The Landslide-Modified Glacimarine Landscape of the Terrace–Kitimat Area, BC

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Abstract

Low-gradient landslides (spreads and flows) involving sensitive clays have modified the uplifted glacimarine landscape of the Terrace–Kitimat area in northern coastal British Columbia. Broad, shallow landslide depressions are clustered throughout the area, along streams, delta fronts, and lake shores, with some occupied by wetlands. Several large landslides have occurred in the past century, and there are earlier oral First Nation's accounts of landslides. Radiocarbon analyses indicate that one-third of dated landslides plot between 3500 and 1900 years ago, perhaps relating to a period of wetter climate. The presence of quick clays, continued stream incision into sensitive sediments, and a projected wetter future climate suggest that this landscape will continue to be modified by low-gradient landslides.

Keywords

Landslide • Glacimarine sediment • Quick clay • Radiocarbon dating • *Naxnox* • British Columbia

25.1 Introduction

Fjord valleys dissect the Coast Mountains of British Columbia including the Coast Mountains near Kitimat and Terrace (Fig. 25.1). At the peak of the last Pleistocene glaciation, thick ice of the Cordilleran Ice Sheet isostatically depressed the underlying crust. During deglaciation, the sea transgressed far inland on the isostatically depressed landscape. One arm of the sea expanded eastward up Skeena River, and the other reached northward from Kitimat past Terrace. The inland seas, however, were short-lived. Rapid isostatic rebound lifted the drowned landscape above sea level, subjecting thick glacimarine sediments to stream incision, lateral erosion, and, over time, to large, low-gradient landslides. The landslides modified the landscape, in many cases forming wetlands that persist to the present. The landslides also play a role in First Nation's oral histories. Today they pose challenges for settlements and infrastructure.

25.2 Setting

25.2.1 Physiography

The Terrace area is located in the Kitimat Ranges, which is one of the ranges of the Coast Mountains of British Columbia (Holland 1976). It occupies a broad, relatively flat-bottomed and steep-walled valley known as the Kitimat–Kitsumkalum trough, which ranges in width from 1 to 15 km (Clague 1984). The valley does not have a single major river along length. Skeena River cuts orthogonally

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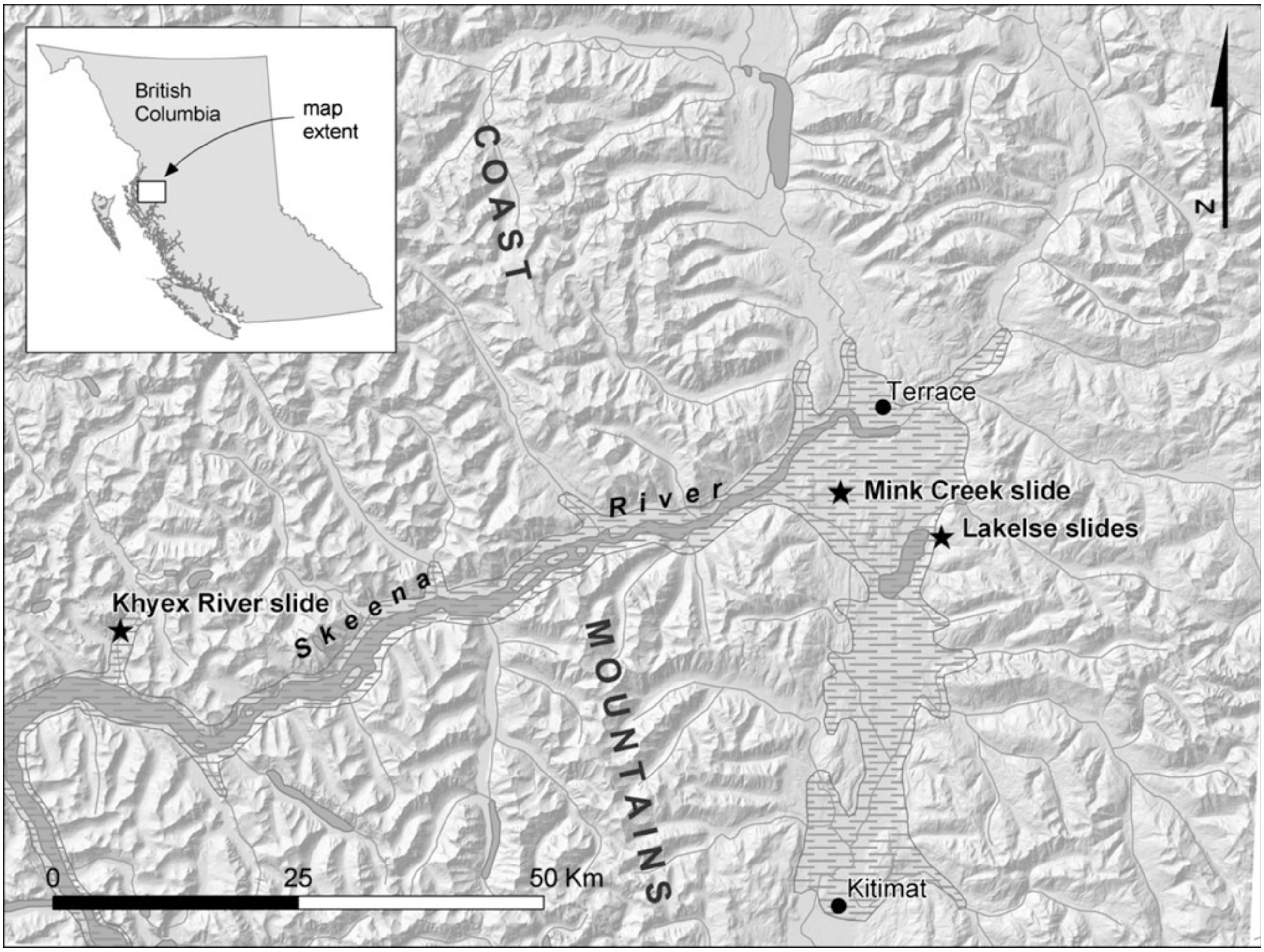

Fig. 25.1 Map of the study area. Note the locations of the 1993–1994 Mink Creek landslide and the 1962 Lakelse landslides. Glacimarine sediments occur within the patterned area (from Geertsema 2004)

across the trough, and Kitimat River enters the valley north of Kitimat. Lack of a major integrated drainage network suggests a formative drainage system different from that of today (Duffel and Souther 1964; Clague 1984).

The forest-covered Kitimat–Kitsumkalum trough is characterized by rolling to flat terrain, composed of gullied glacial and post-glacial sediments and isolated bedrock hills. Most of the valley fill consists of glacial sediments, including glacimarine mud, glacifluvial gravel, and till. Glacimarine sediments are locally more than 50 m thick and deeply gullied. Post-glacial landforms include alluvial floodplains and fans, bogs and fens, and slopes mantled with colluvium. The largest water body in the study area is Lakelse Lake. Steep rock slopes border the Kitimat–Kitsumkalum trough, culminating in peaks up to 1500 m in elevation. Bedrock includes Cretaceous granitic rocks and older Mesozoic and older volcanic and sedimentary rocks (Duffel and Souther 1964).

25.2.2 Climate

The climate of the study area is wet sub-maritime. Mean annual precipitation ranges from 2300 mm at Kitimat to about 1300 mm near Terrace; more than three-quarters of the precipitation falls between October and April. Mean annual temperature ranges from 5.9 °C near Terrace to 6.4 °C at Kitimat. Respective extremes are about −27 and 36 °C near Terrace, and −25 and 36 °C at Kitimat (British Columbia Ministry of Forests 1997).

25.2.3 Deglacial History

At the end of the last (Fraser) glaciation, ice flowing down Skeena Valley bifurcated near Terrace; one lobe flowed southward towards Kitimat and the other flowed westward towards Prince Rupert. The termini of both glaciers were in

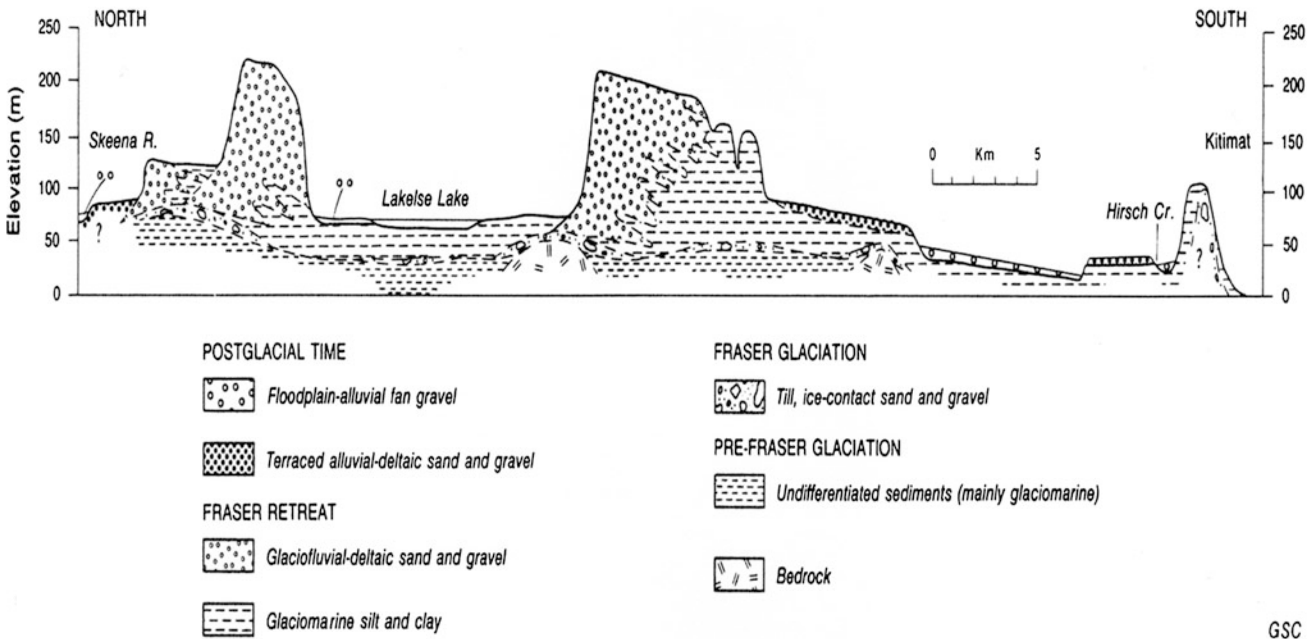

Fig. 25.2 Schematic longitudinal cross section of the valley between Terrace and Kitimat. Note the terminal moraine at Kitimat and two ice-contact deltas graded to late-glacial high sea levels (From Clague 1984)

contact with the sea. The snout of the south-flowing glacier retreated from the present location of Kitimat towards Terrace about 12,500 years ago. Terrace was ice-free by about 11,000 years ago. Recession, although rapid, was interrupted by three significant stillstands. The first is marked by a large arcuate end moraine at the present location of Kitimat. The second stillstand occurred about 20 km north of Kitimat, producing a large ice-contact delta that blocked the northward transgression of the sea. The third stillstand was near Terrace, where another delta was built into the sea (Fig. 25.2).

Isostatic rebound continued for about another 2000 years following deglaciation. Local sea level fell from its highest level at about 200 masl to at or below present sea level by 9000–8500 years ago (Clague 1984). During and soon after deglaciation, the landscape experienced significant change due to paraglacial sediment transfers (Church and Ryder 1972). Floodplains, fans, and deltas formed and evolved rapidly. Paraglacial deposits were subsequently incised in response to falling base level and a reduction in sediment delivery, and many fans and side-valley deltas are now relict features.

25.3 Conditions for Sensitive Clay Development

In most freshwater environments, clay particles settle more slowly than silt and accumulate in stacks of plates parallel to one another. In contrast, in salt water silt and clay particles form aggregates (small floccules) that settle together in a random pattern (Torrance 1983). This random alignment of particles gives the sediment a higher-than-normal amount of pore space and interstitial water. Such floccules formed in the late-glacial sea near Terrace (Geertsema and Torrance 2005).

When interstitial porewater has a high salt content, interparticle bonds are strong. Leaching or diffusion by freshwater gradually lowers the salinity in marine and glacimarine sediments. Some types of clays and mixtures of silt and clay are prone to structural collapse once the salinity of the porewater falls below a threshold value because repulsive forces between the particles increase (Rosenqvist 1953; Bjerrum 1954; Quigley 1980; Torrance 1983). A remarkable characteristic of these fine sediments is the large difference in strength between the undisturbed and disturbed (remoulded) sediment—the remoulded material behaves as a fluid. Clays that exhibit this type of behaviour are called *sensitive clays*, where 'sensitivity' is defined as the quotient of the undisturbed shear strength divided by the disturbed shear strength. In extreme cases, where sensitivity exceeds 30 and remoulded shear strength is less than 0.5 kPa, the deposits are called *quick clays* (Torrance 1983).

25.4 Landslides

25.4.1 Landslide Depressions

Scars of low-gradient landslides are common on the valley floor between Terrace and Kitimat (Fig. 25.3; Geertsema

Fig. 25.3 The Mink Creek landslide occurred 7 km south-west of Terrace on a broad glacimarine plain, 100 m above sea level. The travel angle of the landslide was 2°. Photograph courtesy of British Columbia Ministry of Forests, Lands, and Natural Resource Operations

and Schwab 1997). The landslides have happened in glacimarine mud (Fig. 25.4), although in some instances the mud is covered with post-glacial alluvium or glacifluvial gravel (Fig. 25.5). The landslides can be large, with volumes of up to 10 million m^3 and areas up to 2 km^2. They tend to have high ratios of horizontal retrogression to the height of the scarp above the main rupture surface, thus forming broad, shallow depressions. The travel angles can be <1° (Geertsema and Cruden 2008, 2014), with movement on nearly flat ground.

The landslides are largely translational, and in some cases upright trees are transported over distances of hundreds of metres (Fig. 25.6). The Kitsumkalum people have an oral tradition of the *naxnox*, a supernatural being. One of the ways that *naxnox* would manifest itself is through trees travelling upright into rivers or lakes (Alex Bolton, Kitsumkalum Band, personal communication 1997).

25.4.2 Landslide Distribution

Many of the landslides in the Kitimat–Kitsumkalum trough occur in clusters. Landslides are particularly abundant around Mink Creek (Fig. 25.1), the foreslope of the Onion Lake delta (Figs. 25.7, 25.8) and the Nalbeelah wetlands (Fig. 25.9).

As on the foreslope of the delta fronting the St. Narcisse moraine in Quebec (Lebuis et al. 1983), the abundance of landslides at the front of the Onion Lake delta may be related to the presence of a confined aquifer with water-bearing delta foreslope deposits lying beneath glacimarine mud. Even without excess pore pressures, the movement of water through the aquifer removes salt from the water of the overlying mud, increasing its sensitivity (La Rochelle et al. 1970; Carson 1983). Bank erosion by Kitimat River may be a factor contributing to the large number of landslides in this area.

In contrast, the foreslope of the large delta northwest of Lakelse Lake (Fig. 25.3) has few large landslides. The absence of a major eroding stream in this area may partly explain the lower frequency of landslides. The largest landslides in the area are historic and include two Lakelse landslides in 1962 that destroyed a highway (Clague 1978; Evans 1982; Geertsema 1998) and the Mink Creek landslide in 1993 (Geertsema et al. 2006). Such large landslides undoubtedly have occurred in the prehistoric past, but

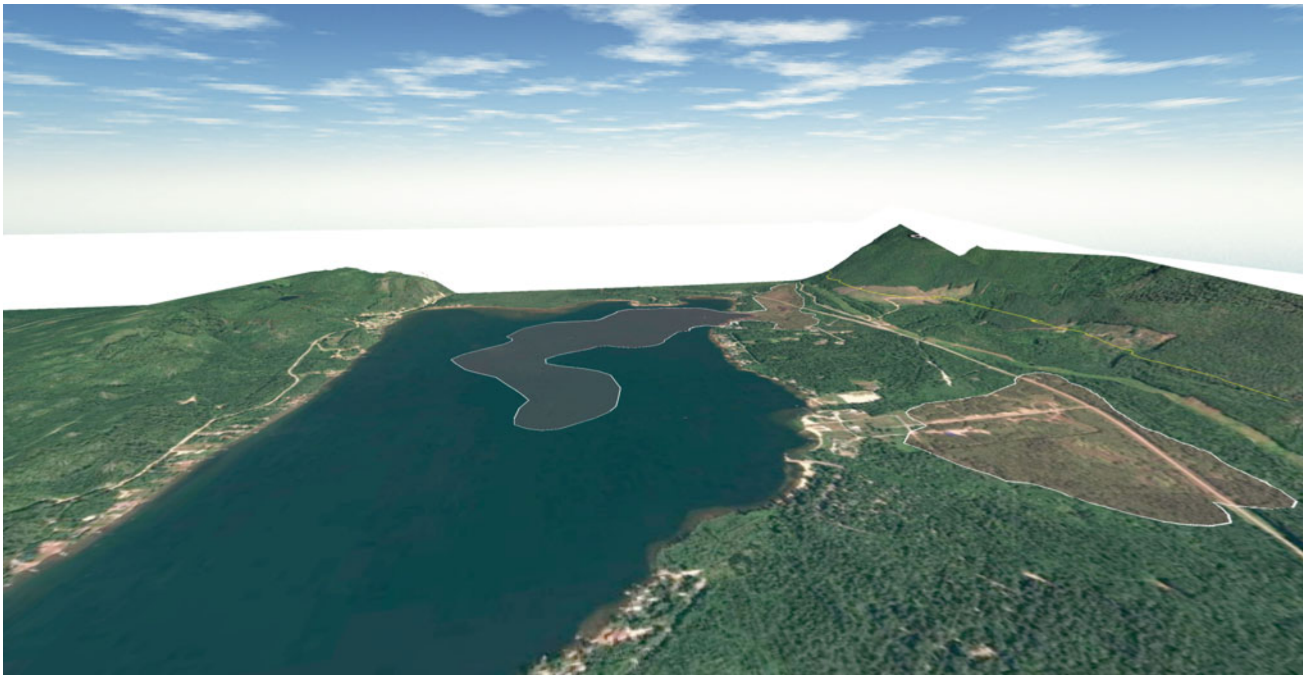

Fig. 25.4 Two (*grey shaded*) landslides that were triggered by highway construction occurred in 1962 on a LiDAR digital elevation model. The landslides both had rupture surfaces <1° gradient, but volumes in excess of 10 million m^3 (Geertsema and Cruden 2014), but only one of them entered Lakelse Lake. The distal (north end of Lakelse Lake is 2.2 km wide. The *yellow* line represents the 200 m marine limit. View north. Data on file at British Columbia Ministry of Forests, Lands, and Natural Resource Operations

Fig. 25.5 Prehistoric earth flow with a bottleneck shape on Nalbeelah Creek—the term bottleneck to describe a landslide was first used by Sharpe (1938). *Dotted line* delineates the headscarp and lateral margins of the landslide. The outlet is 70 m wide. Note the gully to the left of the landslide. This gully may have limited the retrogression of the landslide along its *left side* (from Geertsema 2004)

evidence for them has been lost due to subsequent sliding, gully erosion, or revegetation. Large hanging landslide depressions, presumably prehistoric, are preserved in mud blanketed with glacifluvial gravel (Fig. 25.5). The absence of mapped landslides at the north and southeast ends of Lakelse Lake does not necessarily imply that no landslides

Fig. 25.6 Trees rafted in near-vertical position by the 1993–1994 Mink Creek landslide (from Geertsema 2004)

have occurred there. There are local accounts of trees buried in clay that were exposed during excavations in these areas. The scarps may become obliterated over time by alluvium and organic deposits in these low-lying, flood-prone areas.

25.4.3 Landslide Ages

Radiocarbon ages are available for 16 prehistoric landslides (Fig. 25.10; and tables in Geertsema and Schwab 1997; Geertsema 2004). With one exception, the ages are on basal peat in landslide depressions and thus are minima for the ages of the landslides (Fig. 25.9; Geertsema 1996). The one exception is an age on plant material found along an excavated rupture surface. Although the dated landslides are a small percentage of the total landslides mapped, more than one-third of them appear to have happened between 3500 and 1900 years ago. The largest cluster of peat-filled landslide depressions is the Nalbeelah wetland east of Kitimat River (Fig. 25.9). A landslide at Hirsch Creek in glacimarine clay blanketed by glacifluvial gravel happened before 10,000 years ago, shortly after deglaciation. Although it is an anomaly in Fig. 25.10, other nearby landslides north of Hirsch Creek (Fig. 25.5) may also be early post-glacial in age.

25.4.4 Landslide Legacies

Landslides can have both short-term and enduring impacts on soil, site, and landscape diversity (Geertsema and Pojar 2007; Geertsema and Schwab 1996). Readily apparent effects of flows and spreads include the formation of large scars or scallops (Cruden and Varnes 1996), the filling of valleys with displaced material (Fig. 25.11), and the formation of landslide-dammed lakes. Landslide-dammed lakes may be short-lived or may endure for decades or longer (Fig. 25.3), depending in large part on stream power. Sometimes these lakes transform into peat-filled wetlands. Where the rupture surfaces of these landslides are below the

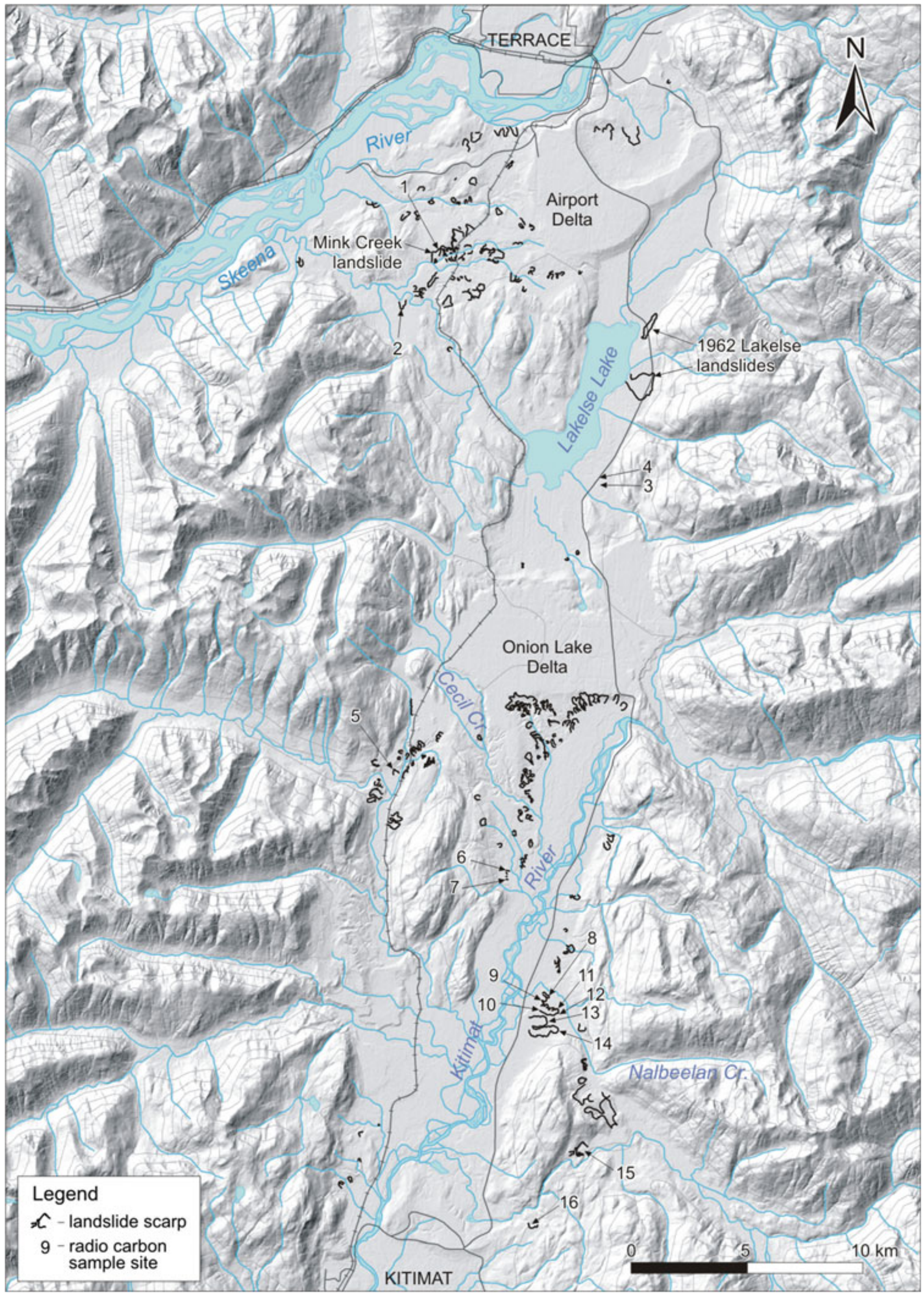

Fig. 25.7 Distribution of landslide scarps in glacimarine sediment in the Terrace–Kitimat area (from Geertsema and Schwab 1997)

water table, wetlands may develop within the bodies of landslides (Fig. 25.9).

Contributions to biophysical diversity may come from mixing of materials by landslides. Figure 25.12 shows a mosaic of patches of brown surface soil interspersed with deeper grey clay at the Mink Creek landslide. The surface soil has a pH lower than 5, whereas the grey clay has a pH above 8 (Geertsema and Pojar 2007).

25.5 Controls on Landsliding

25.5.1 Influence of Valley Formation

Stream erosion is the most common cause of retrogressive landslides in glacimarine sediments (Bjerrum et al. 1969; Lebuis et al. 1983; Viberg 1983). Both Bjerrum et al. (1969) working in Norway and Lefebvre (1986) working in Quebec

Fig. 25.8 View to the northeast of the slope of the late Pleistocene Onion Lake delta (Fig. 25.7). The delta slope is heavily scarred by landslides. Note logging roads on the scarps of some of the landslides. Photograph by M. Geertsema

Fig. 25.9 Wetland-filled earth flows at Nalbeelah Creek (sites 12–14; Fig. 25.7). British Columbia Ministry of Forests, Lands, and Natural Resource Operations imagery

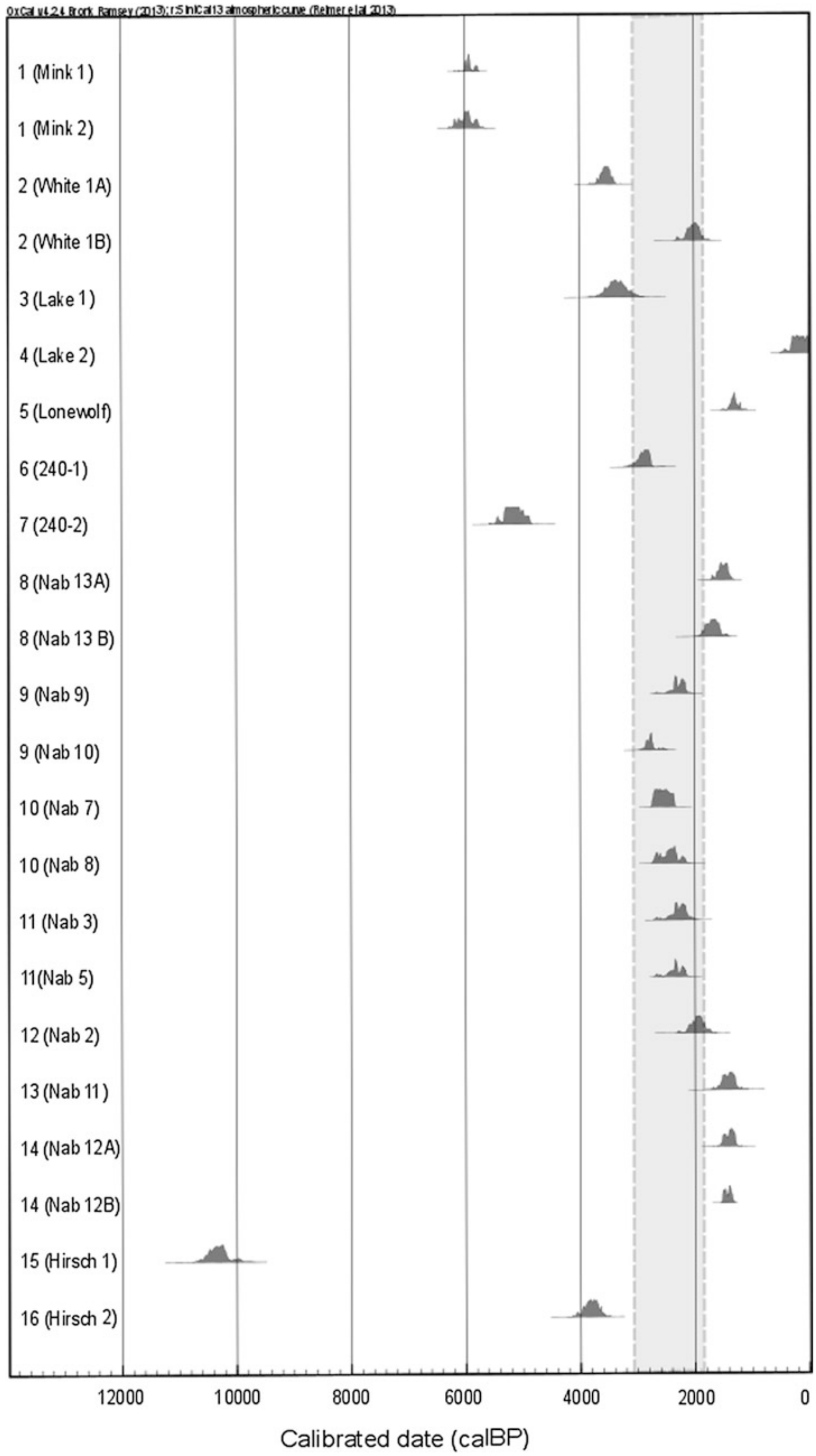

Fig. 25.10 Calibrated radiocarbon age distribution of basal peats from the zones of depletion of landslides (see Fig. 25.7 for locations). The upper two samples (Mink Creek) were not from peats, but organics along a buried rupture surface. Calibration done using OxCal 4.2.4 (Bronk Ramsey 2013). The shaded column represents a cool, wet period identified by Clague and Mathewes (1996). More than one-third of the dates fall within this period

Fig. 25.11 Muddy landslide material completely filling the valley of Mink Creek following the 1993–1994 landslide. Photograph courtesy of British Columbia Ministry of Forests, Lands, and Natural Resource Operations imagery

used landscape evolution approaches involving stream incision to map zones of earthflow potential in sensitive clay areas (Geertsema 2013).

Bjerrum et al. (1969) assumed that stream bank erosion is the main cause of quick clay failures; they proposed equilibrium gradients for streams from which future erosion might be predicted. They defined three zones of stream erosion. The lowest zone is no longer actively downcutting and is characterized by old slide scars and localized cutbank failures at stream bends. This zone is mature, and the danger of quick clay landslides is small. An intermediate zone exists where the stream is flowing almost exclusively on landslide deposits and is eroding back to its old level. Bjerrum et al. (1969) argue that the risk of quick clay failures in this zone is low. However, the Saint–Jean–Vianney slide in Quebec (Tavenas et al. 1971; Potvin et al. 2002) and the Mink Creek landslide at least partly involved remobilization of old landslide deposits. The third, uppermost zone is the original land surface where streams are cutting into undisturbed clay. Bjerrum et al. (1969) termed the boundary between this zone and intermediate zone the 'front of aggression' and argued that the risk of failure is greatest there. When an earth flow carries material into the valley, the intermediate zone is extended and the front of aggression moves upstream.

Working in Quebec, Lefebvre (1986) described three phases of valley formation and associated groundwater flow. An early phase is characterized by relatively shallow stream incision into thick marine mud and groundwater flow that is not influenced by underlying permeable till. An intermediate phase is characterized by moderate valley incision and strong artesian pressures, which facilitate large, retrogressive failures. A late phase is marked by stream incision through permeable till and downward groundwater flow. Only small landslides are expected during this late phase of valley formation. Most streams in the Kitimat–Kitsumkalum trough are incising thick glacimarine sediments (Geertsema 1998, 2013). The area thus is in the early and intermediate stages of valley formation, and large landslides are still occurring there.

Although the zones proposed by Bjerrum et al. (1969) do not relate directly to Lefebvre's (1986, 1996) phases of valley formation, the intermediate zones in both studies have the greatest likelihood of retrogressive flowsliding. Lefebvre's valley formation approach may more applicable to the Terrace–Kitimat area because prehistoric landslides are ubiquitous throughout the area (Fig. 25.7), and large landslides are occurring in areas that have experience retrogressive landslides in the past.

25.5.2 Influence of Climate

The 1993–1994 Mink Creek landslide happened after 8 years of increased precipitation, 9 years of increased warming, and a warmer than average fall and early winter (Geertsema et al. 2006). These hydroclimatic conditions likely contributed to high ground water and stream levels, setting up the landslide. Such conditions have been shown to be important contributors to other large landslides (Patton 1984). Studies of landslide–climate relationships in British Columbia have largely been restricted to shallow debris slides and debris flows in steep mountainous terrain (Schwab 1983; Church and Miles 1987; Evans 1989; Hogan and Schwab 1991). Bovis and Jones (1992), however, showed that large deep-seated earth flows in southern British Columbia were active during wet periods in the Holocene Epoch.

According to Geertsema et al. (2006), most global circulation models predict warmer and wetter conditions for the Terrace area later in this century. Conditions that contributed to the Mink Creek landslide could become more common in

Fig. 25.12 Mosaic of vegetation and soils on the surface of the Mink Creek landslide. Acidic brown soils and mildly alkaline grey clay ridges provide a rich diversity of ecosystems. Photograph by M. Geertsema

the future—a decade of increasing precipitation and temperature and mild wet falls.

Most of the dated prehistoric landslides (Fig. 25.10) happened during a cool wet period (Clague and Mathewes 1996). There might have been more frequent flowslides during Neoglacial time (the last 5000 years) than earlier in the Holocene when it was warmer and drier (Pielou 1991).

25.5.3 Controls on Landslide Size

Glacimarine landslide size is controlled by a number of factors including material characteristics and strength, leaching and diffusion of salt from porewater, topography, and the inclination of bedding (Geertsema and L'Heureux 2014). One of the main requisites for landslide growth is that displaced material must leave the zone of depletion (Carson 1977, 1979; Carson and Lajoie 1981). For continued growth of retrogressive landslides, the failed material must move away from the headscarp and sidescarps to prevent buttressing. Evacuation of sediment from developing scarps is influenced by the ability of material to flow and by the ability of the valley to accommodate the displaced material.

Mitchell and Markell (1974) and Trak and Lacasse (1996) related the length of glacimarine flows and spreads (or the distance of retrogression) to Janbu's stability number, Ns. They found that the stability number (Ns = γH/su, where γ is the bulk unit weight of the soil, H is the height of the slope, and su is the undrained shear strength) must exceed some threshold value (usually 6) for retrogressive movement to occur. Below the threshold, movement becomes rotational and arrests further landslide growth, forming a stable main scarp.

Rupture surfaces in many glacimarine flows and spreads develop along bedding planes. The dip of the strata can play a role in how far a landslide will penetrate into a slope. Counterintuitively, flatter strata allow larger landslides to develop because limiting thresholds are achieved over longer distances along the rupture surfaces (Fig. 25.13). With nearly horizontal rupture surfaces, the limiting Ns threshold may not be met. At Lakelse Lake in 1962, the slopes were gentle and strata were nearly flat; the landslides penetrated

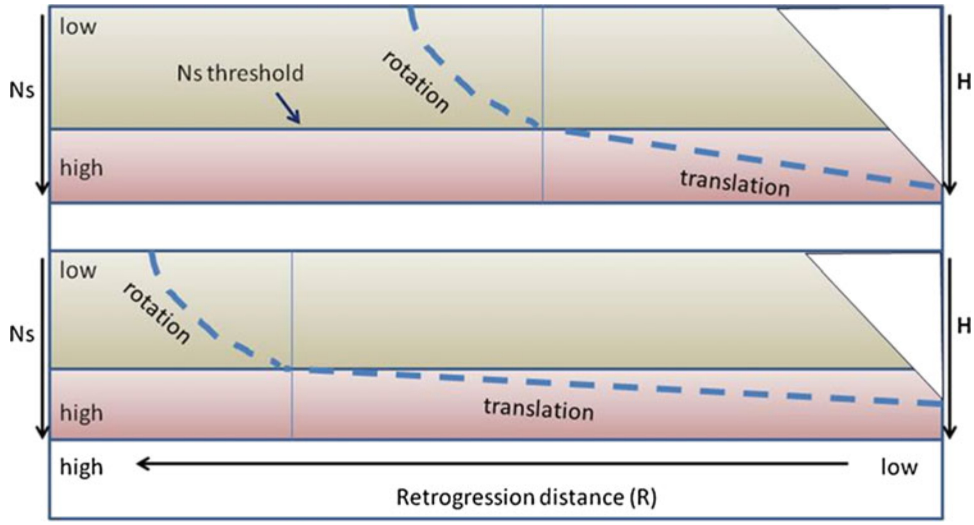

Fig. 25.13 Influence of the inclination of the rupture surface (*dashed blue lines*) on retrogression distance. Steeper inclinations intersect the Ns threshold over a shorter distance than do more gently sloped rupture surfaces. Once the threshold is reached movement transforms from translation to rotation. The intersection of the rotational surface with the ground surface is generally the crown of the landslide (figure adapted from Geertsema and L'Heureux 2014)

along the rupture surface until they encountered the rising bedrock slope on the valley wall (Geertsema and L'Heureux 2014).

Many landslides are bounded by pre-failure gullies (Fig. 25.5). Gullies limit landslide size in three main ways. Gullies provide a negative topography that reduces lateral earth pressure and Ns. They can lower the water table. And a weathered crust can develop in the interfluve areas between gullies, imparting strength deeper into the sediment.

25.6 Conclusions

There are many historic and prehistoric low-gradient translational landslides in glacimarine sediments in the Terrace–Kitimat area. Rapid landslides moving on essentially flat ground typically are not expected, and trees moving in the vertical position in landslides are even less so. Oral histories of *naxnox* manifested as upright moving trees may provide further evidence of these landslides.

These landslides leave a variety of geomorphic traces in the landscape, including landslide-dammed lakes and wetlands, peat-filled landslide depressions, and a mosaic of soil types.

The landslides are especially abundant near Mink Creek, on the foreslope of the Onion Lake delta, and in the Nalbeelah Creek area. The most common trigger for large earth flows is bank erosion, and many prehistoric failures in the Terrace–Kitimat area happened during a period when rivers eroded slopes formed of glacimarine sediments. Streams in this area are still in the early-to-intermediate phases of valley formation when large landslides are most likely.

Three interesting points can be made about climate. First, about one-third of the dated prehistoric landslides in the Kitimat–Kitsumkalum trough occurred during a wet period. Second, almost a decade of increasing precipitation and temperature and a wet warm fall and early winter preceded the large Mink Creek landslide. Third, future climate in the Terrace–Kitimat area is likely to be wetter and warmer than today.

Given the current state of valley formation in the Terrace–Kitimat area, the history of previous landslides, and the clear relation between climate and instability, there is every reason to think that large landslides will happen in the future.

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