Age of Landslides Along the Grande Rivière de la Baleine Estuary, Eastern Coast of Hudson Bay, Quebec (Canada)

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1 Introduction

Landslides are widespread in tectonically active zones, in mountains and in areas where fine-grained deposits predominate, particularly in lowlands influenced by postglacial marine transgression. Late and postglacial marine clays in Norway (Bjerrum 1954a, b) and eastern Canada (La Rochelle et al. 1970; Leroueil et al. 1983) are particularly prone to multiple rotational slips (Hutchinson 1968). Identification of causal processes involved in landslide activity has been discussed by several workers (Sharpe 1938; Terzaghi 1950; Varnes 1958; Selby 1982). In such an attempt one must be able to distinguish between direct and indirect causes. In general, the direct causes were more easily identified, as for example seismic or volcanic activity, oversteepening of slopes undercutting at the toe of a slope by stream action, fluctuations in depth of water bodies, prolonged rainfall, storm surges or rapid snow melting, and overloading of surfaces. While the inherent characteristics of deposits (lithologies, weathering states) and slope were considered as prerequisites for sliding occurrence, climate influence has been generally identified as an indirect cause.

Landslides in many regions are ancient and the conditions under which they were formed may be relict. In some areas, their presence is an indication of shifts in temperature, and in amount, distribution and intensity of rainfall during the Pleistocene and the Holocene. Identification of mode of failure and causal processes is complicated in ancient landslides, because of rapid degradation of the sliding surface (Brunsden and Jones 1972; Carson 1979), lack of geotechnical or meteorological data, and absence of archival records or eye-witness accounts. In areas with a high frequency of mass movements inducing several generations of landslides, it may be useful to establish their chronology in the context of past geomorphic, climatic and

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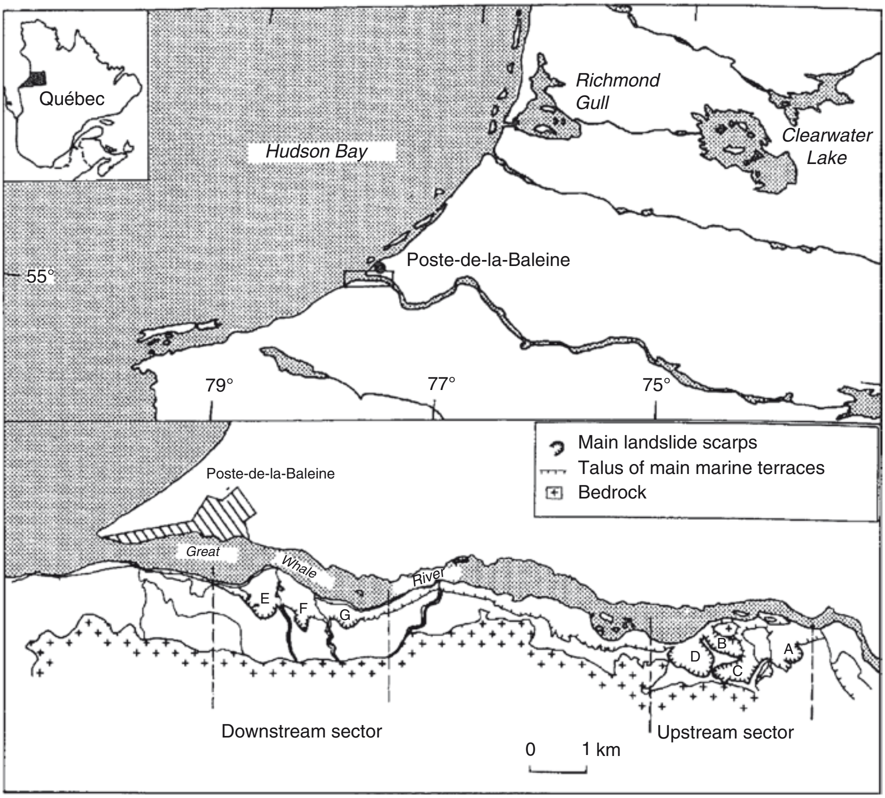

Fig. 1 Location of the study area and landslides discussed in text (A–G)

ecologic conditions. In this connection, the fluvio-marine terraces located at the mouth of the Grande Rivière de la Baleine, northern Quebec (Fig. 1), provide evidence of long-term landslide activity, as the sandy surfaces and underlying marine clay deposits were disrupted by seven major landslides (Demangeot 1974) since their formation around 3,200 BP. (Hillaire-Marcel 1976). The main objectives of this study were therefore to establish the landslide chronology along a 12 km stretch of the Grande Rivière de la Baleine estuary, and to discuss the climatic conditions prevailing at the time of their formation using recent dendroclimatic reconstructions in subarctic Quebec (Parker et al. 1981; Jacoby 1983; Payette and Filion 1985; Payette et al. 1985).

One major problem in reconstructing landslide activity over a long period of time arises from availability of datable material and use of suitable dating techniques. In a recent paper, Goulden and Sauchyn (1986) reviewed briefly some techniques that have been used to date landslides. Some provide absolute dates (radiocarbon dating), while others yield relative dates (morphological parameters, weathering-rind thickness, size and coverage of lichens on boulders exposed by landsliding, soil properties). Tree-ring dating of landslides was not mentioned by these authors, although this technique gives an accurate absolute dating as to the year or even to the season of occurrence. Its application in geomorphological studies has been extensively discussed by Alestalo (1971) and Shroder (1978, 1973, 1975). It was successfully applied in many studies dealing with mass movements (Agard 1979; Begin and Filion 1985). In this study, we have focused on tree-ring analysis to obtain accurate dates of recent landslides, and on the ^{14}C technique for ancient ones. Landslides from the Poste-de-la-Baleine area were considered in this respect, because they developed in a forest environment where buried tree stumps and other organic material could be used in tree-ring and ^{14}C dating.

2 Study Area

The Poste-de-la-Baleine area is located along the eastern coast of Hudson Bay (Fig. 1). The geological basement is made of Precambrian granitic and gneissic rocks (Eade 1966). Deglaciation occurred around 8,000 BP. (Hillaire-Marcel 1976). Three terraces are found along the river, the uppermost being dated at 3,200 BP. According to emersion curves (Hillaire-Marcel 1976; Allard and Seguin 1985). Its surface declines in elevation toward the west, from 45 m above sea level up the river to 30 m near the mouth where it is truncated by the coastline.

The terrace stratigraphy and landslide morphology were described recently (Begin and Filion 1987). The overall stratigraphic pattern shows the following sequence, from bottom to top: morainic material, 10 m thick marine clay sediments, and 15–20 m thick fluvial and deltaic sands. The clay deposits were made of 55–70% of fines (<2 μ). The water content and liquidity limit ranged respectively between 24% and 44% and 28–57%.

Four out of seven major landslides depicted within the 12 km long terraces occurred in the upstream sector of the river, while the other three landslides were located in the downstream sector, in front of Poste-de-la-Baleine settlement (Fig. 1). Occurrence of various sliding levels, and degree of degradation and paludification of some landslide surfaces suggest that they were formed at different periods, although they all belong to the same, single or multiple rotational type (Begin and Filion 1987). This slip-flow double movement is typical of quick-clay deposits overlain by sand and it is most obvious in recent landslides near the Poste-de-la-Baleine settlement. All mass movements in the study area have eroded approximately 10% of the initial surface and about 17 × 106 m^3 of flow material.

3 Methods

Postulated old landslides (A–C) were dated using the ^{14}C method, and dendrochronological techniques were used for dating of recent landslides (D–G). Three ^{14}C dates were performed at Teledyne Isotopes, and three at the Laboratoire de Radiochronologie of Laval'University. The radiocarbon dates (Libby's half-life, 5,568 years) were calibrated to calendar dendroyears using tables and methods from Stuiver and Becker (1986).

Table 1 Summary of landslide chronology. Also indicated type of material and events, dating techniques, laboratory numbers and identification: 1 for samples from Teledyne Isotopes and UL from Laval University

Landslide	Type of material	Geomorphic and ecological events	Dating techniques	^{14}C dates	Calendar years
A	–	–	–	Undated	Undated
B	Buried charcoal	Burying of theoriginal surface	^{14}C	2,200 ± 80 BP (1–13,271)	405–90 BC (p = 0.99)
C	Basal peat	Peat accumulation	^{14}C	890 ± 70 BP (UL-77)	AD 1018–1260(p = 0.99)
C1	Buried organic matter	Minor movement(base of the main scarp)	^{14}C	180 ± 60 BP (UL-78)	AD 1641–1899 (p = 0.83)
C2	Buried organic matter	Minor movement(base of the main scarp)	^{14}C	260 ± 80 BP (1–13,270)	AD 1646–1703 (p = 0.67)
C3	Buried organic matter	Subsidence at theouter limit of theflowage zone	^{14}C	320 ± 80 BP (1–13,273)	AD 1428–1677 (p = 0.90)
D	Buried trees	Burying of trees	^{14}C	160 ± 60 BP(UL-147)	AD 1654–1896(p = 0.83)
D’	Buried trees	Burying of trees	Tree rings light rings	–	AD 1846 spring
E	Stumps	Development ofreaction wood	Tree rings	–	AD 1818 summer
F	Stumps	Development ofreaction wood	Tree rings	–	AD 1818 summer
G	Buried trees	Burying of trees	Tree rings light rings	–	AD 1839 spring

The calibrated AD/BC age ranges are first obtained from intercepts method and then from probability distribution (p) method. The age ranges shown on Table 1 are those with the highest probability of date occurrence within two sigma.

Landslides D–G were dated with dendrochronological techniques. The tree-ring analysis was performed on buried tree stumps found in an upright position in flowed sediments, and also on stumps located at the surface of rotated blocks. In the case of buried trees which died in the hazard, the absolute age of landslides was obtained by dating the last growth-ring year (landslides D and G). The trees found at the surface of rotated blocks have recorded sliding movements by developing reaction wood in response to stem tilting. Sometime after tilting, the trees have been cut by Indians or by the staff of the Hudson Bay Company (Delwaide and Filion 1987). In this case, the age of landslides was obtained by dating the first year of reaction wood (compression wood) on the well preserved side of the stump (landslides E and F). The eccentric growth pattern was not studied in itself because of rotten wood in the opposite direction. All the trees analyzed were white spruce (*Picea glauca*).

The growth-ring analyses were performed on discs sampled at the root collar. Nine stumps were used for dating landslides D and F, and about 20 for landslides E and G. Ring width was measured with a Henson micrometer (precision of 0.01 mm). Cross-dating was facilitated by the presence of light rings (Filion et al. 1986), i.e. annual rings mostly made of earlywood cells with one or a few layers of latewood-cells typical of a shortened growing season. Growth-ring patterns were also used in association with existing master chronologies (Parker et al. 1981; Payette et al. 1985) and a local chronology built from 15 trees growing on the upper terrace.

The age of the largest and presumably oldest trees found in landslides E, F and G was determined for an evaluation of the minimum age of each landslide. This procedure may be useful in absence of other field methods (Shroder 1978). Accordingly, 122 trees were sampled in landslide E, 150 in landslide F, and 33 in landslide G, so as to represent the flowage zone, the floor of flowbowl and the landslide scarp. The increment cores were taken as low as possible, i.e. 30 cm above the ground surface using a Pressler probe.

Archival records from Hudson Bay Company were used for historical information dealing with geomorphic and climatic proxy data. These documents belong to the Public Archives at Ottawa and to the Hudson Bay Company at Winnipeg (Canada), and spanned more or less continuously the 1744–1931 period.

4 Results

4.1 Landslides from the Upstream Sector

Landslide A is presumably the oldest landslide in the study area, because it is found at the highest altitude. The floor of the flowbowl is at 38 m above the present sea level, and the base level of the frontal slope circumscribing the flowage zone is at 30 m.

This elevation corresponded probably to the effective river level at the time of landslide formation. Because the original terrace surface has not been found, no organic material was available for dating. However, it seems likely that it occurred between c. 3,200 and 2,200 BP, i.e. between the time of the upper terrace formation and inception of landslide B located nearby at a slightly lower level (Fig. 1).

The floor of the cavity of landslide B was at a mean elevation of 33 m, about 3 m below the surface of landslide A. The base level of the frontal slope formed into the slipped masses is at 11 m above the present sea level. Landslide B was formed at about 2,200 ± 80 BP (1–13,271) (Table 1). This ^{14}C date was obtained from charcoal recovered from a buried organic horizon corresponding to the original surface of the upper terrace and it gives a maximum age for landslide occurrence. It is the oldest date for landslide formation in the study area. Several soil profiles observed at the edge of this landslide surface showed many microfaults, indicating that the upper part of the deposit was frozen at the time of sliding. This suggests that the landslide occurred probably during spring.

The surface of landslide C is at an altitude of 28 m, 5 m below the surface of landslide B. The sampling of basal peat covering the floor of the flowbowl, about 1.8 m as maximum thickness, yielded a date of 890 ± 70 BP (UL-77) (Table 1) which is an approximate but minimum age for the formation of landslide C. Sliding thus occurred between c. 2,200 (age of landslide B) and 900 BP. Additionally, three young radiocarbon dates (Table 1) were obtained from buried organic matter. Two dates (UL-78:180 ± 60 BP, and I-13,270: 260 ± 80 BP) appear to indicate minor movements at the base of the main scarp (CI and C2, on Table 1) and the last one (1–13,273: 320 ± 80 BP) subsidence of the slope at the lower limit of the flowage zone (C3, on Table 1).

A tree-ring date of AD 1846 has been determined for inception of landslide D. Cross-dating based on growth patterns and light-ring occurrences showed that the last complete ring was formed in 1845 (Fig. 2), and that sliding occurred most likely in spring 1846. A radiocarbon date of 160 ± 60 BP (UL-147) yielded AD 1654–1896 age ranges (probability distribution of 0.83 within two sigma) (D on Table 1). The outer rings were removed from the stem section to avoid contamination during dating. It is the most recent landslide to have occurred in the upstream sector and in the study area.

4.2 Landslides from the Downstream Sector

When landslides E and F occurred their flowage zones merged and the slipped material flowed into the river. At the contact zone between the two earthflows, arrangement of the ridges suggest that the landslides occurred simultaneously. Many trees survived to sliding, particularly those growing at the surface of rotated blocks, and developed reaction wood and eccentric growth pattern later on (Fig. 3a and b). In many samples, the outer portion of 1818-ring was made of compression wood suggesting a change in stem position during the growing season (Fig. 3a). Many trees that toppled over during sliding were unable to grow for the rest of the

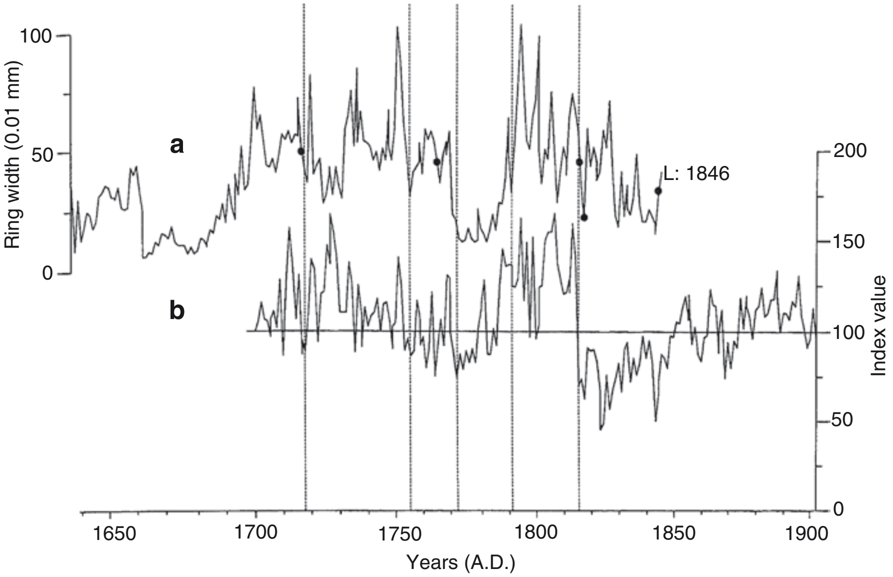

Fig. 2 Age of landslide D (L: AD 1846) using cross-dating of sample D-l (*curve* **a**) with the chronology of Parker et al. (1981) (*curve* **b**) and light-ring years (•) (Filion et al. 1986)

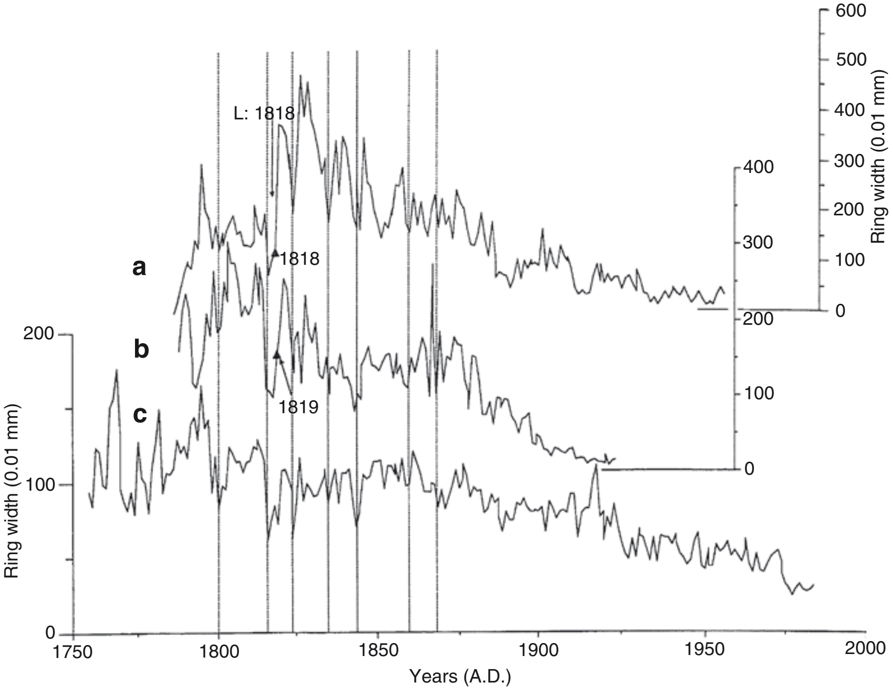

Fig. 3 Age of landslides F and E (L: AD 1818) using cross-dating of samples F-24 (*curve* **a**) and E-l (*curve* **b**) with the local chronology (*curve* **c**). *Triangle* indicates beginning of reaction wood induced by tilting (1818 on curve a and 1819 on curve b). No light rings were depicted on those samples

season, and recovery began in 1819 (Fig. 3b). Cross-dating of these tilted trees with our local chronology (Fig. 3c) allows us to show that landslides E and F occurred in 1818, probably in July (Table 1).

Landslide G occurred in AD 1839. Many trees were found in their normal position buried by landslide debris and exposed by stream erosion. The last complete ring among several sampled trees was formed in AD 1838. (Fig 4a–c), which suggests that sliding occurred in spring 1839 before the beginning of the growing season (Fig. 4a–d and Table 1).

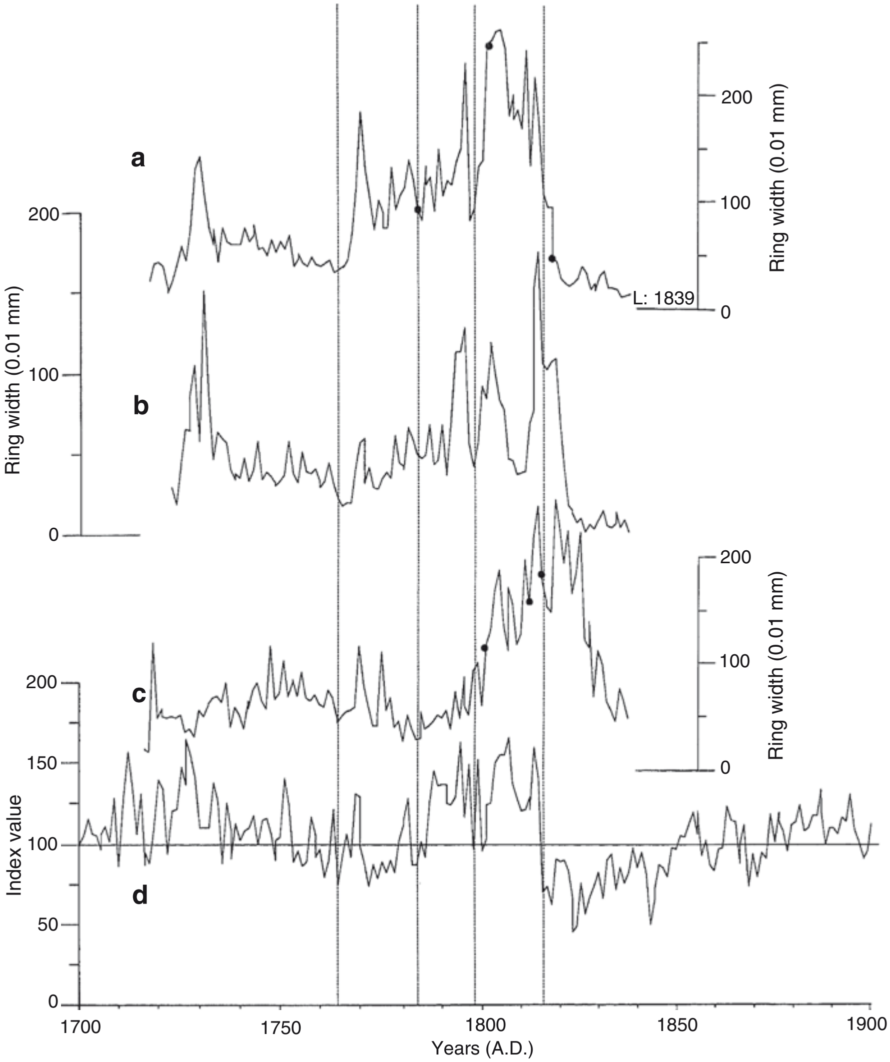

Fig. 4 Age of landslide G (L: AD 1839) using cross-dating of samples G-5 (*curve* **a**), G-7 (*curve* **b**), and G-2 (*curve* **c**) with the chronology of Parker et al. (1981) (*curve* **d**) and light-ring years (•) (Filion et al. 1986)

4.3 Tree Regeneration in Landslides E, F, and G

Age of the oldest spruces growing in landslides from the downstream sector is shown in Fig. 5 according to position in landslide, i.e. along the main scarp, on the floor of the flowbowl, and in the flowage zone. Tree regeneration started 15 years after inception of landslides F and G, and 25 years in landslide E. Spruce establishment began first at the proximity of seed-bearers, i. e. along the scarps near the undisturbed terrace edges where mature trees were growing. The floor of flowbowls were colonized lately and only superficially, because of eolian activity eroding the sandy outcrops. Finally, the flowage zones were characterized by a low potential in spruce regeneration.

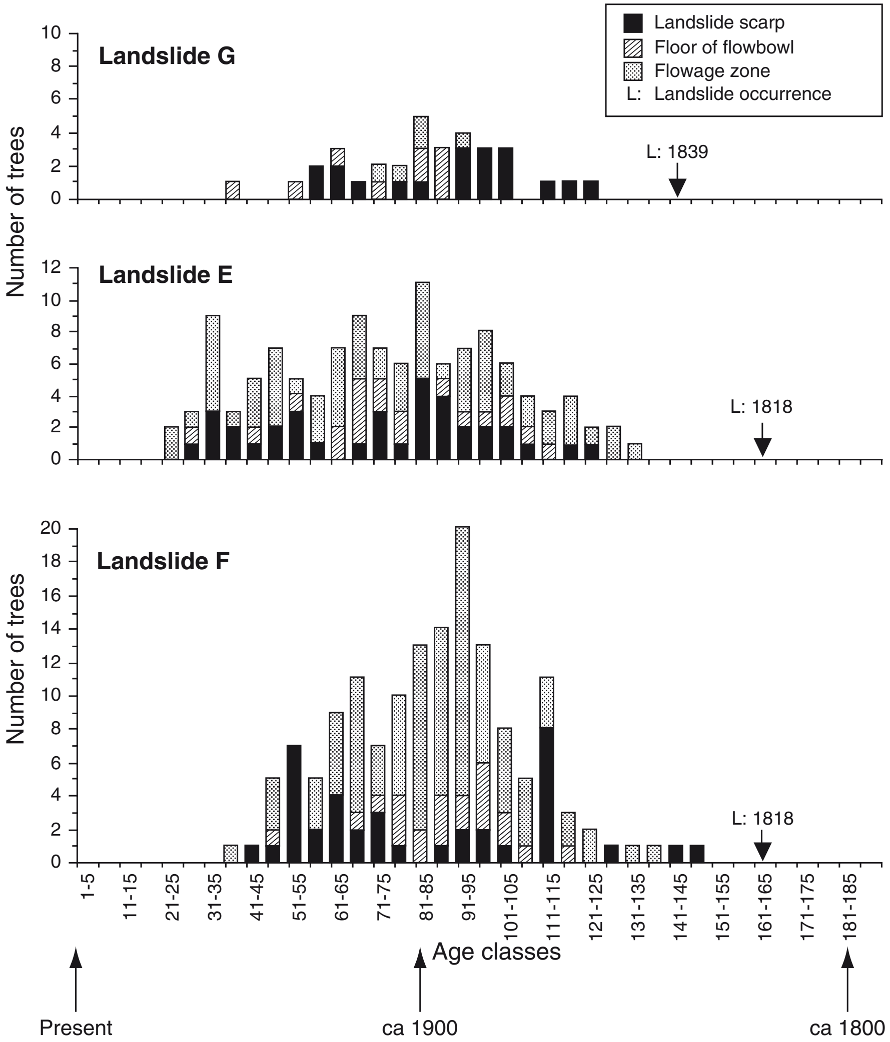

Fig. 5 Age-class frequency distribution of trees from initial establishment following the formation of landslides G, E, and F

5 Discussion

The Grande Rivière de la Baleine terraces were disturbed by seven major landslides since their formation (3,200 BP). The age of the second oldest movement (2,200 BP) gives the minimum age for landslide occurrence in the area, because the presumed oldest landslide A has not been dated. Mass movements reoccurred in the upper part of the river, ate. 900 BP (c. AD 1018–1260). From the eleventh to thirteenth to the nineteenth centuries, the area was relatively stable, showing only minor movements at the base of the main scarp and at the outer limit of the flowage zone in landslide C. The most active period in landslide activity occurred during the first half of the nineteenth century. Between 1818 and 1847 four large landslides occurred, and since that time no major disturbance was observed.

Thus, two contrasted periods appear from the chronology of landslide activity in the area. The first one lasted for a long time and included only three landslides (A–C), i. e. sometime after the inception of the estuarine terraces (3,200 BP) but before occurrence of landslide B (2,200 BP) until the beginning of the nineteenth century. The second period spanned only 30 years, but it was characterized by the occurrence of four landslides (D–G) including two synchronous events (landslides E and F). Because these recent landslides were dendrochronologically dated, it is possible to evaluate the conditions responsible for their formation and the climatic context in which they developed.

5.1 Recent Landslides

The two major landslides (E and F) located in the downstream sector occurred simultaneously in July 1818. In most of the sampled trees used for tree-ring analysis, a sharp reduction in growth was observed in 1816 and 1817. Far from being of local origin, this drop appears to be significant in all tree-ring chronologies from northern Quebec and Labrador (Cropper and Fritts 1981; Parker et al. 1981; Jacoby 1983; Filion et al. 1985; Payette et al. 1985).

Moreover, the 1816 and 1817 tree rings were identified as light rings (Filion et al. 1986), because of the absence of latewood probably caused by low temperatures in August and by an untimely stop of the growing season. These authors showed that about two thirds of the light-ring years corresponded to years (or triads) of major volcanic eruptions around the world. The 1815 Tambora eruption in Indonesia was the most important, and caused a drop in northern-hemisphere temperature of about 0.4–0.7°C (Lamb 1977; Bryson and Goodman 1980). Its influence on the northern Quebec climate lasted for 2 years, as suggested by the successive occurrence of 1816 and 1817 light rings. These two light rings were identified in more than 75% of individual spruce stems sampled in an old-growth lichen-spruce woodland at the tree line (Filion et al. 1986).

According to historical data from New England, the temperature in 1816 was 3–6°C below normal in June and July, and about 2–3°C in August (Hughes 1979;

Stommel and Stommel 1979). Information from the Hudson Bay Company's archives indicated that the Grande Rivière de la Baleine (Great Whale) trading post was abandoned in autumn 1816, and was reoccupied only in 1857. The 1816 and 1817 tree-ring characteristics showed that the climatic conditions were inimical to tree growth. Temperature was lower, which caused most likely a reduction in evaporation. The summer precipitation was probably higher, inducing water-logged ground conditions, and probably a higher river level with accelerated stream erosion. The relationship between precipitation and mass movements has been suggested and, in some cases, demonstrated convincingly by several workers (Terzaghi 1950; Nilsen and Turner 1975; Shroder 1978; Caine 1980; Rogers and Selby 1980). These particular conditions during 2 successive years culminated in July 1818 to produce the two major landslides.

The 1839 and 1846 landslides (G and D) occurred during spring, as suggested by the last complete tree ring. These 2 years are part of a long climatic sequence of reduced tree growth (Fig. 4d). The reduction in growth conditions between 1815 and 1860 appears to be general in tree-ring curves from northern Quebec and Labrador. As deduced from long tree ring records, the first half of the nineteenth century was probably one of the coldest intervals of the Little Ice Age in northern Quebec. Higher landslide incidence during this period seems to reflect the persistence of cold and humid conditions. Slope instability appeared to have been general in subarctic Quebec during this period. Several instability phases associated with slope solifluction were identified by Bégin and Filion (1985).

These climatic conditions have also largely influenced forest succession in the newly-exposed mineral surfaces. The time lag between landslide occurrence and seedling establishment was relatively long, about 15–25 years. A similar time lag was reported by Begin and Filion (1985) in a landslide at Clearwater Lake, about 175 km northeast of Poste-de-la-Baleine. The tree regeneration pattern in subarctic areas is closely associated with climatic conditions, because seed production and germination are typically sporadic (Hustich 1970; Payette and Filion 1985). Landslide dating using age of the oldest trees appears questionable in this context, because it underestimates landslide age; this technique provides at best a minimum age to sliding in subarctic environments.

5.2 *Ancient Landslides*

Only two radiocarbon dates were available for ancient-landslide dating. The undated landslide A occurred probably between 3,200 and 2,200 BP, as suggested by its slightly higher position relative to landslide B. The latter occurred sometime after 2,200 BP. This date gives a maximum age to landslide because it was obtained from a buried charcoal layer corresponding to the top of the original terrace surface. Landslide C would have been formed before 900 BP. This date suggests a minimal landslide age, because there is no indication about the delay in paludification of the floor after its formation.

These few dates cannot give an accurate time scale to evaluate the climatic context initiating landslide activity, as it was for recent landslides with tree-ring analysis. Lebuis et al. (1982) reported frequent landslide activity between 1,250 and 750 BP in the St. Lawrence Lowland, but this time interval overlapped both a cold period (1,600–1,000 BP) and a mild period (1,000–750 BP) in northern Quebec (Filion 1984). The only reliable indication of conditions conducive to landslide activity yet available referred to the season of occurrence. The presence of microfaults in landslide-B topsoils suggests that it was formed during spring. No such evidence was found in landslides A and C.

6 Conclusions

The landslide chronology described here shows temporal discontinuity in mass-movement activity over the last 3,200 radiocarbon years. Three landslides were formed during a period of about three millenia, while four others occurred within a 30-year period. The tree-ring analysis has been a useful dating tool for recent landslide activity. It has provided the exact date and season of landslide occurrence, as well as the short-term climatic context responsible for their inception. The higher landslide frequency recorded in the first part of the nineteenth century was associated with particular climatic conditions (cold and humid). Some landslides occurred during spring, and others during summer. The former were probably induced by snowmelt conditions, and the latter by cool and humid summer conditions. More detailed studies using dendrochronological and archival data could be helpful in determining the seasonal occurrence of a greater number of landslides. On the other hand, landslide dating by the ^{14}C technique does not provide enough information on the particular climatic conditions prevailing at the time of landslide activity, unless several dates are used to build reliable mass-movement chronologies which may be compared to existing geomorphic or ecological chronologies. Nevertheless, this dating technique gives the possibility to define the spatio-temporal sequence of landslide development during the Holocene.

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