STYLE AND SEQUENCE OF MOVEMENT OF A LANDSLIDE IN SENSITIVE GLACIOMARINE CLAYS AT MINK CREEK, NORTHWESTERN BRITISH COLUMBIA

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Abstract

A landslide of 2.5 million m^3 of sensitive glaciomarine sediments, predominantly silty clays, occurred at Mink Creek near Terrace, British Columbia (54° 27'N, 128° 37'W) sometime between Christmas 1993 and early January 1994. We divide the landslide into 8 zones, distinguished on the basis of morphological characteristics. Using both morphological and sedimentological evidence, we interpret processes of flowing, spreading and sliding, often in succession, as the landslide retrogressed. As the landslide had a travel angle of 2-3 degrees and the slope from the crown to the toe of the rupture surface was 3 degrees, extensive areas of these postglacial sediments may be at hazard from landslides.

Résumé

Un glissement de terrain de 2,5 million m^3 de sédiments glaciomarins, composés principalement d'argiles silteuses sensibles, s'est produit au ruisseau Mink près de Terrace en Colombie-Britannique (54° 27'N, 128° 37'W) entre Noël 1993 et le début de janvier 1994. Nous avons divisé le glissement de terrain en huit zones selon leurs caractéristiques morphologiques. En se basant sur les caractéristiques morphologiques et sédimentologiques, nous interprétons qu'il y a souvent une suite de mouvements dans la rétrogression du glissement de terrain, soit un écoulement, un étalement et un glissement. Nous avons observé que le glissement de terrain se déplaçait à un angle de 2 à 3 degrés et que la pente de la surface de rupture (de la couronne au pouce) était de 3 degrés. Or, nous concluons qu'il y a de vastes régions à pente peu prononcée de sédiments post-glaciaires glaciomarins qui sont davantage des zones de dangers de glissements de terrain.

1. INTRODUCTION

The purpose of this short paper is to reconstruct the movement history of a landslide in sensitive glaciomarine sediments that occurred 10 km southwest of Terrace, British Columbia (Figure 1) sometime between December 1993 and January 1994. Forty-three hectares of forest were disturbed while the reservoir formed behind the Mink Creek landslide dam raised the water level in the creek 12 m, backing water 1.2 km upstream. Our landslide terminology follows Cruden and Varnes (1996).

1.1 Setting and Quaternary History

The landslide is situated in a broad north-south trending trough in the Coast Mountains (Figure 1) of the Canadian Cordillera (Holland 1976). The trough, an uplifted fjordal valley, is filled with rolling to flat, gullied glacial and postglacial sediments with occasional bedrock outcrops. The bulk of the valley fill is comprised of glaciomarine mud and glaciofluvial gravels. Based on drilling results, the depth of glaciomarine sediment ranges from extremely shallow to in excess of 60 m.

The climate of the study area is classified as wet submaritime. Mean annual precipitation is 1300 mm, of which 1000 mm occurs between October and April. Mean annual temperature is 5.9°C (British Columbia Ministry of Forests 1997).

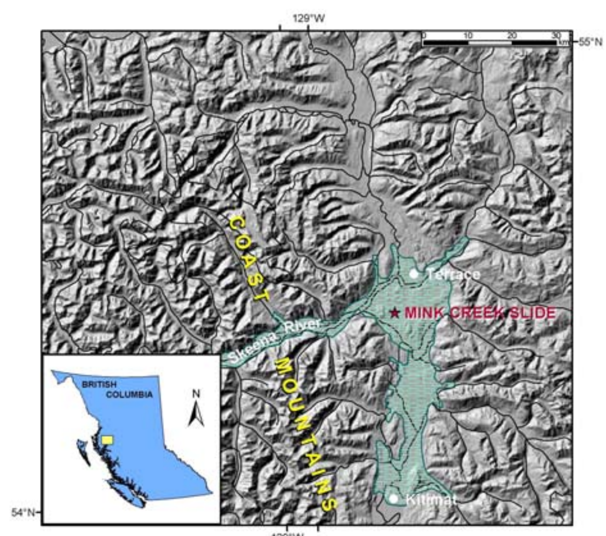

Figure 1. Map of the study area. Dashed area represents area of glaciomarine sediment.

The Quaternary geology and deglacial chronology of the study area has been described and mapped regionally by Clague (1984). Ice, in contact with the sea, retreated northward from Kitimat (at 11,000 ^{14}C yr B.P.) towards Terrace (at 10,100 ^{14}C yr B.P.), and eastward up Skeena Valley (Figure 1). Local sea levels, marked by glaciomarine delta surfaces, were 200 m higher than they are at present, and fell due to glacioisostatic crustal adjustments. Since subaerial exposure, salt from the marine sediments has been removed by freshwater, resulting in widespread sensitive clay development in the area (Geertsema and Schwab 1997). These sensitive clays have been subjected to both historic (Evans 1982) and prehistoric landslides (Geertsema and Schwab 1997).

1.2 Stratigraphy

Stratigraphy was observed from a variety of exposures and excavations in the zone of depletion and from a borehole (site B in Figure 3) above the main scarp. Thick cohesive glaciomarine deposits in excess of 60 m have been encountered in drill holes in the area between Terrace and Kitimat. Essentially the borehole provides a lower limit of 30 m on the thickness of the marine clay deposit. The sediment is composed of bedded silty clay with silt partings, occasional sand lenses, and rare drop stones and shells. In general a fissured upper brown oxidized crust, 3.5 to 4.5 m thick overlaid fissured, colour banded gray sediment. Horsetail (*Equisetum arvense*.) roots, extend vertically to depths of 4 to 4.6 m.

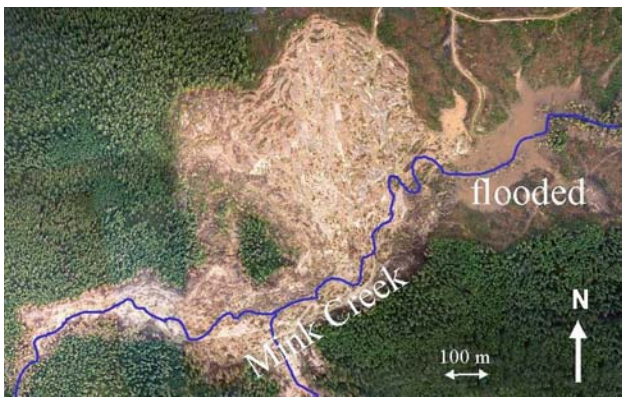

Figure 2. Aerial overview of the Mink Creek landslide in April 1994.

2. MORPHOLOGY OF THE LANDSLIDE

The morphology of landslides can provide important clues to the kinematics of failure. In particular, flowslides, a term used by Mitchell and Markell (1974), show wide variation in plan geometry, the amount of displaced material left in the zone of depletion, and the morphology of that displaced material (Carson and Geertsema 2002).

2.1 Overview of morphologic zones

The displaced material of the Mink Creek landslide covers an area of 43 hectares. The zone of depletion occupies 23 ha of this area, while the zone of accumulation fills 1.2 km of valley downslope of, and downstream of, the zone of depletion (Figure 2). To the east the landslide is bounded by a preslide gully. To the west, a 1 ha remnant of undisturbed forest separates the landslide from a smaller landslide that was probably triggered by the main event.

The zone of depletion forms two prominent arcuate depressions, which we refer to as the eastern and western widenings (Figures 3 and 4). The eastern widening is composed of six zones. These are the east marginal zone, the far east central zone, the east central zone, the inner zone, the butte, arranged from east to west, and the main scarp marginal zone, which separates the other zones from the main scarp. The western widening is composed of three zones: the mid west zone, the far west zone, and the main scarp marginal zone. The zones are differentiated on the basis of morphological features, and/or the orientation of these features.

2.2 Overview of features

The Mink Creek landslide deposits have a variety of patterns in plan form. These include ridges, hummocky topography, and organic debris. Gray ridge crests range from wavy, to cresentic, to slightly curvilinear, to straight with slightly curved ends, to straight (Figure 3). In some cases the ridges have transverse or longitudinal fractures. Vegetated surfaces often follow the patterns of these ridges, but have, in other cases, irregularly shaped plan forms. Most of the surface of the zone of depletion is covered with weathered, brown surficial sediment, in forms that include linear and curvilinear ridges, and broad areas with hummocky surface expression. In the centre of the zone of depletion there are also gray, planar rupture surfaces up to 700 m^2, dipping 2 to 3^{o} to the south. There is only one example where such a surface is convex rather than planar.

Ridges exhibit a variable internal disturbance. Gray ridges may be undisturbed, preserving horizontal preslide bedding, slightly disturbed, tilted, or severely remoulded. Brown ridges of surface material are invariably highly disturbed.

2.3 Brief Description of Zones

We describe the main scarp marginal zone and the remaining zones (Figures 3 and 4), numbered from east to west.

Zone 1, the main scarp marginal zone, 10 to 25 m wide, outlines an area transitional between the zone of depletion and material above the main scarp. The dominant forms in this zone are back-tilted blocks. Less common are areas with lobate ridge patterns where leading ridges are forward-tilted blocks. Here the zone is up to 40 m wide. Occasionally, horizontally stratified ridges occur immediately below the main scarp and parallel to it. In the eastern widening, more of the main scarp is exposed, and ridges are highly disturbed.

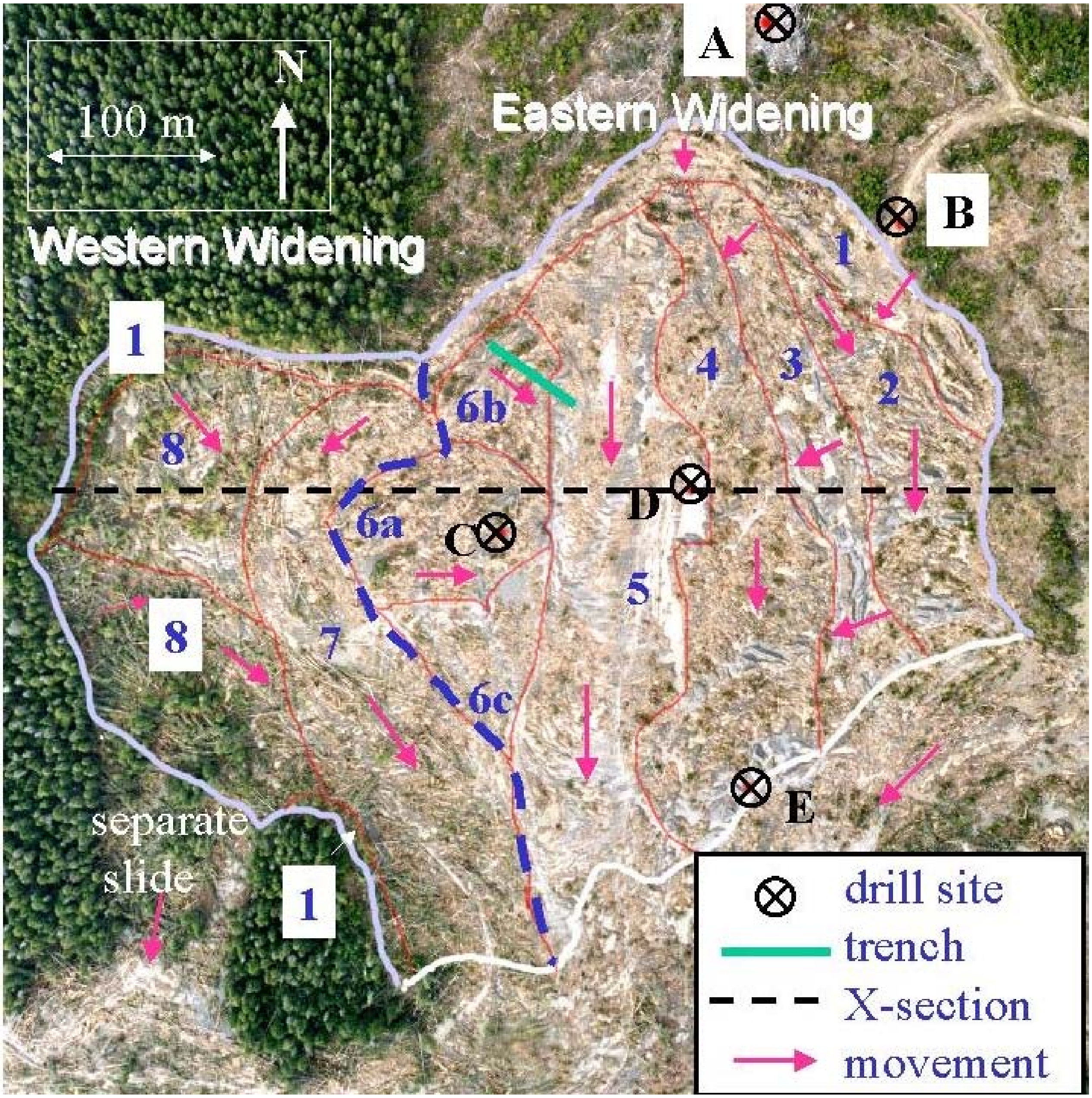

Figure 3. Aerial photo (35 mm) of the zone of depletion, April 1994. Note the locations of numbered zones (see text), vane shear sites (A to E), and the cross-section (Figure 6) and trench (Figure 7).

Zone 2, the east marginal zone, begins 25 m south of the main scarp and extends south about 300 m. At its northern end the zone is about 20 m wide, and widens to about 60 m over a distance of about 200 m. Along this wider section the zone is in contact with the east lateral scarp. The zone is characterized by gray ridges trending roughly east-west. These gray ridges occur in clusters and are separated by areas of brown weathered material. There also appear to be longitudinal shears inside this zone forming offsets in the displaced slide mass.

Zone 3, the far east central zone, 300 m long, is characterized by ridges trending roughly north-south. The zone is narrow, 25 m wide over its southern 75 m, widening to about 50 m in its northern portion. Gray ridges with horizontal bedding in this zone have split during movement. Back-tilted ridges (40° dip E) are stratigraphically higher than the horizontally stratified central ridges. The leading edge of the back-tilted ridge is covered with a thin veneer of oxidized mud.

Zone 4, the east central zone, is 300 m long and up to 100 m wide at its southern end, narrowing to about 30

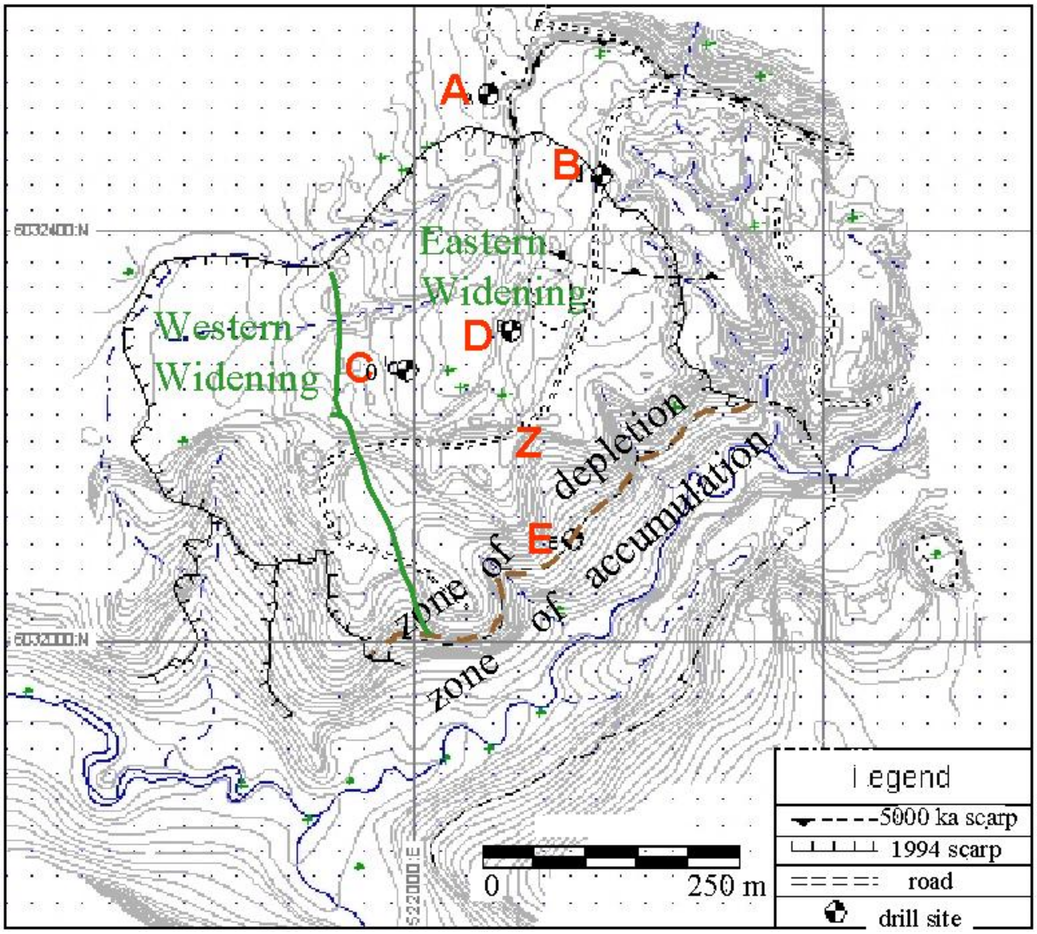

Figure 4. Detailed map of the zone of depletion showing preslide topography. Contour interval is 1 m. The first movement in the landslide probably occurred at site Z. Vane shear sites are lettered, A to E.

m in the north. This zone can be subdivided three ways. The northern subzone is characterized by a broad expanse of hummocks of oxidized surficial material. Occasionally gray unweathered depth material is exposed. The southern two subzones have gray ridges with horizontal stratification. The main difference is that the central part has ridges trending roughly east-west, and the southern part about 240°. The gray ridges occur in clusters and are surrounded by gray surfaces. A convexly curved rupture surface labelled site E (Figures 3 and 4) is exposed at the southern boundary of this zone at an elevation of 73 m.

Zone 5, the inner zone, is about 450 m long and up to 100 m wide over most of its length (Figure 3 and 4). It is flanked to the east by the east central zone (zone 4), and to the west by the escarpment of the butte (zone 6), and by merging flows of the mid west zone (zone 7). This zone contains no undisturbed ridges, and has extensive areas of exposed rupture surface.

Disturbed gray and brown ridges up to 2 m wide are oriented north-south, or in south pointing lobes. Broad gray and brown bands up to 200 m long and 15 m wide, oriented north-south are located in the northern part of the inner zone and south of the butte (zone 6). The orientations of these broad bands essentially mirror the orientation of ridges in zone 3, and are contiguous with ridges on the butte, respectively (Figure 5). Well-developed lateral and internal shear zones occur within this zone.

Zone 6, the butte, is a remarkable feature (Figure 5). In places near vertical walls, with horizontal beds rise from the slide floor to a maximum height of about 6 m (zone 6a), with a lower wall about 3 m (zone 6b) above the main slide surface. Zone 6c represents collapsed material south of the highest butte surface (Figure 3). Ridges up to 3 m high with respect to the surface of surrounding displaced material occur on these perched surfaces (Figure 5). The walls of the butte slope from 45 to 80°, and reveal continuous horizontal banding from the higher wall across the lower walls. Excavations south of the butte indicate a slope height of about 8 m between the basal rupture surface and its upper surface. Ridges, up to 3 m higher than the surrounding butte surface, have steep side slopes and near vertical flanks. The surface consists of preserved, horizontally bedded ridge fragments,

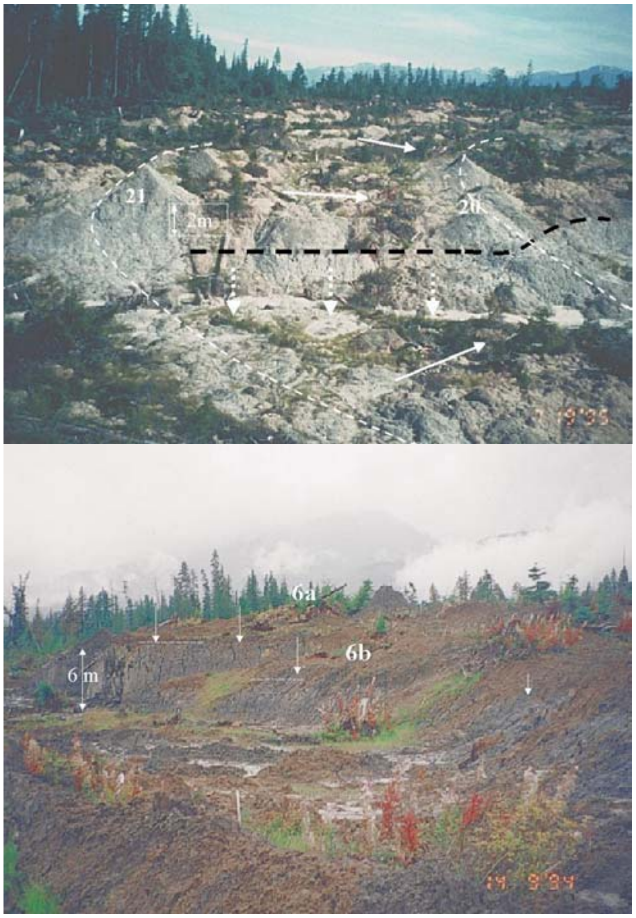

Figure 5. The butte (zone 6). a) Note ridge segments perched on the butte. Retrogressive spreading (solid arrows) was followed by subsidence (stippled arrows) of the southern part of the Butte (zone 6c, below zone 6a (Figure 3)). Black dashed line represents the upper surface of rupture. White dashed curved lines indicate position of ridge crests prior to collapse. Some remnants remain. b) note two rupture surfaces separated by 3 m elevation, the lower zone is 6c (Figure 3).

as well as tilted blocks and collapsed remoulded material. In plan, ridge fragments can be joined to form concave arcuate patterns (Figures 3 and 5a).

Zone 7, the midwest zone, up to 150 m wide and 300 m long is characterized by pronounced lateral and internal shear zones. These shear zones equal the length of this zone and extend beyond it into the zone of accumulation. This zone contains no undisturbed ridges. The zone incorporates two main flows. 1. Flow moving southwest from behind the butte, turning southeast, and flowing over the southwestern middle butte surface (zone 6c, Figure 3) incorporates material from the clearcut. This flow terminates at a longitudinal shear produced by the west margin of the inner zone. 2. A flow path acting as a channel for the western zone flows along the south margin (and at least 2 m below) the southwestern middle butte. The flow merges with the western margin of the inner zone and is separated by a longitudinal shear that extends well into the zone of accumulation. There are also other well-developed internal longitudinal shears, representing out of phase movement. The more southerly flow path is characterized by large coniferous trees, most of them laying oriented parallel to the flow direction. Some trees however, managed to remain standing after considerable displacement.

Zone 8, the far western zone, can be initially distinguished from the other zones by the presence of a large number of standing conifers. The zone contains classic horst graben topography with vertical subsidence and less translational movement than in other zones. As a result, many trees on subsided grabens remain rooted in the vertical position. Some of the prominent gray ridges are separated from the main scarp by a single graben. This zone contains the boundary between flow from the clearcut (around the butte), and southeasterly flow from the forested western zone via the midwest zone. There appears to be increased disturbance of the ridges towards the eastern margin of the zone. Split grabens also occur here.

3. INFERRED MOVEMENT HISTORY

3.1 Movement Indicators

Movement direction in the landslide is interpreted from the orientation of ridges, shear zones, and organic debris, as well as the locations of split cedar stumps. Undisturbed gray ridge crests are oriented transverse to interpreted movement directions. These ridges are similar to those reported in other flowslides (Carson 1977; Evans and Brooks 1994), where it is generally accepted that their alignment is at right angles to local movement. Ridges with crescentic, arcuate planforms indicate centripetal movement, while some tilted gray ridges have parabolic planforms, with centrifugal movement. Brown ridges exhibit lobate planforms, or longitudinal ridges, which are generally parallel to movement.

3.2 Movement Style

The style of movement can be interpreted from morphology and sedimentology. Transverse ridges separated by depressed wedges indicate retrogressive spreading or sliding. Longitudinal shear grooves indicate flow. Collapsed ridges indicate subsidence.

Displaced materials vary from exhibiting no internal deformation, to being slightly disturbed (plastic deformation), to being highly disturbed (full remoulding due to flow).

3.3 Movement Sequence

The detailed morphological descriptions of features in the zone of depletion provide some clues as to how when movements may have occurred relative to each other. Comparison of detailed pre and post landslide topographic maps, and observations of main scarp stratigraphy, and strength characteristics provide additional important data for the reconstruction of movements.

3.3.1 Initial triggering movement

Flow slides are often observed or interpreted to enlarge retrogressively, starting with a small earth slide, and enlarging into spreads or flows (e.g. Carson 1977, Gregersen 1980). A broad depression at location Z (Figure 4) has the rough outline of an old landslide scar. This may have been the location of an initial landslide that began a series of complex and much larger movements. Beside the landslide shaped profile of this slope, two other features support this location as the beginning of the initial landslide. 1. 1988 airphotos show ponded water on the road above the bend to the west of and above this slope. 2. The broad bands in the zone 5 (inner zone) and the ridges in zone 3 (far east central zone) are roughly equidistant from this potential triggering landslide. The orientation of those bands (interpreted as collapsed ridges) and ridges suggest eastward and westward movement, respectively, into a central cavity.

There are other steep locations on the north slope of the valley that could have experienced landslides, but an enlarging cavity at site Z is the only location that corresponds well with the interpreted eastward and westward movements described above.

3.3.2 The first translational landslide

It is assumed that a very sensitive layer was exposed in the main scarp of the assumed landslide at site Z. These sensitive strata would have liquefied, resulting in retrogressive enlargement of a central translational landslide. We assume that the elevation of this rupture surface was about 73 m at the edge of the zone of depletion, increasing up slope along the stratigraphic dip slope (about 3°). This is the map-measured elevation of site E (Figure 3), where the exposed convex rupture surface marks the edge of the zone of depletion and is perched about 10 m above the creek. It is essentially impossible to determine whether this second landslide was a flow or a spread, but there is a strong argument that material moved out of a relatively long narrow zone suggesting flow. Evidence for the presence of a long narrow central zone of depletion is provided in the following section.

3.3.3 Lateral movements into a central zone

This argument for lateral movement into a central cavity is based on the presence and orientation of the broad bands in the zone 5 and the ridges in the zone 3. If the broad bands were once transverse ridges, then the ridges in the zone 3 are, in fact, transverse ridges. We can also see that the north, up-flow end of these ridges bend toward each other. The presence of brown weathered material on ridge faces is generally interpreted to represent the leading, down-flow side of transverse ridges (Carson 1979, Geertsema and Schwab 1996). Accordingly, the brown weathered material draping the west slopes of ridges in the zone 3 suggests movement to the west. In a similar fashion, the broad bands in the zone 5 suggest movement to the east. Both movements are interpreted to have been in the direction of a central zone, normal to the southward stratigraphic dip.

There is evidence to suggest that the eastward movement occurred at a level about 5 m higher than the westward movement in the zone 3. This is further discussed under the section *Subsidence* (section 3.3.5).

3.3.4 Movements in response to lateral movement

Westward movement of ridges in the zone 3 (far east central zone) would have created a longitudinal temporary scarp trending roughly north-south. Following this westward movement, transverse ridges in zone 2 (east marginal zone) moved southward. It is possible that the movement was preceded by a separate earth slide on the slope below this zone. The orientation of several sets of ridges, with inter ridge weathered and surface material, suggest that the movement occurred by retrogressive spreading.

Eastward movement of ridges (later collapsed to broad bands) in zone 5 (inner zone) also triggered more movement. In this case, the surface of rupture was still perched 5 m above the rupture surface in the central zone of depletion. The two arcuate widenings on the butte, with east moving ridges, followed the eastward movement of the broad bands in zone 5.

The southward and westward extent of these widenings is constrained by the preslide topography. Projecting the butte surface southward, using a 4° southward bedding dip, Figure 6 shows that the slope height (H) is rapidly reduced along the south facing preslide slope. Given that the stability number (Ns) must be greater than or equal to 6 for retrogression to occur (Mitchell and Markell 1974), places constraints on Su. Similarly, a range of undisturbed shear strength, Su, values can give a range of constraints on the slope limits to retrogressive sliding.

Figure 6 illustrates why it was possible to have a perched rupture surface at the elevation of the upper *butte* (zone 6a) surface, and why it was impossible to have movements continue at this elevation, where preslide slopes decreased below a certain Ns-dependent threshold. These figures do not explain why movement occurred at this surface, rather than at a perhaps equally suitable lower surface. It is possible that movement simply relates to particularly sensitive layers. It is alternatively possible that the answer lies in the nature of the different colour bands in these sediments. At various locations bluish layers exposed in excavations flowed out of the exposed face. An excavation (trench in Figure 3) showed the rupture surface in a blue stratum (Figure 7). Vane shear tests on similar blue strata showed no striking differences in Su, Sr or S with other strata of different colour. Perhaps the difference lay in the higher rapidity of some of these blue layers. Rapidity is a term introduced by Söderblom (1974) referring to the energy required to transfer from the undisturbed state to the remoulded state, independent of the respective strengths of these two states. An exposed highly rapid layer would be more likely to transport material, than a layer of equal sensitivity, but lower rapidity.

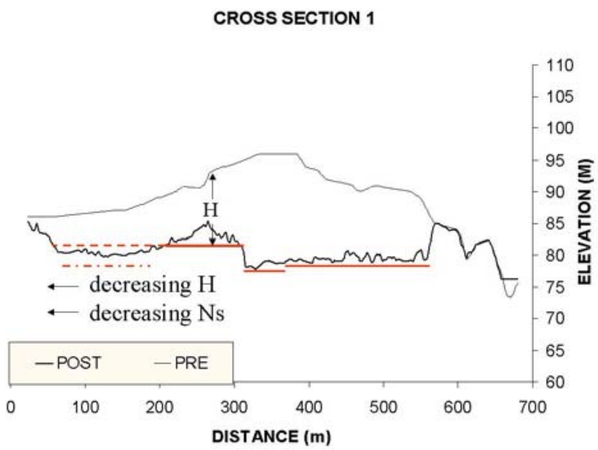

Figure 6. Cross-section showing pre and post landslide surfaces, from west to east. See Figure 4 for location.

Figure 7. A trench on the butte (zone 6b) exposes a rupture surface (white arrows) in a blue stratum. Red arrow indicates direction of movement.

3.3.5 Subsidence

The next major event in the eastern widening involved widespread subsidence. Subsidence south and east of the butte likely occurred first, with squeezed out material flowing south, along the general dip slope into the zone of accumulation. This subsidence was probably shortly followed by subsidence on the northern middle butte surface with flow to the east and southeast. Evidence for subsidence comes in several ways and is presented in the following paragraphs.

1. Transverse ridges on the southern edge of the upper butte surface have steep cross-sectional faces accordant with the butte wall. One such face occurs above the lower surface (Figure 5a), another above the southwestern middle surface.

2. The pattern of broad gray and brown bands, representing ridges and wedges or grabens, respectively on the lower surface south of the butte, conforms to the ridge pattern on the butte and has a similar mid-ridge spacing. Together these bands and ridges form arcuate planform crescents. Using form analogy, the broad bands in the inner zone can also be interpreted as ridges that have subsided along materials beneath the perched rupture surface. These ridges then mirror the orientation of ridges in the far east central zone.

3. The northern middle butte surface has a low horizontally stratified ridge protruding from a split graben. This ridge crest is separated from the mid point of collapsed gray material (a broad gray band) by about 30 m, a distance similar to the ridge spacing on the upper butte and of the broad bands. Particularly noteworthy is the presence of *Equisetum arvense* root channels in the ridge crest at elevation 84 m, while the preslide elevation was about 95 m here. Measured depth of these roots in excavations in the main scarp ranged from 4 to 4.6 m. thus the presence of horsetail roots places this crest about 4 m below the preslide surface. This indicates that the ridge subsided 7 m. The middle rupture surface is about 2.5 m lower than the upper rupture surface, indicating that amount of subsidence between the two surfaces. Thus the original height of the ridge was 4.5 to 5 m, which corresponds to ridge heights of 4.5 m on the upper butte.

3.3.6 Movements in response to subsidence

Lowering of the northern butte surface (zone 6b) triggered retrogressive movement to the northwest resulting in spreading, just east of the divide separating the eastern and western widenings (Figure 3 and 4). As the surface in zone 6c subsided to its present level, it was sufficiently lowered that it was able to become a channel for movement out of the western widening.

3.3.7 Movements in the western widening

The preslide ground surface sloped westward and southward in the western widening (Figure 6), yet the direction of movement of displaced material is primarily to the east and southeast. The preslide topography would suggest the gully east of the forest remnant, would have been a more likely movement route. It is likely that westward enlargement from the initial landslide at site Z (Figure 3 and 4), combined with southward flow from the inner zone, and butte collapse opened a channel for southeastward movement out of the western widening.

Once material began moving southeast through the southwestern zone, radial retrogressive enlargement of two sub-widenings began, and material on the west side of the butte and west of the divide east of zone 6b (Figure

3) moved southwest into the midwest zone. Evidence for westward movement is clearly provided by the displacement of the forest-clearcut boundary (Figure 3), and by transverse faulting of ridge 21 (Figure 5) on the butte. Later stage evidence for westward movement into the western widening is provided by tracing the displaced half of a split cedar stump back to its other half on the main scarp just east of zone 6b.

3.3.8 Late Stage Movements

Final movements in the zone of depletion included rotational sliding in the main scarp marginal zone, stretching and fracturing of ridges, areal exposure of the rupture surface by block sliding, shearing of groups of ridges, and flow between ridges down the stratigraphic dip.

4. CONCLUSIONS

- Detailed mapping of morphologic features and the deposits of the landslide at Mink Creek allow the reconstruction of the style and sequence of the movement.
- The dominant mode of movement was spreading. However, the landslide probably began in sediment which liquefied readily and flowed. This allowed a zone of depletion to retrogress into less easily liquefiable sediments which then spread. The movement ended with rotational sliding close to the present main scarp.
- The landslide clearly shows stepped surfaces of rupture. The general multiplicity of rupture surfaces may be related to multiple soft strata.
- Subsidence occurred not only in wedges, but also in ridges, and up to 8 m below rupture surfaces following spreading.

ACKNOWLEDGEMENTS

We thank M.A. Carson for discussions that contributed to this paper, Vanessa Egginton, Les Higgs, and David Stuart for assistance with some of the figures, and Andrée Blais-Stevens for translating the abstract.

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