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GEOMORPHIC CONTROLS ON LANDSLIDE ACTIVITY IN CHAMPLAIN SEA CLAYS ALONG GREEN'S CREEK, EASTERN ONTARIO, CANADA

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ABSTRACT Landslides in Champlain Sea clays have played an important role in shaping Eastern Ontario's landscape. Despite extensive research, there is a limited understanding of the relations between landslide activity, climatic controls, and the geomorphic evolution of river valleys in Champlain Sea clay deposits. With these issues in mind, a study was undertaken to determine the controls on the spatio-temporal distribution of contemporary landslide activity in valley slopes composed of Champlain Sea clay. The study area was the Green's Creek valley located in the east end of Ottawa, Ontario. Observations and measurements indicate that landslide activity is closely related to valley development. An inventory of landslide activity from 73 years of aerial photographs revealed that landslides occurred preferentially in slopes located on the outside of meander bends, and that they often recurred in the same slope after a period of ripening. The largest and highest density of landslides occurred along a major tributary valley where geomorphic features such as knickpoints, V-shaped valley profiles and bedrock depth-to-slope height ratios reflect an unstable phase of valley development. A small number of landslides incurred successive failures along the slopes of the backscarp for several years-to-decades after the initial failure. Correlation analysis showed that the temporal distribution of landslide activity has fluctuated in response to decadal-scale changes in the amount of precipitation.

RÉSUMÉ *Contrôles géomorphiques de l'activité des glissements de terrain dans les argiles de la Mer de Champlain le long de la vallée Green's Creek, est de l'Ontario, Canada*. Les glissements de terrain qui se sont produits dans les vallées creusées dans les argiles de la Mer de Champlain ont joué un rôle déterminant dans la formation du paysage de l'est de l'Ontario. Malgré de nombreuses recherches, les relations entre les glissements de terrain, le climat et le creusement des vallées fluviales de la région demeurent peu connues. La présente étude a pour but d'identifier les mécanismes qui régissent la distribution spatio-temporelle des glissements de terrain contemporains dans les vallées de la région d'Ottawa, en Ontario, et plus particulièrement dans la vallée de Green's Creek. Des observations et des mesures de terrain ont permis de démontrer que les occurrences de glissements de terrain étaient fortement tributaires des phases de développement de la vallée. Un inventaire des glissements de terrain réalisé à l'aide de photographies aériennes couvrant une période de 73 ans démontre que ceux-ci se produisent sur la berge externe des méandres et qu'ils ont tendance à se répéter aux mêmes endroits. Les plus grandes densité et diversité de glissements ont été observées le long d'un ruisseau tributaire présentant de nombreuses ruptures de pente, un profil transversal en V et un rapport profondeur de la roche-mère/ hauteur de la pente indiquant que la vallée passe par une phase instable de son développement. Quelques glissements de nature régressive sont demeurés actifs plusieurs années après leur formation. Une analyse de corrélation entre la fréquence des glissements de terrain et la quantité des précipitations indique que la répartition temporelle des glissements est étroitement liée aux variations de précipitations à l'échelle de la décennie.

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INTRODUCTION

Landslides have played an important role in the post-glacial geomorphic development of Eastern Ontario's landscape. They range from massive ancient landslides situated along the margins of broad paleovalleys, to scars several orders of magnitude smaller situated along younger river valleys. Despite relatively low relief, portions of Eastern Ontario have been predisposed to landsliding because of the widespread occurrence of a glaciomarine clay informally known as Champlain Sea clay or Leda clay. This clay was deposited during a marine transgression known as the Champlain Sea (13 000-10 000 BP) which followed the retreat of the Laurentide Ice Sheet to the north. Champlain Sea clay is notorious for its sensitivity, that is, the ratio of its undisturbed strength to its remolded or residual strength at natural water content. Once disturbed, the clay's shear strength may reduce considerably, leading to liquefaction and the rapid propagation of failure.

Surficial mapping and radiocarbon dating have revealed that the landslides in Eastern Ontario are much smaller today than they were in the past (*cf.* Eden, 1967; Gadd, 1976; Aylsworth *et al.*, 2000). Nowadays, most landslides are situated along the slopes of active river valleys which have incised the Champlain Sea clay deposit. They occur almost annually and pose a substantial risk to development in the vicinity of the river valleys. Considerable research has been undertaken in the last fifty years in an attempt to better understand and ultimately reduce the hazard associated with landslides in Champlain Sea clays. Significant progress has been made in understanding the chemical and mechanical properties of the clay deposits (Mitchell, 1970; Quigley, 1980; Torrance, 1983, 1988; Tavenas, 1984), the mechanics of the landslides (Eden and Mitchell, 1970; Mitchell and Markell, 1974; Lefebvre, 1981; Demers *et al.*, 1999), triggering factors (La Rochelle, 1975; Aylsworth *et al.*, 2000), and slope stability (Crawford and Eden, 1967; Lo and Lee, 1974; Lefebvre, 1981). Several studies have developed inventories of landslides in clay deposits and have demonstrated the importance of erosion on landslide activity in active river valleys (Bjerrum *et al.*, 1969; La Rochelle *et al.*, 1970; Williams *et al.*, 1979; Lebuis *et al.*, 1983; Locat *et al.*, 1984). In spite of important progress, there remains a limited understanding of the spatio-temporal characteristics of the landslides and their relation to valley development in Champlain Sea clay deposits.

To address these issues, a study was undertaken to investigate landslide activity in a small river valley in the east end of Ottawa, Ontario (Fig. 1). This river valley occurs within a major urban area and is crossed by many roads and bridges. Although the landslide hazard in this valley is well known and development is limited, there are a few large buildings and several roads running alongside the valley in the upper reach. Many geotechnical studies were undertaken in the area during the early and mid 1970s (Eden and Mitchell, 1970; Mitchell,

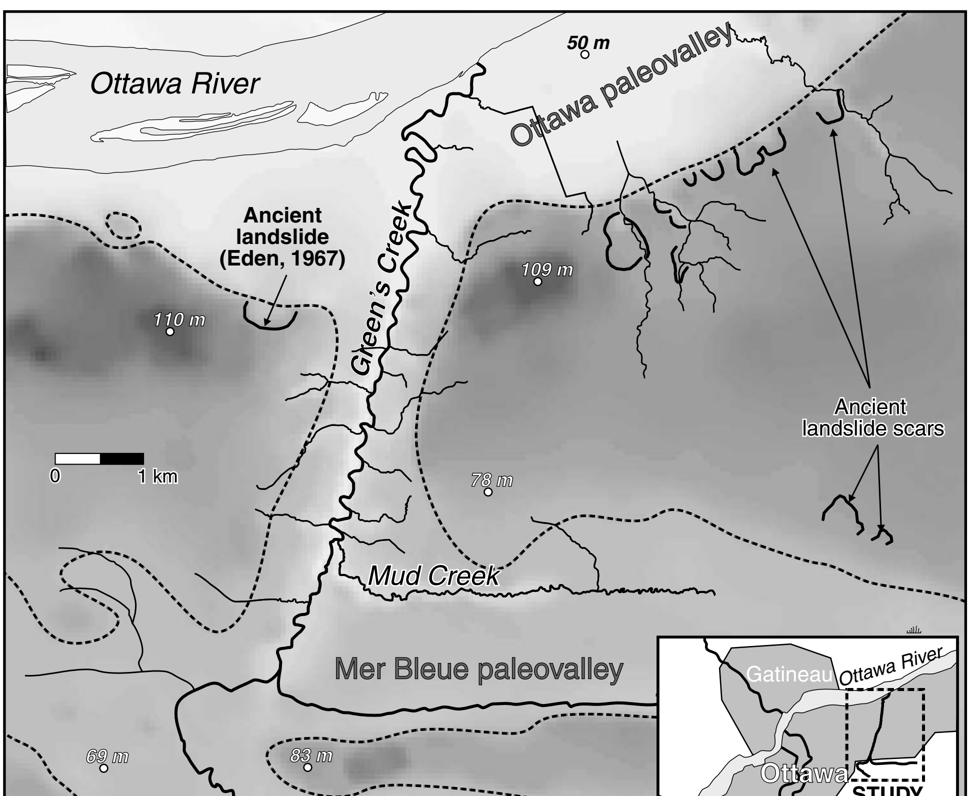

Figure 1. Location of study area. Ancient landslide scars are indicated by the thick dashed lines. Spot elevations given in metres above sea level. The dashed lines indicate the approximate boundaries of the Ottawa and Mer Bleue paleochannels (*cf.* Aylsworth *et al.*, 2000).

Localisation du site d'étude. Les cicatrices des anciens glissements de terrain sont indiquées par les traits hachurés épais. Les altitudes sont en mètres au-dessus du niveau de la mer. Les lignes hachurées minces indiquent la limite approximative des anciens chenaux de la rivière des Outaouais et de la tourbière de la Mer Bleue (Aylsworth et al.*, 2000).*

1970; Sangrey and Paul, 1971; Mitchell and Eden, 1972; Klugman and Chung, 1976); however, many landslides have occurred since that time and there remains a limited understanding of the controls on landslide activity in this valley. The main objective of the study was to investigate the characteristics and controls on the spatio-temporal distribution of landslides with a particular focus on the relation between landslide activity, valley development, and climatic controls. The approach involved observations from historical aerial photographs in order to develop an inventory of landslides, digital image processing and photogrammetry to map changes in the landscape, GIS analysis to investigate controlling variables, and analysis of historical precipitation trends.

STUDY AREA

The Green's Creek valley (Fig. 1) was chosen as the study area because a lengthy and detailed aerial photograph record (1928-1999) exists and numerous landslides have occurred in modern times. The creek drains northward into the Ottawa River and is the principle drainage route for the Mer Bleue Bog. A prominent tributary of Green's Creek is an east-west trending creek named Mud Creek. The main body of Green's Creek is entrenched in a paleovalley connecting the informally-named Ottawa and Mer Bleue paleovalleys (Aylsworth *et al.*, 2000). The paleovalleys are part of the Proto-Ottawa River which developed during recession of the Champlain Sea around 10 000 BP and consisted of a broad network of interconnecting channels (Fransham and Gadd, 1977). Most of the paleovalleys were probably abandoned by about 8000 BP (Aylsworth *et al.*, 2000). The Ottawa River occupied its modern position within the northern channel around 4600 BP (Fulton and Richard, 1987).

Incision of modern valley systems in Eastern Ontario occurred sometime after 8000 BP in continuing response to regional base level lowering. The latter was a byproduct of isostatic rebound. As the base level lowered, the groundwater regime evolved from hydrostatic to down-drained conditions (Jarrett and Eden, 1970; Fransham and Gadd, 1977). In the Green's Creek valley, the timing of incision is broadly constrained by a basal peat age of 7600 BP (68 m asl) from the Mer Bleue Bog (Aylsworth *et al.*, 2000), which establishes the latest date for abandonment of the Mer Bleu and Green's Creek paleovalleys (Fig. 1). Incision of Green's Creek probably began sometime around 7600 BP.

A synthesis of borehole logs in and around the Green's Creek valley (Sangrey and Paul, 1971; Bozozuk, 1976; Bélanger, 1994) reveals that four major stratigraphic sequences are commonly found overlying Paleozoic bedrock. In some areas the oldest sequence overlying the bedrock is a thin layer of till. In other areas there is glaciofluvial sediment instead of till. These sediments, herein referred to as the till/glaciofluvial sequence, are overlain by a freshwater varved sequence containing variable amounts of silt and clay (Gadd, 1962). The varved sequence is generally 2-8 m thick (Fransham and Gadd, 1977) and grades into a massive clay sequence. The clay sequence also contains variable amounts of silt and clay and is locally subdivided into two facies: a lower marine clay facies and an upper stiff, weathered clay facies. The initial stages of landslides in the Green's Creek valley appear to be confined to the upper facies (Sangrey and Paul, 1971; Eden, 1975), which is up to 12 m thick (Eden and Mitchell, 1970; Sangrey and Paul, 1971; Eden, 1975) and interbedded with narrow silt layers that reflect variations in material and currents transporting the sediment. Gadd (1962) and others have inferred that the upper clay facies was re-worked and re-deposited in an estuarine or prodelta environment during the late stages of the Champlain Sea. Geochemical analyses of borehole samples indicate that the two clay facies can be distinguished according to pore water chemistry; higher quantities of sodium and iron are found in the marine clay while there is more calcium and magnesium in the upper clay (Sangrey and Paul, 1971; Haynes, 1973). The sensitivity of the upper clay facies is much lower than the marine clay (*cf.* Eden and Mitchell, 1970; Sangrey and Paul, 1971), and it is generally recognized that the dramatic flow-like or "quick clay" landslides are generated when the more sensitive clay is involved. The term "quick clay" defines a clay with a sensitivity of 50 or more and a fully remoulded shear strength of less than 0.4 kPa (Rankka *et al.*, 2004). Engineering properties from boreholes in the Green Creek valley (*cf.* Sangrey and Paul, 1971) indicate that the upper clay facies generally has low (<8) to moderate (8-30) sensitivity, but it can be highly sensitive (>30) near the interface with the lower marine clay facies. The top-most sequence found in the study area, where present, consists of fluvial or deltaic sands deposited during the post-marine fluvial regime (10 000-8000 BP). The sands are highly variable in thickness but generally do not exceed 3 m locally.

Contemporary and ancient landslides have been studied within and around the Green's Creek valley (Crawford and Eden, 1967; Eden, 1967; Eden and Mitchell, 1970; Sangrey and Paul, 1971; Mitchell and Eden, 1972; Klugman and Chung, 1976; Fransham and Gadd, 1977). Several large ancient earthflows and retrogressive slumps occur along the northern and eastern margins of the valley (Fig. 1). The largest ancient landslide in the study area is the Beacon Hill landslide which involved approximately 1.5 million m^3 of material (Eden, 1967). The spoil apron seems to be unaltered since the original failure, which implies a lack of fluvial erosion at the time of failure. Larger ancient earthflow complexes have been reported by Gadd (1976) and Aylsworth *et al.* (2000) further east and northeast (30-45 km) of the study area, ranging in size from an estimated 10^6 to 10^8 m^3.

DATA SOURCES AND ANALYSES

AERIAL PHOTOGRAPH ANALYSIS

Aerial photographs from the National Air Photo Library and the City of Ottawa were obtained for the study area for 30 intervals from 1928 to 1999. Photographs were used to develop an inventory of landslides, to map their activity through time, and to map changes in planimetric channel geometry induced by the landslides. The scales of the photographs used in this study ranged from 1:15 000 to 1:6 000. In many cases it was possible to determine the timing of landslides at an annual or a seasonal interval; however, this was not possible for all segments of the valley due to irregular photograph coverage. Most segments of the valley were flown at the beginning and middle of each decade starting with 1950 (*i.e.*, 1950, 1955, 1960, …, 1995). This provided a means of classifying landslides into two time intervals: 5-year and 10-year. The 5-year interval spans the period from 1970 to 2000, corresponding to a period in which air photos were acquired almost annually. The 10-year interval spans the period from 1950 to 2000. Air photos were supplemented by ground observations along the entire valley in the spring of 2000 and 2001.

From the inventory, landslides were classified into four modes of failure modified from Varnes (1978) and Poschmann *et al.* (1983): (i) simple rotational slides, (ii) retrogressive rotational slides, (iii) translational slides, and (iv) flows. In a simple rotational slide the surface of rupture is concave upward and the mass rotates along the concave shear surface. Simple rotational slides involve a single shear surface whereas retrogressive rotational slides involve multiple or successive shear surfaces. In a translational slide, the surface of rupture is a planar or gently undulatory surface. Translational slides tend to be shallow and are often referred to as sheet slides (Poschmann *et al.*, 1983) or surficial slides (Lefebvre, 1986). Landslides classified as flows exhibit signs of fluid-like movement. They may start as a rotational slide, but liquefaction of the displaced material quickly evacuates debris from the scar. Examples of each type of landslide are presented in Figure 2.

Digital photogrammetric techniques were used to measure changes occurring in the valley as the result of landslide activity. A review of the available aerial photographs was undertaken to select photographs with comparable properties. Some of the photographs could not be used due to significant shadowing effects or poor photographic film quality. Scanning of the photographs was done at a resolution of 600 dpi and included the fiducial marks. Following scanning, the images were digitally rectified to produce planimetrically true images. The approach developed for this procedure was

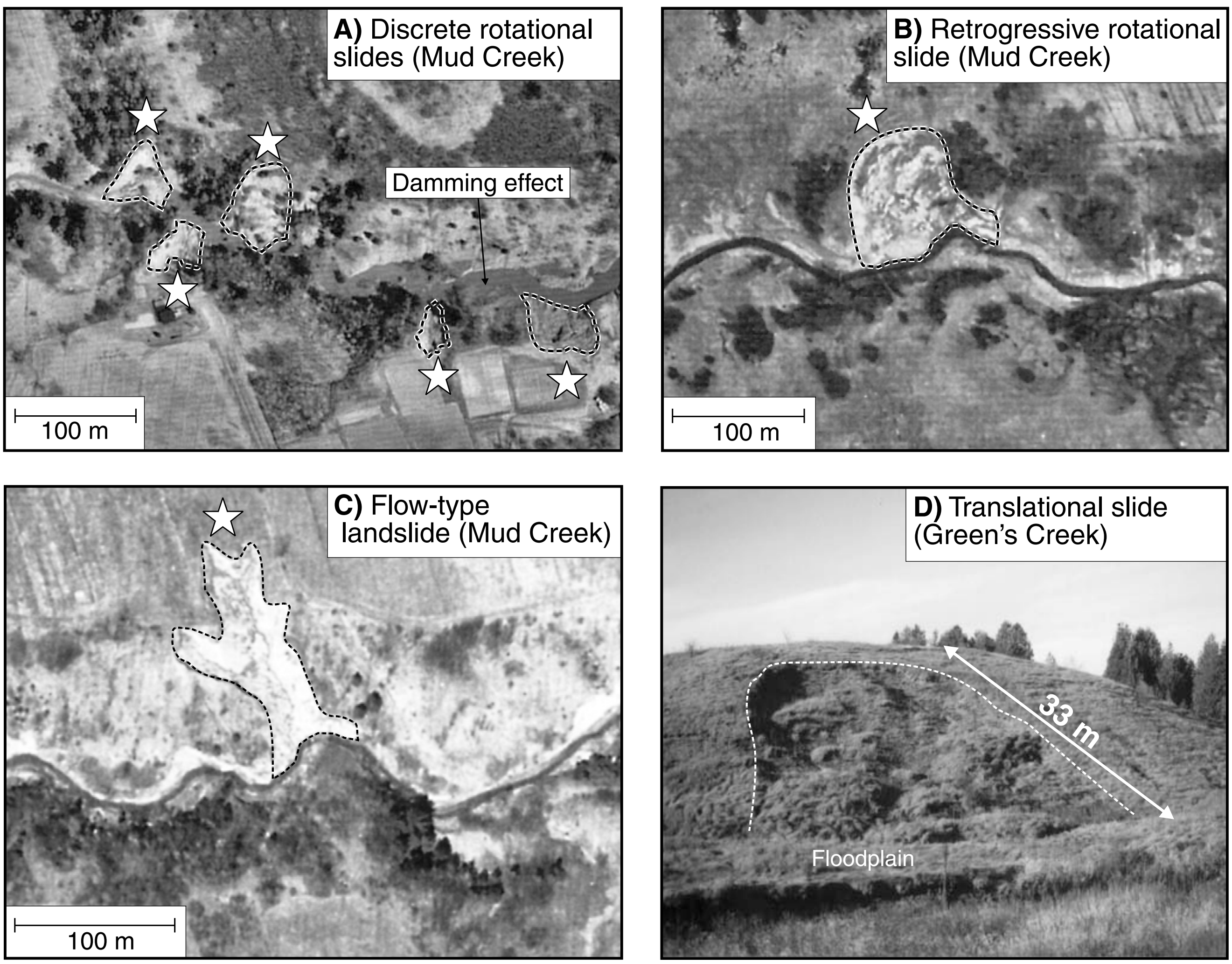

Figure 2. Examples of different types of landslide in the study area. The stars indicate the location of landslides in the photographs. Photographs A, B and C were obtained from the National Air Photo Library (photograph no. A24850-33, A27272-146, and A23958-20, respectively).

Exemples des différents types de glissements de terrain observés sur le site d'étude. Les étoiles indiquent la localisation des glissements de terrain sur les photos. Les photos A (A24850-33), B (A27272-146) et C (A23958-20) ont été fournies par la Photothèque nationale de l'air.

based on the selection of a master photograph for a given segment of the valley. The master photograph was rectified to a cubic polynomial surface using a total of 7-11 Ground Control Points (GCPs) collected with a GPS. The remaining photographs were rectified relative to the master photograph using 7-11 tie points. Changes resulting from landslide activity were mapped in a GIS by digitizing the landslide scars and channel geometry from the rectified images.

GIS AND PRECIPITATION DATA

GIS data were used to assess the impacts of landsliding on valley development and to determine possible controls on their spatial distribution. The GIS data included borehole logs, hydrology coverages and digital elevation models (DEMs). The borehole logs were compiled from several sources (Sangrey and Paul, 1971; Bozozuk, 1976; Bélanger, 1994). A photogrammetrically-derived 10 m DEM was obtained from the City of Ottawa and used to investigate the morphological characteristics of the valley. Borehole logs and a 30 m DEM were used to develop a map of the bedrock elevation which was compared with landslide activity. Previous studies have demonstrated that the depth to the till/glaciofluvial sequence overlying the bedrock may indirectly control the distribution and type of landslides that develop (La Rochelle *et al.*, 1970; Lafleur and Lefebvre, 1980; Lefebvre, 1986). A map of bedrock depth was used as a surrogate for the elevation of the till/glaciofluvial sequence. The map was produced by interpolating the borehole data. Several different interpolation algorithms were tested and then verified using two different approaches. The first approach involved a comparison of the interpolation models with bedrock elevations obtained from seismic refraction surveys conducted in 1999 along Mud Creek. The second approach involved excluding a small selection of boreholes from the interpolation and then using them to verify the accuracy of the different interpolation models. Ultimately, the data obtained from the kriging model showed that the error was very small, with only some locations showing any sizeable departures from the actual elevations. The interpolated map was very similar to an existing map of bedrock depth (*cf.* Bélanger, 2001), though the map produced in this study exhibited greater detail in terms of elevation classes.

Monthly precipitation data were examined to determine possible hydrometeorological controls on the temporal distribution of landslides. The data were acquired from a climate station operated by Environment Canada at the Central Experimental Farm (Climate ID: 6105976) approximately 12 km to the southwest of the confluence of Green's Creek and Mud Creek. Missing data were estimated by averaging values from five nearby stations.

RESULTS

HISTORICAL LANDSLIDE ACTIVITY

A total of 52 landslides were identified between 1928 and 2001 (Fig. 3). The highest density of landslides occurred along Mud Creek followed by the lower and middle reaches of Green's Creek, respectively. Very few landslides were observed in the upper reach of Green's Creek beyond the confluence with Mud Creek where slopes are much lower and bedrock is exposed in many areas above the level of the creek. A unifying characteristic of the landslides observed in the aerial photographs is their preferential occurrence in slopes situated on the outside of meander bends (n = 50), which is expected since flow impingement concentrates fluvial erosion at the outer bank. This characteristic confirms previous reports concerning the importance of fluvial erosion and oversteepening in setting up the geometric conditions for landsliding to occur in clay deposits (*cf.* Bjerrum *et al.*, 1969; La Rochelle *et al.*, 1970; Williams *et al.*, 1979; Lebuis *et al.*, 1983; Locat *et al.*, 1984). The only exceptions to this trend are the two translational landslides near the confluence of Green's Creek and Mud Creek. These slopes are rarely subjected to fluvial erosion as there is an intervening floodplain (Fig. 2D).

The types of the landslides, also identified in Figure 3, are dominated by simple rotational slides (75 %) followed by retrogressive rotational slides (13 %), flows (8 %), and translational slides (4 %). The prevalence of simple rotational slides supports the perception that most landslides are restricted to the upper weathered clay facies. However, the occurrence of four landslides classified as flows in the early 1970s indicates that some failure surfaces may extend down to the sensitive marine clay. The size ranges of the different classes of landslides determined from field measurements is as follows (length x width): (i) simple rotational slides ranged from 25 x 25 m to 40 x 60 m; (ii) retrogressive rotational slides ranged from 47 x 60 m to 48 x 94 m; (iii) translational slides ranged from 30 x 33 m to 42 x 40 m; and (iv) flows ranged from 40 x 50 m to 57 x 90 m. There is a subtle trend in which larger landslides have occurred more frequently between 1928 and 2001 along Mud Creek. The largest landslide in terms of total volume was a retrogressive rotational slide along Mud Creek which measured 55 m across, 78 m in length and was more than 7 m deep in places (estimated volume is 28 000 m^3). The smallest landslide was a simple rotational slide (Fig. 2D) which measured 25 m across, 25 m in length, and 2 m deep (estimated volume is 1 250 m^3).

In addition to having larger landslides, the valley along Mud Creek also has a greater diversity of landslide types. Retrogressive rotational slides are almost completely restricted to this section of the valley. Furthermore, three of the four landslides classified as flows are located along Mud Creek. One of the flows along Mud Creek jeopardized construction of the Ottawa Detention Centre in the spring of 1972 and produced a scar 85 m in length and 26 m wide.

It is important to note that the valley along Mud Creek has experienced significant changes in land cover over the course of the aerial photograph record (1928 to 1999). Forest cover has steadily increased since the 1960s as agricultural activities have been abandoned in nearby fields. Similar changes have occurred along the lower reach of Green's Creek, however very little land cover change has occurred in the middle reach of Green's Creek where the forest cover adjacent to the creek has remained high throughout the 73 year photograph record. The latter observation may elucidate why the frequency

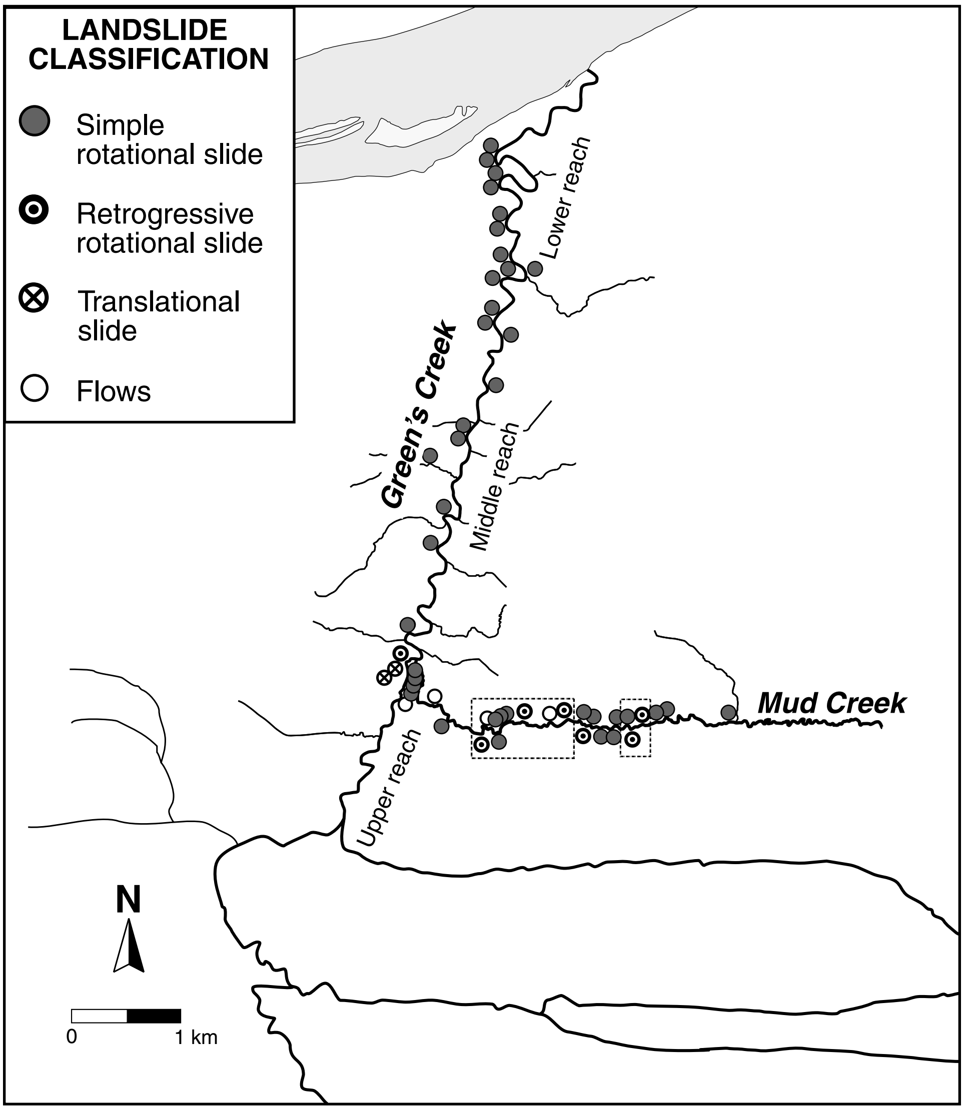

Figure 3. Distribution and types of landslides in the study area between 1928 and 2001. The dashed boxes identify segments of Mud Creek mapped in Figures 4A and 4B.

Répartition et types de glissements de terrain signalés dans la région d'étude entre 1928 et 2001. Les cadres hachurés circonscrivent les segments de Mud Creek cartographiés aux figures 4A et 4B.

and diversity of landslide types is much lower along the middle reach because forest cover, particularly the tree root system, helps stabilize the hillslopes by reinforcing soil shear strength (Greenway, 1987). A similar observation was made by Locat *et al*. (1984) for landslides in the rivière Chacoura Valley near Louiseville, Québec. It is possible that a continued increase in forest cover will reduce the size and number of landslides along Mud Creek.

The lengthy aerial photograph record made it possible in many cases to review the slope characteristics before landslides occurred. From a review of 36 landslides with detailed antecedent photograph coverage, 30 occurred in slopes that exhibited signs of earlier landslide activity, suggesting that many slopes in the study area experience recurrent episodes of landslide activity. The other six landslides appear to be first-time occurrences. The main indication of antecedent landslide activity is the presence of a bowl-shaped hollow (concavity) on the slope prior to the most recent landslide. The bowl-shaped hollows are interpreted as former scar surfaces from previous landslides. An aerial photograph taken at a low sun angle in 1973 showed that bowl-shaped hollows are a major morphological feature of virtually all segments of the valley. The hollows are also a prominent feature when viewed from ground level and many of them terminate well above the present channel.

Observations of successive aerial photographs over two sections of Mud Creek showed that some landslides expanded dramatically for up to several decades after the initial failure. Furthermore, it was noted that some of the spoil debris from landslides caused changes to the planimetric geometry of the creek. To quantify these characteristics, change detection was applied to planimetrically corrected aerial photographs (Fig. 4). The most significant and prolonged changes occurred at the retrogressive rotational slides where large slide blocks were dislodged along the backscarp. One of the retrogressive landslides along Mud Creek incurred more than 30 years of episodic failure following the initial landslide in the late 1940s (Fig. 4B). By the time this landslide stabilized in the early 1980s,

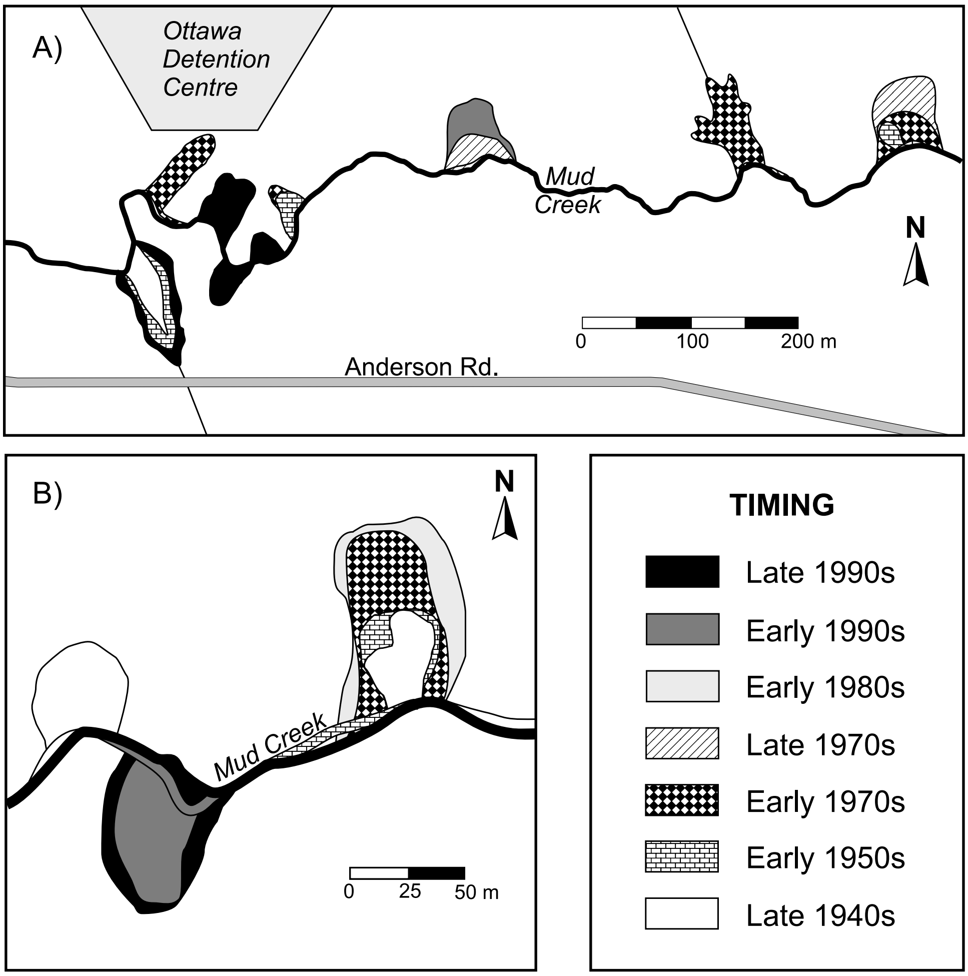

Figure 4. Landslide activity maps along two segments of Mud Creek. The location of the segments is depicted in Figure 3.

Cartographie de l'activité des glissements de terrain le long de deux segments de Mud Creek. Ces segments sont localisés à la figure 3.

the scar was more than six times larger than initially (*i.e.*, from 625 m^2 to 4 300 m^2). Several landslides not shown in Figure 4 also exhibited multiple decades of retrogressive activity, including the Pineview 'Golf Course' landslide previously reported by Mitchell (1970) and Sangrey and Paul (1971). The scars of landslides classified as flows did not show any signs of continued activity after the initial landslide which suggests that they were effective at reducing slope instability. Similarly, the simple rotational slides showed minimal post-landslide activity aside from some sloughing along the backscarp.

The change maps in Figure 4 indicate that some landslides caused changes to the channel geometry. Many of the simple rotational landslides and flows had temporary impacts on creek hydrology such as flooding, which occurred when spoil debris blocked the channel (Fig. 2a). The only type of landslide to have any lasting impact on creek geometry (*i.e.*, years-to-decades) was the retrogressive rotational slides, which reduced the local meander amplitude adjacent to the landslide.

LANDSLIDE ACTIVITY AND VALLEY DEVELOPMENT

When individual landslides are examined, as is often the case in site-specific studies, it can be difficult to determine whether some aspect of valley development may have influenced the location and size of the landslide. However, given a large sample of landslides, as is the case here, some general relations may become more apparent. This is illustrated in Figure 5 where the distribution of landslides is plotted against the longitudinal creek gradient. The most notable relation in Figure 5 is the clustering of landslide activity along one of two knickpoints in Mud Creek. Knickpoints are points of abrupt change in bed slope usually associated with a lagged adjustment to changes in base level. From a spatial perspective, knickpoints form a boundary between landforms that have adjusted to the new base level and those that have not. The latter interpretation suggests that the valley slopes along Mud Creek are continuing to adjust to the present base level (lagged response) while the valley slopes along the lower and middles reaches of Green's Creek are closer to a steady state with the present base level.

Another aspect of valley development that may influence landslide activity is the cross-valley profile. Analysis of spatial variations in cross-valley profiles helps determine whether the phase of valley development (incision) has exerted an influence on the level of landslide activity (*cf.* Palmquist and Bible, 1980; Schmidt, 2001). Fifteen cross-valley profiles extracted from the 10 m DEM are shown in Figure 6. The profiles reveal a spatial transition of the valley character, from a trough valley

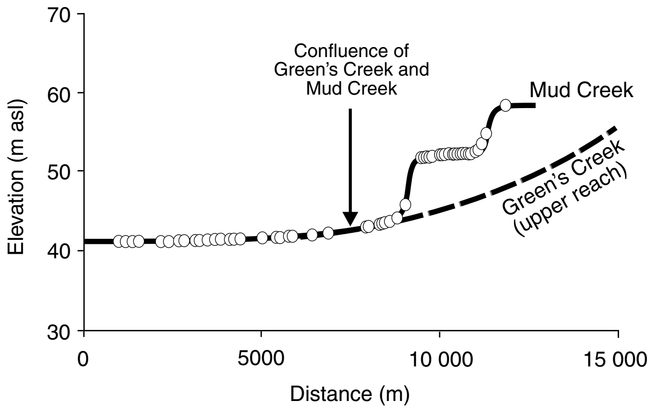

Figure 5. Longitudinal gradients of Green's Creek and Mud Creek derived from a 10 m digital elevation model (DEM) provided by the City of Ottawa. The location of landslides (small circles) was derived from the inventory in Figure 3.

Profils longitudinaux de Green Creek et Mud Creek obtenus à partir d'un modèle numérique de terrain (MNT) de 10 m de résolution fourni par la ville d'Ottawa. La localisation des glissements de terrain (cercles) est dérivée de la distribution observée à la figure 3.

in the lower reach to a V-shaped form along Mud Creek. The trough valley in the lower reach has relatively low relief and wide floodplains. Relatively minor changes in channel elevation along the lower reach suggest low incision rates and steady state conditions with respect to the present base level. The transition between the lower and middle reaches occurs abruptly between profiles 2 and 3, where the Green's Creek paleovalley intersects the Ottawa paleovalley (Fig. 1). The middle reach is slightly wider than the lower reach and is much deeper. Similar to the lower reach, minimal changes in the elevation of the channel suggest low incision rates. The transition between the middle and upper reaches of the valley is gradual. The latter is much narrower and shallower than the other valley segments. The most unstable profiles in the context of valley development are found along Mud Creek. Here the cross-valley profiles are dominantly V-shaped and the slopes commonly exhibit benched profiles (Fig. 6B). The V-shaped profiles are related to active incision and the convex slope profiles are a sign of erosion and oversteepening.

The geometry of the valley profiles has an important influence on the seasonal water level fluctuations in the creek, which in turn affects slope stability and landslide activity. During the spring floods, which can vary significantly in magnitude from year to year, flood water is spread out more evenly in the reaches of the valley with broad flood plains, particularly the lower reach. Consequently, toe erosion is limited to a narrow vertical zone on exposed slopes. In contrast, the narrow channel and V-shaped profiles along Mud Creek allow for higher water levels during spring floods that result in toe erosion. This effect is also enhanced by numerous beaver (*Castor canadensis*) dams along Mud Creek which periodically burst and lead to rapid drawdown. The latter occurs if pore water pressure in the slopes fails to adjust rapidly to the lower water levels in the creek.

INFLUENCE OF BEDROCK DEPTH

The elevation of the lower till/glaciofluvial sequence has an important effect on the groundwater flow regime (*cf.* Lafleur and Lefebvre, 1980). Depending on its elevation with respect to the valley bottom, the lower till/glaciofluvial sequence (*i.e.* lower boundary) may influence slope stability conditions and the type of landslide that may develop (Lefebvre, 1986). In this way, slope stability and landslide activity evolve concomitantly with valley development.

Lefebvre (1986) suggested that the stability of slopes and the size of landslides pass through three broad phases as the valley deepens and the more permeable till/glaciofluvial sequence becomes exposed at the base of the slope (Fig. 8). In the early phase, this lower boundary is deep relative to the valley bottom and the groundwater pattern is characterized by a slight downward gradient at the top of the slope and a slight upward gradient at the toe. Landslides that occur in the early phase are generally small. As the valley continues to deepen from fluvial incision, the valley bottom progressively approaches the elevation of the lower boundary. The intermediate phase occurs when the stream has not yet reached the lower boundary and a thick clay still underlies the bottom of the valley. The intermediate phase results in a downward gradient in the back of the slope and a strong upward gradient (artesian) in the lower zone of the slope. This can produce a significant reduction in the clay's shear strength near the toe of the slope and lead to deep landsliding. Lefebvre (1986) posited that the intermediate stage is characterized by an increase in landslide activity and an acceleration of valley development. The final or late phase occurs when the lower boundary is exposed at the bottom of the valley resulting in free discharge of groundwater into the stream. In the final phase the groundwater conditions are characterized by strong downward gradients which have a beneficial effect on slope stability. Landslides that occur on the late phase are generally shallow and restricted to the weathered crust.

We tested Lefebvre's (1986) model by mapping bedrock depth as a surrogate measure for the elevation of the lower till/glaciofluvial sequence. Profiles of bedrock depth below the base of Green's Creek and Mud Creek are shown in Figure 8. Two assumptions have been made: (i) the till/glaciofluvial sequence is present throughout the study area and (ii) the bedrock depth is laterally homogeneous within the immediate vicinity of the landslides. The profiles in Figure 8 show that bedrock depth varies considerably along the entire length of Green's Creek. In some parts of the upper reach of Green's Creek, the bedrock and overlying glaciofluvial sands have been eroded and are exposed well above the base of the channel. The most dominant characteristic in the profiles is the relatively consistent depth to bedrock along Mud Creek (22-25 m) where modern landslide activity is most densely concentrated. Slope heights range between 15-22 m along Mud Creek. The bedrock depth-to-slope height ratios are between 1.2 and 1.5 (average = 1.3). According to Lefebvre's model (Fig. 7), these values correspond to the intermediate stage of valley development. Given the relatively slow rates of valley incision in Champlain Sea clays (Lefebvre *et al.*, 1985; Lefebvre, 1986), Mud Creek will likely persist in the intermediate phase for at

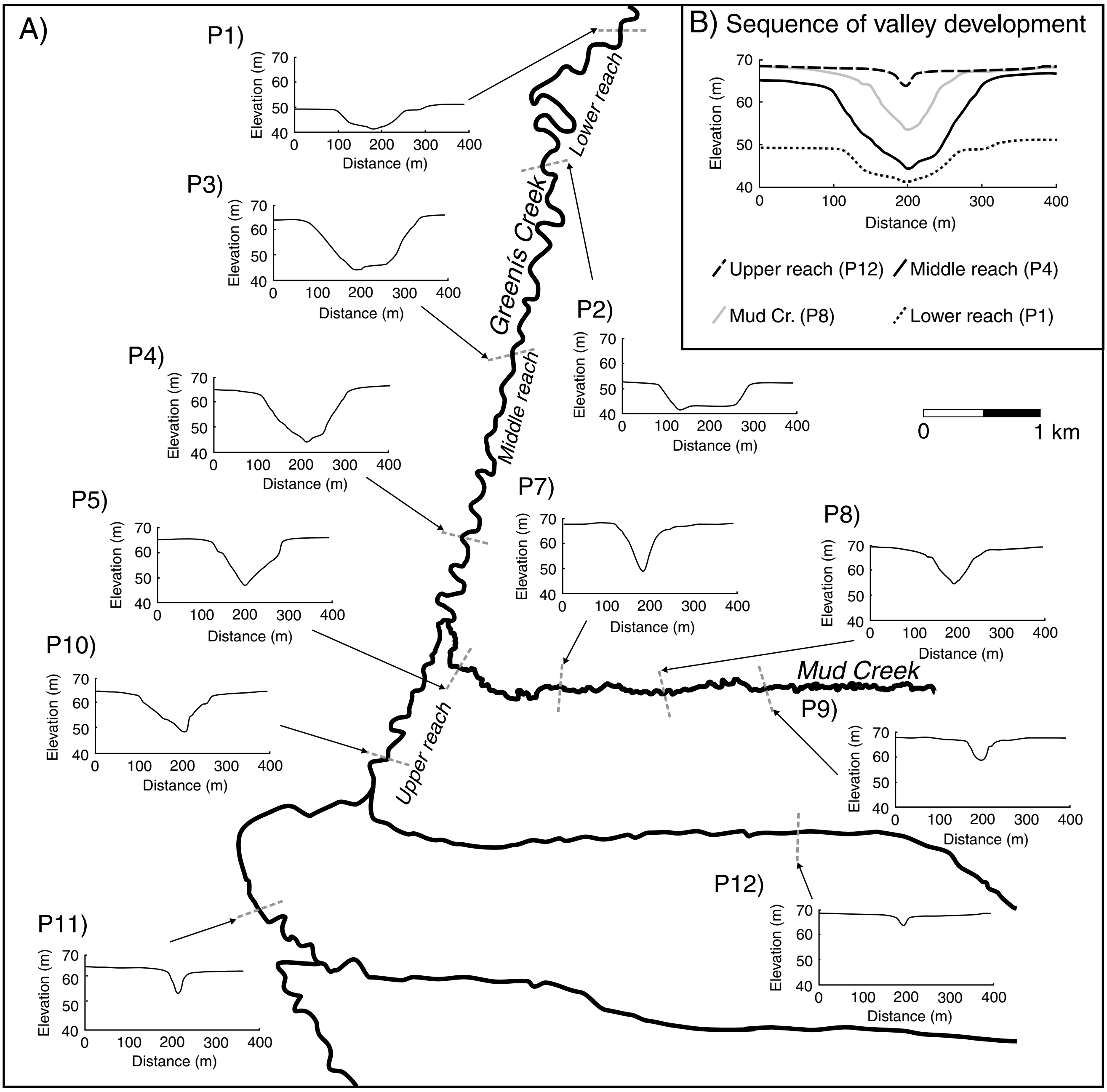

Figure 6. Cross-valley profiles from different valley segments in the study area. Inset diagram (6B) summarizes the main differences between the different valley segments. The profiles were derived from a 10 m DEM provided by the City of Ottawa. Vertical exaggeration of cross-valley profiles is uniformly 5.8.

Profils transversaux des différents segments de vallée au site d'étude. La cartouche (6B) présente un sommaire des différences entre les segments principaux. Les profils sont dérivés d'un MNT d'une résolution de 10 m fourni par la ville d'Ottawa. Les profils sont exagérés 5.8 fois.

least the next several decades, which is relevant in the context of engineering design.

Figure 8 also shows that many slopes along the valley that have been influenced by modern landslide activity are underlain by relatively shallow or very deep bedrock (*i.e.*, Lefebvre's phases 1 and 3, see Fig. 7). This suggests that a direct relation between bedrock depth and landsliding is not straightforward and that bedrock depth is not the only control on landslide activity. Although Lefebvre's (1986) model was developed from field studies and analytical modeling (*e.g.*, Lafleur and Lefebvre, 1980), it is difficult to validate the model on the scale of an entire river valley like Green's Creek where borehole data are sparse. It is possible that the presence of the till/glaciofluviual sequence is limited and in many areas the marine clay or varved facies may lie directly over the bedrock. Ultimately, this could have a significant effect on the groundwater flow regime, which could diverge considerably from the patterns presented by Lefebvre (1986). Thus, while we cannot

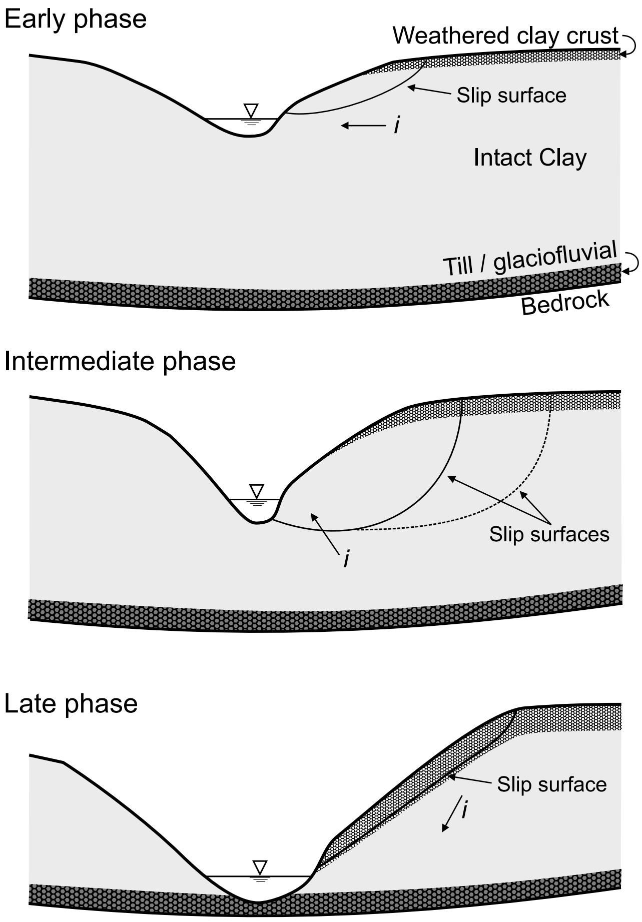

Figure 7. Model of landsliding and valley development in Champlain Sea clays (adapted from Lefebvre, 1986). The symbol *i* denotes groundwater flow direction and the triangle denotes the water level in the channel.

Schéma illustrant le processus de formation des glissements de terrain et le développement de la vallée dans les argiles de la Mer de Champlain (adapté de Lefebvre, 1986). Le symbole i *indique la direction de la circulation des eaux souterraines et le triangle, le niveau d'eau dans le chenal.*

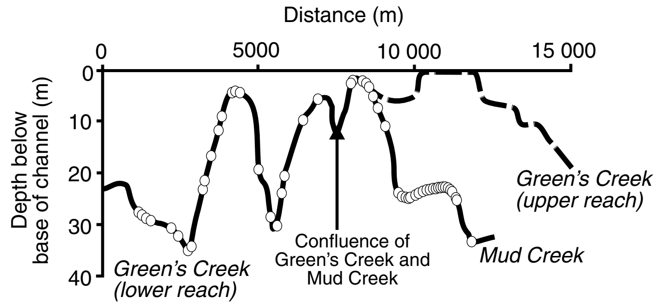

Figure 8. Profiles of bedrock depth below Green's Creek (dashed line) and Mud Creek (solid line). The location of landslides (small circles) was derived from the inventory in Figure 3.

Profil topographique indiquant la profondeur de la roche-mère sous Green Creek (trait hachuré) et Mud Creek (trait plein). Les glissements de terrain (cercles) sont positionnés d'après la distribution observée à la figure 3.

unequivocally confirm or deny the model presented by Lefebvre (1986), it appears that the bedrock depth, in association with other factors, has influenced the clustering of landslide activity along Mud Creek. In this way, Lefebvre's (1986) model provides a useful approximation of the spatial distribution of landslide activity in Green's Creek.

HYDROMETEOROLOGICAL CONDITIONS

Precipitation, particularly rainfall, is widely regarded as an important hydrologic trigger for various types of landslides worldwide. Hydrological triggering can be defined generally as a decrease in shear strength due to an increase in pore water pressure on a potential failure surface which ultimately results in a landslide (Terlien, 1998). While considerable progress has been made in establishing precipitation thresholds for shallow landsliding in a variety of different environments, understanding the role of precipitation in Champlain Sea clay landslides remains limited.

Figure 9 shows the frequency of landslides plotted with the annual precipitation departure from the long-term mean (1895-2001). The highest number of landslides occurred in the 1970s (n = 13), corresponding to a period when annual precipitation was greater than the long-term mean. A total of eleven landslides occurred between the early 1950s and the late 1960s when annual precipitation persisted well below the long-term mean. It is interesting to note that the four flow landslides that occurred in the study area all took place in the early 1970s following two decades of well-below average precipitation. Several other well known clay landslides occurred in the Ottawa region in the early 1970s: South Nation River, Ontario (1971); Le Coteau, Québec (1971) (Eden *et al.*, 1971; Eden, 1972; respectively); as did the Saint-Jean Vianney landslide, Québec (1971) (Tavenas *et al.*, 1971).

Least-squares regression was used in order to examine the process-response relation between precipitation and landslide activity. The variables used in the analysis were the number of landslides in a particular time period and the cumulative precipitation during that period. The results from the analysis (Fig. 10) show a positive correlation between the number of landslides and cumulative precipitation at 5- and 10-year intervals, indicating that wet intervals produce greater landslide activity. The confidence level at the 5-year interval (86 %) is much lower than the confidence interval at the 10-year interval (97 %). R^2 values indicate that 5-year variability in cumulative precipitation explains only 46 % of the variability in landslide activity, whereas decadal-scale variability in cumulative precipitation explains 82 %.

The differences between the 5- and 10-year correlations indicate that the relation between annual precipitation and landslide activity is improved at a coarser temporal resolution. The concept of 'event sequencing' may provide a clue as to why this occurs. Brundsen (2001) defined event sequencing as the combination of events at any frequency, magnitude, and duration, which achieves a recognizable effect as a sequence.

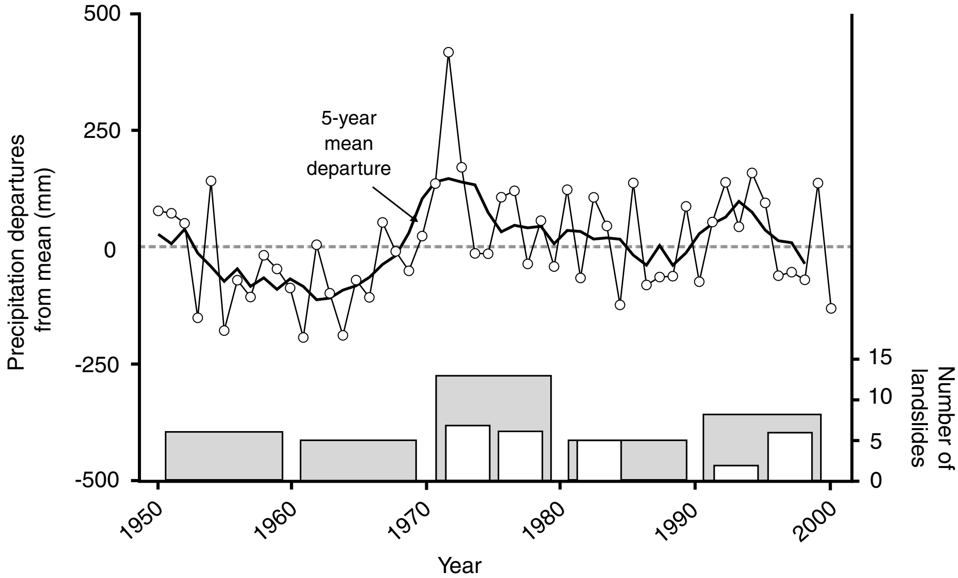

Figure 9. Trends in precipitation and landslide frequency. The precipitation departures were calculated from the long-term mean (1895-2001). The gray bars denote number of landslides at the 10-year interval (1950-2000) and white bars denote number of landslides at the 5-year interval (1970-2000).

Relation entre les précipitations et la fréquence des glissements de terrain. Les écarts de précipitations ont été calculés à partir de la moyenne à long terme (1899-2001). Les barres grises illustrent le nombre de glissements de terrain par intervalles de 10 ans (1950-2000) et les barres blanches, le nombre de glissements de terrain par intervalles de 5 ans (1970-2000).

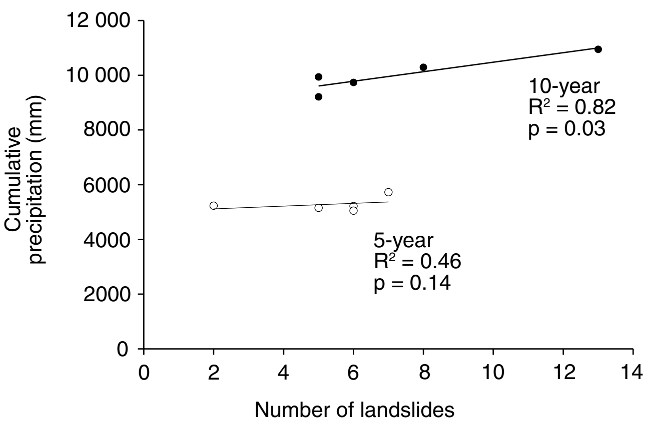

Figure 10. Results of correlation analysis between the number of landslides and the total precipitation in the intervals between 1970-2000 (5-year interval) and 1950-2000 (10-year interval).

Corrélation entre le nombre de glissements de terrain et les précipitations totales pour les périodes 1970-2000 (intervalles de 5 ans) et 1950-2000 (intervalles de 10 ans).

One possible scenario involving event sequencing relates to effects of precipitation on toe erosion. When annual precipitation is high, the erosive power of streams also tends to be high, particularly during the spring freshet. This leads to increased toe erosion that may not be severe enough to trigger landslides in a particular year, but may be enough to reduce the factor of safety. With a reduced factor of safety erosion events in subsequent years may be more likely to trigger a failure. In this way the slope experiences a progressive degradation of stability over time, ultimately leading to a failure.

DISCUSSION

Like many geomorphic systems, landslides in valley slopes composed of Champlain Sea clay are complex phenomena. The factors controlling the instant of failure, distribution and morphology are both numerous and complexly interrelated. Attention must be given, not only to the stability of slopes obtained from geotechnical slope stability assessments, but also to the geomorphic characteristics of landslide activity in a particular area.

REGIONAL CONTEXT

While the focus of this study has been landslide activity in a small river valley in the east end of Ottawa, Ontario, the results can be placed in a much broader context in terms of the post-glacial development of other valleys that incise the Champlain Sea clay deposit in Eastern Ontario. From a regional synthesis, three broad groups of landslides are recognized: (1) massive ancient landslides situated along the margins of the paleovalleys of the Proto Ottawa River (Gadd, 1976; Aylsworth *et al.*, 2000); (2) large modern landslides situated along large river valleys (*e.g.*, South Nation River landslides in 1971 and 1993); and (3) small modern landslides situated along small river valleys (*e.g.*, Green's Creek). The magnitude of the ancient landslides is on the order of 10^6 to 10^8 m^3, many of which consist of coalesced complexes (*cf.* Gadd, 1976). Radiocarbon ages from fifteen ancient landslides along paleovalleys 30-50 km east and northeast of the study area cluster at around 4550 BP, which is well after abandonment of the Proto-Ottawa river channels. Many of these landslides also have relatively unaltered spoil material, implying a lack of fluvial erosion at the time of failure or thereafter. For these reasons, among others, Aylsworth *et al.* (2000) posited that many of the landslides along the paleovalleys were triggered by Holocene earthquake activity around 4550 BP.

Modern landslides along younger river valleys which have incised the paleovalleys and adjacent terraces are typically many orders of magnitude smaller than the ancient landslides (*i.e.*, 10^3 to 10^6 m^3). In addition to the difference in size, the two groups of modern landslides are also differentiated according to their geological setting and the geotechnical characteristics of the clays (*cf.* Fransham and Gadd, 1977). The small modern landslides, such as those in Green's Creek, tend to occur in areas where there is a thick crust of weathered clay exposed at the surface or very close to the surface. Most landslides in Green's Creek appear to be restricted to the weathered clay facies, and with the exception of the landslides classified as flows and some of the retrogressive landslides, few of the failure surfaces probably extend down to the sensitive marine clay. Conversely, the large modern landslides along the South Nation River occur where there is a thick topset of sand underlain by a layer of interbedded silt and clay. Although the role of the topset sequence in landsliding is not yet completely understood, it may have played a protective role for the marine clay at depth by buffering various weathering effects at the surface (*e.g.*, leaching, frost action, oxidation, and desiccation). Consequently, the mode of failure is quite different at the South Nation River and quick clay landslides are more prevalent.

The difference between the ancient and modern groups of landslides cannot be attributed solely to slope geometry since all three groups occur in slopes with similar heights and gradients. Gadd (1976) speculated that the smaller width of the younger valleys (*i.e.*, several hundred meters at most), compared to the broader paleovalleys (*i.e.*, several kilometers), could have a limiting effect on the removal of spoil material. The same characteristic may also explain the difference between the two modern groups of landslides. Smaller valleys may regulate retrogression and the size of landslides that may develop because the spoil material can act as reinforcement along the toe of the slope and also protects nearby slopes by buttressing.

A final factor distinguishing the ancient and modern groups of landslides is the triggering mechanism. As Aylsworth *et al.* (2000) posited many of the ancient landslides were triggered by earthquake activity around 4550 BP. In this way, many of the ancient landslides are the consequence of a discrete high magnitude event which produced near-instantaneous and significant modifications to the landscape. In comparison, earthquake activity does not appear to be a significant trigger in recent historic landslide activity along younger river valleys. Instead, the modern landslides in the Ottawa region appear to be more closely related to high levels of precipitation (*e.g.*, Eden *et al.*, 1971; Evans and Brooks, 1994; this study). Overall, landslide activity along the younger river valleys appears to have had a more localized and gradual effect on landscape development.

LANDSLIDE ACTIVITY IN GREEN'S CREEK

The frequency of landslides observed in Green's Creek between 1928 and 2001 (n = 52) is much smaller than the frequency of landslides observed by Locat *et al.* (1984) in the rivière Chacoura valley near Louiseville, Québec. A total of 354 landslides were identified along the rivière Chacoura and its tributaries between 1948 and 1979. This is equivalent to an average of more than ten landslides per year in the Chacoura valley, whereas only one landslide occurs about every two years in Green's Creek. Similar to Green's Creek, most of the landslides along the rivière Chacoura occurred along meander bends and in slopes that exhibited signs of antecedent landsliding. Another similarity between the two river valleys is that the most active period in terms of landslide activity was between 1970 and 1975, corresponding to a period of increased precipitation in these regions. The high frequency of modern landslides in the rivière Chacoura valley reflects, in part, the fact that it is a slightly larger valley with many more tributaries than Green's Creek.

The examination of valley development and landslide activity in the Green's Creek valley indicates several important relations, many of which may have application to other valleys which have incised Champlain Sea clay deposits. The most notable relation is revealed by the spatial distribution of landslide activity, whereby the greatest number and type of landslides were found along Mud Creek which is the youngest and arguably the most dynamic segment of the river valley in terms of valley development. Another important relation is evident between the bedrock depth, a surrogate for the elevation of the lower till/glaciofluvial sequence, and the high concentration of recent landslide activity along Mud Creek. Following Lefebvre's proposal of valley development in Champlain Sea clay deposits (Fig. 7), it appears that the valley along Mud Creek is in an intermediate phase of development in which elevated landslide activity is favored.

The combined tendencies for landslides to occur preferentially in slopes on outside meander bends and their propensity for recurring in the same location confirms the strong relation observed in other studies between erosion, oversteepening and landsliding (Bjerrum *et al.*, 1969; La Rochelle *et al.*, 1970; Williams *et al.*, 1979; Lebuis *et al.*, 1983; Locat *et al.*, 1984). Williams *et al.* (1979) recognized that many landslides along the Ottawa River occurred repeatedly in the same locations with an intervening period of relaxation and ripening. To account for this behavior Williams *et al.* (1979) proposed an erosion-landslide cycle (Fig. 11). The cycle begins with a slope oversteepened by toe erosion. Following a triggering mechanism, a landslide develops and transports material into the channel. Lateral erosion of the spoil progressively removes the material until the slope adopts a benched profile. Further toe erosion causes the sequence of processes to be repeated. Williams *et al.* (1979) proposed a return interval of between 30 to 70 years for landslides along the Ottawa River, but the same interval probably does not apply for landslides in Green's Creek. Although the stratigraphy and slope heights are similar, unlike the Ottawa River, discharge from Green's Creek is several orders of magnitude lower than the Ottawa River and wave action is negligible; therefore, removal of spoil material is likely to proceed at a much slower pace. A further complicating factor in identifying a return interval for landslides in Green's Creek is the wide diversity of landslide morphologies. Small and shallow landslides produce a limited amount of spoil material and may be conditioned for renewed landsliding within several decades, whereas the larger and deeper landslides may take several centuries-to-millennia before unstable conditions return. In this regard, the return interval of landslides in the Green's Creek Valley is likely to be highly heterogeneous.

A significant observation from the temporal analysis of 73 years of aerial photographs over the Green's Creek valley

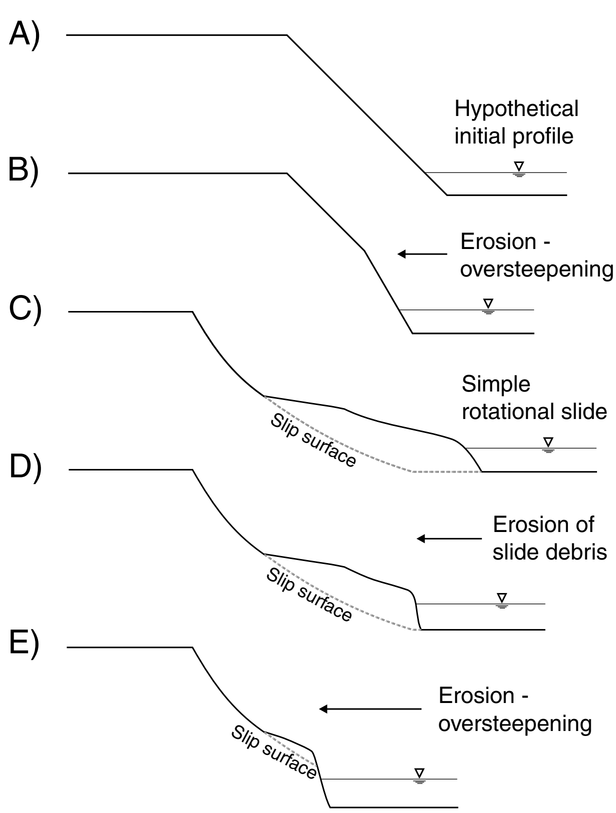

Figure 11. Erosion-landslide model (adapted from Williams *et al.*, 1979). The triangle denotes the water level in the channel

Schéma d'érosion-glissements de terrain (adapté de Williams et al.*, 1979). Le triangle indique le niveau d'eau dans le chenal.*

is that some landslides incurred retrogressive failures for several years-to-decades after the initial landslide. This behavior underscores the operation of an extended interval of system relaxation, which is the period of adjustment from one steady state or threshold to another (Chorley and Kennedy, 1971; Allen 1974). Leroueil (2001) identified four states in the development of landslides: pre-failure, failure, post-failure, and reactivation. Pre-failure involves the development of a shear surface or slip surface at depth and includes all the deformation processes leading to failure. The onset of failure is characterized by the development of a continuous slip surface throughout the entire soil mass. During the post-failure state the landslide body moves along the slip surface, eventually coming to rest where it persists in a quasi stable state until it is reactivated. The latter involves old landslide bodies, or parts of them, sliding along the existing slip surface when the shear stress exceeds the residual value.

It appears that the prolonged retrogression at certain landslides observed in this study is the product of repeated cycles of pre-failure, failure, and post-failure in the slopes of the backscarp. Reactivation along a pre-defined slip surface may have occurred as well, although it cannot be confirmed by the air photos. Retrogression is commonly observed in Champlain Sea clay landslides and the causes, mechanisms, and prediction of retrogressive phenomena are well known from several studies (Mitchell and Markell, 1974; Tavenas *et al.*, 1983). Many renowned landslides in Champlain Sea clays have exhibited retrogression intervals that ranged from several hours (*e.g.*, Lemieux landslide, Evans and Brooks, 1994; Saint-Jean Vianney landslide, Tavenas *et al.*, 1971) to several days (*e.g.*, Le Coteau landslide, Eden, 1972). For these and other landslides with short-term retrogressive behavior, the relaxation intervals between pre-failure, failure, and post-failure occur rapidly, which contrasts with the lengthy intervals observed at certain landslides in Green's Creek.

A possible mechanism which may extend retrogressive landslide activity at a particular site is a slow adjustment of the groundwater regime after the initial landslide has occurred. Several well-documented studies of landslides in Champlain Sea clays have shown that artesian groundwater flow along the base of failed slopes can extend for long periods after the initial landslide (*cf.* La Rochelle *et al.*, 1970; Mitchell, 1970). Another way in which retrogression could be prolonged is through a positive feedback effect setup by the initial landslide. Once the initial landslide has occurred, instability may propagate into the slope due to the loss of lateral support. This can lead to the development of one or several slip surfaces along the slopes of the backscarp. Over time, successive failures in the backscarp can trigger further development of slip surfaces which eventually terminate when a given failure is incapable of leading to further propagation of instability into the backscarp. Owing to the residual strength conditions that arise once a slip surface develops, the triggering threshold required for retrogressive failure is much smaller than that required to initiate the original landslide.

The triggering of recent historic landslides in the Ottawa region is often ascribed to elevated precipitation inputs, particularly the amount of snowfall in the preceding winter (Eden *et al.*, 1971; Evans and Brooks, 1994). Precipitation acts as a trigger for landslides through its effect on the groundwater conditions in the slopes and the water levels or discharge in the rivers. The bulk of previous research concerning the role of precipitation as a triggering mechanism for Champlain Sea clay landslides has been in the form of case studies of individual landslides and the short term hydrometeorological conditions preceding them (with the notable exception of studies by Bjerrum *et al.*, 1969, and Lebuis *et al.*, 1983). In this study, we attempted to expand on the case studies by incorporating a large number of observations of landslide occurrences at a relatively coarse temporal resolution. Results from correlation analysis revealed a positive relation between landslide activity and precipitation at 5- and 10-year intervals. The correlation was stronger at the 10-year interval, which suggests that landslide activity in the study area is strongly influenced by decadal-scale variations in precipitation amounts. Rather than suggesting that short term events are un-important in the occurrence of landslides in the study area, we suggest that short-term process-response relations (*e.g.*, annual records) are often masked by the effects of event-sequencing and dampening mechanisms. Perhaps for this reason, previous studies were not entirely revealing when they examined individual landslides and the short-term antecedent hydrometeorological records (*e.g.*, Eden *et al.*, 1971; Tavenas *et al.*, 1971; Evans and Brooks, 1994; Demers *et al.*, 1999). An important area of further research is to constrain the hydrologic triggering of Champlain Sea clay landslides at a finer temporal resolution and attempt to determine the importance of event-sequencing and thresholds. Indeed, Mitchell and Williams (1981) have examined the role of groundwater in the failure of a natural test slope over-steepened by toe erosion. However, there are no long-term records of groundwater in natural Champlain Sea clay slopes at various degrees of stability. One approach that may help in this regard is a long-term study of pore water pressures concurrent with other geotechnical instruments at stable, marginally stable, and unstable natural slopes.

CONCLUSIONS

Findings from this study indicate that the spatial distribution of landslide activity is closely related to valley development. Three of the most important relations include: (1) the preferential occurrence of landslides in slopes situated on the outside of meander bends where fluvial erosion is most pronounced, (2) the tendency for landslides to recur in the same slope after a period of ripening, and (3) the concentration of landslide activity along a major tributary valley where a multitude of geomorphic features (*i.e.*, knickpoints, V-shaped valley profiles, and bedrock depth-to-slope height ratios) reflect an unstable phase of development. The former two findings lend support to the erosion-landslide model originally proposed by Williams *et al.* (1979) for slopes along the Ottawa River.

In the context of their temporal distribution, the findings from this study show that landslide activity fluctuates in response to changes in the amount of precipitation. A positive and statistically significant correlation was obtained when landslide activity and precipitation amounts were compared at a 10-year interval, however the correlation was much weaker when the data were examined at a 5-year interval ($p = 0.14$). The differences in the correlations of the two time intervals suggests that event-sequencing, dampening mechanisms, and slope stability degradation over time are important in the timing of recent historical landslide activity such that relations become more apparent at coarser time intervals.

Collectively, the results from this study highlight the importance of incorporating geomorphic concepts and methods in order to broaden the understanding of the distribution, type, and timing of landslides in Champlain Sea clay deposits. Ultimately, the most comprehensive assessments will be achieved through a fusion of geotechnical, geological, hydrogeological, and geomorphic approaches.

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