Article

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AGE OF ROTATIONAL LANDSLIDES IN THE CYPRESS HILLS, ALBERTA-SASKATCHEWAN*

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ABSTRACT The topography of the west block of the Cypress Hills indicates that fluvial dissection of the plateaux and subsequent rotational landsliding of valley sides have been the dominant Quaternary geomorphic processes. This paper presents a preliminary chronology of rotational landslides based on the relative ages of 17 landslides and on 3 absolute dates. Four indices of relative age were used: organic content in Ah and B soil horizons, the size and coverage of lichens and weathering rind thickness on boulders exposed by landsliding, and the concavity and gradient of gullies in landslide debris. One landslide occurred in 1965. Organic materials collected from buried soil horizons beneath depressions on 3 other landslides were radiocarbon dated at 1235 ± 105, 1635 ± 105 and 7259 ± 165 yrs. BP. Microscopic analysis of the organic material revealed that the oldest sample was contaminated with older carbon. Cluster analysis of the relative age data in conjunction with 3 acceptable absolute dates suggests that the landslides under study have occurred during late Holocene time.

RÉSUMÉ *La datation des glissements de terrain par rotation dans les Cypress Hills, Alberta-Saskatchewan.* La topographie du secteur ouest des Cypress Hills révèle qu'au Quaternaire les principaux processus géomorphologiques ont été l'érosion fluviatile, sur les plateaux, et les glissements de terrain par rotation, sur les versants. Le présent article propose une chronologie des glissements de terrain, 17 ayant une datation relative, et 3, une datation absolue. Quatre indices ont été utilisés pour déterminer l'âge relatif : la teneur en matière organique des horizons pédologiques Ah et B, la concavité et la pente des ravins creusés dans les matériaux, la taille des lichens et la surface qu'ils occupent sur des blocs mis au jour par les glissements de terrain, ainsi que l'épaisseur de la couche altérée sur ces blocs. Il y eut un glissement en 1965. À la suite du prélèvement de matière organique dans des horizons pédologiques enfouis, on a pu dater au radiocarbone trois autres glissements (1235 ± 105; 1635 ± 105; 7259 ± 165 BP). L'analyse des échantillons au microscope révèle que la matière organique la plus ancienne renfermait du carbone. Une analyse d'ensemble (datations relatives et absolues) laisse penser que les glissements de terrain se sont produits à la fin de l'Holocène.

ZUSAMMENFASSUNG *Datierung der Erdrutsche in den Cypress Hills, Alberta-Saskatchewan.* Die Topographie des Westteils der Cypress Hills läßt erkennen, daß die fluviatile Gliederung der Plateaus und anschließende Erdrutsche der Talseiten die wichtigsten geomorphologischen Prozesse im Quaternär gewesen sind. Dieser Artikel gibt eine vorläufige Chronologie der Erdrutsche, gestützt auf die relative Datierung von 17 Erdrutschen und auf drei absolute Datierungen. Vier Anhaltspunkte wurden für die relative Datierung benutzt: Der organische Gehalt in den Ah und B Boden-Horizonten, die Größe und Ausdehnung der Flechten und die Dicke der Verwitterungskruste auf den durch die Erdrutsche bloßgelegten Blöcken und die Höhlung und Neigung der Rinnen in den Erdrutsch-Gesteinstrümmern. Ein Erdrutsch ereignete sich 1965. Organisches Material, das aus vergrabenen Boden-Horizonten unterhalb der Senken von drei anderen Erdrutschen stammt, wurde mit Radiokarbon auf 1235 ± 105, 1635 ± 105 und 7259 ± 165 Jahre BP datiert. Die mikroskopische Analyse des organischen Materials ließ erkennen, daß die älteste Probe älteren Kohlenstoff enthielt. Eine Block-Analyse der relativen Datierungen im Zusammenhang mit den drei annehmbaren absoluten Datierungen legt nahe, daß die untersuchten Erdrutsche während des späten Holozän stattgefunden haben.

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INTRODUCTION

Of the three blocks of the Cypress Hills, the west block, which straddles the Alberta-Saskatchewan border (Fig. 1), is the largest and has the highest elevation (1465 m). The topography of the west block (Fig. 2) reflects extensive modification by fluvial and mass wasting processes. Rotational landsliding has been the dominant process of hillslope evolution. Although fluvial processes have been operative with varying intensity throughout the Quaternary, the continuity of rotational landsliding is not as readily supposed. The objective of this study is to establish a preliminary landslide chronology for the west block of the Cypress Hills using methods of relative and absolute dating.

The west block is a unique landscape in the context of the surrounding northern Great Plains and is a key area for the study of Quaternary environmental change. Approximately 300 km^2 of the west block remained unglaciated during the Pleistocene (STALKER, 1965). Given a relatively large variation in slope gradient, aspect and elevation, the Cypress Hills are characterized by a variety of geomorphic systems which are responsive to environmental change. JUNGERIUS (1969) and JUNGERIUS and MÜCHER (1969) inferred periods of middle Holocene landscape stability and late Holocene geomorphic activity from the ages of soils buried under colluvium and an alluvial fan. Geologic surveys of the region, on the other hand, generally described Holocene landscape modification as slight (*e.g.* BROSCOE, 1965). The dating of landslides in the Cypress Hills has not been previously attempted.

PREVIOUS RESEARCH

A relatively limited number of techniques have been used to date landslides. KUJANSUU (1972) used radiocarbon dating and pollen analysis of peat beds to establish the minimum age of landslides in Finnish Lapland. The absolute dates placed these landslides in the time frame of continental deglaciation. CHINN (1981) measured weathering rind thickness on 280 surface boulders on a large landslide near the Ryton River, New Zealand. He calibrated a weathering rind curve with a ^{14}C date from wood buried by the landslide. STOUT (1969) dated carbonized wood fragments located below two landslides in southern California. Movement of the landslide represented by the oldest date is correlated with the maximum Late Wisconsinan low stand of sea level.

BRUNSDEN and JONES (1972) examined landslide activity in southwest Dorset, England within the local chronology of landscape evolution. The authors suggested that landslide activity was episodic, with quiet periods of slow degradation alternating with dynamic phases corresponding to periods of river incision and periglacial activity. Although no absolute ages were established, a minimum age of 500 years was determined from the age of roads and tracks which cross landslides and clearly postdate them.

NASMITH (1964) classified landslides in the Meikle River valley of northern Alberta as "youthful" or "mature". Similarly, SHRODER (1970) used qualitative morphologic criteria to establish 9 stages of evolution among 28 landslides in Utah. Shroder (p. 125) noted that "this age-classification was developed in Utah and thus problems might be found in applying it to other areas". Neither Shroder nor Nasmith reported absolute age ranges for their stages of landslide evolution.

Techniques of relative dating have generally been devised and used for research on glacial deposits (BIRKELAND, 1984).

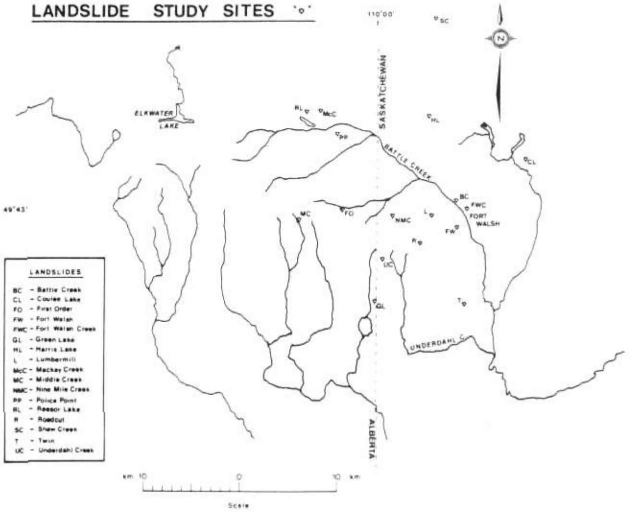

FIGURE 1. Location of the landslide study sites within the west block of the Cypress Hills, southwestern Saskatchewan and southeastern Alberta.

Localisation des sites de glissements de terrain dans la partie ouest des Cypress Hills, sud-ouest de la Saskatchewan et sud-est de l'Alberta.

FIGURE 2. Ridged and hummocky topography produced by rotational landsliding is widespread in the valleys of the Cypress Hills.

Les reliefs en creux et en bosses causés par les glissements de terrain sont courants dans les vallées des Cypress Hills.

Combinations of dating methods provide the most reliable relative age data (BIRKELAND, 1973; STORK, 1963). Although several problems and potential sources of error are associated with relative dating (BENEDICT, 1967; BIRKELAND, 1973, WEBBER and ANDREWS, 1973; JOCHIMSEN, 1973; WORSLEY, 1981), parameters such as lichen size (CALKIN and ELLIS, 1980; DOWDESWELL, 1984), weathering rind thickness (ANDERSON and ANDERSON, 1981; GELLATLY, 1984) and soil properties (CROCKER and DICKSON, 1956; BIRKELAND, 1978) have been used repeatedly with apparent success.

METHODS

The 17 rotational landslides identified in Figure 1 were chosen for study on the basis of their distinct and characteristic morphology: steep arcuate scarps, parallel elongated undrained depressions, and associated hummocky topography. In an attempt to determine the recentness of extensive large scale landsliding in the study area, site selection was biased toward the most evident paleo-landslide topography.

At the landslide study sites, the following parameters were measured as possible indices of relative age: organic content in Ah and B soil horizons, weathering rind thickness and the size and coverage of lichens on boulders exposed by landsliding, upper scarp gradient and the morphometry of gullies in landslide debris (Table I). Measurements of these parameters were used in conjunction with radiocarbon dates to establish a landslide chronology. The field procedures were developed largely from observations at Police Point landslide which occurred in 1965 (ROED, 1967a) and, thus, is a modern analogue of the landslides of the Cypress Hills.

TABLE I

Relative dating measurements

		Lichenometry												Weathering rinds (mm)			Soil development		Gully morphometry
		Diam. of individual *R.g.** thalli (mm)			Diam. of *R.g.** thalli clusters (mm)			% *R.g.** cover			% Total lichen cover						% organic content		
Landslide	Elevation (m)	mean	s.d.	range	mean	s.d.	range	mean	s.d.	range	mean	s.d.	range	mean	s.d.	range	Ab horizon	B horizon	concavity/ gradient
Battle Creek	1204	—	—	—	—	—	—	—	—	—	82.1	11.9	50.0	4.8	2.5	8.0	8.2 8.3	6.7 6.2	—
Coulie Lake	1219	—	—	—	—	—	—	—	—	—	42.5	23.8	75.0	1.0	0.5	1.5	7.3 9.3	7.4 5.3	0.0
First Order	1372	14.2	3.1	12.0	24.3	15.6	79.0	26.2	16.6	75.0	63.5	19.8	75.0	0.6	0.4	2.0	19.8 23.3	14.9 12.2	2.4
Fort Walsh	1158	—	—	—	—	—	—	—	—	—	59.3	21.3	80.0	0.9	0.4	1.5	14.6 14.4	9.8 9.8	—
Fort Walsh Cr.	1189	—	—	—	—	—	—	—	—	—	62.5	22.6	75.0	1.2	0.5	1.5	13.1 13.0	8.9 9.1	—
Green Lake	1158	—	—	—	—	—	—	—	—	—	85.9	10.0	40.0	1.9	1.0	3.5	19.3 19.3	7.6 6.9	1.6
Harris Lake	1250	—	—	—	—	—	—	—	—	—	62.2	17.0	63.0	2.4	1.3	4.0	15.5 17.3	7.7 13.0	3.7
Lumbermill	1234	—	—	—	—	—	—	—	—	—	75.8	15.9	50.0	1.4	1.0	3.5	14.6 8.4	5.5 8.7	—
Mackay Creek	1494	14.8	2.4	10.0	21.4	7.5	38.0	26.6	14.6	60.0	58.3	18.8	70.0	0.9	0.5	2.0	19.2 18.5	8.5 9.6	1.6
Middle Creek	1402	13.1	3.1	10.0	19.3	6.9	30.0	21.6	11.4	45.0	59.8	17.3	60.0	0.8	0.4	1.5	16.2 14.8	8.6 7.2	0.5
Nine Mile Creek	1341	16.8	3.8	13.0	35.4	12.9	50.0	37.8	14.9	65.0	75.9	13.0	60.0	1.5	0.6	2.0	22.2 15.8	8.2 11.2	.2
Police Point	1311	—	—	—	—	—	—	—	—	—	0.0	0.0	0.0	0.3	0.3	1.0	— —	— —	1.4
Reesor Lake	1478	—	—	—	—	—	—	—	—	—	80.8	18.7	80.0	0.9	0.5	1.5	14.4 11.7	8.8 9.1	—
Roadcut	1372	13.6	2.4	10.0	16.3	5.1	20.0	15.3	6.7	30.0	61.8	16.1	70.0	0.6	0.6	2.0	17.9 18.1	13.7 11.9	0.9
Shaw Creek	1006	—	—	—	—	—	—	—	—	—	22.6	20.9	65.0	0.9	0.5	1.5	6.1 8.7	4.8 6.7	—
Twin	1158	—	—	—	—	—	—	—	—	—	82.1	15.6	60.0	1.0	0.5	2.5	20.7 20.7	6.3 6.2	— 4.5
Underdahl Cr.	1372	14.5	4.5	18.0	28.2	10.4	43.0	35.0	18.5	65.0	68.1	17.4	60.0	1.1	0.7	2.5	12.5 11.1	8.4 7.9	1.8

* *Rhizocarpon geographicum*

RADIOCARBON DATES

Material ideally suitable for ^{14}C dating is buried by the landslide debris and, thus, not readily accessible. Unsuccessful attempts at locating such material necessitated selection of an alternate source of dateable material, if absolute dates for the landslide were to be obtained. Undrained intermittent ponds formed by landsliding support the growth of hygrophytic vegetation. The eventual decay and burial of this vegetation produces a ^{14}C dateable horizon immediately above the landslide debris, the age of which would represent a minimum age for the landslide. Such horizons were located at depths of 0.72 to 1.12 m below the surface of pond sediments on three landslides (Fig. 3).

LICHENOMETRY

Lichens were measured on fifty boulders sampled from boulder accumulations deposited at the base of upper scarps. These boulders have weathered out of the Cypress Hills formation which is exposed in the upper scarps of all the landslides studied. Measurements consisted of the diameter of individual *Rhizocarpon geographicum (R.g.)* thalli, diameter of *R. g.* thalli clusters, percentage *R.g.* thalli cover, and percentage total lichen cover. The problem of inhibited concentric growth within the limited exposed surface area (BESCHEL, 1961) is especially significant when sampling lichen diameters on boulders. Under these conditions, the measurement of the diameter of *R.g.* thalli clusters is perhaps a better relative age dating index than the diameter of individual *R.g.* thalli. The boulder accumulations at the base of the upper scarps were limited enough in both size and number of boulders that an exhaustive search for maximum *R.g.* thalli was feasible.

WEATHERING RINDS

The thickness of a weathering rind is the extent to which oxidation of minerals has penetrated below the surface of a clast (GELLATLY, 1984). The use of weathering rind thickness as a relative age indicator assumes that the thickness of the oxidized zone is directly related to the duration of subaerial weathering.

Weathering rinds were measured to the nearest 0.5 mm on 50 quartz sandstone, sandstone or quartzite boulders contained in the boulder accumulations at the base of the landslide upper scarps. Three separate zones can generally be distinguished in all but the youngest rinds: 1) an outer pink layer which increases in thickness from 0 to 1 mm with age and grades into, 2) a prominent whitish zone with a diffuse inner boundary, and 3) an inner dark band of variable thickness. The measure of rind thickness employed is adopted from CHINN (1981): the thickness from the boulder surface to the inner limit of the whitish zone. Recorded values represent an average of 4 measurements per clast.

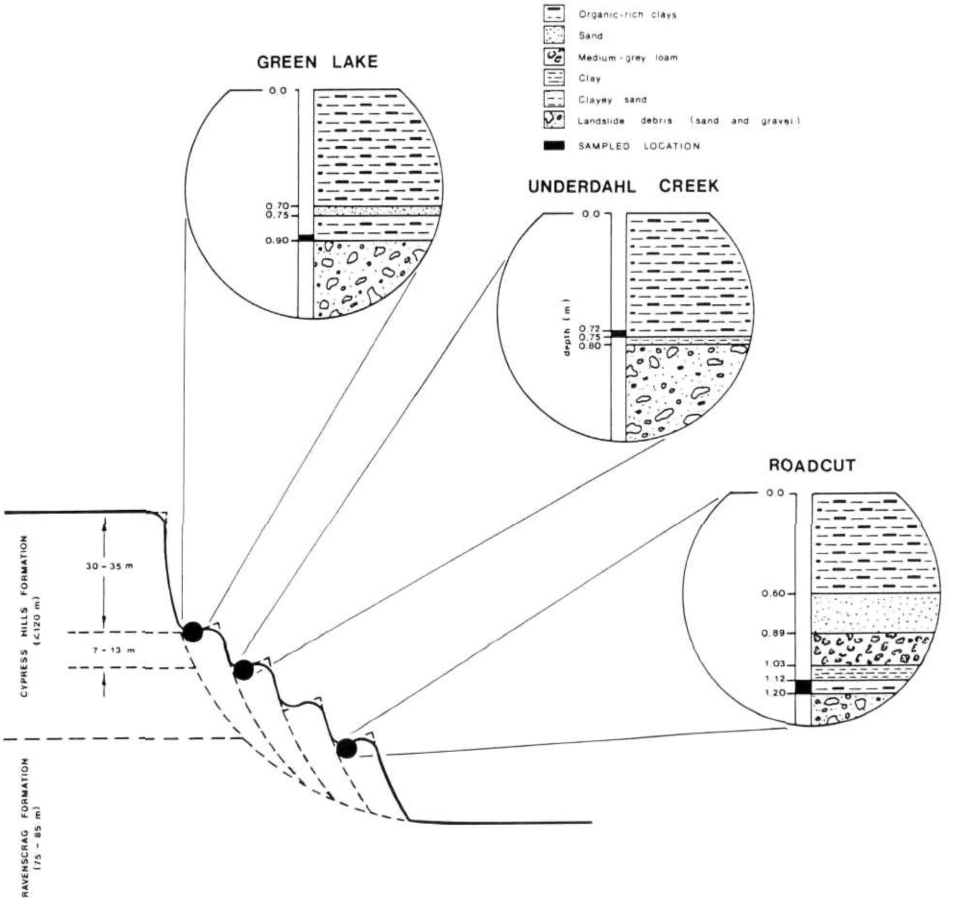

FIGURE 3. A cross-section of a typical landslide study site showing the location of soil pits from which radiocarbon dated sediments were obtained.

Coupe d'un site de glissements de terrain caractéristique montrant la localisation des trous où les sédiments datés au radiocarbone ont été prélevés.

The sampling of previously weathered boulders derived from the plateau surface or from oxidized horizons exposed by landsliding would yield rind thicknesses which overestimate the relative landslide age. In most weathering rind studies, the mean and standard deviation of the measurements have been used as indicators of the deposit age. Other workers (*e.g.* BIRKELAND, 1973; CARROLL, 1974) have used the maximum rind thickness. In either case, anomalously thick, previously formed weathering rinds would result in overestimation of the true age of the deposits. Modal rind thickness (CHINN, 1981; GELLATLY, 1984), on the other hand, is not affected by anomalously large values, unless these values represent the modal class. Significant rank correlations ($p < .05$) of the mode with the mean and the maximum rind thickness, indicate that anomalously thick, previously formed weathering rinds either were not sampled or, if present, have a negligible effect on the data.

SOIL DEVELOPMENT

Soil properties which change continuously with time can be used as indicators of relative age (RICHMOND, 1962). Three of these properties were used to date the studied landslides: organic content in the Ah horizon, organic content in the B horizon and depth from the surface to the base of the Ah horizon. The soil horizons were sampled for organic matter at their midpoints. The organic content of these samples is expressed in Table I as the % difference in weight of 3 gm of dehydrated soil (sifted through a 250 um sieve to remove non-decayed organic matter) before and after two hours in an ashing furnace at 450°C.

LANDSLIDE MORPHOMETRY

Upper scarp gradient and the morphometry of gullies are two properties of the landslides that change systematically over time and thus may be indices of relative landslide age. The predominant factors governing gully morphometry are ephemeral stream discharge, geology and time. The necessary, although risky, assumptions of minimal variation in stream discharge and geology among landslide sites leaves time as the one controlling variable. Younger landslides should thus have steeper upper scarps and gully gradients, and lower values of gully concavity.

Gully longitudinal profiles and upper scarp gradients were surveyed with an Abney level to the nearest 10 minutes and a tape measure to the nearest 1.0 cm. Stream profile concavity was calculated using the formula:

> Concavity = A1/A2, where A1 = area between the profile and a straight line connecting its end points and A2 = area of the right triangle where the line connecting the profile end points is the hypotenuse (after LEOPOLD *et al.*, 1964).

ANALYSIS AND RESULTS

The five categories of relative age dating parameters discussed above are independent in the sense that casual links, for example, between lichen size and stream channel morphometry, cannot be supposed. Therefore, statistically significant correlations between indices must result from correlation with a common variable. Kruskall Wallis analysis of variance indicates that rock type (Table II) does not significantly ($p > .05$) affect either *R.g.* thalli diameter, lichen cover or weathering rind thickness. Similarily, the rate of change of any of the above indices or the rate of accumulation of soil organic content does not appear to be affected by landslide elevation (Spearman rank correlation, $p = .05$) or landslide aspect (Fig. 4).

Thus, the common variable related to the correlated yet physically independent measures of relative age is landslide age. The indices used to establish a relative chronology of landsliding are those which significantly correlate ($p < .10$) with two or more variables. These indices are: 1) all lichen parameters, 2) organic content in both the Ah and B soil horizons, 3) weathering rind thickness, and 4) gully concavity/gully gradient (Table III).

The landslide chronologies were established from the mean proportional ranks for these selected indices (Table IV). Missing data necessitated the use of a proportional or standardized rank, the rank expressed as a proportion of the number of ranks for a particular index. Most of the missing data reflect the absence of *Rhizocarpon geographicum* at 11 of the 17 study sites. The proportional ranks are given in Table IV where 5 landslide chronologies have been derived from different combinations of the age dating indices. The landslides are listed from youngest to oldest, in order of increasing mean proportional rank.

Differences in the chronologies lie in the positions of a few landslides which do not conform to the rank correlations among

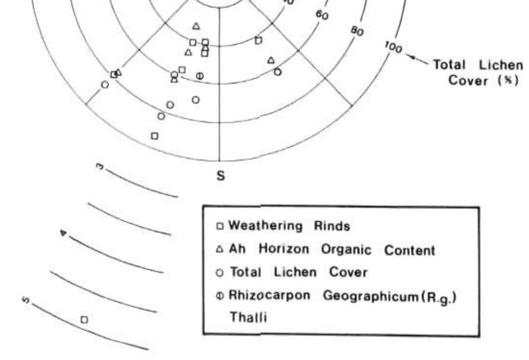

FIGURE 4. Graphical representation of the relationship between the relative dating parameters and landslide elevation.

Représentation graphique qui montre la relation entre les paramètres de datation relative et l'altitude des glissements de terrain.

TABLE II

Relationship of rock type with lichen parameters and weathering rinds

	Quartzite					Quartz sandstone					Sandstone				
LDSL	Weathering rinds n = 50	Lichen parameters				Weathering rinds n = 50	Lichen parameters				Weathering rinds n = 50	Lichen parameters			
	mean w.r. thickness (mm)	mean diam R.g.* thalli** (n)***	mean diam R.g.* thalli clusters	mean % R.g.* cover	mean % total lichen cover (n = 50)	mean w.r. thickness (mm)	mean diam R.g.* thalli	mean diam R.g.* thalli clusters	mean % R.g.* cover	mean % total lichen cover	mean w.r. thickness (mm)	mean diam R.g.* thalli	mean diam R.g.* thalli clusters	mean % R.g.* cover	mean % total lichen cover
B.C.	5.4	—	—	—	85.9	4.3	—	—	—	84.0	4.6	—	—	—	88.8
C.L.	1.5	—	—	—	42.0	1.0	—	—	—	37.5	0.9	—	—	—	43.9
F.O.	1.3	14.8 (18)	22.4	23.3	57.2	0.5	13.2	31.1	29.3	64.7	0.7	14.5	19.9	26.7	71.7
F.W.	0.8	—	—	—	56.4	0.9	—	—	—	63.2	0.9	—	—	—	58.6
F.W.C.	1.2	—	—	—	57.3	1.2	—	—	—	74.5	1.3	—	—	—	57.3
G.L.	1.3	—	—	—	89.7	1.6	—	—	—	85.7	2.7	—	—	—	85.6
H.L.	2.2	—	—	—	63.7	2.2	—	—	—	60.7	3.0	—	—	—	58.3
L.	1.6	—	—	—	75.3	1.5	—	—	—	74.3	1.3	—	—	—	71.4
Mc.C.	0.9	14.0 (13)	23.1	29.2	55.0	0.7	15.1	20.6	23.6	61.2	1.0	15.0	21.6	30.0	58.2
M.C.	1.0	13.0 (17)	19.3	19.2	61.8	0.7	12.6	20.4	24.7	60.0	1.0	14.0	17.9	22.0	57.5
N.M.C.	2.0	16.3 (24)	35.0	37.5	75.5	1.8	17.7	34.0	34.7	69.3	1.4	16.5	11.4	45.0	84.5
P.P.	0.6	—	—	—	0.0	0.3	—	—	—	0.0	0.2	—	—	—	0.0
R.L.	0.8	—	—	—	79.0	1.0	—	—	—	77.1	0.9	—	—	—	86.9
R.	0.3	14.0 (13)	15.7	12.7	58.1	0.8	14.0	17.3	15.9	56.8	0.6	12.9	16.0	16.3	66.1
S.C.	1.1	—	—	—	17.7	0.7	—	—	—	23.1	0.8	—	—	—	27.5
T.	1.3	—	—	—	82.0	0.8	—	—	—	86.3	1.1	—	—	—	81.1
U.C.	1.3	14.4 (10)	23.7	22.5	63.5	1.5	14.8	27.2	31.3	66.3	1.1	14.6	30.5	41.3	70.0
Mean	1.4	14.4	23.2	24.1	60.0	1.3	14.6	25.1	26.6	61.4	1.4	14.6	19.6	30.2	62.8
S.D.	1.1	1.1	6.5	8.5	23.2	0.9	1.8	6.7	6.7	22.7	1.1	1.2	6.4	11.1	23.0
Range	5.1	3.3	19.3	24.8	89.7	4.0	5.1	16.7	18.8	86.3	4.4	3.6	19.1	28.7	88.8

* *Rhizocarpon geographicum*
** *R.g.* thalli diameter measurements are in mm
*** (n) = sample size of *Rhizocarpon geographicum* at each landslide

indices. Some of the potential sources of error associated with the age dating methods discussed above may be more prevalent at these sites. Thus some indices may suggest somewhat different relative ages for the same landslide. Although the exact ordering of the landslides varies between the different chronologies, cluster analysis of each chronology reveals distinct groups of landslides which retain their position regardless of the combination of indices used. Consistency among the relative ages determined by different dating methods is further evidenced by significant correlations ($p < .05$) among the mean proportion ranks used to establish the three chronologies.

Absolute dates were obtained for 3 landslides besides Police Point, which occurred as several events between 1965 and 1967 (ROED, 1967a). The ^{14}C dates of buried organic material from Roadcut, Green Lake, and Underdahl Creek landslides are 7259 ± 165 (S-2629), 1635 ± 105 (S-2630) and 1235 ± 100 (S-2631) yrs BP, respectively. Comparison of these dates with the chronologies in Table IV indicates that the oldest date (derived from the Roadcut landslide sample) conflicts with the relative age data. Microscopic analyses of polished sections of the three samples revealed that the sample from Roadcut landslide contains lignite while lignite was not identified in either the Green Lake or Underdahl Creek samples (L. Stasiuk, Coal Petrology Lab, Univ. of Regina; pers. comm.). Thus the ^{14}C date of 7295 ± 165 yrs. BP is considered a gross overestimate of the age of Roadcut landslide. The lignite likely was derived from the Ravenscrag formation which is exposed on the lower parts of many of the landslides under study. Figure 3 illustrates that the sample containing lignite was obtained from a depression on the lower part of Roadcut landslide, while the other two landslides were sampled beneath higher elevation scarps where only the sands and gravels of the Cypress Hills formation are exposed. The ^{14}C dates from Underdahl Creek and Green Lake landslides represent the age of bulk organic materials consisting of the remains of vegetation which first colonized the landslides and possibly organic matter from soil predating the landslide and humus illuviated from the overlying contemporary soil (rootlets and bicarbonates were removed during pretreatment of the samples). Since the carbon from pre-existing and overlying (post-dating) soil would cause the ages of landslides to be over- and under-estimated, respectively, the ^{14}C dates are regarded as approximate ages of the corresponding landslides.

DISCUSSION

The exclusion of the ^{14}C date from Roadcut landslide leaves three landslides for which acceptable absolute dates have been obtained. Fortunately, each of these landslides falls in a different relative age cluster (Table IV). Within the youngest

TABLE III

Correlation among relative age dating indices

	Diameter of *R.g.* thalli clusters	Percentage *R.g.* cover	Percentage total lichen cover	Upper scarp gradient	Organic content in Ah horizon	Organic content in B horizon	Thickness of Ah Horizon	Thickness of weathering rinds	Gully concavity	Gully gradient	Gully concavity/ gradient
Diameter of *R.g.* thalli	0.771 * 6	0.886 ** 6	— 6	— 6	— 6	— 6	−0.714 * 6	0.857 ** 6	0.821 ** 6	— 6	0.857 ** 6
Diameter of *R.g.* thalli clusters		0.943 *** 6	0.771 * 6	— 6	— 6	— 6	— 6	−0.829 ** 6	0.886 ** 6	— 6	0.886 ** 6
Percentage *R.g.* cover			— 6	— 6	— 6	— 6	— 6	0.941 *** 6	0.771 * 6	— 6	0.771 * 6
Percentage total lichen cover				— 17	— 15	— 15	— 16	0.596 ** 16	0.564 * 11	— 11	0.736 *** 11
Upper scarp gradient					— 15	— 15	— 16	— 16	— 11	— 11	— 11
Organic content in Ah horizon						0.879 **** 14	−0.521 ** 15	— 14	0.733 ** 9	— 9	0.700 ** 9
Organic content in B horizon							−0.484 * 15	— 14	0.816 *** 9	— 9	0.767 ** 9
Thickness of Ah horizon								— 15	−0.499 *** 10	— 10	−0.590 * 10
Thickness of weathering rinds									— 11	−0.556 * 11	0.564 * 11
Gully concavity									—	— 11	0.946 **** 11
Gully gradient											— 11
Gully concavity/gradient											

Spearman rank correlation coefficients
prob /r/ under Ho: Rho = O
number of observations

— $p > 0.10$
* $p < 0.10$
** $p < 0.05$
*** $p < 0.01$
**** $p < 0.001$

R.g.: *Rhizocarpon geographicum*

TABLE IV

Landslide	Proportional rank					Mean proportional ranks					Chronologies (youngest to oldest)				
	All *R.g.** indices (1)	Percent total lichen cover (2)	Weathering ring thickness (3)	Gully concavity/ gradient (4)	Organic content (Ah & B horizons) (5)	Indices 1,2,3,4&5	Indices 1,2,3&4	Indices 1,2,3&5	Indices 3,4&5	Indices 1,2,4&5	Indices 1,2,3,4&5	Indices 1,2,3&4	Indices 1,2,3&5	Indices 3,4&5	Indices 1,2,4&5
Battle Cr.	—	0.938	1.000	—	0.188	0.709	0.970	0.709	0.594	0.563	Police Point	Police Point	Police Point	Police Point	Shaw Cr.
Coulee L.	—	0.125	0.500	0.000	0.125	0.188	0.209	0.250	0.208	0.083	Shaw Cr.	Roadcut	Shaw Cr.	Shaw Cr.	Coulee L.
First Order	0.400	0.563	0.125	0.700	1.000	0.558	0.485	0.522	0.608	0.666	Coulee L.	Shaw Cr.	Roadcut	Coulee L.	Police Point
Fort Walsh	—	0.250	0.375	—	0.688	0.438	0.313	0.438	0.532	0.469	Roadcut	Middle Cr.	Coulee L.	Roadcut	Roadcut
Fort Walsh Cr.	—	0.500	0.688	—	0.437	0.542	0.595	0.542	0.563	0.469	Middle Cr.	Coulee L.	Middle Cr.	Middle Cr.	Middle Cr.
Green L.	—	1.000	0.875	0.400	0.625	0.725	0.758	0.833	0.633	0.675	Fort Walsh	Fort Walsh	Fort Walsh	Lumbermill	Fort Walsh Cr.
Harris L.	—	0.438	0.938	0.900	0.750	0.757	0.759	0.709	0.863	0.696	Mackay Cr.	Mackay Cr.	Mackay Cr.	Underdahl Cr.	Fort Walsh
Lumbermill	—	0.688	0.750	—	0.250	0.563	0.720	0.563	0.500	0.469	Fort Walsh Cr.	First Order	First Order	Mackay Cr.	Lumbermill
Mackay Cr.	0.600	0.188	0.250	0.500	0.812	0.470	0.385	0.463	0.521	0.525	First Order	Fort Walsh Cr.	Fort Walsh Cr.	Fort Walsh	Mackay Cr.
Middle Cr.	0.200	0.313	0.188	0.100	0.437	0.248	0.201	0.285	0.242	0.263	Lumbermill	Reesor L.	Lumbermill	Fort Walsh Cr.	Battle Cr.
Nine Mile Cr.	1.000	0.750	0.818	0.800	0.875	0.848	0.841	0.861	0.831	0.856	Underdahl Cr.	Underdahl Cr.	Underdahl, Cr.	Battle Cr.	Underdahl Cr.
Police Point	—	0.000	0.000	0.300	0.000	0.075	0.100	0.000	0.100	0.100	Battle Cr.	Lumbermill	Twin	First Order	First Order
Reesor L.	—	0.813	0.438	—	0.938	0.730	0.625	0.730	0.688	0.876	Green L.	Green L.	Battle Cr.	Green L.	Green L.
Roadcut	0.000	0.375	0.063	0.200	0.431	0.215	0.160	0.218	0.232	0.252	Reesor L.	Harris L.	Harris L.	Reesor L.	Harris L.
Shaw Cr.	—	0.063	0.313	—	0.063	0.146	0.188	0.146	0.188	0.063	Twin	Twin	Reesor L.	Twin	Twin
Twin	—	0.875	0.563	1.000	0.562	0.750	0.813	0.667	0.708	0.812	Harris L.	Nine Mile Cr.	Green L.	Nine Mile Cr.	Nine Mile Cr.
Underdahl Cr.	0.800	0.625	0.625	0.600	0.313	0.593	0.663	0.591	0.513	0.585	Nine Mile Cr.	Battle Cr.	Nine Mile Cr.	Harris L.	Reesor L.

Hierarchical cluster
——— Major cluster boundary
- - - - - - - - Minor cluster boundary

* *R.g.* — *Rhizocarpon geographicum*

cluster, the absolute age of Police Point landslide is 20 yrs. BP. The intermediate cluster contains Underdahl Creek landslide dated at 1235 ± 100 yrs. BP. Among the youngest landslides in the oldest cluster is Green Lake, dated at 1635 ± 105 yrs. BP. A 400 year difference in age between clusters indicates relatively limited age variation within the intermediate and older age groups. If one or more landslides were anomalously old, a cluster boundary would separate these landslides from the others in the age group. Given a greater age variation between landslides from different clusters than between landslides within a cluster, the age difference between landslides in the oldest cluster should not exceed 2400 years (given a maximum of 6 landslides in the oldest cluster of any of the five chronologies, multiplied by a maximum 400 year age difference between landslides). The age limit for the oldest landslide thus would be 4140 yrs. BP (2400 + 1634 + 105 yrs. BP). Alternatively, 4140 yrs. BP may be the approximate limit of significant change in the relative age dating parameters. That is, the difference in age between the landslide of greatest age (Nine Mile Creek) and the landslide represented by the oldest ^{14}C date (Green Lake) may be greater than that indicated by the relative age data.

Much controversy surrounds the maximum age attainable by *Rhizocarpon geographicum* (*R.g.*). It is extremely difficult to determine the end of active growth or arrival of senescence for lichens (CALKIN and ELLIS, 1980) and the ultimate lifespan of the Rhizocarpons (BESCHEL, 1961). BENEDICT (1967) and CARROLL (1974) suggest that the maximum size of *R.g.* in the Colorado Front Range is reached in 3000 years. Consequently, *R.g.* thalli on a 10,000 year old deposit in this region may be no larger than on a 3000 year old deposit. LUCKMAN and OSBORN (1979) believe the species is only useful for absolute dating of early Neoglacial or pre-Altithermal glacial advances. However, *R.g.* has been reported to be capable of attaining an age in excess of 9000 years (DENTON and KARLEN, 1973; ANDREWS and BARNETT, 1979; and LOCK, ANDREWS and WEBBER, 1979).

Weathering rind thickness is limited only by the radius of the weathering boulder. CERNOHOVZ and SOLC (1966) and OLLIER (1969) suggest that rates of rind development decrease logarithmically, because the buildup of weathered products retards weathering of the core. Although the duration of linear change in the rate of rind formation is not conclusively established, substrate older than 10,000 years have been dated with apparent success by assuming linear growth rates (CARROLL, 1974; PORTER, 1975; ANDERSON and ANDERSON, 1981; CHINN, 1981; GELLATLY, 1984).

Soil properties also eventually reach a steady state. BIRKELAND (1984) suggests that the time required for a steady state in organic content may range from as little as 200 to more than 3000 years. The greater variation in organic matter between samples from different landslides than between samples from the same landslipe implies that a steady state has not been reached under the grassland conditions which characterize the study sites. Also, gully concavity and gradient continue to change only until a graded condition is achieved. The marked degree of irregularity in all of the gully profiles surveyed suggests that graded conditions have not been reached.

The degree of uncertainty associated with the upward age limit of these relative age dating parameters does not rule out the possibility that these limits have been reached at the study sites. This possibility is recognized and demands further research. It is improbable, however, that all of the parameters have reached their maximum age limit, given successful application beyond 4140 yrs. BP of at least 2 parameters in previous studies (DENTON and KARLEN, 1973; CHINN, 1981).

CONCLUSIONS

Of the 5 methods used to date the 17 landslides, 4 appear to be measures of relative age, given that they are rank correlated, that is, they produce similar landslide chronologies. Only the gradient of the main scarp is not significantly correlated with other independent indices of relative age. Main scarp gradient is probably controlled by bedrock structure, scarp aspect and/or vegetation more so than by the age of the scarp itself. Only those indices which exhibited the highest number of significant ($p < .10$) correlations with indices from other categories of relative age parameters were used to establish the landslide chronology. Although minor variations in the ordering of the landslides exist among chronologies based on different combinations of indices, the validity of a general ordering (Table IV) is supported by: significant correlation between mean proportional ranks, the marked comparability in groups of landslides determined by cluster analyses of each chronology, and compliant absolute dates.

The relatively small difference in absolute age between landslides from different relative age clusters suggests that landsliding has been a more or less continuous process throughout the late Holocene, or at least, that episodes of landsliding have not been interrupted by long periods of inactivity. Thus environmental conditions favourable to landsliding must have existed throughout this time period, and Police Point Landslide, which occurred in 1965 indicates that these conditions still exist.

Landsliding in the Cypress Hills is favoured by the fluvial dissection of sedimentary rocks, including a permeable cap rock, groundwater bearing strata and multiple clay beds. Much of the surface water seeps through the capping Cypress Hills formation into montmorillonitic and bentonitic clays, and silts of the Ravenscrag Formation and occasionally emerges springs along the valley sides (ROED, 1967b). Since the clays and, to a lesser extent, silt are subject to high porewater pressure when saturated, landsliding occurs primarily when and where groundwater underlies and emerges from the valley sides. Post-altithermal climatic change towards wetter and cooler climatic conditions would have produced higher water tables in response to increased recharge and decreased evaporation. Thus, the climatic conditions which prompted neoglaciation of the Cordillera apparently led to landsliding in the Cypress Hills.

By studying distinct landslide topography, features such as scarps, depressions, gullies and boulder accumulations were more easily identified and researched. However, the subdued landslide topography is not represented by the sample of landslides under study and may constitute a separate population of landslides. These landslides may correspond in age to Pleistocene episodes of glaciation of the surrounding plains or fluvial and glaciofluvial dissection of the plateaux. We can further hypothesize that a population of late Holocene landslides represented by those studied here is separated in time from older landslides by a period of altithermal hillslope stability. The testing of these hypotheses requires more research of the kind described here.

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