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Soil Development in Quaternary Glacial Deposits, Waterton Park Area, Southwestern Alberta
La formation de sols dans des dépôts glaciaires quaternaire, région du parc Waterton, sud-ouest de l'Alberta
Die Bildung der Böden in den glazialen Quaternär-Ablage-rungen im Gebiet des Waterton-Parks, Südwest-Alberta

Eric T. Karlstrom

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Résumé de l'article

Les recherches pédologiques menées dans la région du parc Waterton ont permis de vérifier les subdivisions des dépôts glaciaires quaternaires fondées sur les relations géomorphologiques. Les sols de la région, incluant les podzols, les brunisols, les luvisols et les sols chernozémiques, reflètent également l'influence d'autres facteurs de formation que le temps. On peut tout de même établir une chronoséquence en comparant les propriétés relatives au temps des sols développés sur différentes unités géomorphologiques situées dans des régions dont le climat, la végétation, les pentes et le matériau parental sont similaires. Les propriétés considérées comme étant les plus indicatives de l'âge relatif des sols comprennent l'épaisseur et le degré d'accumulation d'argile dans les horizons B. Deux indices de développement de sols, qui font la moyenne du degré d'évolution d'un certain nombre de propriétés, fournissent aussi des indications relatives à l'âge. Les données pédologiques et géomorphologiques laissent croire que les dépôts de surface comprennent des tills de montagne de trois ou quatre glaciations distinctes et des tills d'origine continentale de deux glaciations distinctes. Les tills de montagne sont à titre d'essai mis en corrélation avec le Wisconsinien supérieur (environ 18 ka BP), le Wisconsinien supérieur ou le Wisconsinien inférieur (environ 100 à 65 ka BP), l'Illinoien supérieur (environ 200 à 132 ka BP), et l'Illinoien inférieur ou le pré-lllinoien (environ 400 à 700 + ka BP), tandis que les tills d'origine continentale sont mis en corrélation avec les dépôts du centre des États-Unis datant du Wisconsinien supérieur et de l'Illinoien supérieur.

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SOIL DEVELOPMENT IN QUATERNARY GLACIAL DEPOSITS, WATERTON PARK AREA, SOUTHWESTERN ALBERTA*

Eric T. KARLSTROM, Department of Geography, University of Wyoming, Laramie, Wyoming 82071, U.S.A.

ABSTRACT Pedological investigations in the Waterton Park area provide a useful means of testing subdivisions of Quaternary glacial deposits based on geomorphic relations. Soils in the region, however, including Podzols, Brunisols, Luvisols, and Chernozemics, also reflect the influence of soil forming factors other than time. Nonetheless, a chronosequence can be established by comparing time-diagnostic properties of soils on different geomorphic units in areas with similar climate, vegetation, slope and parent material. Properties thought to be most diagnostic of relative soil age include thickness and degree of clay buildup in B horizons and two soil development indices which average degree of development of a number of properties. Pedologic and geomorphic data suggest surface deposits include mountain tills of three or four separate advances and continental tills of two separate advances. Mountain tills are tentatively correlated with the Late Wisconsinan (about 18 ka BP), Late and/or Early Wisconsinan (about 100 to 65 ka BP), Late Illinoian (about 200 to 132 ka BP), and Early Illinoian and/or pre-Illinoian (about 400 to 700 + ka BP), whereas continental tills are tentatively correlated with the Late Wisconsinan and Late Illinoian deposits of the U.S. Midcontinent.

RÉSUMÉ *La formation de sols dans des dépôts glaciaires quaternaire, région du parc Waterton, sud-ouest de l'Alberta.* Les recherches pédologiques menées dans la région du parc Waterton ont permis de vérifier les subdivisions des dépôts glaciaires quaternaires fondées sur les relations géomorphologiques. Les sols de la région, incluant les podzols, les brunisols, les luvisols et les sols chernozémiques, reflètent également l'influence d'autres facteurs de formation que le temps. On peut tout de même établir une chronoséquence en comparant les propriétés relatives au temps des sols développés sur différentes unités géomorphologiques situées dans des régions dont le climat, la végétation, les pentes et le matériau parental sont similaires. Les propriétés considérées comme étant les plus indicatives de l'âge relatif des sols comprennent l'épaisseur et le degré d'accumulation d'argile dans les horizons B. Deux indices de développement de sols, qui font la moyenne du degré d'évolution d'un certain nombre de propriétés, fournissent aussi des indications relatives à l'âge. Les données pédologiques et géomorphologiques laissent croire que les dépôts de surface comprennent des tills de montagne de trois ou quatre glaciations distinctes et des tills d'origine continentale de deux glaciations distinctes. Les tills de montagne sont à titre d'essai mis en corrélation avec le Wisconsinien supérieur (environ 18 ka BP), le Wisconsinien supérieur ou le Wisconsinien inférieur (environ 100 à 65 ka BP), l'Illinoien supérieur (environ 200 à 132 ka BP), et l'Illinoien inférieur ou le pré-Illinoien (environ 400 à 700 + ka BP), tandis que les tills d'origine continentale sont mis en corrélation avec les dépôts du centre des États-Unis datant du Wisconsinien supérieur et de l'Illinoien supérieur.

ZUSAMMENFASSUNG *Die Bildung der Böden in den glazialen Quaternär-Ablagerungen im Gebiet des Waterton-Parks, Südwest-Alberta.* Pedologische Forschungen, die im Gebiet des Waterton-Parks durchgeführt wurden, erlaubten die Unterteilungen der glazialen Ablagerungen im Quaternär, die sich auf geomorphologische Beziehungen stützen, zu überprüfen. Die Böden des Gebiets, einschliesslich der Podsole, der Brunisole, der Luvisole und der Chernozemiks, spiegeln auch den Einfluss anderer bodenbildender Faktoren als der Zeit. Dennoch lässt sich eine Chronosequenz erstellen, indem man zeitdiagnostische Eigenschaften von Böden in verschiedenen geomorphischen Einheiten vergleicht, in Gebieten, deren Klima, Vegetation, Abhänge und ursprüngliches Material gleichartig sind. Zu den Eigenschaften, von denen man glaubt, dass sie am besten das relative Alter der Böden anzeigen, gehören die Dicke und der Akkumulationsgrad des Tons in den B-Horizonten. Zwei Anhaltspunkte zu der Entwicklung der Böden, die den Durchschnitt des Entwicklungsgrades einer bestimmten Zahl von Eigenschaften ermitteln, liefern auch Hinweise, das Alter betreffend. Die pedologischen und geomorphologischen Daten lassen vermuten, dass die Oberflächen-Ablagerungen Berg-Tills von drei oder vier verschiedenen Vereisungen enthalten. Die Berg-Tills hat man probeweise in Beziehung zum späten Wisconsinan (etwa 18 ka v.u.Z.), dem späten und/oder frühen Wisconsinan (etwa 100 bis 65 ka v.u.Z.), dem späten Illinoium (etwa 200 bis 132 ka v.u.Z.) und dem frühen Illinoium und/oder prä-Illinoium (etwa 400 bis 700 + ka v.u.Z.) in Beziehung gebracht, während die Tills kontinentaler Herkunft mit den Ablagerungen des Zentrums der Vereinigten Staaten korreliert werden, die aus dem späten Wisconsinan und dem späten Illinoium stammen.

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INTRODUCTION

Glacial chronologies postulated for the Waterton-Glacier Parks area vary significantly (Table I). Most of the important differences in these reconstructions are represented in the contrasting interpretations of Horberg (1954) and Stalker and Harrison (1977). Specifically, whereas Stalker and Harrison (1977) distinguish mountain tills of four separate glacial advances, Horberg (1954) recognizes only three. In addition, whereas Stalker and Harrison (1977) recognize continental tills of two separate events (Illinoian and Early Wisconsinan), Horberg (1954) maps all continental till in the area as Late Wisconsinan. This difference of interpretation reflects a wider controversy concerning the dating of the last Laurentide glacier advance into the region. Whereas some workers (Horberg, 1954; Harrison, 1976; Clayton and Moran, 1982; Mickelson *et al.*, 1983; Richmond, 1986) place this event in the Late Wisconsinan (about 18,000 to 20,000 BP), others (Alley, 1973; Reeves, 1973; Stalker and Harrison, 1977; Rutter, 1980; Jackson, 1983; Stalker, 1983; Barendregt and Stalker, 1984) postulate that it occurred during the Early Wisconsinan prior to about 50,000 BP. Terminology for glacial deposits varies; whereas some workers have applied local names (Stalker, 1963; Alley, 1973; Stalker and Harrison, 1977; Richmond 1986), others have adopted nomenclature from the U.S. Mid-continent (Alden, 1924; Horberg, 1954; Karlstrom, 1981) and the U.S. Rocky Mountains (Richmond, 1965; Reeves, 1975).

In the absence of absolute dating criteria, workers have estimated relative ages of surface deposits on the basis of geomorphic relations and, in some cases, degree of soil development based on field criteria (Horberg, 1954; Wagner, 1966; Richmond, 1986). Although the Canada Soil Survey (Coen and Holland, 1974, 1976) has described both field and laboratory properties of soils in the Waterton region, laboratory data has not previously been utilized in the assignment of relative ages to glacial deposits. This paper, then, presents detailed field and laboratory soil data in order to 1) test the hypothesis that relative degree of soil development can be useful in recognizing different-age surface tills, and 2) help determine which of the previously defined glacial chronologies are best supported by pedological data.

Establishing a soil chronosequence in this region, however, is complicated by the fact that differences in soil properties also reflect regional variations in climate, vegetation, parent material, and slope, as well as differences in soil age. Hence, it is imperative to 1) focus on regions where soil forming factors other than time are most similar, and 2) define, as best as possible, rates at which specific soil properties develop so that relative ages of different soil types may be estimated.

REGIONAL SETTING

PHYSIOGRAPHY AND GLACIAL GEOMORPHOLOGY

Soils of the Waterton Park area (Fig. 1) are developed in mountain and continental tills, glacial outwash, alluvial fans, deltas, eskers, drumlins, lacustrine and eolian deposits, and colluvium. Bedrock in the Lewis Range west of the Lewis Thrust consists of Purcell Precambrian sedimentary rocks, including argillite, quartzite, limestone, dolomite, and some diorite. The mountains reach heights of about 3200 m and their rugged topography reflects numerous episodes of glacial erosion. The foothills and plains east of the mountain front, including the Belly River Valley and the Waterton drainage east of Middle Waterton Lake, are underlain by fine-grained Upper Cretaceous shales and sandstones of the Belly River and Wapaibi formations.

TABLE I

Glacial chronologies postulated for Waterton Park area

10^3 Year BP	N. Montana* (Alden, 1932)	Waterton Park (Horberg, 1954)	Porcupine Hills, Alta. (Alley, 1973)	Waterton Park (Reeves, 1975)	Waterton Park (Stalker and Harrison, 1977)
10					
				Pinedale 3,4 (M)	
20	Late Wisconsinan (M)	Late Wisconsinan (L + M)	Hidden Creek (M)	Pinedale 1,2 (M)	Waterton IV (M)
40					
60		Drywood Soil			
	Early Wisconsinan (L,M)	Early Wisconsinan (M)	Buffalo Lake (L) Ernst (M)	Bull Lake 2 (M,L) Bull Lake 1 (M,L)	Waterton III (M)
100					
140	Iowan or Illinoian (L + M)		Maunsell (L) Maycroft (M)		
200					
300		Soil			
			Labuma (L) Albertan (M)		Waterton I (M,L)
500		Kennedy Drift (M)			

* M = advance of mountain glaciers; L = advance of Laurentide glacier.

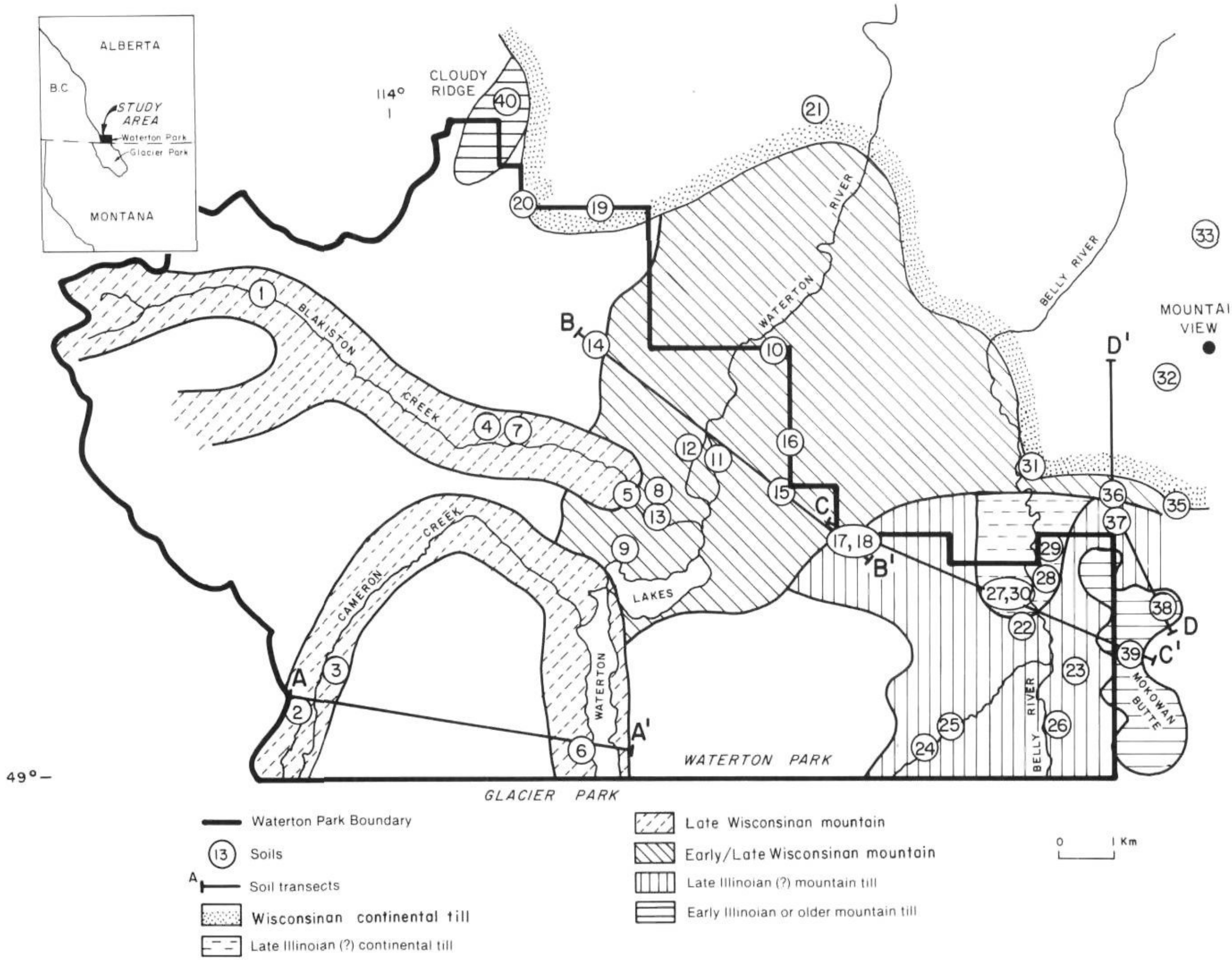

FIGURE 1. Location of 40 soils, 4 soil transects, and inferred distribution of surface tills of various ages in the Waterton Park area.

Localisation de 40 sols et de 4 transects ainsi que la répartition probable des tills de surface de divers âges dans la région du parc Waterton.

Located in the foothills east of the mountains, Mokowan Butte and Cloudy Ridge, are considered remnants of the Flaxville (Miocene to Pliocene?) and No. 2 (early Pleistocene) Bench erosion surfaces, respectively (Alden, 1932). These interfluves are underlain by Cretaceous sandstones and shales and mantled with some 30 to 70 ± m of pre-Wisconsinan diamict (including till and outwash/alluvium), termed Kennedy drift, derived from the nearby mountains (Alden and Stebinger, 1913; Horberg, 1956). Karlstrom (1987a, 1988) has identified up to five strongly to very strongly developed paleosols on and between five superposed pre-Wisconsinan diamicts on Mokowan Butte. The upper three paleosols and tills have reversed magnetic polarity (Barendregt, pers. comm., 1987). Hence, these three tills were probably deposited during the Matuyama Reversed Epoch between 2.4 to 0.7 Ma BP. The geomorphic position and advanced degree of soil formation in the upper tills on Mokowan Butte and Cloudy Ridge also suggest these tills are Early Illinoian (about 500 to 400 ka BP) or pre-Illinoian in age (Stalker, pers. comm., 1984; Karlstrom, 1987c).

The Waterton and Belly River valleys are incised some 549 and 427 m, respectively, below the level of the Flaxville surface and are mantled with tills and other deposits derived from both mountain and Laurentide glaciers. Horberg (1952, 1954) and Stalker and Harrison (1977) each map four main terminal and/or recessional positions of the Laurentide glacier east of Waterton Park, the outer two of which are located near the eastern Park boundary. However, whereas Stalker (pers. comm., 1984) concludes the older two Laurentide tills (termed Waterton I and II) are Early Illinoian and Early Wisconsinan (about 350 to 400 and 70 ka BP, respectively), Horberg (1954) and Harrison (1976) consider them to be Late Wisconsinan. In addition, although there is a paucity of good terminal moraines in mountain valleys, Stalker and Harrison (1977) note four main breaks in slope along bedrock walls of the Waterton Valley and thereby postulate four main positions of piedmont and valley glaciers (Table I). According to their interpretation, till from the earliest and oldest glaciation (Waterton I, or the Illinoian "Great Glaciation") mantles the Belly River Valley and Mokowan Butte. Large piedmont glaciers during subsequent Waterton II and III (Early Wisconsinan?) advances deposited the prominent Fire Lookout and Sofa Creek lateral moraines which flank the Waterton drainage northeast of the Waterton townsite. Finally, the Waterton IV advance (probably Late Wisconsinan) terminated near the mouths of valleys along the mountain front.

Correlating the Waterton glacial sequence with the U.S. Rocky Mountain glacial chronology, Reeves (1973) estimates the Fire Lookout and Sofa Creek lateral moraines are of Bull Lake age (Early Wisconsinan or Illinoian) and that four Pinedale (Late Wisconsinan) advances were confined to mountain valleys (Table I). Citing numerous ^{14}C dates from archaeological sites in Waterton Park, he postulates that the mountains were ice-free by 10,500 to 12,000 years BP. Osborn (1985) finds Mazama ash on the youngest cirque moraines and thereby postulates that these moraines are Early Holocene or latest Pleistocene in age.

Stalker and Harrison (1977) and Stalker (1983) describe numerous sections east of the study area which expose multiple continental tills and intercalated mountain tills. In addition, continental erratics of the Illinoian "Great Glaciation" were emplaced at elevations up to 1650 m in the Porcupine Hills north of the Park and 1432 to 1554 m near the Park entrance, "the lower figure where the Laurentide glacier was fended off by Cordilleran ice" (Stalker and Harrison, 1977). The younger (Waterton II) continental glacier, then, deposited continental erratics at about 1380 m near the Porcupine Hills and 1350 m elevation near the Park. Horberg (1954) postulated the occurrence of Glacial Lakes Waterton and Belly River which were temporarily impounded by the continental glacier(s) and which emptied through a series of spillways along the northern flanks of Mokowan Butte.

Whereas some workers (Wagner, 1966; Mickelson *et al.* 1983; Fullerton and Colton, 1986) conclude that the last Laurentide glacier actually coalesced with mountain piedmont glaciers in this area, others (Horberg, 1954; Alley, 1973; Stalker and Harrison, 1977) maintain that mountain glaciers advanced and partially or completely retreated prior to the advance of the corresponding Laurentide glaciers. Evidence for the former interpretation includes interbedding of mountain and Laurentide tills near Dungarvan Creek and Beaverdam Lake and converging moraines of piedmont and Laurentide glaciers in Willow Creek drainage, Montana (Karlstrom, 1987b). However, Stalker (pers. comm., 1984) and I (Karlstrom, 1987b) have observed a weakly developed soil (including a 9-cm thick A horizon, a 10-cm thick Bm horizon, and a 10+ – cm thick Cca horizon) intercalated between mountain and Laurentide tills near Kimball, Alberta, which suggests the maximum advances of the two ice sheets were separated by a weathering episode.

The elevation of the younger Laurentide end moraine (Horberg's "Kimball moraine") drops from about 1480 m in the Yarrow Creek and Willow Creek drainages to about 1280 m in the Belly and Waterton drainages, suggesting that either; 1) advance of the Waterton lobe of the Laurentide glacier was blocked by the stagnating or retreating Waterton piedmont glacier, or, more likely, 2) the Laurentide glacier terminated in a proglacial lake and halted due to ice-calving (Karlstrom, 1987b). Distribution of continental boulders suggest the older Laurentide glacier advanced to within 6 km of the international border (Stalker and Harrison, 1977). However, Jackson (pers. comm., 1985) has observed continental lithologies south of the International Boundary, suggesting a continental glacier may have advanced even farther upvalley at some time and/or boulders were ice-rafted across a proglacial lake. In any event, oscillations of continental glacier margins resulted in considerable mixing of sediments in unstable proglacial environments.

SOIL FORMING FACTORS: CLIMATE, VEGETATION AND PARENT MATERIAL

The Waterton region, like the rest of Alberta, experiences a continental climate with long, cold winters and short, cool summers. However, due to the influence of Pacific maritime storms, Waterton has a summer-wet, winter-dry climate with slightly more precipitation and higher temperatures than the rest of the province (Ogilvie, 1962). In addition, local variations in altitude and proximity to the mountains result in variations in climate, vegetation and soils. Mean annual precipitation (MAP) ranges from 108 cm at Waterton Park Headquarters to 47 cm at Cardston, Alberta, and about 54% of all precipitation falls as snow (Table II). Mean annual temperatures (MAT) vary from about 5°C at Waterton Park Headquarters to an

TABLE II

Climate data for Waterton Park area

Station	Elevation (m)	MAT[a] (C)	January Max.	January Min.	July[b] Max.	July[b] Min.	MAP[c] (cm)	MAR[d] (cm)	MAS[e] (cm)	# Days[f] w/Prec.
Waterton Park Headquarters	1280	5.0	−3.8	−13.9	23.9	10.6	108	51	573	130
Belly River Station	1371	N.A.	N.A.	N.A.	N.A.	N.A.	98	42	547	101
Carway	1359	3.9	−2.8	−13.6	23.4	10.6	53	28	247	82
Cardston	1166	4.8	−2.8	−13.2	25.1	9.6	47	21	256	87

* Data from Coen and Holland (1976). a) mean annual temperature; b) average maximum and minimum temperatures; c) mean annual precipitation; d) mean annual rain; e) mean annual snow; f) number of days with precipitation.

estimated 2.3°C at the top of Mokowan Butte. Hence, the soil moisture regime ranges from udic at Waterton Park Headquarters to ustic at Cardston and the entire region has a frigid soil temperature regime (Soil Survey Staff, 1975).

Forest vegetation in the mountains and foothills includes *Pinus contorta* (lodgepole pine), *Picea glauca* (white spruce), *Abies lasciocarpa* (alpine fir), *Pinus albicaulis* (whitebark pine) *Pseudotsuga menzeisii* (Douglas Fir), and *Populus tremuloides* (aspen), while common grassland vegetation in the prairies includes *Festuca idahoensis* (bluebunch fescue), *Festuca scabrella* (rough fescue), and *Danthonia parryi* (parry oat grass) (Weaver and Clements, 1938).

Tills derived from the mountains generally include about 40 to 50% clasts in a sandy loam matrix. Lithologies include dominantly Precambrian Purcell Group sedimentary rocks, including 57 to 69% red and green argillite, 6 to 14% quartzite, 10 to 20% limestone and dolomite, 1 to 4% diorite and basalt. In areas east of the mountain front, mountain till includes about 4 to 10% Cretaceous sandstone and shale. Laurentide drift, by contrast, has a more clayey texture and fewer, smaller and more rounded clasts (2-5%). Lithologies include about 3 to 10% Precambrian granite and gneiss from the Canadian Shield, 12% Cretaceous sandstone and shale, 0 to 36% limestone and dolomite, 20 to 32% quartzite, and 21 to 40% argillite.

Soils in the region seem to reflect the dominant influences of climate and length of soil formation. Soil orders formed in the mountains under an udic soil moisture regime include Podzols (Spodosols), Brunisols (Inceptisols), and Luvisols (Alfisols), whereas those formed under an ustic soil moisture regime and grassland vegetation are Chernozemic (Mollisols) (Canada Soil Survey Committee, 1978; Soil Survey Staff, 1975; Coen and Holland, 1974, 1976; Karlstrom, 1981). In this region, Brunisols and Podzols form under subalpine coniferous forest in areas where MAP exceeds about 100 cm, whereas Brunisols and Luvisols form under lodgepole pine, alpine fir, white spruce and aspen at lower elevations where MAP is less than about 100 cm. Azonal soils, including Regosols (Entisols) and Gleysols (Aquic suborders), occur throughout the park, but are not discussed in this study.

SOIL CHRONOSEQUENCES AND RATES OF SOIL DEVELOPMENT

Ideally, the establishment of a soil chronosequence requires that climate, vegetation, parent material and slope be held nearly constant so the influence of the fifth soil forming factor, time, can be measured (Jenny, 1949). Unfortunately, this is not always possible in the Waterton region, where these other factors vary significantly and partially mask the effects of time on soil development. This problem can be mitigated by 1) estimating rates at which various soil properties form under different environments in the region, and 2) wherever possible, comparing soils on different age materials which occur in similar parent materials and similar climatic, vegetative and topographic situations.

Yaalon (1971) distinguishes three groups of time-diagnostic soil properties. Reversible soil properties, such as mollic epipedons (organic-rich A horizons), form and alter in less than 1000 years and therefore have limited usefulness in subdividing glacial deposits. By contrast, metastable properties such as cambic (Bw or Bm) and spodic (Bs or Bf) horizons and irreversible properties such as argillic (Bt) and petrocalcic (Bkm or Bc) horizons form and alter in greater than 10^3, and 10^4 to 10^6 years, respectively, and are quite useful properties for subdividing glacial deposits. More specifically, a minimum of about 1000 to 2000 years are required to form cambic (Bw or Bm) horizons in the U.S. Rocky Mountains (Shroba and Birkeland, 1983) and about 4000 to 6000 years are required to form podzolic (Bf or Bfh) horizons in the Canadian Rockies (McKeague *et al.*, 1978). By contrast, Shroba and Birkeland (1983) conclude that at least 10,000 to 40,000 years are required to form argillic horizons in the mountains of the western U.S., but suggest that they form more rapidly in semi-arid grassland regions than under forests. Rates of argillic horizon formation, are apparently faster in the Midcontinent, however, perhaps due to higher clay content of parent materials and/or wetter soil-moisture regimes (Birkeland, 1984). Likewise, McKeague *et al.* (1972) describe Luvisols in Late Wisconsinan calcareous till in Alberta which have 40 to 50-cm thick argillic horizons with 3 to 15% more clay (absolute) than underlying C horizons. Finally, several workers estimate that a minimum of 400 ka are required to form pedogenic petrocalcic horizons (Stage IV carbonate buildup, Birkeland, 1984). However, rates at which different soil properties develop vary depending upon the unique combinations of environmental factors in each different region.

According to Birkeland (1984), soil properties most diagnostic of relative age include: 1) thickness and degree of clay buildup in Bt horizons, 2) degree of rubificiation in B horizons, 3) depth of leaching and degree of development of calcic and petrocalcic (Bk and Bkm or Bca and Bc) horizons, 4) and degree of clay mineral alteration. In addition, two profile development indices may offer the best potential for comparing relative degree of formation of different soil types because they average the relative development of a number of time-diagnostic soil properties. The Harden profile index (HPI) is based on relative development of field properties, including *horizon thickness, texture, structure, consistence, rubification,* pH, and clay films (Harden, 1982). Clay accumulation index (CAI) is a measure of argillic horizon development and equals Σ(Bc-Cc) X T), where Bc is % clay in Bt horizons, Cc is % clay in C horizons, and T is thickness of Bt horizon(s) (Levine and Ciolkosz, 1983).

However, due to the complexities of soil formation, many post-incisive chronosequences (Vreeken, 1975) may permit only gross chronologic subdivisions of surface deposits. For example, Wigley *et al.* (1976) report that Pinedale and Bull Lake deposits in the Copper Basin, Idaho cannot be differentiated on the basis of soils alone. Nonetheless, many workers have demonstrated that soils can be a useful relative dating technique (Birkeland, 1984), particularly in regions where rates of soil development are known.

METHODS

This chronosequence includes 40 soils. I described and sampled 19 soil profiles on mapped glacial deposits of presumed different ages (Horberg, 1954; Stalker and Harrison, 1977) according to procedures of the Soil Survey Staff (1962, 1975) and Canada Soil Survey Committee (1978). Sites were chosen in well-drained areas which had minimal potential for soil stripping in order to maximize the probability that degree of soil formation reflects the true age of the surface. Samples were analyzed to determine particle size composition by pipette (Piper, 1950) using U.S.D.A. size limits, pH (using a 1:1 soil:water paste), organic matter composition (Sims and Haby, 1971), and percentage of calcite and dolomite (Dreimanis, 1962). Clay minerals of selected horizons were identified by X-ray diffraction following the procedures of Millot (1970). In addition, 21 soils already sampled, described and analyzed the Canada Soil Survey (Coen and Holland, 1974, 1976) were added to the study in order to increase the data base. These soils also occur at well-drained sites and are considered representative or average for particular soil mapping units.

RESULTS

WATERTON DRAINAGE

Coarse to medium-grained tills, alluvium and colluvium in the Waterton Valley upstream from the Waterton townsite and in the Cameron and Blakiston Creek valleys are considered Late Wisconsinan or younger in age by Horberg (1954), Reeves (1975), and Stalker and Harrison (1977) (Fig. 1). Well-drained soils in these mostly forested valleys include weakly to moderately-developed Degraded Eutric Brunisols (Inceptisols), Orthic Humo-Ferric Podzols (Spodosols), and Orthic Dark Brown Chernozemics (Figs. 1 and 2, Table III). Of nine representative profiles, seven are Brunisols with 26- to 31-cm thick Bm horizons (or in one case, a 23-cm thick Bf horizon), one is a Chernozemic soil with a 41-cm thick Bm horizon, and two, in the far western part of the Park, are Podzols with 21- to 31-cm thick Bf horizons. B horizons are commonly oxidized to 7.5 or 5YR hues and sola are leached to an average depth of greater than 59 cm (Tables III and IV). Clasts in upper horizons are generally unweathered or only slightly weathered and clay minerals inherited from parent materials have undergone little or no weathering and alteration. Average HPI and CAI values for these soils are 6.40 and 0, respectively. Relatively weak profile development suggests these soils are all post-Late Wisconsinan in age (Figs. 3 and 4).

The prominent Fire Lookout and Sofa Creek lateral moraines which flank the southern portion of the Waterton Valley at about 1646 and 1524 m elevation, have been assigned Early and Late Wisconsinan ages, respectively, by Horberg (1954), whereas Stalker and Harrison (1977) consider both to be Early Wisconsinan (Waterton II and III) in age. Soils on these forested moraines are Luvisols with 14- to 52-cm thick Bt horizons (average is 34 cm) which have about 9% more absolute clay than underlying C horizons and common thin to moderately thick clay films on ped faces (Figs. 1 and 2, Tables III and IV). Argillic horizons are generally oxidized to yellowish brown to strong brown (10YR 5/4 m to 7.5YR 5/6 m) colors and include many weathered clasts. Clay mineral assemblages include moderate to dominant amounts of smectite in addition to mica, chlorite and kaolinite inherited from Purcell rocks. The smectite could be pedogenic and/or inherited from Cretaceous rocks. HPI and CAI values of these soils average 17.36 and 270, respectively, and are higher than those of post-Wisconsinan soils in the Cameron and Blakiston Creek valleys and the Waterton Valley upstream from the Waterton townsite (Fig. 4). However, except that Soils 16 and 17 on the Fire Lookout moraine show greater color oxidation than Soils 14 and 15 on the Sofa Creek moraine, these soils have similar degrees of development, suggesting that these moraines are nearly the same age, and/or, at least, should not be assigned to different glacial stages on the basis of soils data alone. Chernozemic soils developed under grassland vegetation in tills, outwash, drumlins, eskers and alluvium of various ages (Late and/or Early Wisconsinan?) along the valley bottom at about 1316 m elevation (Fig. 2) commonly include 16- to 56-cm thick (average is 32 cm) Bm horizons and have average HPI and CAI values of 12.42 and 29, respectively. One of these soils includes a 16-cm thick argillic horizon.

Laurentide tills overlying mountain tills in the northeastern part of the park are mapped as Late Wisconsinan by Horberg (1954) and as Early Wisconsinan by Stalker and Harrison (1977). These deposits are covered by forest along the mountain front and grasses farther east. Soils 18, 19, and 20 are Brunisolic or Chernozemic soils which lack argillic horizons but have 0- to 43-cm thick Bm horizons. HPI and CAI values average 16.32 and 0, respectively (Fig. 5). These soils lack argillic horizons and have similar HPI and CAI values as the soils in mountain till upvalley from the Waterton townsite. However, although they are generally less well developed than soils on the Fire Lookout and Sofa Creek moraines (Figs. 3 and 5), geomorphic relations and similar HPI values suggest they are approximately the same age.

BELLY RIVER DRAINAGE

Mountain and Laurentide tills in the forested Belly River Valley (Fig. 1) have been mapped as Wisconsinan by Alden (1924), Horberg (1954), and Harrison (1976) and as Illinoian by Stalker and Harrison (1977). Soils in mountain tills in this area are moderately to strongly developed Luvisols which have 30- to 89-cm thick (average is 63 cm) Bt horizons with an average of 19% more clay than underlying C horizons (Figs. 1, 2 and 3, Tables III and IV). Argillic horizons commonly have continous, thin to thick clay films on ped faces, and include high percentages of weathered clasts and smectite in the clay mineral assemblage. HPI and CAI values for these soils average 27.83 and 1128, respectively, and are consistently higher than those of soils in the Waterton drainage (Fig. 4).

Laurentide till and lacustrine deposits from the Waterton I advance of Stalker and Harrison (1977) and "outer continental" advance of Horberg (1954) mantle the Belly River Valley to within about 6 km north of the International Border. Soils in this till are nearly as well developed as those in the mountain till it overlaps and thus, are probably time-equivalent. Argillic horizons in Soils 26 through 29 average 53-cm thick, have 2 to 22% more absolute clay than underlying C horizons, and contain highly weathered clasts and continuous, thick, clay films on ped faces. HPI and CAI values average 36.57 and

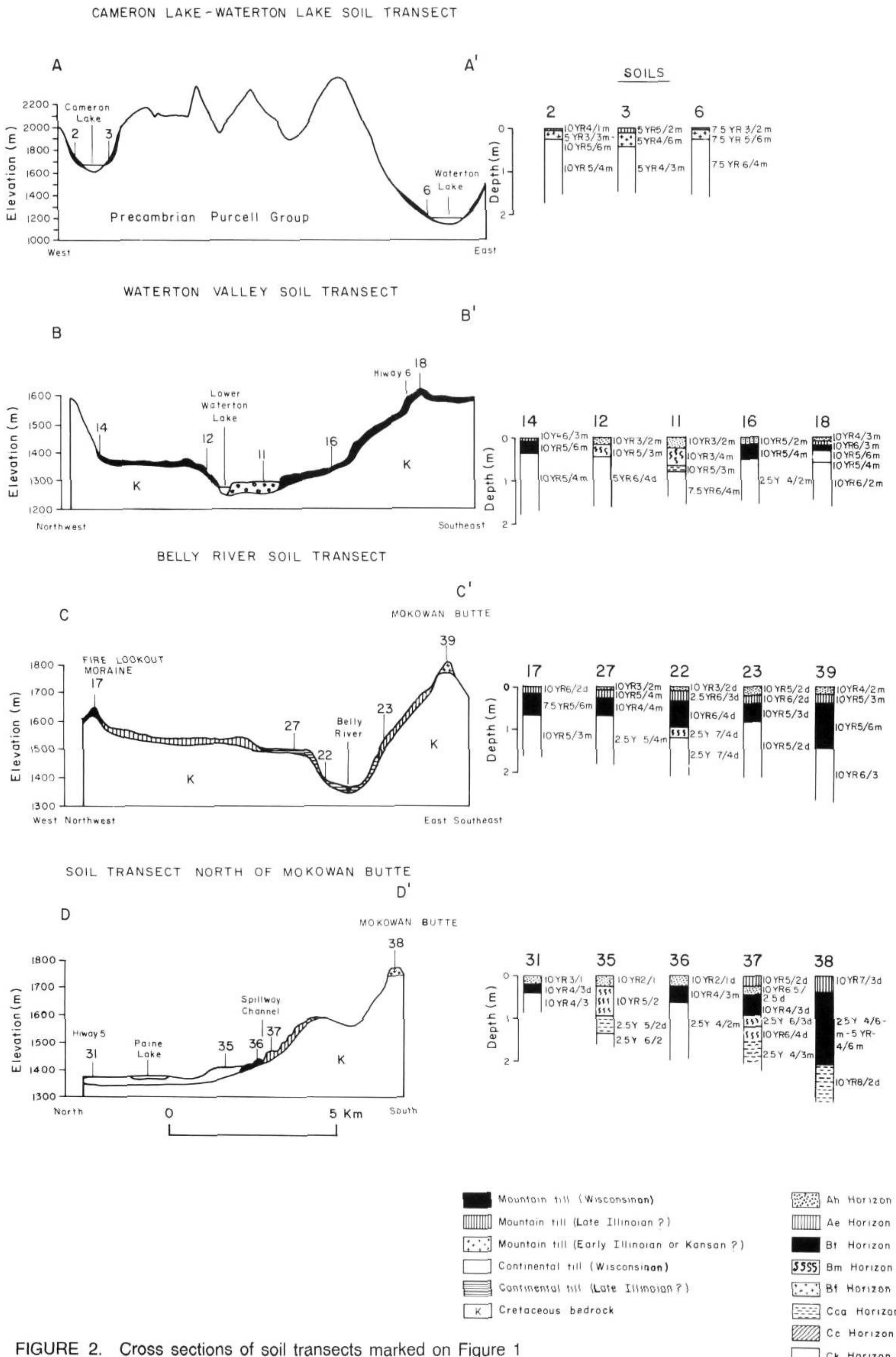

FIGURE 2. Cross sections of soil transects marked on Figure 1 and profile diagrams.

Transects vus en coupe (voir la fig. 1) et diagrammes des sols.

TABLE III

Summary of soil characteristics and soil development index values

Soil	Classification	Elevation (m)	PM-Veg[a]	Bt[b] (cm)	% clay increase Bt hor.	Bf[c] (cm)	Bm[d] (cm)	max. rub.[e] in B hor.	max.[f] c.f.	HPI[g]	CAI[h]	DOL[i]
WATERTON DRAINAGE												
Soils in (Late Wisconsinan) mountain till and alluvium upvalley from Waterton Lakes												
1*	Brunisol	1554	MA-F	0	0.0	0	30	0.42	0.00	8.01	0	64+
2*	Podzol	1676	MT-F	0	0.0	21	0	0.21	0.00	5.22	0	97+
3*	Podzol-Brunisol	1798	MC-F	0	0.0	31	0	0.33	0.00	10.63	0	76+
4	Brunisol	1402	MA-G	0	0.0	0	27	0.33	0.00	4.45	0	60+
5	Brunisol	1341	MT-F	0	0.0	0	27	0.66	0.00	8.51	0	10
6*	Brunisol	1372	MT-F	0	0.0	23	0	0.33	0.00	4.26	0	76+
7*	Chernozemic	1417	MA-S	0	0.0	0	41	0.00	0.00	3.70	0	30
mean =		1509		0	0.0	11	18	0.32	0.00	6.40	0	59+
Soils in (Early and/or Late Wisconsinan) mountain till and outwash northeast of Waterton townsite — valley bottoms												
8*	Chernozemic	1341	MO-G	0	0.0	0	56	0.00	0.00	8.47	0	33
9*	Chernozemic	1311	MO-G	0	0.0	0	22	0.11	0.00	3.02	0	30
10*	Chernozemic	1280	MO-G	0	0.0	0	30	0.21	0.00	8.47	0	33
11*	Chernozemic	1279	MA-S	0	0.0	0	41	0.31	0.00	17.43	0	66
12*	Chernozemic	1356	MT-S	0	0.0	0	28	0.00	0.00	7.73	0	43
13	Chernozemic	1326	MO-G	16	8.0	0	16	0.21	0.00	29.64	176	98
mean =		1316		3	1.0	0	32	0.14	0.00	12.42	29	51
Soils in (Early and/or Late Wisconsinan) mountain till and alluvium northeast of Waterton townsite — moraine slopes												
14*	Luvisol	1585	C-F	30	00.0	0	0	0.42	0.38	13.16	0	38
15*	Luvisol	1432	A-F	36	14.0	0	0	0.31	0.46	12.63	434	45
16*	Luvisol	1310	MT-F	35	13.0	0	0	0.32	0.69	16.25	380	45
17*	Luvisol	1585	MT-F	52	12.0	0	0	0.42	0.61	21.72	196	45
18	Luvisol	1631	MT-F	14	6.5	0	26	0.32	–	18.82	70	32
mean =		1509		33	9.1	0	5	0.36	0.54	16.52	216	41
Soils in (Late Wisconsinan) continental till												
19*	Brunisol	1554	CT-F	0	0.0	0	26	0.21	0.00	7.08	0	28
20*	Chernozemic	1554	CT-F	0	0.0	0	43	0.21	0.00	19.61	0	23
21	Chernozemic	1295	CT-G	0	0.0	0	17	0.21	0.23	22.27	0	60
mean =		1468		0	0.0	0	29	0.21	0.08	16.32	0	37
BELLY RIVER DRAINAGE												
Soils in (Illinoian?) mountain till and outwash												
22	Luvisol	1402	MT-F	62	16.0	0	23	0.21	0.61	42.40	992	97
23	Luvisol	1432	MT-L-F	89	20.0	0	0	0.10	—	32.69	1752	180
24*	Luvisol	1554	MO-F	30	22.0	0	0	0.00	0.61	13.29	690	38
25*	Luvisol?	1493	MT-F	74	—	0	20	0.26	0.69	25.68	—	94+
26*	Luvisol?	1408	MT-F	58	17.0	0	16	0.26	0.77	24.70	1077	74+
mean =		1458		63	18.8	0	12	0.21	0.67	27.83	1128	97
Soils in (Illinoian?) continental till and lacustrine deposits												
27	Luvisol	1462	CT-F	42	22.0	0	0	0.32	—	27.56	552	114
28*	Luvisol	1402	L-F	46	18.0	0	88	0.21	0.69	67.45	570	152
29*	Luvisol	1417	L-F	61	2.0	0	25	0.10	0.69	35.78	107	117
30	Luvisol	1417	CT-O-F	62	2.8	0	0	0.42	0.23	15.49	174	72
mean =		1424		53	11.2	0	28	0.26	0.54	36.57	351	114
Soils in (Late Wisconsinan) continental till												
31	Chernozemic	1326	CO-G	23	—	0	0	0.00	0.23	9.67	—	40
32	Chernozemic	1326	CT-G	46	—	0	0	0.21	0.23	20.53	—	76
33	Chernozemic	1347	L-G	32	—	0	0	0.21	0.23	16.30	—	37
34	Chernozemic	914	CT-G	21	2.7	0	0	0.11	0.23	12.60	43	41
mean =		1228		31	—	0	0	0.13	0.23	14.78	—	49

Soil	Classification	Elevation (m)	PM-Veg[a]	Bt[b] (cm)	% clay increase Bt hor.	Bf[c] (cm)	Bm[d] (cm)	max. rub.[e] in B hor.	max.[f] c.f.	HPI[g]	CAI[h]	DOL[i]
SOIL TRANSECT NORTH OF MOKOWAN BUTTE												
35	Chernozemic	1402	Ct-G-F	0	0.0	0	71	0.21	0.38	35.81	0	93
36	Luvisol	1448	MT-F	38	—	0	0	0.21	0.23	16.20	—	83+
37	Luvisol	1463	MT-F	46	—	0	0	0.11	0.69	34.79	—	150
SOILS IN (EARLY ILLINOIAN OR OLDER) MOUNTAIN TILL ON MOKOWAN BUTTE AND CLOUDY RIDGE												
38	Luvisol	1768	MT-F	173	34.4	0	0	0.74	0.69	124.50	3448	210
39	Luvisol	1768	MT-F	114	22.0	0	0	0.42	0.69	47.25	1646	146
40	Luvisol	1585	MT-G	183	14.0	0	187	0.58	0.69	69.12	2192	536
mean =		1707		157	23.5	0	62	0.58	0.69	80.29	2427	297

* Data from Coen and Holland (1976), a) parent material and vegetation, M = mountain, C = continental, T = till, O = outwash, A = alluvium, C = colluvium, F = forest, G = grasses, S = shrubs; b) thickness of Bt horizn; c) thickness of Bf horizon; d) thickness of Bm horizon; e) maximum rubification index (Harden, 1982); f) maximum clay film index (Harden, 1982); g) Harden profile index (Harden, 1982); h) clay accumulation index (Levine and Ciolkosz, 1983); i) depth of leaching of calcium carbonate.

TABLE IV

Field and laboratory characteristics for typical soils in Waterton Parks area

Soil	Horizon	Depth (cm)	Color[a]	Structure[b]	% Gravel	% Sand	% Silt	%[c] Clay	pH (H20)	pH ($CaCl_2$)	%[d] O.M.	% $CaCO_3$	%[e] Dolo.	Clay Minerals[f]
2*	L-H	2.5-0	10YR 3/2d											
	Ae	0-2.5	10YR 4/1m	2 co pl	19	25	68	7	3.4		3.9	0.0		
	Bf1	2.5-13	5YR 3/3m	1 m sbk	30	29	59	12	4.4		10.3	0.0		
	Bf2	13-23	10YR 5/6m	1 co sbk	22	37	58	5	4.9		4.4	0.0		
	C1	23-71	10YR 5/4m	m	62	67	25	8	4.6			0.0		
4	L-F	2-0	7.5YR 3/2m						7.0					
	Ah	0-6	10YR 3/2d	1 f gr		72	16	12	7.0		6.2	0.0	0.0	2M,1K,1C
	Ae	6-13	10YR 4/3d	1 m gr		72	20	8	7.0		7.8	0.0	0.0	
	Bm	13-30	7.5YR 5/2d	1 m gr		82	10	8	7.2		1.1	0.0	0.0	3M,2K,2C
	IIBm	30-40	7.5YR 5/2d	1 f gr		86	8	6	7.6		0.9	0.0	0.0	
	IIC	40-60+	—	sg		96	2	6	7.8		0.0	0.0	0.0	2M,1K,1C
5	L-F	4-0	7.5YR 3/2m						7.4		3.7			
	A	0-10	10YR 5/3d	1 f gr		52	34	14	7.7		3.0	0.0	0.0	
	Ae	10-23	7.5YR 5/2d	1 f gr		52	36	12	7.8		0.8	1.4	3.8	
	Bm	23-29	7.5YR 7/2d	1-2f sbk		52	34	14	8.4		1.3	5.6	14.0	
	Bm2	39-50	2.5Y 6/2d	1 f gr		54	34	12	8.5		0.4	4.2	9.4	
	Ck	50+	2.5Y 6/2d	1-f gr		54	34	12	8.5		—	1.2	8.0	
8*	Ah1	0-20	10YR 4/2d	1 f gr	34	64	27	9		5.2	8.5			
	Bm1	20-38	7.5YR 4/2d	1 co sbk	74	54	35	11		5.1	5.3			
	Bm2	38-76	7.5YR 5/2d	1 co sbk	94	68	27	5		6.5	2.1	0.9		
	Ck	76-102+	5YR 5/2d	sg	76	77	18	5		7.3	—	8.3		
13	L-H	7-0	10YR 2.5/1m						6.9		5.2			
	Ah	0-18	10YR 2.5/1m	1 m gr		68	18	14	6.0		3.7	0.0	0.0	
	Ae	18-44	10YR 3/2m	1 m gr		70	18	12	5.9		2.3	0.0	0.0	
	A	44-66	10YR 4/2m	1-2 f-c sbk		70	18	12	5.8		0.7	0.0	0.0	
	Bt	66-82	10YR 6/3d	2 f-c sbk		62	22	16	5.8		1.1	0.0	0.0	
	IIBm	82-98	10YR 5/4d	1 f gr		72	18	10	6.2		0.3	0.0	0.0	
	IIC	98-155	—	sg		82	12	6	6.9		—	2.2	0.0	
	L-H	5-0	10YR 3/2m						6.2					
	Ahe	0-15	10YR 5/2m	2 co pl		25	60	15	5.1		2.2			
	Bt1	15-30	10YR 5/4m	2 m sbk		16	54	30	5.5		1.5			
	Bt2	30-50	10YR 5/4m	2 m sbk		11	66	23	5.7		1.2			

Soil	Horizon	Depth (cm)	Color[a]	Structure[b]	% Gravel	% Sand	% Silt	%[c] Clay	pH (H20)	pH ($CaCl_2$)	%[d] O.M.	% $CaCO_3$	%[e] Dolo.	Clay Minerals[f]
	Ck1	50-64	2.5YR 4/2m	mass.	7	9	72	19	7.1			24.1		
	Ck2	64-125	5Y 6/3m		5	5	79	16	7.3			22.9		
17*	L-F	2.5-0	10YR 3/3m											
	Ae1	0-8	10YR 5/2m	1 f pl	34	54	38	8		4.3	2.4			
	Ae2	8-14	10YR 6/4m	1 m pl	35	39	50	11		4.3	2.0			
	Bt1	14-44.5	7.5YR 5/4m	2 m sbk	41	36	38	26		4.9	1.2			
	Bt2	44.5-66	7.5YR 5/6m	2 m sbk	35	38	41	21		6.8	1.2	2.9		
	Ck	66-81 +	10YR 5/3m	mass.	35	41	43	16		7.3		7.4		
18	L-H	5-0	10YR 2.5/1m						6.2					
	Ah	0-7	10YR 4/3m	1 m gr-sg		66	26	8	6.7		2.0	0.0	0.0	2M,1K,1C
	Ae	7-18	10YR 6/3m	1 f gr-sg		60	38	12	6.5		2.0	0.0	0.0	
	Bt	18-32	10YR 5/6m	2 f gr-sg		50	32	18	7.1		1.2	0.0	0.0	3S,2M,1K,1C
	Bm	32-58	10YR 5/4m	1 f sbk-sg		60	34	6	7.4		0.8	0.5	13.0	
	C1	58-118	10YR 5/3m	1 f sbk		70	18	12	7.8		0.0	0.0	7.0	3S,2M,1K,1C
	C2k	118-143 +	10YR 6/2m	1 f sbk		66	20	14	8.1		0.0	0.3	11.0	
21	Ah	0-43	10YR 4/1d	3 co gr-sbk	9	40	45	15	7.0		3.9			
	Bm	43-60	10YR 5/3d	3 co abk	15	33	35	31	7.3		1.7			
	Ck	20-200 +	10YR 6.5/1d	3 co abk	5	20	39	40	7.6		0.8			
22	L-H	3-0							6.4					
	Ah	0-10	10YR 3/2d	1 vf-co gr		56	34	10	6.6		1.0	0.0	0.0	
	Ae	10-35	2.5Y 6/2d	1 vf-co gr-sbk		54	34	12	6.2		0.8	0.0	0.0	
	Bt1	35-53	10YR 5/3d	3 vf-co sbk		38	34	28	6.3		0.7	0.0	0.0	
	Bt2	53-97	10YR 6/4d	3 vf-co c-sbk		28	44	28	7.0		0.9	0.0	0.0	
	Bm	97-120	2.5Y 7/4d	3 vf-co sbk		40	48	12	7.6		0.8	1.0	6.0	
	Ck	120-230 +	2.5Y 6/4d	3 vf-co sbk		45	43	12	8.2		0.5	3.0	13.0	
23	Ah	0-23	10YR 5/2d	1 vf-m gr		32	44	18	7.0			0.0	0.0	
	Ae	23-39	10YR 6/2d	1-2 vf-co gr		22	42	26	7.1			0.0	0.0	
	Bt1	39-59	10YR 5/3d	3 vf-co sbk-pr		30	36	34	7.4			0.0	0.0	
	Bt2	59-82	10YR 5/3d	3 vf-co sbk-pr		26	34	40	7.8			0.0	0.0	
	Bt3	82-128	10YR 5/3d	3 vf-co sbk-abk		4	54	42	7.6			0.0	0.0	
	C	128-256 +	10YR 4/2d	2-3 vf-co sbk		41	39	20	8.0			0.2	0.8	
27	Ah	0-7	10YR 3/2m	1 vf-m gr		64	24	12	6.0		5.4	0.0	0.0	2M,1K,1C
	Ae	7-26	10YR 5/4m	1 vf-m gr-sbk		58	30	12	6.3		1.2	0.0	0.0	
	Bt1	26-50	10YR 5/4m	2 vf-m gr-sbk		46	20	34	6.3		0.8	0.0	0.0	
	Bt2	50-68	10YR 4/4m	2 vf-co gr-sbk		54	18	18	6.4		0.5	0.0	0.0	3S,2M,2K,1C
	Bt3	68-114	2.5Y 5/4m	2-3 vf-co sbk		58	20	22	6.7		0.0	0.0	0.0	
	IIC	114-171	2.5Y 5/4m	1 vf-co gr-sg		72	18	10	7.6		0.6	1.0	6.0	
	IIIC	171-217 +	2.5Y 5/2m	2 vf-co sbk-gr		34	54	14	7.9			3.0	7.0	3S,2M,1K,1C
34	Ah	0-20	10YR 4/2d	3 co cr		35	41	24	6.9		3.1			
	Bt	20-41	10YR 5/3d	3 vco col	0	38	25	37	7.6		1.5			
	Cca	41 +	2.5Y 7/3d	3 co abk	1	37	29	34	8.0		1.0			

* Data from Coen and Holland (1974, 1976), a) d = dry, m = moist, b mass = massive, sg = single grain, 1 = weak, 2 = moderate, 3 = strong, vf = very fine, f = fine, m = medium, co = coarse, gr = granular, sbk = subangular blocky, abk = angular blocky; gravel, ⇒ 2mm, sand = 2-0.05 mm, silt = 0.05-0.002 mm, clay = < 0.002 mm; c) percentages, d) organic matter; e) dolomite, f) M = mica, S = smectite, K = kaolinite, C = chlorite, 3 = abundant, 2 = moderate, 1 = minor quantities.

351, respectively (Tables III and IV). Hence, the relatively greater degree of soil formation of Soils 22 through 29 suggests they are older than soils in the Waterton valley and are pre-Wisconsinan (probably Illinoian), as postulated by Stalker and Harrison (1977).

Soils 30 through 33 are developed in Wisconsinan continental till behind the "Kimball moraine" of Horberg (1954) and Waterton II moraine of Stalker and Harrison (1977). These soils are not as strongly developed as Soils 26 through 29, but resemble Soils 19 through 20 developed in continental till in the Waterton Valley. They have 23- to 46-cm thick argillic horizons and HPI values averaging 15.50.

THE SOIL IN LATE WISCONSINAN CONTINENTAL TILL AT LETHBRIDGE

Soil 33 in continental till on the Lethbridge moraine is a moderately developed Chernozemic soil which has a 21-cm thick argillic horizon with 2.7% more clay than the underlying

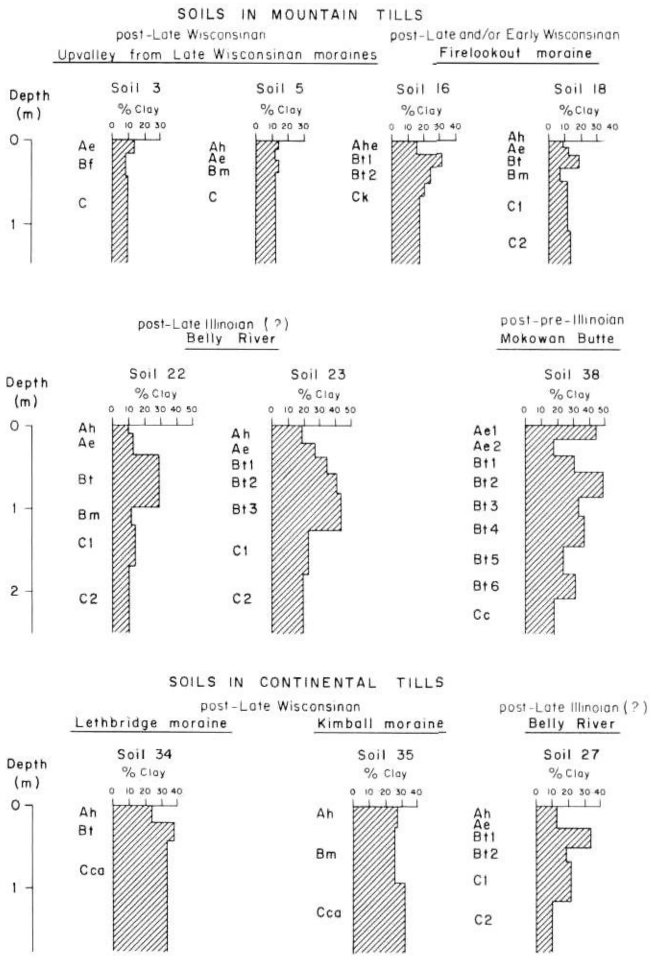

FIGURE 3. Distribution of clay-size particles in selected soil profiles of presumed different ages.

Granulométrie des argiles dans quelques coupes de sols présumés d'âges différents.

C horizon (Tables III and IV). The soil parent material, mapped as Late Wisconsinan Buffalo Lake Till (Stalker, 1963, 1977) appears to be less weathered than the Waterton II continental till in the Waterton Park area, which is more mottled and oxidized and has a higher percentage of weathered clasts. However, the HPI and CAI values for soil 33 (12.60 and 43, respectively) are not significantly different from other continental tills to prove a difference in soil age. Thus, soils evidence does not provide a satisfactory means of differentiating ages of these tills. Indeed, the greater weathering and mottling of soils and tills near the Park boundary could reflect increased precipitation near Waterton Park as well as differences in soil age.

PALEOSOILS ON MOKOWAN BUTTE AND CLOUDY RIDGE

The paleosoils developed in the uppermost tills on Mokowan Butte and Cloudy Ridge are much more strongly developed than any of soils developed in deposits of modern valleys. As noted above, the upper till on Mokowan Butte has reversed magnetic polarity and is considered older than 0.7 Ma or pre-Illinoian in age. The till capping Cloudy Ridge is also probably pre-Illinoian in age. However, because Cloudy Ridge is a lower and presumably younger erosion surface, till on Cloudy Ridge could possibly be as young as Early Illinoian (about 500 to 400 ka) in age. Paleosols on Mokowan Butte and Cloudy Ridge include 114- to 183-cm thick, yellowish brown to yellowish red to red (10YR to 5YR to 2.5YR 5/6m) paleoargillic horizons with 14 to 34% more absolute clay in Bt horizons than in underlying C horizons. Bt horizons include up to 80% highly weathered clasts and thick, continuous clay films on ped faces. The clay mineral assemblages include mixed-layer chlorite-vermiculite, chlorite-smectite, and a mineral tentatively identified as kaolinite-smectite, in addition to mica, chlorite, kaolinite, and some smectite. The paleoargillic horizons overlie leached Bm horizons and/or massive 4 to 13-m thick calcrete or petrocalcic (Cc) horizons. The calcretes uniformly underlie leached paleoargillic horizons, but may locally include groundwater as well as pedogenic carbonates. HPI and CAI values for these very strongly developed soils average 80.29 and 2429, respectively. The great thickness and degree of clay buildup and rubification in paleoargillic horizons of these soils suggest they formed over prolonged time intervals (estimated 400 to 700 + ka) during periodically warmer and moister interglacial climates (Karlstrom, 1987c). Similar paleosols cap each of the Flaxville and No. 2 Bench remnants along the eastern boundary of Glacier Park, Montana (Karlstrom, 1988).

SOIL TRANSECT NORTH OF MOKOWAN BUTTE

A soil transect from Mokowan Butte to the Laurentide drift plain to the north (Figs. 1 and 2) shows good correspondence between geomorphic and pedolologic evidence. As noted previously, the very strongly developed Luvisols (Paleudalfs, Soil Survey Staff, 1975) capping the uppermost till on Mokowan Butte (Soils 37 and 38) are considerably thicker and better developed and therefore probably older than soils developed in surficial deposits of the Belly and Waterton River Valleys (Table III). A series of lateral moraines parallel the northern flanks of Mokowan Butte. Although some ice-rafted granite and gneiss boulders from the Canadian Shield mantle the surface of these moraines, underlying tills are composed almost exclusively of mountain rocks. Hence, the lateral moraines were probably deposited by piedmont glaciers emanating from the Waterton and/or Belly River drainages (Karlstrom, 1987b).

Soils 35 and 36 were sampled from the crests of two prominent moraine surfaces separated by a spillway channel. Soil 35, located on the higher moraine, is markedly more strongly developed than Soil 36. It has a 46-cm thick Bt horizon with about 80% rotten clasts and thick, continuous argillans and organs on ped faces, a 23-cm thick Ae horizon, a 55-cm thick Bm horizon and a 37-cm thick Cca horizon with Stage I carbonate development (Birkeland, 1984). Soil 36, by contrast, has a thinner (38 cm) argillic horizon with very few rotten clasts and thin, discontinuous clay films on ped faces. Thus, the two soils, and their respective parent tills are probably two different ages (Illinoian and Wisconsinan?). Soil 37 is developed in continental till at the outer Waterton II or "Kimball moraine" which is locally interbedded with

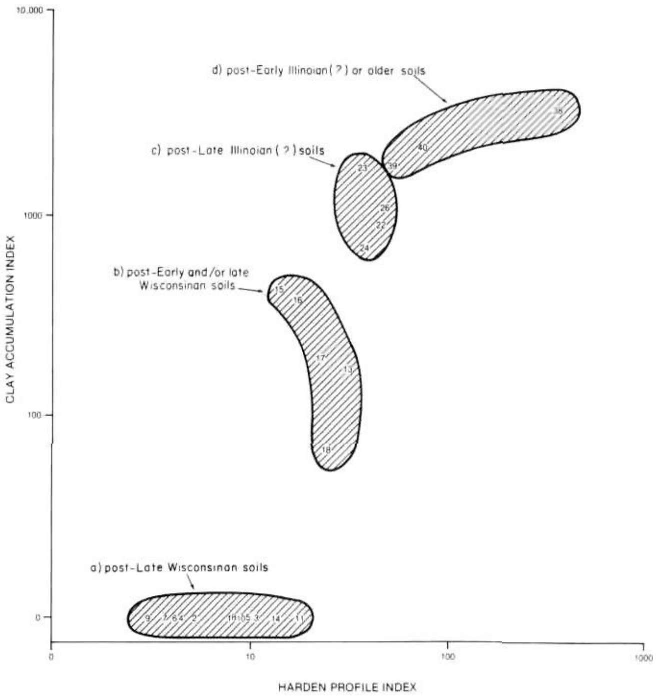

FIGURE 4. Plot of clay accumulation index versus Harden profile index for 24 soils developed in mountain till in the Waterton Park area and suggested age correlations. Soil groups occur: a) upvalley from the Waterton townsite; b) in the Waterton valley northeast of Waterton townsite on Fire Lookout and Sofa Creek moraines; c) in the Belly River drainage; and d) on Mokowan Butte and Cloudy Ridge.

Graphique du rapport entre l'index d'accumulation de l'argile et l'index de développement de Harden de 24 sols développés sur des tills de montagne dans la région du parc Waterton et corrélations présumées des âges. On trouve ces groupes de sols; a) dans la vallée en amont de la ville de Waterton; b) dans la vallée du Waterton au nord-est de la ville de Waterton sur les moraines de Fire Lookout et de Sofa Creek; c) dans le bassin versant de la rivière Belly; et d) sur la butte Mokowan et le Cloudy Ridge.

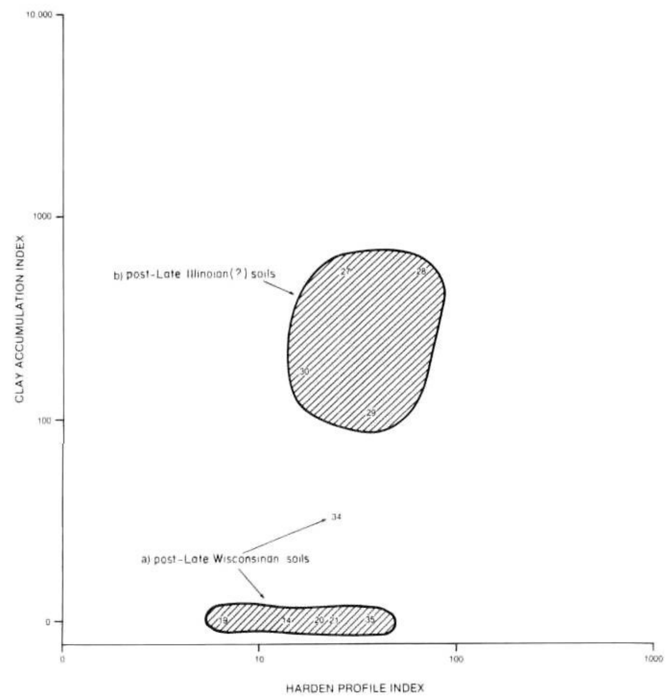

FIGURE 5. Plot of clay accumulation index versus Harden profile index for 10 soils developed in continental tills and suggested age correlations. Soil groups occur: a) behind the "Kimball" or "Waterton II" moraine of Horberg (1954) and Stalker and Harrison (1977), respectively; and b) in the Belly River drainage.

Graphique du rapport entre l'index d'accumulation de l'argile et l'index de développement de Harden de 10 sols développés sur des tills d'origine continentale et corrélations présumées des âges. On trouve ces groupes de sols; a) derrière la moraine de "Kimball" de Horberg (1954) ou de "Waterton II" de Stalker et Harrison (1977); et) dans le bassin versant de la rivière Belly.

mountain till north of Beaverdam Lake. Hence, this soil should be approximately the same age as Soil 36 and other soils in the younger continental deposits behind the "Kimball" or Waterton II moraine.

The proposed correlation of soils and lateral moraines of this soil transect suggests that moraines along the northern flank of Mokowan Butte represent two glaciations. This interpretation suggests the following scenario: During the earlier of these glaciations (Late Illinoian?), mountain piedmont glaciers included trunk glaciers from both the Waterton and Belly River drainages. After partial or total retreat of the mountain glacier, the corresponding Laurentide glacier advanced up the Belly River to within 6 km of the International Boundary. During the (Early or Late?) Wisconsinan, a piedmont glacier emanating from the Waterton Valley deposited lateral moraines (including the Fire Lookout moraine) up to 366 m above the valley floor. These deposits were subsequently overlapped by Laurentide drift of the Waterton II advance or "Kimball moraine" (Stalker and Harrison, 1977; Horberg, 1954).

DISCUSSION

As noted previously, different soil types in the Park reflect local differences in climate, vegetation, slope and parent material as well as differences in length of soil formation. However, a soil chronosequence can be established using Brunisols and Luvisols developed on forested mountain tills and Luvisols and Chernozemic soils on forest and grass-covered continental tills. Because argillic horizons do not form in Podzolic soils, comparisons using thickness and degree of clay buildup in B horizons should mainly involve Brunisolic, Luvisolic and Chernozemic soils. However, since Podzolic soils occur only on post-Wisconsinan deposits, this does not pose a severe problem.

Variations in key soil properties, including thickness and degree of clay buildup in argillic horizons and the Harden and clay accumulation development indices, suggest a subdivision of soils into three or four age groups which generally correspond with mapping of different age tills (Figs. 3, 4 and 5). These differences in relative degree of soil development can be attributed largely to differences in soil age because locally they occur in areas with similar vegetation, parent material and climate.

SOILS IN MOUNTAIN TILLS

Relative differences in soil profile development suggest three to four ages of mountain tills in the Waterton Park area (Fig. 4): 1) Weakly developed soils (Brunisols and Podzols with HPI and CAI values averaging 6.40 and 0, respectively) occur in deposits upvalley from terminal positions of moraines mapped as Late Wisconsinan (Stalker and Harrison, 1977). 2) Thicker, moderately developed Luvisols capping lateral moraines of the Waterton Valley with average HPI and CAI values of 17.36 and 270, respectively, could be older (post-Early Wisconsinan?) and/or possibly the same age (post-Late Wisconsinan). 3) Strongly developed Luvisols in the Belly River Valley drainage have average HPI and CAI values of 31.67 and 739, respectively, and are probably yet older (post-Late Illinoian?). 4) Finally, the very strongly developed Luvisols (Paleudalfs, Soil Survey Staff, 1975) in the surface tills on Mokowan Butte and Cloudy Ridge have HPI and CAI values averaging 80.29 and 2429, respectively, and are considered post-Early Illinoian or older in age. Distributions of clay-size particles through typical profiles are illustrated in Figure 3.

Although Figure 4 suggests the soils on the Firelookout and Sofa Creek moraines are older than post-Late Wisconsinan in age (Karlstrom, 1981), there are problems with this interpretation. Because continental till overlies this mountain till in the northeastern part of the Park, geomorphic relations suggest these deposits are about the same age as the con-

TABLE V

Properties of typical soils in Wisconsinan and Illinoian tills in the Rocky Mountains, Midwestern states, and Denmark

Soil	Classification[a]	PM-Veg[b]	MAP[c] (cm)	MAT[d] (C)	Bt[e] (cm)	% clay in Bt(w)	% absolute[f] C. I. Bt	Harden[g] C.F.I.	CAI[h]	color	Harden[i] R.I.
POST-WISCONSINAN SOILS											
Rocky Mountain National Park, Colorado (Shroba, 1977) and McCall, Idaho (Colman and Pierce, 1986)											
Colorado	Inceptisol	T-F	77	2	0	7	1	0.00	7	7.5YR 4/3	0.11
Pilgrim Cove	Inceptisol		65	2	0	4	0	0.00	0	7.5YR 4/4	0.23
McCall	Inceptisol		65	2	35	5	2	—	81	10YR 5/6	0.53
Alberta (McKeague *et al.*, 1972), Alberta and Montana (Williams and Bowser, 1951)											
Cooking Lake	Luvisol	T-F	47	2	40	35	6	0.38	240	10YR 4/3	0.23
Uncas 1	Luvisol	T-F	47	2	40	30	3	0.46	120	10YR 5/2	0.11
Uncas 2	Luvisol	T-F	47	2	50	45	15	0.38	750	10YR 5/3	0.23
Whitefish	Gray Wooded	MT-F	51	7	32	25	14	N.A.	320	N.A.	N.A.
Breton	Gray Wooded	MT-F	48	2	11	42	0	N.A.	0	N.A.	N.A.
Northern Minnesota and Michigan (Nygaard *et al.*, 1952), Iowa (Ruhe, 1969)											
Minn.	Gray Wooded	CT-F	102	N.A.	43	29	18	N.A.	773	10YR 4/3	0.11
Minn.	Brown Forest	CT-F	102	N.A.	42	17	6	N.A.	239	5 YR 5/3	0.00
Minn.	Chernozem	CT-G	61	N.A.	30	26	4	N.A.	131	10YR 4/3	0.11
Mich.	Podzol	CT-F	254	N.A.	53	6	1	N.A.	37	5YR 4/3	0.23
Tama, Iowa	Chernozem	CT-G	74		73	33	8	N.A.	310	10-7.5YR	N.A.
Fayette, Iowa	Alfisol	CT-F	84		62	31	4	N.A.	171	10-7.5YR	N.A.
Denmark (Dalsgaard *et al.*, 1986)											
	Glossoboralf	T-F	60	8	30	26	7	0.69	215	7.5YR 4/6	—
mean for Luvisols-					39	31	8		314		
mean for Chernozems-					52	30	6		221		
POST-ILLINOIAN SOILS											
Western United States (Shroba, 1977; Colman and Pierce, 1986; Williams and Bowser, 1952)											
Rocky Mountain	Alfisol	T-F	77	2	61	19	13	N.A.	612	7.5YR 4/4	0.23
National Park, Colorado	Alfisol	T-F	21	6	73	18	11	N.A.	470	7.5YR 5/3	0.11
Bull Lake, Wyoming	Alfisol	T-	65	2	73	24	14		687	7.5YR 4/5	0.32
Williams Creek, Idaho	Alfisol	T-	65	2	60	21	16		844	7.5YR 4/4	0.23
Timber Ridge, Idaho	Alfisol	T-F	51	7	89	52	6	N.A.	358	N.A.	N.A.
Montana	Gray Wooded										
Iowa (Ruhe, 1974)											
Sangamon	Alfisol	CT-F	100	13	140	51	29	N.A.	2222	7.5-5YR	N.A.
mean for Luvisols-					83	31	15		866		

a) Canada Soil Survey Committee (1978), Soil Survey Staff (1975); b) parent material and vegetation; c) mean annual precipitation; d) mean annual temperature; e) thickness of Bt horizon; f) % absolute clay increase in Bt horizon; g) Harden clay film index; h) clay accumulation index; i) Harden rubification index.

tinental till. If they are about the same age, argillic horizons apparently form faster in Luvisols than in Brunisolic or Chernozemic soils in close proximity. Comparison of profile characteristics with those of dated soils elsewhere may yield additional insight. Birkeland and Shroba (1983) conclude that average post-Pinedale (= post-Wisconsinan and about 10,000 to 30,000 years old) soils in the U.S. Rocky Mountains have weak 25-cm thick Bs or Bt horizons with 1 to 7% (average = 1%) more clay than unweathered parent material, and no clay films (Table V). By contrast, post-Bull Lake (or post-Illinoian, estimated at about 150 ka years old) soils have 35- to 75-cm thick (average is 55 cm) Bt horizons with about 9% more clay than underlying C horizons, and few, thin, clay films. Thus, if rates of soil formation in the mountains of the western U.S. apply to the Waterton region, the soils in the Belly River drainage and on the Fire lookout and Sofa Creek moraines of the Waterton Valley are probably post-Bull Lake (or post-Late Illinoian) in age.

However, as noted previously, post-Late Wisconsinan Luvisols developed in calcareous till in Alberta have 40- to 50-cm thick Bt horizons with 3 to 15% (average 8%) more clay than underlying C horizons, discontinuous clay films, and average CAI values of 370. Likewise, Williams and Bowser (1951) describe Gray Wooded soils (Luvisols) in Alberta and Montana which have 23- to 66-cm thick Bt horizons with 0 to 12% more clay than C horizons and average CAI values of 160. Thus, based on their resemblance to post-Wisconsinan Luvisols in Alberta and Montana, the Luvisols on the Fire Lookout and Sofa Creek moraines could be post-Late Wisconsin (Tables III, IV and V). Thus, soils evidence is ambiguous, and comparison of soil properties with those of dated soils elsewhere suggests these soils could be either post-Early Wisconsinan and/or post-Late Wisconsinan. Hence, other dating techniques will be needed to help resolve this problem.

The soils of the Belly River Valley, however, are sufficiently better developed than those in the Waterton drainage that they should probably be considered pre-Wisconsinan. These soils, on average, have 63-cm thick Bt horizons with 19% more absolute clay than underlying C horizons and HPI and CAI values of 27.83 and 1128, respectively (Table III, Fig. 4). They resemble post-Bull Lake soils described in Rocky Mountain National Park, Bull Lake, Wyoming, McCall, Idaho, and Ronan, Montana (Shroba, 1977; Colman and Pierce, 1986; Williams and Bowser, 1952, Table V). Finally, the paleosols in surface tills on Mokowan Butte and Cloudy Ridge are much more strongly developed than soils in surface tills of the Belly and Waterton drainages, hence, these tills are considered Early Illinoian and/or pre-Illinoian (Fig. 4).

The various stages of calcic horizon development recorded in the New Mexico region (Gile *et al.*, 1966) are not completely represented in this region. Soils in Wisconsinan and Illinoian deposits of the Waterton and Belly River drainages which have calcic horizons generally occur in the drier, eastern part of the Park and have Stage I carbonate development, whereas the very strongly developed paleosols on Mokowan Butte and Cloudy Ridge have Stage III+ petrocalcic horizons. Depth of leaching and oxidation in soil profiles probably reflects the influences of MAP and MAT as well as length of soil formation and therefore is not considered as temporally diagnostic as other soil properties.

SOILS IN CONTINENTAL TILL

Two ages of continental tills are suggested by soil development indices (Fig. 5). Luvisols in the Belly River drainage on deposits mapped as Waterton I by Stalker and Harrison (1977) have, on average, 53-cm thick Bt horizons with 11.2% more absolute clay than C horizons and HPI and CAI values of 36.57 and 351, respectively. Thus, despite differences in parent material, these soils resemble the "post-Late Illinoian" soils developed in mountain till in the Belly River Valley. By contrast, Brunisols and Chernozemic soils northeast of the Waterton II or "Kimball moraine" in the Waterton and Belly River drainages are much less developed and have HPI and CAI values of 15.91 and 0, respectively. The soil on the Lethbridge moraine has HPI and CAI values of 12.60 and 43, respectively, and is not sufficiently different to postulate a major difference in soil age. Agriculture Canada Soil Survey workers have concluded that the apparent lack of differences in soils across the plains of southern Alberta reflects that either; 1) parent materials are approximately the same age (Late Wisconsinan), or 2) the influence of periglacial processes was so strong during the last glaciation that differences in soil ages were obliterated (W. Pettapiece, pers. comm., 1984). Although I find evidence for rigorous periglacial erosion and stripping of older soils on higher benches east of the Waterton-Glacier Park area (Karlstrom, 1986), I have found no evidence for cryoturbation in numerous gravel pits behind the limit of the "Waterton II" moraine east of Waterton Park. Hence, their relatively weak soil development suggests to me that these deposits are Late Wisconsinan.

CONCLUSIONS

Systematic variation of time-diagnostic soil properties from some 40 soil profiles suggests, but does not prove, at least three and possibly four different ages of mountain tills and two different ages of continental tills in the Waterton region. Tills are provisionally correlated with Late Wisconsinan, Late and/or Early Wisconsinan, Late Illinoian, and Early Illinoian and/or pre-Illinoian tills, respectively, in the U.S. Midwest. Specifically, soils in combination with geomorphic evidence suggest the following: 1) The youngest soils are weakly to moderately developed Brunisols and Podzols in tills and deposits in the mountains upvalley from mapped Waterton IV (Late Wisconsinan) end moraines (Stalker and Harrison, 1977). These soils may be younger than or approximately the same age as the moderately developed Luvisolic and Chernozemic soils on tills (Waterton II and III, Stalker and Harrison, 1977) deposited by mountain piedmont glaciers and the continental glacier in the Waterton drainage northeast of the Waterton townsite. It may not be possible to subdivide Late and Early Wisconsinan deposits on the basis of soils evidence alone. 2) The strongly developed Luvisols capping mountain and continental tills in the Belly River drainage appear older than those in the Waterton drainage, thus corroborating Stalker and Harrison's (1977) conclusion that the Belly River Valley was largely ice-free during the Wisconsinan. 3) Very strongly developed paleosols (Luvisols or Paleudolls) in pre-Wisconsinan mountain tills on Mokowan Butte and Cloudy Ridge are older than those found in modern valleys and represent periodically warmer and moister paleoclimates. 4) At least two continental tills are present in the study area, and they are tentatively correlated with the Illinoian and Late Wisconsinan.

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