red bars indicate approximate locations of earthen berms, thought to have been the triggers of these landslides. Only the northern landslide entered Lakelse Lake. The white dashed line outlines the deposit in the lake. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

appear to be spreads suggesting movement along thin zones of sensitive clay (Geertsema and L'Heureux, 2014). The LiDAR data show, however, evidence of both flowing and spreading at these landslides (Figs. 5, 6). Geertsema (2004) and Geertsema et al. (2006b) described a complex sequence of movements at the Mink Creek landslide (Fig. 5), involving an initial slide at the valley slope break, followed by sliding, spreading, collapse, and flowing. In the LiDAR hillshade image, the transverse ridges of spreads contrast with the more streamlined, smaller, and more chaotically distributed hummocks of flows (Fig. 5); thus these features enable us to identify both movement type and direction.

The landslides are thought to have initiated at earthen berms (Brawner, 1962) associated with highway construction (Fig. 6), at least 0.5 km from valley slope breaks. They must then have undergone progressive failure similar to those described by Locat et al. (2013). While the points of initiation contrast with the valley slope initiation at Mink Creek, similar zones of spreading and flowing are recognizable from LiDAR-based morphologies. According to our LiDAR data, the

southern landslide travelled some 650 m down a gentle slope (0.7°) and covered an area of some 58 ha. The much smaller and narrower northern landslide travelled over 1.5 km on an average gradient of 0.3° over an area of 48 ha before it entered Lakelse Lake. The 1978 Rissa landslide in Norway (Gregersen, 1981; L'Heureux et al., 2012) has many similarities with the northern Lakelse landslide. Both were triggered by the placement of earthen berms, and both flowed into lakes, causing landslide-generated waves.

Closer inspection of the LiDAR data (Fig. 5) allows further characterization of the landslides. While the bulk of movement in sensitive clay landslides is translational, often with failure along a subhorizontal bedding plane (Geertsema et al. 2006b), in many cases the final stages of retrogression into the slope (between the landslide body, immediately in front of the main scarp) are rotational (Geertsema 2004; Geertsema and L'Heureux, 2014) (Figs. 5, 7). A sensitive clay landslide's driving energy is related to the thickness of the material above the rupture surface (Geertsema and L'Heureux, 2014). With a down sloping rupture surface (often along bedding), the thickness of translational landslide

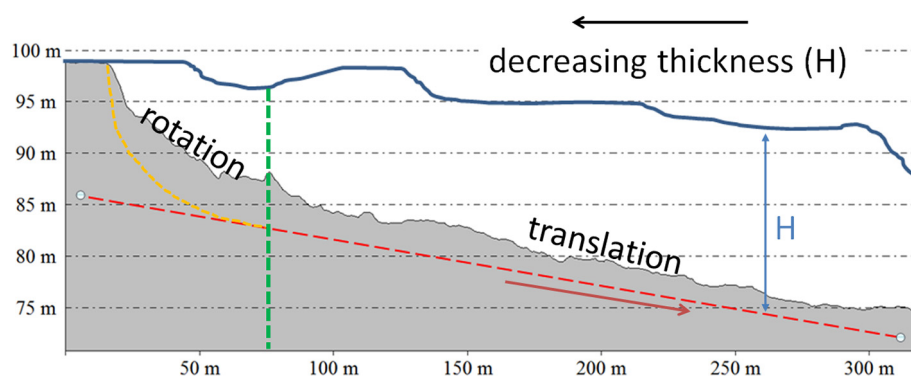


Fig. 7. Pre and post slide profile of the Mink Creek landslide (see Fig. 5 for location). Thick blue line is a photogrammetrically-generated pre-landslide surface from Geertsema (2004). This overlies the LiDAR-generated post-landslide surface (gray). The straight red dashed lines represent the translational rupture surface, mobilized (red arrow) along a bedding plane (Geertsema, 2004). The dashed green line represents the transition between translational and rotational movement, marking a threshold which is governed, in part, by the thickness (H) of the material between the rupture surface and the original ground surface. The orange curved line represents late-stage rotational movement, marking the final and furthest penetration of the landslide into the slope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

material may diminish with distance into the slope, until finally a threshold is encountered where the weight of the overlying material is insufficient to support further translation. At this point, the movement becomes rotational (Fig. 7), and usually marks the upper boundary of the landslide, or the furthest penetration, or retrogression into the slope. In the rotational zone, ridges tend to be back-tilted rather than horizontal, and are usually arcuate in planform (Geertsema, 2004; Geertsema et al., 2006b).

4.3. Multibeam bathymetric evidence of landslides

Our data show that the subaqueous portion of the northern landslide at Lakelse Lake was much larger (131 ha) than its subaerial counterpart

(48 ha). After travelling 1.5 km on land, the landslide flowed another 2.7 km under water on a gradient of 0.54° , coming to rest in the deepest part of Lakelse Lake (Fig. 8). Rising topography likely arrested further movement down-lake.

Not only do the multibeam data allow us to detect the extent of the 1962 landslide deposit, the detailed surface model allows for the interpretation of morphologic zones (Fig. 9). From these data, it appears that there was a widely distributed flow producing a field of dispersed hummocks, and outside of this a thin, amorphous zone often marking the upper and distal flanks of the deposit. This was followed by a more channelized flow, with conspicuous flow-parallel ridges. Distally these ridges underwent extension and broke into hummock trains, maintaining the planform of the original ridges (Fig. 9 inset). The distal

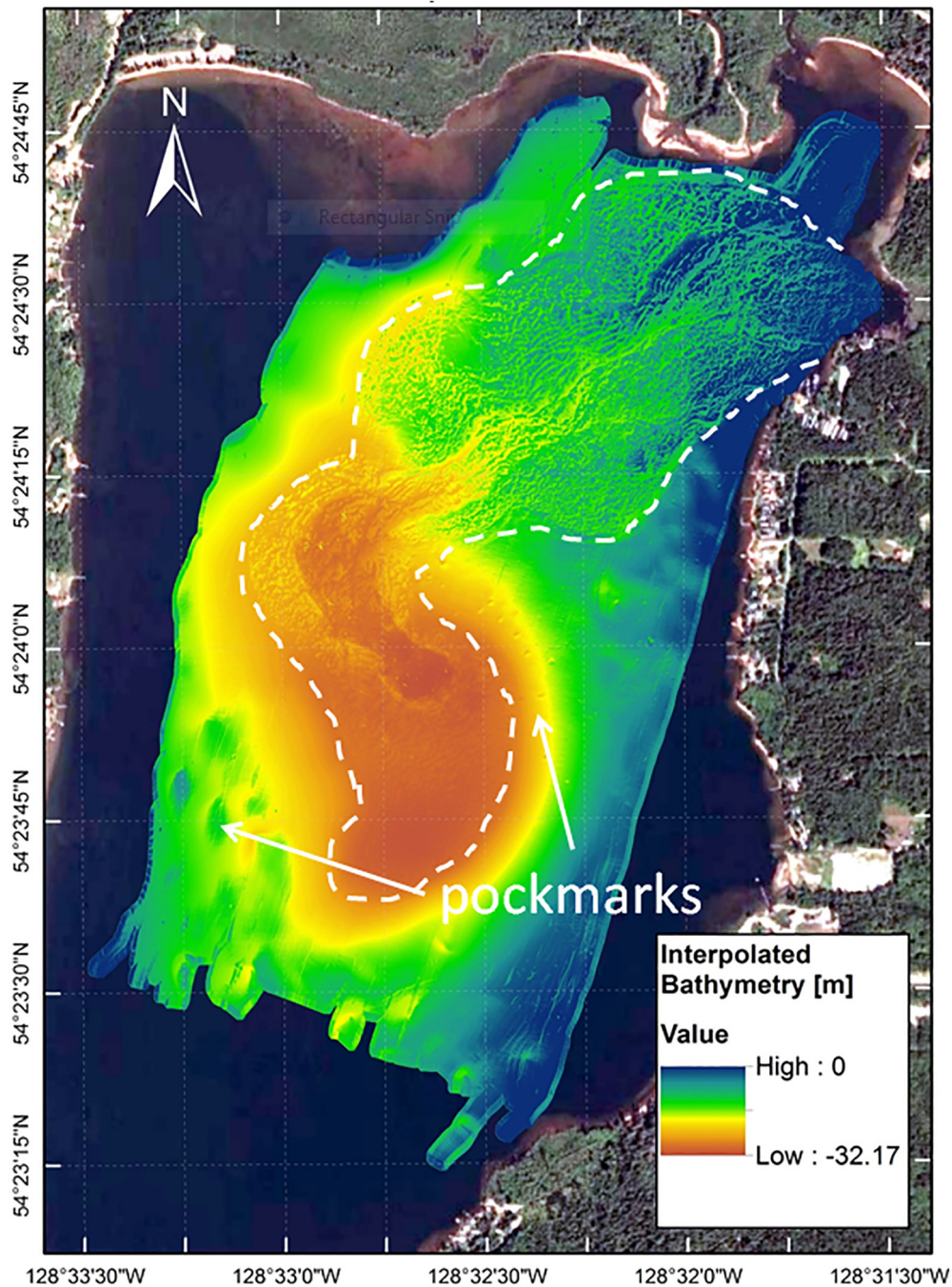


Fig. 8. Bathymetric map generated from 2016 multibeam sonar data showing the 1962 Lakelse Lake landslide (outline by white dashed line). Note the central channelized flow and that the landslide deposit settled into the deepest part of the lake. Also note both large and small pockmarks.

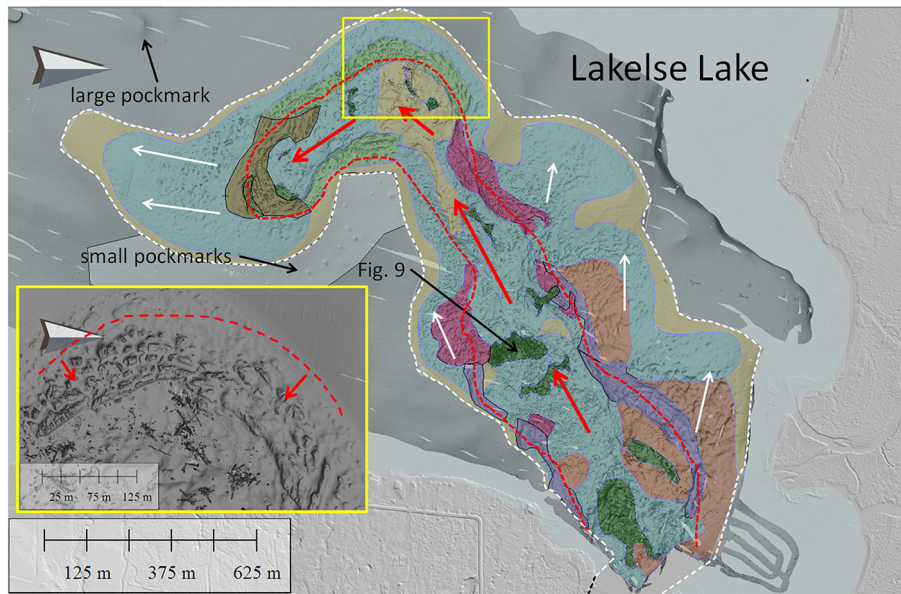


Fig. 9. Morphologic map generated from bathymetry derived from a 2016 multibeam survey of Lakelse Lake. The bathymetry records the initial wide distribution of the debris (white arrows) and its channelized flow (red dashed line) into the deepest part of the lake. Parallel-to-movement ridges (purple) indicate the debris was flowing. More distally, parallel ridges underwent extension and fragmented into lineations of hummocks (light green) as indicated in the by the offset red dashed line (inset box). These lead into distal arcuate ridges that appear to display compression (dark olive). Pink zones depict isolated zones with spreading transverse ridges. Proximal brown zones show ridges, blocks, and hummocks of various dimensions and orientations. These grade into a much larger zone (blue) of smaller dispersed hummocks. The outer margin of the landslide deposit is amorphous, with few hummocks (yellow-green) and forms something of an upper trimline. There are conspicuous rafts of trees that remain in the vertical position (see Fig. 9). The larger rafts are zoned (dark green). Outside the landslide margin is a zone of pockmarks - perhaps products of loading. Dark gray area shows multibeam swaths. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zone of this secondary flow appears to have formed a toe of arcuate compressional ridges similar to those at the Rissa landslide in Norway (L'Heureux et al., 2012). The ridges may overprint the more extensive zone of dispersed hummocks. The evolution of these hummocks likely arises from similar processes of formation and dispersion described in Carson (1977, 1979), Geertsema (2004) and also experimental results of Paguican et al. (2014) for hummocks, albeit in rockslide-debris avalanche deposits. Rafts of vertically-oriented trees, up to several ha in area, can be found in this central channel (Fig. 10) and may be in the same position they were in 1962 (Fig. 3). Perhaps these islands of trees represent the monolithic, translational movement of intact glaciomarine clay as described at Rissa, by Gregersen (1981). More morphometric analysis (beyond the scope of this paper) could provide a more detailed failure and movement history of the deposit.

The multibeam data also revealed a group of small (10–15 m diameter) pockmarks that form a string along the eastern distal margin of the landslide (Figs. 8, 9) and are much smaller than other (100 m) pockmarks in our data (Figs. 8, 9) and even larger ones that are not shown. We suspect these smaller landslide-marginal depressions may

be fluid escape structures caused by landslide loading. Similar fluid escape structures in the Terrace area were documented by Schwab et al. (2004) at the Khyex landslide (Fig. 2).

4.4. Subbottom acoustic evidence of landslides

Good acoustic penetration of the Lakelse sediments occurred except in sandy terrain near stream inflows or in sediments containing gas (e.g., CH₄, H₂S). Most of the sediment package revealed in the acoustic record is interpreted as horizontally to sub-horizontally bedded glaciomarine mud (Figs. 11–14). Holocene lacustrine deposits appear to be thin (up to 15 cm) throughout most of the lake (Fig. 14). Some of the glaciomarine beds are truncated erosionally at the surface. Intercalated between these sediments are landslide deposits with sharp upper and lower contacts (Figs. 13, 14).

We identified seven subaqueous landslides including the 1962 deposit (Figs. 12–14). Each landslide deposit was traced and correlated from the subbottom profiles and assigned a relative unit number from recent (June 1962, event = 7) to oldest (1) (Blais-Stevens et al.,

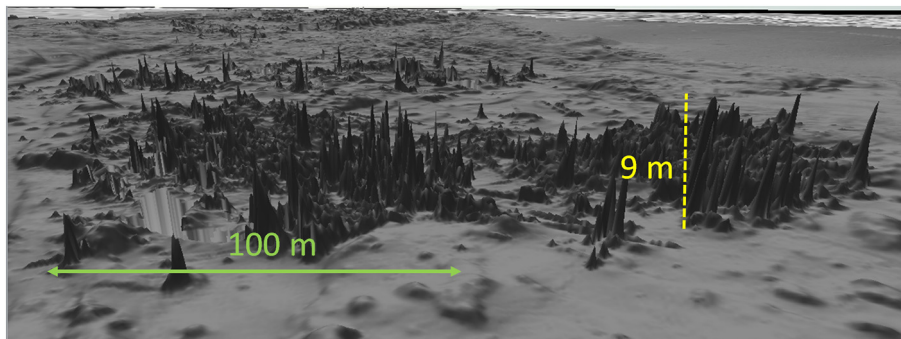


Fig. 10. The multibeam data show large rafts of upright trees in the 1962 Lakelse landslide deposit. View to East. Compare with Figs. 3 and 9.

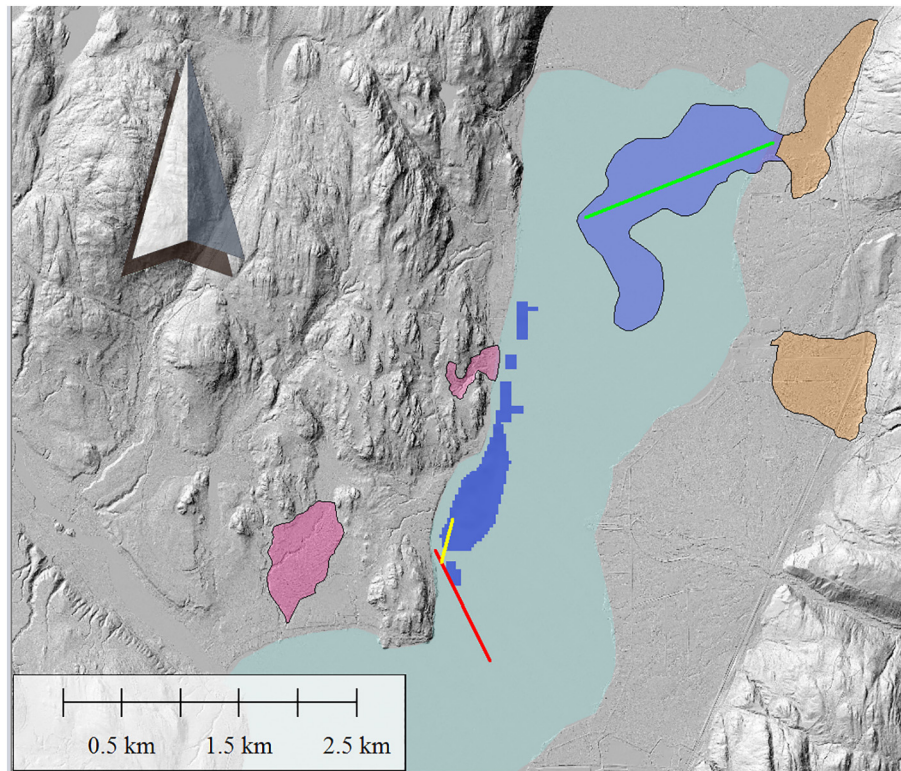


Fig. 11. Map showing the distribution of subaqueous landslide deposits (blue). These are minimum estimates. The 1962 landslide deposit is delimited with multibeam data, but the others are estimated based on intersections with subbottom profiles. The green, yellow, and red lines represent profiles in Figs. 12, 13, and 14, respectively. The 1962 sensitive clay landslides are shown in beige and older prehistoric subaerial landslides in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2017). Evidence of the June 1962 landslide event is visible in the northeastern portion of the lake bottom. The landslide is characterized by disturbed material at the top of the sediment column overlying undisturbed horizontal to sub-horizontal beds in the subbottom profiles with an average thickness of approximately 5 m. The landslide deposit extends for a distance of about 2.7 km towards the centre of the lake, as also seen in the multibeam data (Figs. 8, 9). It is also the only subaqueous deposit that definitively originated as a subaerial landslide.

Landslide units 1–6 are below bedded glaciomarine mud constraining them to the time when the area was inundated by seawater – a period of <1000 years, during deglaciation (Fig. 42 in Clague, 1984). At that time, the area was a fjord connected to the sea, implying that these landslides may be glaciomarine in origin. For sensitivity to develop, the salt content of the porewater needs to be lowered from some initial 30 g L^{-1} to $<1 \text{ g L}^{-1}$ (Torrance, 1983), by the leaching or diffusion of freshwater. This is often achieved by precipitation, which is only relevant for subaerial deposits, but could also be achieved through upward, artesian flows of freshwater as described by La Rochelle et al. (1970) in Quebec. The Lakelse area is known for its hot springs, and the multibeam bathymetry shows hundreds of pockmarks, which we interpret to be fluid escape structures. Thus artesian removal of salts may have begun syndepositionally with glaciomarine deposition. Furthermore,

not all translational landslides in soft sediments require sensitivity. For example, translational landslides in glaciolacustrine sediments may also display horst and graben morphology, similar to sensitive clay spreads (Geertsema et al., 2006a). It is possible that sensitivity was achieved early on while the sediments were being deposited in a fjordal sea, or alternatively the sediments were soft and anisotropic enough to fail without being sensitive. Another possibility is that these landslides were seismically triggered during deglaciation. Both Brooks (2016) and Lajeunesse et al. (2017) attributed landslide units in subbottom profile records from glacial lake basins in Quebec to early postglacial seismicity.

Unit 6 is the only landslide deposit in the acoustic record that shows evidence consistent with a spread. Here, horsts clearly display preserved horizontal bedding, similar to that found in other spreads (Locat et al., 2017). Two subbottom profiles display horsts with preserved bedding (spread) (Fig. 13) and completely disturbed bedding (flow) (Fig. 14); both having mobilized along very low gradients (Fig. 1).

4.5. Implications for landslide hazards

Our aerial and lacustrine geospatial surveys have identified a greater number and extent of landslides in the Lakelse Lake area, compared

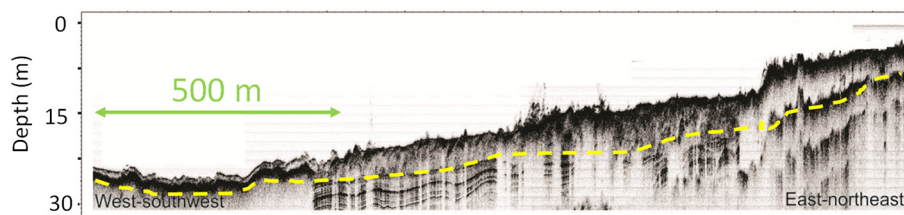


Fig. 12. Subbottom profile of the 1962 landslide suggests a mean deposit thickness of some 5 m. Vertical exaggeration is 16. See green line in Fig. 11 for location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

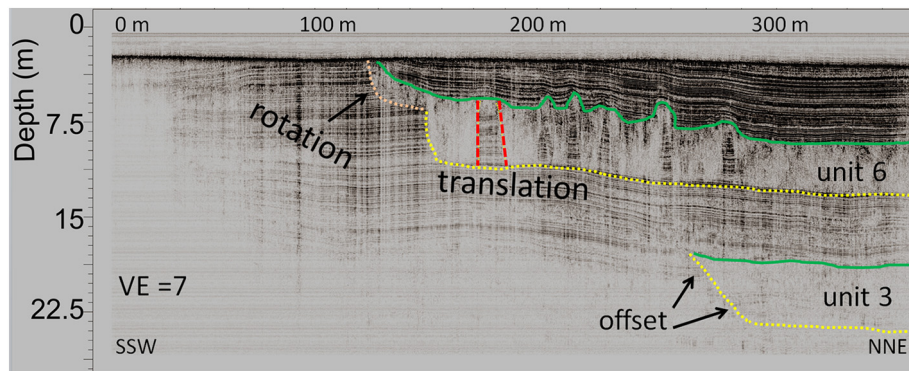


Fig. 13. Subbottom profile of two landslides. Unit 6 displays ridges (horsts) characteristic of spreading (Fig. 2) in a subbottom profile (see Fig. 11 for location). Note the final stage of rotation (pink dotted line) as described in Fig. 6. Yellow dotted lines represent translational rupture surfaces, mostly along bedding. The green solid lines represent the top of the landslide deposits. Note that the horsts (one outlined in red) have preserved bedding, or source stratigraphy. Also note the offset in unit 3. This older landslide does not display horst and grabens, but nonetheless preserves the preslide stratigraphy, indicating translational movement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to previous mapping efforts relying on airphoto interpretation alone. LiDAR allowed us to detect the extents of prehistoric and historic landslides on land, but we caution that some prehistoric landslide deposits may have been covered with alluvium, making them undetectable even with LiDAR. Multibeam surveys allowed us to identify and map the June 1962 landslide, and acoustic subbottom profiling provided a means to map landslides beneath the lake floor. Corroborating archival and published data increased our understanding of landslide circumstances and behaviour.

In terms of landslide hazards, our study reiterates the point that unstable terrain can fail multiple times as displayed at nearby Mink Creek (Geertsema et al., 2006b) and the landslide units contained in the sediments of Lakelse Lake. This co-occurrence of landslides in glaciomarine sediments differs from the “front of aggression” hazards approach (Bjerrum et al., 1969) where hazards are considered greatest where streams cut into undisturbed clays.

Earlier studies of sensitive clay landslides in the Terrace-Kitimat area (Geertsema et al., 2017) show that a third of the dated prehistoric landslides occurred within a wet period some 2000–3000 years ago (Clague and Mathewes, 1996), and the Mink Creek landslide occurred after a decade of increasingly wet conditions. Most climate models project an increase in precipitation for northwest British Columbia under moderate emission scenarios for the remainder of this century (IPCC, 2014). Increased precipitation may thus elevate the probability of sensitive clay landslides in the decades ahead.

Our landslide detection also revealed morphological details of the landslides that allow differentiation between the transverse ridges of spreading and the more streamlined, dispersed hummocky, or even amorphous texture (with no hummocks) of flowing. A number of our mapped landslides show both spreading and flowing behavior (Figs. 5, 6, 9, 13), with some spreads appearing to turn into distal flows, which may have extended the travel distances of the landslides. Sensitive

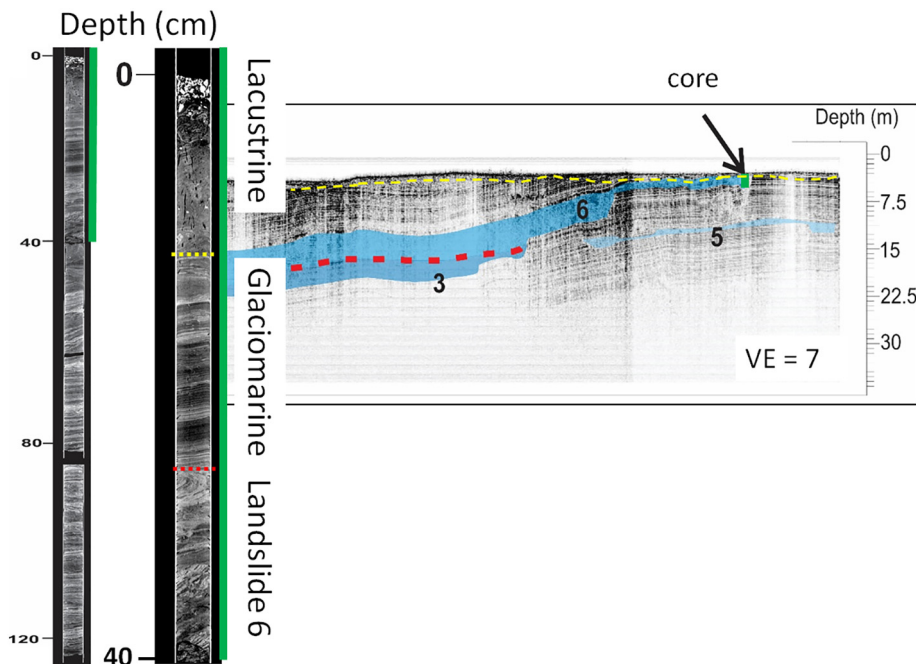


Fig. 14. A short sediment core intersects landslide 6 in one of our subbottom profiles. Compare green bars. Only the upper 15 cm of the core is lacustrine. The landslide occurred in thick glaciomarine sediments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

clay flows in Quebec tend to have longer travel distances than spreads (Locat et al., 2017), partly due to the more complete remoulding and higher mobility of the clay. Landslides with a flow component in our study area should thus have the ability to travel a great distance on low travel angles, such as the northern landslide on Lakelse Lake which travelled 4.2 km. Unfortunately, our data set is too small to distinguish between the mobility of flows versus spreads in the Lakelse Lake area, and moreover landslide runout zones coalesce (Fig. 4), making measurement from any one particular source difficult.

We consider the hazard of subaqueous landslides in Lakelse Lake to be low. As stated in Section 4.4, the evidence of the prehistoric submarine landslides, in what is now Lakelse Lake, appears to constrain the movements to a period of less than one millennium duration in the early deglacial period. External loads such as pile driving in the lake could, however, destabilize slopes underwater. A larger potential hazard may originate from landslide-generated displacement waves on the lake surface.

The smaller Rissa sensitive clay landslide (33 ha on land and 76 ha under water) in Norway produced a much higher water wave at 6.8 m (L'Heureux et al., 2012) than the larger Lakelse landslide (48 ha on land and 131 ha under water), which, according to one eyewitness account, produced a wave between 1 and 2 m high. The difference may relate to the style of movement. The Rissa landslide involved several large cohesive flakes (large translational rafts of soil), which would likely produce a greater impulse than a broken-up flow. Despite this difference, the risk of landslide-generated waves from subaerial landslides into Lakelse Lake remains.

5. Conclusions

We employed varied geospatial survey techniques to identify and map landslides in terrain where prior methods proved difficult. The combination of archived data, including eye witness interviews, LiDAR, multibeam bathymetry, and acoustic subbottom profiles provided unique and corroborating evidence to help identify and characterize past landslides. Both LiDAR and multibeam data were useful for identifying previously unrecognized landslide deposits and for measuring morphometric parameters and making geomorphic interpretations, such as distinguishing flowing and spreading landslide behaviour.

The acoustic subbottom profiling data also helped identify landslides and characterize thickness and flow versus spread morphology. Only the June 1962 landslide was definitively triggered onshore. The other six previous landslides were triggered in glaciomarine sediments, and likely occurred within a 500–1000 year window while the sediments were still under seawater. Such early landsliding raises some questions about the development of sensitivity from salt removal. Perhaps this was achieved by flushing of artesian groundwater, as there are many springs and pockmarks in the area. Or alternatively they failed without becoming sensitive, perhaps induced by deglacial seismicity.

From a hazards perspective our data have taught us the following:

- the area covered by sensitive clay landslides is larger than was previously known;
- sensitive clay landslides occur in areas with previous landslides, rather than only in undisturbed areas;
- while spreads appear to dominate, many landslides are composites of flows and spreads, often with spreads turning into distal flows;
- although the probability of subaqueous landslides has diminished, the risk of subaerial sensitive clay landslides may increase under a wetter future climate.

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