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ARTICLE

Time for nonilluvial Bt horizons?[1]

Dan Pennock and Kendra Fisher

Abstract: The Bt horizon is the diagnostic horizon of the Luvisolic Order in Canada. According to the Canadian System of Soil Classification (CSSC), the Bt must be formed from clay illuviation through the processes of lessivage (i.e., physical transport of clay). In a study of a Luvisol catena in the central Saskatchewan, we demonstrate that Ae/Bm horizons overlying IIBt horizons are formed in a sandy mantle overlying till (i.e., a lithological discontinuity) and that the sandy mantle contributed negligible amounts of illuvial clay despite the presence of clay skins on ped surfaces in the IIBt horizon. We extended the results of this study to the regional scale by examining sand fractions in 63 pedons of Luvisol-dominated soil associations from soil surveys in the Northern Forest Reserves (between latitudes 53°N and 55°N). Of the 63 pedons, 13 had lithological discontinuities identified in their profile description and a further 27 had discontinuities identified through shifts in the sand fractions between horizons. For the profiles with discontinuities, inherited particle size differences are a more likely cause of coarse-over-fine textural contrasts than lessivage. A regional analysis of the distribution of Luvisol-dominated associations showed distinct zonations that account, in part, for the differences in the occurrence of lithological discontinuities. Based on these results, we suggest that the criteria for Bt horizons in the CSSC should be broadened to include nonilluvial coarse-over-fine texture-contrast horizons and that the criteria for the Luvisolic order also be broadened to include these nonilluvial Bt horizons.

Key words: lithological discontinuity, alfisol, abruptic, cambic, Bt, E horizon, till, soil taxonomy, lessivage.

Résumé : L'horizon Bt est l'horizon caractéristique de l'ordre des luvisols, au Canada. Selon le Système canadien de classification des sols (SCCS), cet horizon doit être issu de l'illuviation d'argile par lessivage (c'est-à-dire, le transport physique de l'argile). Lors de l'étude d'une caténa de luvisols dans le centre de la Saskatchewan, les auteurs ont constaté que les horizons Ae/Bm qui surplombent les horizons IIBt se forment dans un manteau sableux reposant sur du till (donc une discontinuité lithologique) et que la quantité d'argile illuvial fournie par le manteau sableux est négligeable, malgré la présence d'une pellicule argileuse à la surface des pédons, dans l'horizon IIBt. Les auteurs ont extrapolé les résultats de leur étude à l'échelle régionale en examinant la fraction sableuse de 63 pédons dominés par un luvisol venant des levés réalisés dans les réserves de forêt boréale (entre 53° et 55° de latitude nord). Parmi ces 63 pédons, treize présentaient une discontinuité lithologique dans leur profil et 27, une discontinuité attribuable au déplacement de la fraction sableuse entre les horizons. Dans les profils présentant une discontinuité, la granulométrie variable des particules héritées est sans doute plus vraisemblable que le lessivage pour expliquer la présence du matériau grossier sur le matériau fin. Une analyse régionale de la répartition des associations dans lesquelles domine un luvisol révèle l'existence de zones distinctes, ce qui explique en partie la variabilité des discontinuités lithologiques. Compte tenu de ces résultats, les auteurs suggèrent qu'on élargisse les critères qui définissent les horizons Bt dans le SCCS afin d'y inclure les horizons non illuviaux à texture contrastante de matériaux grossiers sur matériaux fins et qu'on élargisse les critères applicables aux luvisols pour que cet ordre comprenne désormais les horizons Bt non illuviaux. [Traduit par la Rédaction]

Mots-clés : discontinuité lithologique, alfisol, abruptique, cambique, Bt, horizon E, till, taxonomie des sols, lessivage.

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Introduction

Soils of the Luvisolic Order are widespread in forested landscapes throughout Canada and normally have developed in glacial parent materials derived from sedimentary rocks. Luvisols are texture-contrast soils (Paton et al. 1995), where a coarser textured upper horizon overlies a finer textured lower horizon. The diagnostic horizon for the Luvisolic Order is the Bt: "an illuvial horizon enriched with silicate clay", according to the Soil Classification Working Group (SCWG 1998, p. 15). The transport of clay within the profile to form the illuvial horizon is termed *lessivage* and hence the process of lessivage is integral to the formation of Luvisolic soils.

Research from other regions with Luvisolic-like soils has, however, increasingly questioned the assumption that lessivage is the dominant process responsible for texture-contrast soils in a high proportion of Luvisols. This counter argument was originally developed in the soil genesis volume by Paton et al. (1995), who challenge the primacy of eluviation-illuviation in the formation of these soils and instead develop a bioturbation/soil geomorphic explanation for the soils. Phillips (2004) explores six distinct processes (beyond inheritance or deposition of coarse sediments over fine sediments) that can lead to coarse-over-fine texture-contrast horizons and, in several field settings, demonstrates that multiple processes may be operating at any given site. In later papers, Phillips (2007) and Phillips and Lorz (2008) demonstrate how multiple processes can interact to form texture-contrast horizons in field sites in North Carolina and Arkansas, the United States and in Germany. The need to examine multiple pathways is now well established in the literature (e.g., Bockheim and Hartemink 2011).

The most comprehensive examination of multiple genetic pathways for texture-contrast horizons has been by French pedologists. Quénard et al. (2011) use multiple criteria to assess the dominant process(es) responsible for texture-contrast horizons in 2034 Luvisols and Albeluvisols from the French national soil database. They conclude that lessivage is the dominant process in only 1% of Luvisol profiles and 12% of Albeluvisol (since reclassified as Retisol (IUSS Working Group WRB 2015)) profiles, and that while lessivage may be a secondary factor in the other profiles, changes in parent material, bioturbation, or chemical weathering are more important in forming the horizonation sequence. Later studies have examined lessivage under laboratory conditions (Cornu et al. 2014) and the formation of albic material (i.e., uncoated and light-colored soil material caused by removal of clay and free iron oxides (Montagne et al. 2016).

Our goal is to examine Gray Luvisolic soils from central Saskatchewan (Fig. 1) in light of these alternative hypotheses for the development of texture-contrast soils. We begin by documenting a specific soil catena with distinctive horizonation and then move to a regional examination of Luvisolic soils using historical soil survey information. Finally, we discuss the implications of the work for assigning horizon labels in the Canadian System of Soil Classification (CSSC) and for a broader interpretation of the origin of the Luvisolic soils.

Processes responsible for formation of texture-contrast soils and their relevance for saskatchewan conditions

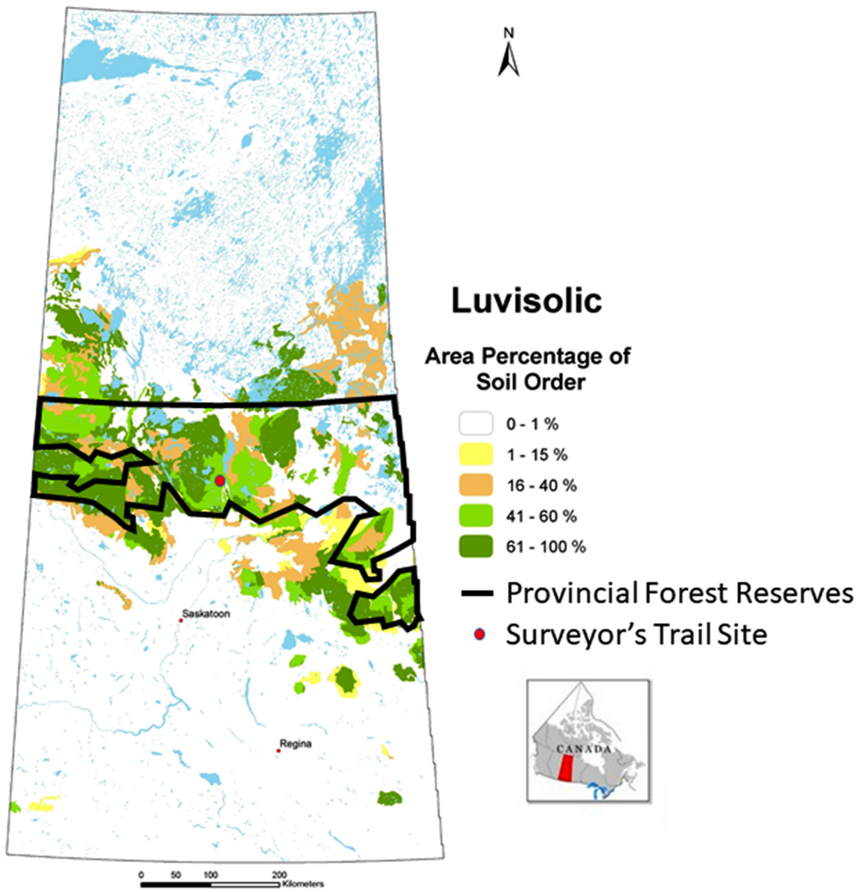
The variety of processes suggested for coarse-over-fine horizon formation can be broadly grouped into three main genetic pathways: textural stratification from the combined action of bioturbation and geomorphic processes; development in situ solely from pedological processes; and layering from sediment deposition.

Bioturbation-erosional winnowing pathway

Paton et al. (1995) developed a three-stage bioturbation-erosional winnowing pathway for the formation of texture-contrast horizons. First, geological materials at the earth's surface undergo physical and chemical transformation by weathering processes. Second, the surface layer of soil is continually mixed (bioturbation) by soil organisms and vegetation — primarily animals but also roots through both growth and toppling of trees. This mixing brings subsoil material onto the soil surface. Third, geomorphic processes such as wind and water erosion and soil creep preferentially remove fine particles, leaving behind a coarser residual layer at the soil surface. Bioturbation continues to replenish the supply of fines to the surface, and over long time periods, this leads inexorably to a coarser textured surface layer overlying a finer textured layer of weathered (to varying degrees) geological material. In some situations, resistant stones accumulate at the contact between the bioturbated mantle and the underlying weathered layer to form a stone line. The volume by Paton et al. (1995) contains many examples of texture-contrast horizons developed through operation of these processes.

The coupled bioturbation-erosional winnowing pathway proposed by Paton et al. (1995) and others is not, however, likely to be operating in the Central Boreal Plains Ecozone region of Saskatchewan, as bioturbation is limited in soils of this region. Aspen (*Populus tremuloides* Michx.) is the dominant deciduous tree of the Mixedwood forest; it is a clonal species with large, interconnected root structures. When aspen dies, the aspen boles tend to snap rather than toppling over and creating mound and pit topography (Lee and Sturgis 2001); indeed, these authors found that at the aspen-dominated sites they studied, pits and mounds accounted for only 0.01% to 0.05% of the forest floor compared with 10% to 50% of the forest floor in other studies of temperate forest. Burrowing by animals is also very limited — the distribution maps of burrowing animals of biogeomorphic significance presented by Zaitlin and Hayashi (2012) show that only the least chipmunk (*Tamias minimus*) is

Fig. 1A: Locations of Northern Provincial Forest Reserves and Surveyor's Trail Site superimposed on map of Luvisol-dominated polygons derived from Soil Landscapes of Canada versions 3.1 and 2.2. Luvisol distribution map prepared by Darrel Cerkowniak, Agriculture and Agri-Food Canada. [Colour online.]



active in the boreal region. Moreover, these ground squirrels typically live in open meadows of alpine areas (Bihr and Smith 1998) and are uncommon in the more closed tree canopies of the southern boreal forest. Earthworms were extirpated in this region by the Pleistocene glaciations, and although invasion of the region by European earthworms has begun in the past 30 to 60 years (Cameron et al. 2007), they are not currently a significant bioturbation agent in the region.

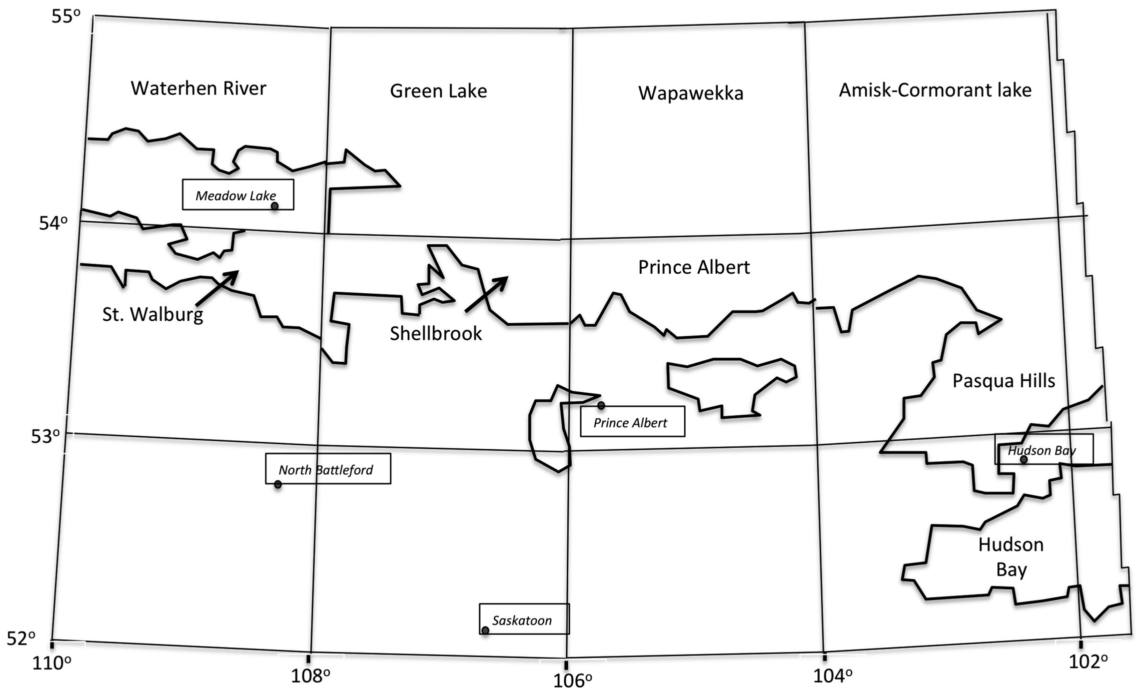
Pedological pathways

This integrated process model of Paton et al. (1995) differs greatly with the pedological explanations for texture-contrast soils, especially the lessivage model that currently dominates the pedological literature (summarized for Canadian soils by Lavkulich and Arocena 2011). In the process of lessivage, clay-sized particles (mainly fine clay (<0.2 μm)) separate (or disperse) from the soil mass and are suspended in the soil solution. The particles move downward, or translocate, through soil pores until at some depth movement ceases and the clay is reintegrated back into the soil mass, typically as a coating (termed clay skins or cutans) on the surface of the pores. Dispersion of the clay-sized particles is limited where calcium carbonate ($CaCO_3$) is present and hence decalcification of the surface layer is a required prerequisite to clay translocation. Dispersion of clay is also limited in acidic (pH < 4.5) conditions where Al^{3+} in solution can cause flocculation of clay minerals.

Lessivage has been documented to occur in Gray Luvisols in similar conditions to those found in Saskatchewan (Howitt and Pawluk 1985). They found that micaceous clays, organic constituents in solution and in colloidal form, Fe and Al in solution and complexed with organic constituents, and a small amount of silt-sized quartz were all transferred between the Ae and Bt horizon in the Gray Luvisol they investigated using lysimeters. Clays and colloidal material deposition (or illuviation) occurred in both the upper Bt and (after heavier rainfall) in the lower Bt horizons.

In Canadian Luvisols, three main horizons result from the operation of lessivage and decalcification (Lavkulich and Arocena 2011). The layer of clay deposition is designated as the Bt horizon. The upper A horizon that is presumed (in the illuviation model) to be the source of clay is left with a higher percentage of coarser silt- or sand-sized particles and this horizon is designated an

Fig. 1B: Location of Northern Provincial Forest in Saskatchewan and the names of the soil surveys of the Forest. The two isolated areas in the Prince Albert and Shellbrook surveys have small areas of Luvisolic soils and are not discussed in this paper. Map redrawn from index map in Rostad and Ellis (1972).



Ae in the CSSC (Note that this horizon is labeled as an E horizon in Soil Taxonomy (Soil Survey Staff 2015.) and the World Reference Base (IUSS Working Group WRB 2015). In some cases, mixing of organic materials with this surface layer occurs, forming an Ahe, but more commonly the clay-depleted layer is overlain by a layer of unincorporated forest floor. Finally, the $CaCO_3$ dissolved from the surface layers precipitates from solution at depth and forms secondary carbonate minerals; this horizon is designated as a Cca in the CSSC and is common to many soil orders.

Ae horizons commonly have higher color values than the subsequent underlying horizon and often exhibit platy structures (although neither is diagnostic for recognition of Ae horizons). The Ae horizon experiences surface bleaching of quartz grains that gives it a light gray color. This bleaching occurs when percolating solutions from overlying organic materials strip surface coatings of iron compounds from grain surfaces (Paton et al. 1976) or due to iron coating removal under gley conditions (Zaidel'man, 2007). The Ae horizon can be found in all forest soil orders in the CSSC and is not unique to the Luvisolic Order; indeed, Zaidel'man (2007) argues that lessivage alone cannot result in bleached horizonation. An additional feature of Ae horizons in Luvisols is platy structure composed of thin layers of mineral material; this structure is usually attributed to freeze and thaw processes (Howitt and Pawluk 1985) especially when the soil is saturated (Dumanski and St. Arnaud 1966), not to the loss of clay minerals. Hence, while both the bleached color and the platy structure of the Ae horizon are associated with lessivage, neither is caused by it.

The CSSC identifies three diagnostic criteria for lessivage-formed Bt horizons. The first is higher clay content in the B horizon than the overlying eluvial (i.e., Ae, Ahe, or Ap) horizon; the specific threshold for the difference in clay content to meet the criteria for the Bt differs depending on the clay content of eluvial horizon. The second criterion is the presence of clay skins (i.e., clay coatings) on some ped faces or in fine pores. The third is the presence of at least 1% of oriented clay of a cross section of the Bt horizon when viewed microscopically in a thin section.

Papers in the 1980s by McKeague and other pedologists across Canada challenged the reliability of both clay skins and illuvial clay as criteria for Bt horizons. In a study of 71 pedons with Bt horizons from across Canada, McKeague et al. (1981) stated that clay skins caused by illuviation were difficult to distinguish from those caused by diffusion and from stress cutans in some soils. In addition, the requisite skills needed to identify and quantify clay skins with the aid of a 10-power lens were lacking among survey staff at that time. They also found that three-quarters of the pedons that were classified as Bt horizons in the field had oriented clay levels below the 1% threshold. Previously, McKeague et al. (1980) had also found wide variation (coefficients of variation of between 39% and 64%) in an interlaboratory comparison of oriented clay estimates by 10 operators, and they stated that this variation cast doubts on the usefulness of oriented, apparently illuvial clay in thin sections for identification of illuviation.

Although lessivage is the most common pedological explanation for texture-contrast soils, several other pedological causes have also been proposed. Ferrolysis (Brinkman 1970) occurs where alternating cycles of oxidation and reduction cause clay dissolution (weathering) in the upper soil. It requires seasonal or permanent saturation of soils to create the alternating redox conditions. Another pedological pathway is neoformation of clay or the formation of clay minerals through crystallization or precipitation of solution or gels. Neoformation requires significant chemical weathering of minerals through time and is likely to be associated with stable landscapes that have undergone considerable weathering through time such as the unglaciated landscapes (Sanborn 2016) in central Yukon (Tarnocai and Smith 1989) and the Cypress Hills Plateau (Jungerius 1966). Finally, there is some evidence that chemical weathering in the rhizosphere of forests may selectively weather clay-sized minerals in the upper soil horizon (Calvaruso et al. 2009).

The likelihood of these alternative pedological pathways occurring in Saskatchewan Gray Luvisols is small. Luvisols in Saskatchewan occur primarily on well-drained slope positions, limiting the possibility of alternating redox conditions (and hence the possibility of ferrolysis), although slow permeability of the Bt horizon may lead to a perched water table and weathering of primary minerals in the Ae (Santos et al. 1985). Additionally, very limited alteration of clay minerals in Canadian soils in glaciated landscapes has been observed across many studies (Kodama 1979), except for Podzolic soils, where neoformation can occur in short (100 to 500 year) time frames (discussed in Sanborn 2016). Kodama (1979) found that there was virtually no change in clay mineral composition and distribution between horizons for Luvisolic soils in Saskatchewan, suggesting that selective chemical weathering in the rhizosphere of these soils, if present, is not a significant factor in their pedogenesis.

Sedimentological origin of texture-contrast layers

The final pathway for texture-contrast soil formation is through deposition of layers of sediments with contrasting textural characteristics. When contrasting sediment layers occur in a soil profile, the clay content of each layer was determined by the geomorphic process responsible its formation and is unrelated to the clay content of any other layers. Hence, a difference in clay content between layers cannot be assigned solely to illuviation of clay, and the change-in-clay criteria used in the CSSC to identify illuviation are irrelevant. Raad and Protz (1971) suggested that such inherited layers form a lithologic profile that should be distinguished from the pedogenic profile formed by soil-forming processes.

Differences in texture of inherited layers are termed lithological discontinuities in the CSSC. The CSSC lists five criteria for recognition of a lithological discontinuity (SCWG 1998, p. 21): strongly contrasting textures (differing by two textural classes); different mineralogical composition; appearance of gravel; a change in the ratio between the various sand separates; and (or) the presence of a stone line.

Two major types of sedimentological texture-contrast layers exist for Canadian soils. In the first, deposition or formation of contrasting sediment layers occurs prior to the onset of soil formation and the contrasting layers are inherited by the soil. The second type occurs where a contrasting upper layer is deposited over a soil during the postglacial period after the onset of soil formation. This situation is common where a sand or silt-dominated eolian layer is deposited over a soil.

An important distinction between these two modes of origin is that soils formed through the second mode of origin (i.e., burial of an existing soil during the postglacial period by younger sediments) are paleosols, whereas soils that have inherited sediment layers are not buried soils — soil formation had not begun at the time when the contrasting sediment layers were deposited.

The existence of a lithological discontinuity does not preclude subsequent changes in clay content due to clay illuviation during soil formation in the contrasting sediments. The CSSC states that when a lithological discontinuity occurs between the eluvial horizon and the Bt, the horizon needs only to show clay skins in some parts (i.e., in some fine pores or on some ped faces) to be designated as a Bt; additionally, thin sections should show that the horizon has about 1% of more of oriented clay bodies. If neither condition is met, then presumably the texture-contrast layer would be assigned a Btj or a Bm horizon designation and the profile would be placed in the Brunisolic Order.

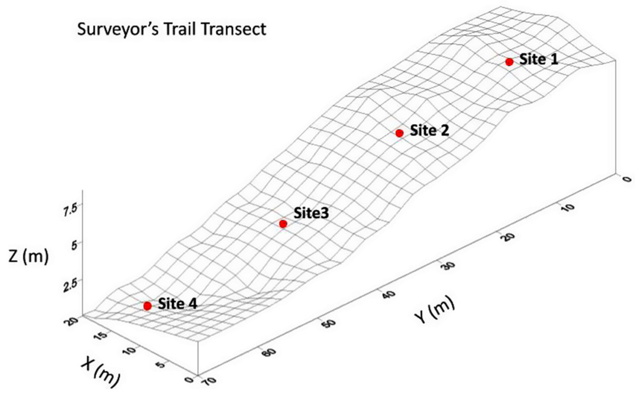
In this paper, we draw upon two types of data to assess the possible contribution of illuviation to the formation of texture-contrast layers in Saskatchewan. The first is a field study of a texture-contrast soil in the southern Mixedwood forest. The second source of data is from 63 pedons described and analyzed during the soil survey of Provincial Forest Reserves during the 1970s and 1980s.

Field Study of A Texture-Contrast Soil

Study area

The Surveyor's Trail catena is located in south-central Saskatchewan at 53°48′05′′N and 105°53′34′′W. The study area is located near the southern boundary of the boreal forest and is dominated by vegetation typical of the region. Trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca* Moench) dominate the canopy. The understory is sparse but there is a thick groundcover of mosses including knight's plume moss (*Ptillum crista-castrensis* Hedw.) and stairstep moss (*Hylocomium splendens* Hedw.). The map unit surrounding the site was mapped

Fig. 2. Wireframe diagram of the slope and profile locations for the Surveyor's Trail catena. [Colour online.]



as the Bittern Lake Association (Anderson and Ellis 1976), and Brunisolic Gray Luvisols are the dominant soil.

Field and laboratory methods

Four points in a catenary sequence situated to span the complete slope (Fig. 2) were excavated to a depth of at least 1 m and described using standard terminology for describing soils in the CSSC. Clay skins were described using the terminology from Watson (2009). Samples were taken at 5 cm increments from Sites 1 and 2 to allow for detailed evaluation of the depth profile of clay between the two sites and from whole horizons in the remaining two soils to allow the spatial continuity of sediment characteristics to be assessed. The average slope at the hillslope is 10% and the four profiles span the complete slope at the site (Fig. 2). The hillslope was surveyed using a Total Station electronic theodolite.

Particle size analysis was completed using the standard methods of the Saskatchewan Soil Survey. Silt and clay were measured using the pipette method following treatment with 30% hydrogen peroxide to remove organic matter. Sodium hexametaphosphate was used for dispersion. Fine clay was determined using a No. 2 International centrifuge. The sand fraction was analyzed with laser diffraction using the Horiba LA-920. Soil pH was measured in calcium chloride (Hendershot et al. 2008). Organic carbon was determined using an LECO CR-12 (LECO Corp. St. Joseph MI) following exposure to concentrated hydrochloric acid vapors, and inorganic C was calculated by difference following LECO analysis of an untreated sample.

Results for the Surveyor's Trail site

The main profile characteristics are consistent across the four profiles: a sandy loam/loamy sand upper layer overlies a loam/sandy clay loam basal layer (Table 1; Fig. 3). At all four sites, there is an Ae and a Bm horizon in the upper sandy layer and at least two IIBt horizons and a IICca horizon in the basal layer. The thickness of the upper sandy layer is consistent (21 cm to 28 cm) across the four pits, and auger probes at 5-m intervals between the profiles showed that the upper sandy layer was a consistent thickness along the entire slope. The depth to calcium carbonate is least (65 cm) in the shoulder slope profile, greatest (135 cm) in both midslope profiles, and 94 cm in the footslope profile. In Site 3, there is a 28 cm thick A and B horizon with bands of sandy clay loam material within a matrix of sandy loam (Fig. 2) that underlies the upper sandy layer.

Clay skins were observed on ped faces (all profiles) and in root channels (Site 1) (Table 1). The clay films were continuous and moderately thick on the ped faces.

The excavation of Site 2 revealed a very different profile sequence on the southern face of the soil pit: a 25 cm to 30 cm wide tongue of medium loamy sand material that extends to a depth of 80 cm and which, at a depth of 70 cm, has a lateral projection of 100 cm across the profile, giving the entire tongue a shape reminiscent of the Italian peninsula (Fig. 4). A sequence of thin (2 cm to 6 cm thick) clay bands with a dendritic branching pattern occurs at the top of the tongue (Fig. 4). As with the bands in Site 3, the bands have a color and texture similar to those of the bounding loam/sandy clay loam material. The tongue was further excavated back from the face and extended approximately one meter south of the face; the thickness of the tongue decreased until at one m it merged with the overlying sandy layer.

The sand tongue is dominated by medium and fine sand fractions, and it becomes coarser with depth: the percentage of silt and clay decreases with depth and the fraction of coarse sand increases (Table 2). With the exception of the 45 cm to 50 cm increment (which contains a clay band), the clay content of the tongue is low, ranging from 1.2% to 6.2%. Calcium carbonate is absent from the tongue (Table 2).

The Ae/Bm1 horizons overlying the tongue not only have higher silt contents than the tongue itself but also have very low clay contents, ranging from 2.3% to 4.6% (Table 2).

The Ae/Bm1 horizons in the profile in Site 2 without the sand tongue are very similar in particle size to the profile with the tongue (Table 3). The silt content and very low clay content (ranging from 4.0% to 9.6%) are similar. The particle size of this layer contrasts strongly with the underlying IIBt1 horizon, where clay content averages at 24.1% and silt at 23.5%; fine sand is the dominant sand fraction. The IIBt1 horizon also has very low calcium carbonate contents, which increase to 11.9% in the IICk horizon. The absence of calcium carbonate is evident in the pH values of the IIBt1, which have a narrow range from 4.9 to 5.4.

The face without the sand tongue at Site 2 is very similar to the profile at Site 1 (Tables 1 and 4). The Ae and uppermost Bm horizon increments have an average clay content of 3.7% and average silt content of 28.3%; the IIBt1 and IIBt2 horizons have average silt and clay

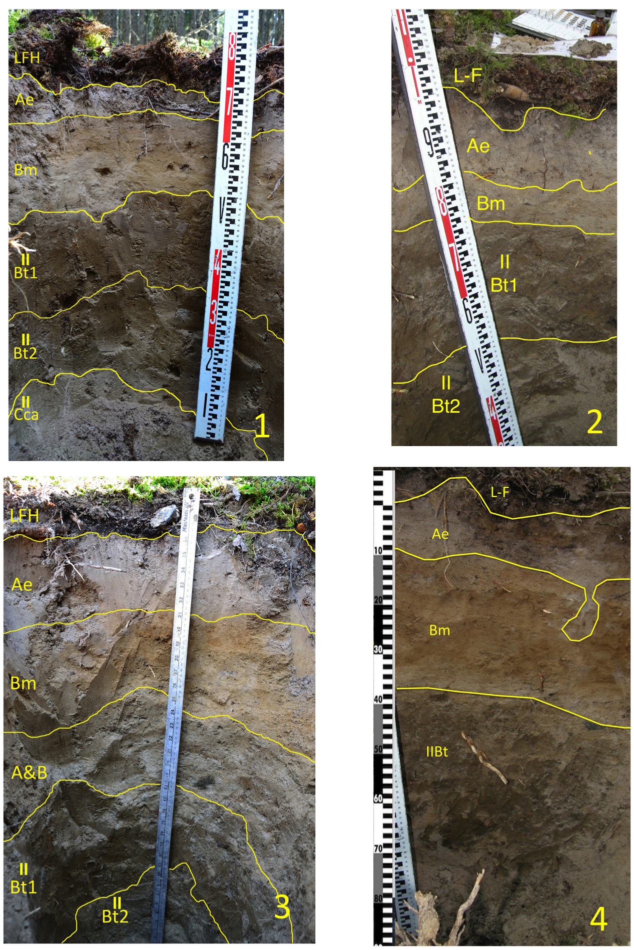
Table 1. Horizon descriptions for the five profiles in the Surveyor's Trail catena.

Horizon	Depth (cm)	Description
		Site 1
LFH	4–0	Dark grayish brown (10YR 4/1) semidecomposed organic matter; fibrous, many fine and medium roots; abrupt smooth boundary
Ae	0–10	Light brownish gray (10YR 6/2) sandy loam; weak, fine platy, clear wavy boundary
Bm	10–28	Light yellowish brown (10YR 6/4) sandy loam; single grain; abrupt, wavy boundary
IIBt1	28–48	Dark yellowish brown (10YR 3/4) loam-sandy clay loam; moderate, medium sub-angular blocky; 1% gravel; clear, wavy boundary
IIBt2	48–65	Dark yellowish brown (10YR 4/4) sandy clay loam; moderate, fine subangular blocky; abrupt, wavy boundary
IICca	65–135+	Brown-dark brown (10YR 4/3) loam, massive; weakly effervescent; streaks of 10YR 7/1 secondary carbonates along root channels
		Site 2 (profile without the sand tongue)
L-F	6–0	Dark grayish brown (10YR 4/1) semidecomposed organic matter; fibrous, many fine and medium roots; abrupt smooth boundary
Ae	0–13	Light gray (10YR 6/1) sandy loam; weak, coarse platy; clear wavy boundary
Btj	13–21	Grayish brown (10YR 5/2) sandy loam; moderate, fine sub-angular blocky; abrupt, wavy boundary
IIBt1	21–42	Dark brown (10YR 3/3) sandy clay loam; moderate, medium sub-angular blocky; clear, wavy boundary
IIBt2	42–78	Brown - dark brown (10YR 4/3) loam-sandy clay loam; moderate, medium sub-angular blocky; abrupt, wavy boundary.
IIBt3	78–135	Dark grayish brown (10YR 4/2) loam; moderate, medium sub-angular blocky; abrupt, wavy boundary
IICca	135–148	Dark grayish brown (10YR 4/2) loam; massive; weakly effervescent; streaks of 10YR 7/1 secondary carbonates along root channels
		Site 2 (sand tongue)
Bm2	To 70 cm	Light gray (10YR 5/3) grading to 10YR 4/4 at depth; loamy sand; single-grained; 25 cm at top of wedge; at a depth of 70 cm extends laterally for 100 cm, rising towards surface at the end; abrupt boundary
Clay bands in wedge		1 to 3 cm thick; 10YR 3/3 to 4/3; dendritic branching pattern with preferred orientation towards horizontal; abrupt boundary
		Site 3
L-F	6–0	Dark grayish brown (10YR 4/1) semidecomposed organic matter; fibrous, many fine and medium roots; abrupt smooth boundary
Ae	0–14	Light gray (10YR 6/1) loamy sand; weak, fine platy; gradual wavy boundary
Bm	14–26	Light yellowish brown (10YR 6/4) loamy sand; single-grained; abrupt, smooth boundary
A and B	26–54	Dominantly Bm horizon with 2 to 6 cm bands of sandy clay loam within matrix of grayish brown (10YR 5/2) sandy loam; bands are folded over within matrix
IIBt1	54–84	Dark brown/brown (10YR 4/3) loam; moderate, medium sub-angular blocky; clear, wavy boundary
IIBt2	84–91	Dark yellowish brown (10YR 4/4) loam; moderate, fine sub-angular blocky; abrupt, smooth boundary
IIBm	91–92	Dark yellowish brown (10YR 4/4) loamy sand; single-grained; abrupt, smooth boundary
IIBt3	92–110	Dark brown/brown (10YR 4/3) loam; moderate, fine sub-angular blocky; abrupt, wavy boundary
IICca	110-	Dark brown/brown (10YR 4/3) loam; massive; weakly effervescent; streaks of light gray (10YR 7/1) secondary carbonates along root channels

Table 1. (*concluded*).

Horizon	Depth (cm)	Description
		Site 4
L-F	7–0	Dark grayish brown (10YR 4/1) semidecomposed organic matter; fibrous, many fine and medium roots; abrupt smooth boundary
Ae	0–8	Brown (10YR 5/3) loamy sand; single grained; abrupt irregular boundary
Bm	8–34	Yellowish brown (10YR 5/4) loamy sand; single-grained; abrupt, smooth boundary
IIBt1	34–63	Dark grayish brown (10YR 4/2) sandy clay loam; moderate, fine sub-angular blocky; clear, wavy boundary
IIBt2	63–94	Brown/dark brown (10YR 4/3) sandy clay loam; moderate, medium sub-angular blocky; abrupt, wavy boundary
IICca	94–165+	Grayish brown (10YR 5/2) sandy clay loam; massive; weakly effervescent

Fig. 3. Photos of the four soil pits along the catena. The numbers in the lower right-hand side of each photo correspond to the profile number. [Colour online.]



contents of 25.8% and 23.2%, respectively. This upper slope profile is thinner (with appreciable $CaCO_3$ present at 65 cm) and more acidic than the profile at Pit 2, and the four increments of the IICk horizon samples have marginally higher silt contents (average of 31.6%) and lower clay contents (average of 20.8%) than the IIBt horizons. The IIBt horizons have low levels of $CaCO_3$ present and the IICk horizons have levels ranging from 13.2% to 15.0%.

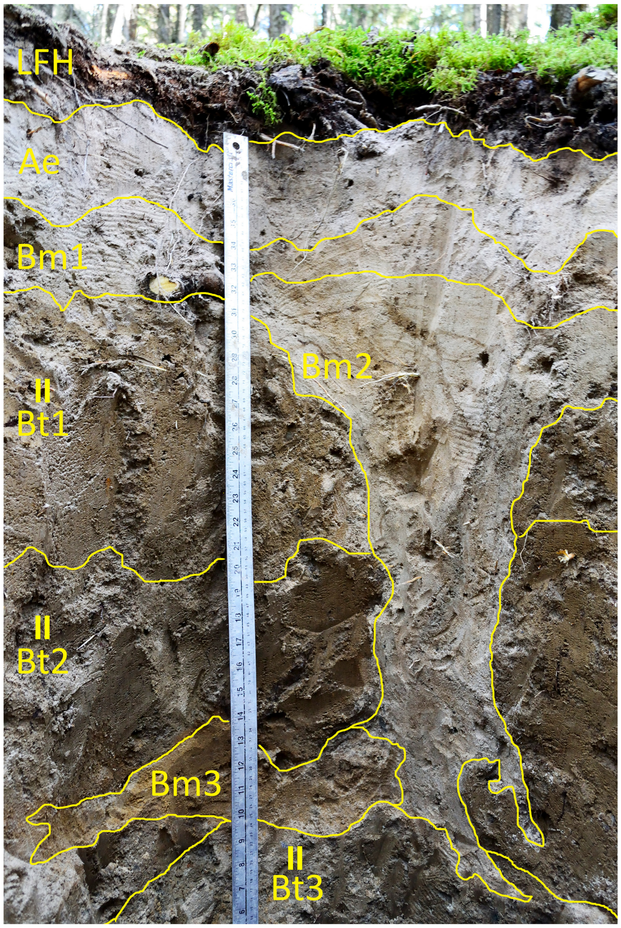
The major contrast in clay content between the overlying Ae/Bm horizons and underlying IIBt and IICk horizons is present in the other two profiles as well. In the CSSC, shifts in sand fractions are the main criterion used to identify lithological discontinuities, and the contrast between the high clay IIBt/IICk horizons and the overlying Ae/Bm horizons is clear in a ternary diagram of all the profile data (Fig. 5), with a generally clear separation between the two layers; only transitional increments with both horizons present and increments with clay bands depart from the general result. It is also clear that the sand fractions of the sand tongue are very similar to those of the Ae/Bm horizons from all four profiles.

Discussion

The field description and results of the particle size analysis suggest the existence of two distinct sediment layers (and hence a lithological discontinuity) at the Surveyor's Trail site: a lower loam-sandy clay loam layer and an upper layer of medium sandy loam. The upper sandy layer forms a mantle with a consistent thickness over the landscape. The sand tongue in Site 2 consists of the same sandy sediment as the overlying mantle. The most likely origin for this tongue is the infilling of a crack that opened in the underlying sediment layer either contemporaneously with or immediately after deglaciation. During the survey of the Prince Albert Forest Preserve (Anderson and Ellis 1976), similar cracks were noted in other locations, and surveyors speculated that they were of periglacial origin (D. Anderson, personal communication, 2021) The medium sandy sediment that was deposited as a mantle over the landscape also filled in the crack, forming the sandy tongue. The origin of the sandy sediment is discussed further in the following section. Importantly, soil formation had not begun when crack formation and deposition of the mantle occurred, and hence this is not a buried soil.

The properties of the lower sediment are consistent with the tills that form the parent material for soils of the Loon River Association (Anderson and Ellis 1976).

Fig. 4. Photo of the sand tongue on the southern face of the soil pit at Location 2. [Colour online.]



These tills have lower $CaCO_3$ contents than tills associated with the Waitville Association (discussed below) and have greater depths to $CaCO_3$ than the Waitville Association.

Subsequent to deposition of the sandy mantle, the soil profile has undergone decalcification of the upper sandy mantle and upper part of the till. The upper part of the sandy mantle has undergone bleaching and development of weakly expressed platy structure, characteristic of Ae horizons in this region. The Ae overlies a redder Bm horizon or (in profile 3) both a Bm horizon and a transitional A and B horizon with prominent clay banding. The sandy mantle has an abrupt, smooth, or wavy boundary with the underlying till.

The presence of clay coatings in the IIBt horizons is sufficient (according to the CSSC) to designate the horizon as being of illuvial origin (and hence a Bt horizon); however, the low clay content of the sandy sediment throughout the sand tongue (average clay content of 4.1% for increments without clay bands) is very similar to that of the Ae/Bm horizons (average clay content of 4.5%). The similarity in clay content suggests that the sandy mantle had inherently low clay content and could not have contributed clay for illuviation and clay coating formation in the underlying horizon.

The occurrence of two distinct sediments in similar profiles in this region was recognized by the soil surveyors (principally D. Anderson and R. Button) during field mapping of this region in 1970. They proposed a new soil association for these soils, the Bittern Lake Association, which consisted of "a group of Gray Luvisol (Gray Wooded) soils developed from medium to moderately fine textured, moderately calcareous glacial till overlain by coarse to moderately coarse materials" (Anderson and Ellis 1976, p.3).

In summary, the difference in clay content between the upper Ae/Bm horizons and the lower B horizons formed in the underlying till is very unlikely to be from clay illuviation and was instead inherited from the sediments in which the soil profile has formed. Hence, the horizon cannot (according to the CSSC) be a Bt horizon, since this designation is restricted to illuvial horizons enriched with silicate clay.

Regional occurrence of texture-contrast soils

A limitation of single-site soil genesis studies (such as that developed above) is their lack of generality. The regional applicability of such a study can, however, be made by linking the site to the data available from soil surveys of the region in which that site is found. The purpose of this broader assessment is to determine how common profiles with lithological discontinuities are in the Luvisol-dominated map units of Saskatchewan, and hence to judge whether the Surveyor's Trail profiles are a rare anomaly or are typical of an appreciable proportion of Luvisols in Saskatchewan.

The great majority of soils of the study region (Fig. 1) have formed in glacial sediment from the final glacial advance of Laurentide ice in the region (termed the Wisconsinan glaciation in North America). The retreat of the Laurentide Ice Sheet from the study area occurred between 12 and 10 kyr BP (Christiansen 1979; Dalton et al. 2020). Low-lying areas in the NE part of the study area were inundated by the waters of Glacial Lake Agassiz, which reached a maximum in the region about 9 to 9.5 kyr BP (Mann et al. 1999). The dominant glacial sediment in the region (discussed in greater detail below) is sandy loam to clay loam till; smectites and mica clay minerals are the most common clay minerals in the region (Kodama 1979).

The study region is located in the Boreal Transition and Mid-Boreal Uplands Ecoregions of the Central Boreal Plains Ecozone (Statistics Canada 2017). The mean annual temperature of the ecozone is 1 °C, with mean summer temperature of 14 °C and mean winter temperature of −13.5 °C. Annual precipitation ranges from 450 to 500 mm; mean annual potential evapotranspiration is approximately 520 mm, creating a small annual mean water deficit (ESWG 2008). Despite the small annual moisture deficit, high volumes of water infiltrate into

Table 2. Particle size fractions and chemical characteristics of Site 2 profile with the sand tongue.

Horizon	Depth (cm)	VCSa (%)	CSa (%)	MSa (%)	FSa (%)	VFSa (%)	Silt (%)	Coarse clay (%)	Fine clay (%)	pH	SOC (%)	$CaCO_3$ (%)
LFH	4–0										41.4	
Ae	0–5	1.8	13.7	29.4	21.0	6.1	23.9	2.3	0.2	4.3	0.5	0.3
Ae	5–10	1.6	12.6	27.2	23.5	5.7	25.8	2.6	1.6	4.0	0.3	0.4
Bm1	10–15	1.8	12.9	24.5	20.0	6.0	30.0	1.0	2.9	6.3	0.2	0
Bm1	15–20	0.8	10.8	27.0	20.3	4.5	31.1	1.4	3.2	4.9	0.2	0
Bm1	20–25	0.4	8.3	24.9	17.1	6.8	37.7	1.0	3.2	5.3	0.3	0
Bm2	25–30	1.5	13.9	31.2	23.0	3.6	21.4	3.4	2.8	5.0	0.2	0
Bm2	30–35	0.9	12.1	35.2	27.8	4.4	13.7	1.3	2.7	4.8	0.2	0
Bm2	35–40	1.3	13.2	33.0	30.8	5.2	11.5	1.4	2.6	4.8	0.2	0
Bm2	40–45	0.9	11.2	28.4	28.8	6.5	18.6	0.4	3.2	4.9	0.2	0
Bm2	45–50	0.7	7.3	13.6	22.0	7.6	26.0	1.0	20.4	5.0	0.2	0
Bm2	50–55	2.4	16.8	35.1	30.2	3.5	8.2	1.4	1.8	5.3	0.1	0
Bm2	55–60	5.7	12.8	35.8	32.9	3.2	4.8	0	1.2	5.1	0.2	0
Bm2	60–65	1.2	14.0	36.4	32.9	4.3	8.5	0.8	2.6	4.9	0.2	0
Bm2	65–70	2.7	17.9	37.0	25.4	3.7	10.5	1.4	0.8	4.8	0.2	0
Bm2	70–75	1.3	14.0	36.9	31.4	5.0	8.5	1.2	2.0	5.0	0.2	0
Bm2	75–80	6.3	13.5	30.4	29.6	7.3	6.1	0.6	1.5	5.1	0.2	0

Note: VCSa, very coarse sand; CSa, coarse sand; MSa, medium sand; FSa, fine sand; VFSa: very fine sand; SOC, soil organic carbon. Sand tongue cells are shaded.

Table 3. Particle size fractions and chemical characteristics of Site 2 profile without the sand tongue.

Horizon	Depth (cm)	VCSa (%)	CSa (%)	MSa (%)	FSa (%)	VFSa (%)	Silt (%)	Coarse clay (%)	Fine clay (%)	pH	SOC (%)	$CaCO_3$ (%)
LFH	4–0										42.4	
Ae	0–5	1.2	11.9	28.7	23.1	6.9	24.2	1.6	2.4	4.0	0.3	0.4
Ae	5–10	1.0	12.0	29.6	20.5	4.0	27.9	2.5	2.5	4.3	0.2	0.4
Ae/Bm	10–15	1.3	13.5	27.4	19.9	8.2	24.2	2.8	2.8	4.6	0.2	0.1
Bm	15–20	2.1	11.6	18.8	20.4	10.7	26.8	5.7	3.9	4.7	0.2	0.6
IIBt1	20–25	4.0	12.8	16.7	18.3	6.7	23.2	11.5	6.8	4.9	0.3	0.5
IIBt1	25–30	2.6	10.4	16.6	18.4	5.8	21.9	13.1	11.3	4.9	0.3	0.2
IIBt1	30–35	0.3	5.9	14.0	20.4	10.9	21.1	15.5	11.7	5.0	0.2	0
IIBt1	35–40	6.7	11.3	12.8	14.0	4.1	23.4	13.8	13.2	4.9	0.4	0
IIBt1	40–45	0.7	6.8	12.0	20.2	12.7	22.1	14.6	10.8	5.1	0.3	0
IIBt2	45–50	0.7	7.1	13.1	18.8	10.7	23.2	12.9	13.5	5.1	0.3	0
IIBt2	50–55	0.6	6.3	12.5	20.6	10.0	24.5	14.4	11.2	5.2	0.3	0
IIBt2	55–60	7.3	10.3	14.5	17.3	6.3	20.9	11.4	11.2	5.4	0.2	0
IIBt2	60–65	0.8	8.1	14.2	21.1	10.0	21.9	13.7	10.2	5.4	0.3	0
IIBt2	65–70	4.8	8.7	12.2	16.6	6.2	27.3	14.7	9.2	5.3	0.3	0
IIBt2	70–75	1.3	10.2	18.2	19.8	7.1	23.1	12.1	8.3	5.3	0.3	0
IIBt2	75–80	1.6	8.5	14.2	18.3	6.1	26.6	13.7	11.1	5.2	0.3	0
IIBt2	80–85	0.6	7.2	13.6	20.5	8.5	26.2	14.9	8.5	5.4	0.3	0
IICk	135–140	1.3	8.4	14.2	17.2	7.7	32.6	12.6	6.1	No Data	0.3	11.9

Note: VCSa, very coarse sand; CSa, coarse sand; MSa, medium sand; FSa, fine sand; VFSa: very fine sand; SOC, soil organic carbon.

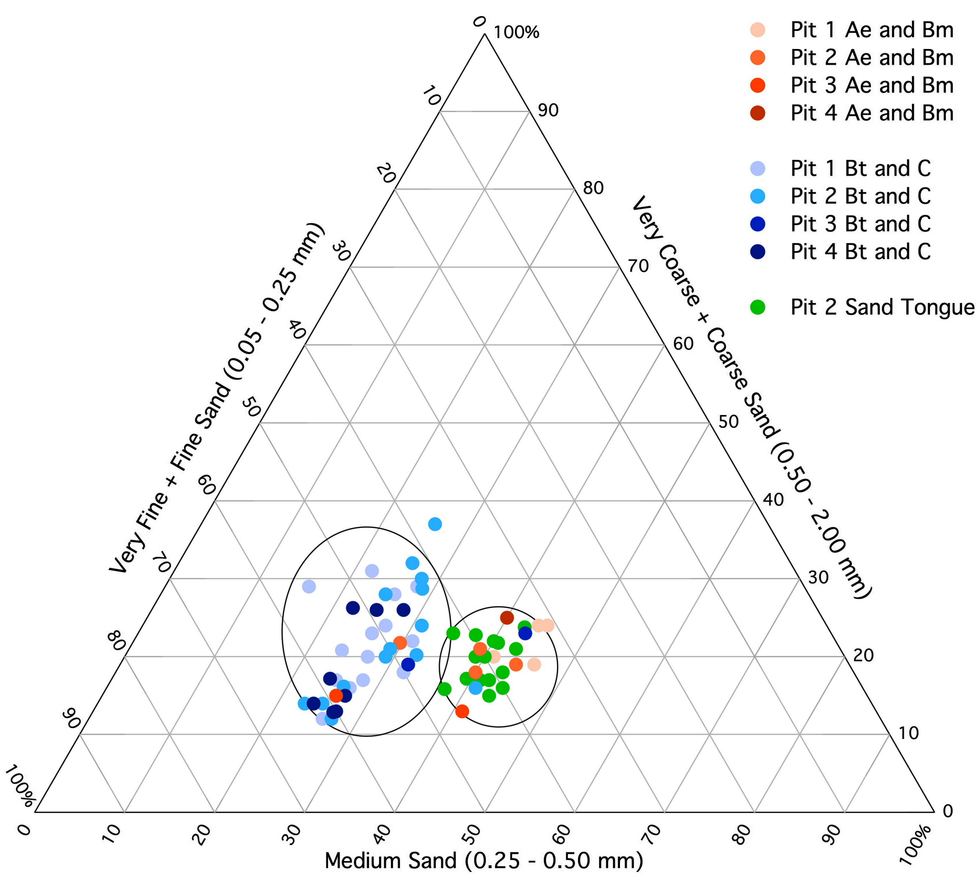
the soil during snowmelt and during occasional spring/summer heavy rainfalls and create a seasonal moisture surplus (Redding and Devito 2011). Trembling aspen (*Populus tremuloides* Michx.) is the dominant tree species and white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) Mill.) are climax species (ESWG 2008). In central Saskatchewan, the vegetation assemblage was largely in place by 10 kyr BP (Strong and Hills 2005) and the boundary between the Central Boreal Plains forest and the Aspen Parkland to the south was either stable (from 10 to 6 kyr BP) or migrated southward (after 6 kyr BP) (Williams et al. 2009).

Table 4. Particle size fractions and chemical characteristics of Site 1 profile.

Horizon	Depth (cm)	VCSa (%)	CSa (%)	MSa (%)	FSa (%)	VFSa (%)	Silt (%)	Coarse clay (%)	Fine clay (%)	pH	SOC (%)	$CaCO_3$ (%)
LFH	0–5										17.40	
Ae	5–10	1.8	14.7	30.6	18.6	3.2	28.8	2.4	0.0	4.5	0.8	0.6
Ae	10–15	1.0	12.3	32.2	20.6	3.9	26.3	3.1	0.7	3.5	0.5	0.0
Bm	15–20	1.7	13.7	29.3	17.5	3.0	30.8	3.3	0.7	3.5	0.6	2.7
Bm	20–25	1.2	12.5	27.8	19.1	7.6	27.2	4.1	0.5	3.5	0.3	0.0
Bm	25–30	0.7	8.1	14.4	18.9	9.7	29.3	13.6	5.4	4.1	0.6	0.6
Bm/IIBt1	30–35	0.6	6.1	7.6	9.1	8.7	36.6	17.0	14.3	5.2	0.5	0.2
IIBt1	35–40	4.3	8.2	11.7	15.3	5.1	26.1	15.2	13.8	5.5	0.4	1.3
IIBt1	40–45	0.8	9.7	18.4	21.6	7.3	22.6	10.3	9.3	5.8	0.3	0.3
IIBt1	45–50	3.8	7.5	12.7	16.1	8.3	23.2	15.4	11.5	5.8	0.3	0.5
IIBt1/IIBt2	50–55	4.8	8.7	12.2	17.5	5.2	27.3	15.1	9.0	5.8	0.4	0.9
IIBt2	55–60	7.0	8.3	11.2	15.4	8.3	25.8	14.8	7.9	5.9	0.3	0.9
IIBt2	60–65	1.5	9.9	16.0	19.5	5.0	27.1	15.5	5.6	6.5	0.3	1.3
IIBt2	65–70	0.2	6.1	13.9	19.0	13.6	28.1	15.2	3.8	6.2	0.5	7.4
IICk	70–75	3.8	10.2	13.3	15.3	4.9	32.6	16.3	3.7	6.5	0.3	14.9
IICk	75–80	7.9	5.2	7.4	14.8	9.9	31.6	17.8	3.3	6.5	0.4	15.0
IICk	80–85	2.5	8.7	12.9	17.5	5.3	31.7	18.2	3.1	6.7	0.5	14.6
IICk	85–90	0.7	7.3	12.2	17.1	11.3	30.5	18.2	2.7	6.4	0.4	13.2

Note: VCSa, very coarse sand; CSa, coarse sand; MSa, medium sand; FSa, fine sand; VFSa: very fine sand; SOC, soil organic carbon.

Fig. 5. Ternary diagram of sand fractions for profiles and sand tongue of the Surveyor's Trail site. [Colour online.]



Methods

The data used in this section are drawn from nine soil surveys of the Provincial Forest Reserves of Saskatchewan published between 1970 and 1996 (Fig. 1) (Anderson and Ellis 1976; Ayres et al. 1978; Crosson et al. 1970; Head et al. 1981; Padbury et al. 1978; Rostad and Ellis 1972; Staff, Saskatchewan Centre for Soil Research (SCSR) 1996; Saskatchewan Institute of Pedology 1983; Stonehouse and Ellis 1983). All but one survey report include full profile and analytical data for modal profiles of each soil association mapped during the field studies. The exception is the soil survey for the Amisk-Cormorant Lake Area (63L,K) (Saskatchewan Institute of Pedology 1983), where the soil map was published but no supporting report was produced. The profiles selected for inclusion in the reports represent the most typical profile characteristics for that particular soil in the mapped area (D. Anderson, personal communication, 2021). This study focuses on particle size data, which was measured in all reports using the pipette method following treatment of the samples with HCl to remove carbonates and with H_2O_2 to remove organic matter. Sodium hexametaphosphate was used for dispersion of the sample. Fine clay was determined using a No. 2 International centrifuge. Analytical data were available for 63 pedons from 24 associations (described in Table 5).

The mapping units used in soil survey in Saskatchewan are soil associations. An association is a group of associated soil series (i.e., Orthic Gray Luvisol, Gleyed Gray Luvisol) developed from similar parent material and occurring under essentially similar climatic conditions. For this study, all associations where Luvisolic soils were dominant (i.e., between 40% and 100% of the polygon was mapped as Luvisolic soils) were selected.

The profiles were described using the 1974 version of the System of Soil Classification for Canada (Canada Department of Agriculture 1974). The criteria for the Bt horizon were largely unchanged between the 1974 and 1998 editions. The 1974 edition, however, does not contain any criteria (field or laboratory) for the recognition of lithological discontinuities, nor does the 1982 manual for describing soils in the field (Expert Committee on Soil Survey 1983).

The aerial extent for all associations was compiled from values presented in the reports except for the Green Lake (73J) and Waterhen River Map Area (SCSR 1996) and the Amisk-Cormorant Lake (63L,K) surveys (Saskatchewan Institute of Pedology 1983); reports were not finalized for these surveys. The areas for the associations in these surveys were estimated from the paper map products using an area-counting method. The area of Prince Albert National Park included in the Green Lake Map Areas was excluded from the Green Lake tabulation and the areas from Prince Albert National Park survey (Padbury et al. 1978) were used instead.

One of the methods suggested in the CSSC for identifying lithological discontinuities is a shift in sand fractions between horizons. A commonly used method for this identification is the Uniformity Ratio developed by Creemens and Mokma (1986), where:

$$\text{Uniformity Ratio} = \{[(\text{silt} + \text{very fine sand})/(\text{total sand} - \text{very fine sand})\ \text{for overlying horizon}]/[(\text{silt} + \text{very fine sand})/(\text{total sand} - \text{very fine sand})\ \text{for underlying horizon}]\} - 1$$

If the value for the Uniformity Ratio exceeds ±0.60, a lithological discontinuity occurs at the lower boundary of the overlying horizon.

Shifts in sand fractions alone do not, however, indicate if the lithological discontinuity is associated with a coarse-over-fine horizon sequence or a fine-over-coarse horizon sequence. The type of horizon sequence was identified by comparing the ratio of (silt+very fine sand/total sand – very fine sand) down each profile that had a lithological discontinuity identified.

To assess the regional distribution of the Luvisol-dominated associations, the boundaries of the associations were superimposed on to a hillshade digital elevation model for the 3-arc second (90 m resolution) Shuttle Radar Topography Mission (STRM) imagery (imagery courtesy of NASA-JPL). The mapping of boundaries was done by on-screen digitization of boundaries from soil survey maps and should be considered a schematic representation rather than a geo-registered product.

Lithological discontinuities in Luvisol-dominated associations

The 24 associations can be divided into four main groups based on their origin (Table 5). The dominant group is Luvisol profiles developed in till (15 553 km^2; 63%). The two dominant associations are Loon River and Waitville. A second group are profiles developed in till with a coarse sand overlay, which includes the Bittern Lake Association discussed above. This group of associations covers an area of 3607 km^2 (15% of total). A third group consists of soils developed in modified till. Till modification generally refers to postdepositional reworking of till by water in fluvial or lacustrine settings. Typically, this would remove fines from the reworked layer and hence result in a coarser overlying sediment layer. The modified till group covers 2624 km^2 or 11% of the total. A fourth and final group consists of profiles developed in glacio-fluvial, glacio-lacustrine, or glacio-fluvial-lacustrine sediments. These sediments range from coarse sand glacio-fluvial sediments to very fine clayey glacio-lacustrine sediments. They cover 2626 km^2 of the region (or 11% of the total). A fifth group (Luvisols that occur in a complex with other soils) has limited

Table 5. Areas and parent sediments of Luvisol-dominated soil associations in the Provincial Forest Reserves of Saskatchewan.

Association	Area (km^2)	Description
		Till
Bainbridge	1277	Till containing pieces and flecks of Cretaceous clay-shales
Bow River	2180	Sand to sandy loam till with incorporation of sandstone bedrock from Lac La Ronge lowland; B horizons frequently banded or discontinuous
Loon River	6114	Unmodified till; usually sandy loam but ranges from sandy loam to clay loam; less than 12% $CaCO_3$ equivalent and greater depth to calcium carbonate in profiles than in Waitville soils
Waitville	5896	Unmodified till; moderately to strongly calcareous; Precambrian granite and gneiss common; greater than 12% $CaCO_3$ equivalent
		Modified till
Battle Heights	526	Eroded till; eroded by waters of former Lake Agassiz
Elk Trail	44	Modified till; upper deposit (15 to 50 cm thick) of coarse sediments partly sorted by water that overlies a till similar to Waitville association
Garrick	39	Resorted till often mixed with lacustrine deposits; associated with shorelines of former glacial lakes
Kakwa	1185	Resorted glacial till derived largely from Paleozoic limestone; often shallow and overlies limestone
Swan Plain	39	Slightly resorted till; surfaces have undergone slight water modification in upper 20 to 30 cm
		Coarse sediment over till
Bittern Lake	2343	Till overlain by coarse to moderately coarse sediments; sandy overlay ranges from 15 to 60 cm thick; upper boundary of till corresponds to top of Bt horizon; similar to till in Loon River soils
Piprell	42	Till overlain by coarse textured stony materials; till similar to Loon River and Bittern Lake Associations; no red colored Bt as in Wapawekka
Wapawekka	1222	Noncalcareous, coarse-textured materials 30 to 90 cm thick overlying calcareous till with bright red Bt horizon developed in till
		Glacio-lacustrine/Glacio-fluvial/Glacio-fluvial-lacustrine
Bodmin	69	Coarse-textured, gravelly glacio-fluvial deposits
Dorintosh	248	Silty clay to clay glacio-lacustrine deposits
Eldersley	887	Fine textured, clayey glacio-lacustrine deposits; often shallow and overlie till.
Flotten	18	Coarse glacio-fluvial and fluvial-lacustrine deposits overlying fine-textured glacio-lacustrine deposits; some clay banding (similar to Waterhen Lake Association) in uppermost sediment
Kelvington	620	Clayey glacio-lacustrine and lake-modified till deposits; till deposited as flows and slides into a long-lived supraglacial lake
La Corne	303	Sandy glacio-lacustrine deposits with >15 % clay; often shallow (<1.2 m) and overlie till or clay glacio-lacustrine deposits; deposition by meltwater in ice-walled channels or valleys in the ice
Nistum	172	Clayey glacio-lacustrine deposits
Porcupine Plain	219	Silty glacio-lacustrine deposits
Sylvania	302	Sandy glacio-fluvial and glacio-lacustrine deposits with less than 15% clay
Waterhen Lake	408	Coarse textured fluvial-lacustrine sands with thin (6 mm to 7.5 cm) bands of clay; bands are often discontinuous and can be horizontally or vertically orientated
		Complex
Jan Lake	136	One map unit of Jan Lake (Jan Lake 4) consists of till Luvisols in complex with Precambrian bedrock
Smeaton	172	Complex of till mixed with coarse textured glacio-fluvial and glacio-lacustrine sands and gravels; associated with margins of former glacial lakes and wave erosion of till.

information available and are not discussed further in this paper.

Lithological discontinuities are common in the 63 profiles examined in this study (Table 6). Lithological discontinuities were identified in the field for 18 pedons, 13 of which had lithological discontinuities in the Ae, AB, Bm, or Bt horizons. Lithological discontinuities were identified in the field in all five profiles of the Bittern Lake association as well as the other two associations in the coarse sediment over till group.

Lithological discontinuities based on shifts in sand fractions in the A or B horizons were identified in 40 profiles, including 11 of the 13 profiles where

Table 6. Discontinuities associated with Luvisol-dominated associations.

Association	Number of profiles	Discontinuity identified in field description			Discontinuity in sand fractions of A or B horizons	Coarse-over-fine layers	Fine-over-coarse layers
		A horizon	B horizon	C horizon			
Till							
Bainbridge	3				1		1
Bow River	1			1	0		
Loon River	6				4		4
Waitville	8				3		3
Modified till							
Battle Heights	1				0		
Elk trail	1		1		1		1
Garrick	2				1	1	
Kakwa	2				1		
Swan Plain	2				2		1
Coarse sediment over till							
Bittern Lake	5	3	2		5	3	2
Piprell	1		1				
Wapawekka	1	1			1	1	
Glacio-Lacustrine/Glacio-Fluvial/Glacio-Fluvial/Lacustrine							
Bodmin	4				4	3	1
Dorintosh	3		1		2	1	
Eldersley	4			1	2	1	1
Flotten	1		1		1	1	
Kelvington	2				1	1	
La Corne	5		2		3	4	
Nistum	0				-		
Porcupine Plain	3			2	2	1	
Sylvania	5		1		5	4	
Waterhen Lake	1				0		
Complex							
Jan Lake	1			1	1		
Smeaton	1				0		
Total	63	4	9	5	40	21	14

lithological discontinuities were identified in the field in upper soil horizons.

Lithological discontinuities based on sand fractions were least common for profiles in the till group (8/18 profiles) (Table 6). All of these lithological discontinuities were associated with fine-over-coarse horizon sequences. All seven of the till profiles with lithological discontinuities had high percentages of silt in the uppermost Ae horizon (e.g., the Loon River profile in Table 7) or upper horizons (e.g., the Waitville profile in Table 7).

Lithological discontinues based on sand fractions were more common in the coarse sediment over till (6/7), modified till (5/8), and glacio-lacustrine/glacio-fluvial profiles (20/28). Twenty-one of these profiles had coarse-over-fine horizon sequences and five had fine-over-coarse sequences. The five profiles of the Bittern Lake Association included two fine-over-coarse sequences (e.g., the Bittern Lake profile from the Green Lake survey, Table 7) and three coarse-over-fine sequences (e.g., the Bittern Lake profile from the Prince Albert National Park survey, Table 7). The fine-over-coarse profiles of the Bittern Lake soils differ from the silty upper horizons in the till profiles insofar as those in the till profiles have an appreciable percentage of coarse-medium and fine sand, whereas the Bittern Lake profiles are well sorted, with over 90% of the particle size distribution composed of silt and very fine sand. The origin

Table 7. Examples of fine-over-coarse (Waitville, Loon River, and Bittern Lake (Green Lake map)) and coarse-over-fine (Bittern Lake (Prince Albert National Park)) profiles.

Horizon	Depth	Coarse-medium sand	Fine sand	Very fine sand	Silt	Clay	Fine clay
	cm	% of total soil					
Fine-over-coarse profiles							
Waitville (Hudson Bay- Swan Lake)							
Ahe	0–3	18.5	12.9	11.3	42.8	14.5	7
Ae	3–14	19.9	18.2	11	44.4	6.5	3.1
AB	14–22	16.0	15.1	11.3	42.2	15.4	8.7
Bt	22–38	30.5	21.2	9.5	19.2	19.6	14.9
BC	38–51	29.7	22.7	11	25.6	11	6.7
Cca	51–66	28.4	17.4	9.6	31.7	13.9	6.7
Ck1	66–95	23.0	22.9	13.9	26	14.2	8.4
Ck2	95–119	24.6	18.8	10.9	30	15.7	7.9
Loon River (Shellbrook)							
L-H	5–0						
Ae	0–13	13.8	9.3	7.7	57.8	11.4	1.9
Bt1	13–28	20.9	14.2	9.5	24.4	24.4	19.2
Bt2	28–43	24.3	15.4	9.8	21.2	29.3	20.5
Bt3	43–58	21.9	16	10.2	23.8	28.1	20.1
Bt4	58–70	24.5	15.2	9.1	23.5	27.7	19
Bt5	70–83	25.8	16.3	8.8	22.3	26.8	18.6
Ck1	83–98	25.8	16.3	9.7	23.4	25.3	16.6
Ck2	98–110	26.2	16.1	9.2	24.8	23.7	13.6
Ck3	110–115	25.4	15.6	9.2	25.5	24.3	14.7
Bittern Lake (Green Lake)							
l-H	5–0						
Ae1	0–10	1.5	1.4	21.4	71.5	4.2	0.6
Ae2	10–33	0.9	1	23.2	69.8	5.4	1.6
IIAB1	33–60	21.9	20.1	11.2	22.8	24.2	15.2
IIAB2	60–78	22.0	19.4	10.5	21.6	23.6	16.1
IIBt1	78–105	19.9	19	11	23.2	26.9	17.7
IIBt2	105–145	20.2	17	10.3	23.6	28.7	18.7
IIBt3	145–168	19.8	17.2	10.7	22.9	29.2	18
IICk	168–170	21.4	18.6	10.9	24.8	24.3	15.4
Coarse-over-fine profile							
Bittern Lake (Prince Albert National Park)							
L-H	3–0						
Ae	0–10	44.6	26.9	7.8	18.9	1.6	1.2
Bm1	10–23	39.5	25.3	7.2	23.9	3.9	1.8
Bm2	23–50	43.5	34.5	7.8	11.4	2.7	NR
Bm3	50–71	45.4	37.2	8	6.2	3	NR
IIBt1	71–102	21.2	17.6	10.7	29.3	21.1	10.8
IIBt2	102+	24.0	19.3	13	28.5	15.2	8

Note: NR, not recorded. Shaded horizon indicates that the lithological discontinuity occurs at the base of the horizon.

of these layers is discussed in more detail in the following section.

The silty surface layers in the till profiles may be explained by weathering of the coarser sand fractions to finer silt-sized particles (St. Arnaud and Whiteside 1963; St. Arnaud and Sudom 1981). In the Orthic Gray Luvisol examined by St. Arnaud and Whiteside (1963), the medium and coarse silt-sized fractions of quartz particles are approximately 10% more than the underlying horizons and the fine sand and medium-and-coarse sand quartz fractions are approximately 10% less, which they attribute to breakup of coarser quartz sand by physical weathering due to frost action. In the Orthic Gray Luvisol examined by St. Arnaud and Sudom (1981), they note considerable chemical weathering of Ca-, Na- and K-feldspars in sand fractions of the soil they examined. The generality of these weathering patterns is difficult to assess from two profiles and certainly many profiles (e.g., the profiles discussed above at the Surveyor's Trail site) do not show any evidence of higher silt contents in the upper horizons.

Two associations had characteristics that raise additional questions about the origin of their texture-contrast horizons. Soils of the Wapawekka association consist of 30 to 90 cm of coarse, excessively stony sediments overlying a red-colored till; the Bt horizons are developed in the lower till. Head et al. (1981) speculate that the upper material is an erosional lag and that the lower red till is a remnant of a soil developed in an earlier interglacial period (i.e., a paleosol).

Soils of the Waterhen association are dominantly coarse to moderately coarse textured fluvial or lacustrine sand deposits with thin clay bands (or lamellae) in the B horizons (Figs. 6, 7). The Bt designation is assigned based on these clay bands. The bands vary from 6 mm to 8 cm in thickness and occur at intervals of 5 to 32 cm (Head et al. 1981; Staff, SCSR 1996). They are frequently discontinuous and while most bands parallel the surface in a wavy pattern, some are vertically orientated. The description of the Bow River association in the Wapawekka survey report (Head et al. 1981) also mentions that B horizons in that association are frequently banded or discontinuous, but this is not apparent in the single Bow River pedon included in the report.

Coen et al. (1966) examined clay bands similar to those in the Waterhen Lake association in the Stony Plain region of Alberta. They found that a thick overlying Ae horizon overlying the horizons with clay bands was probably an aeolian cap and that both original sediment stratification and pedogenesis was likely responsible for band formation. In a review of lamellae formation, Rawling (2000) concludes that pedogenic, sedimentological (termed petrogenic in his review), and combined pedogenic-sedimentological origins have all been demonstrated in the literature. The sole Waterhen profile in the pedon dataset did not exhibit a significant shift in sand fractions, but a sedimentological origin of the clay bands seems at least as plausible as a pedogenic origin.

The extent of inherited texture-contrast horizons on an area basis can only be broadly estimated. The coarse sediment over till group (which includes the Bittern Lake association), glacio-lacustrine/glacio-fluvial group, and the modified till groups are dominantly inherited texture-contrast soils; they cover approximately 37% of the area. The till group of profiles covers 63% of the area,

Fig. 6. Photo of a Brunisolic Gray Luvisol of the Waterhen Lake Association (slide RSA-46, Saskatchewan Centre for Soil Research). [Colour online.]

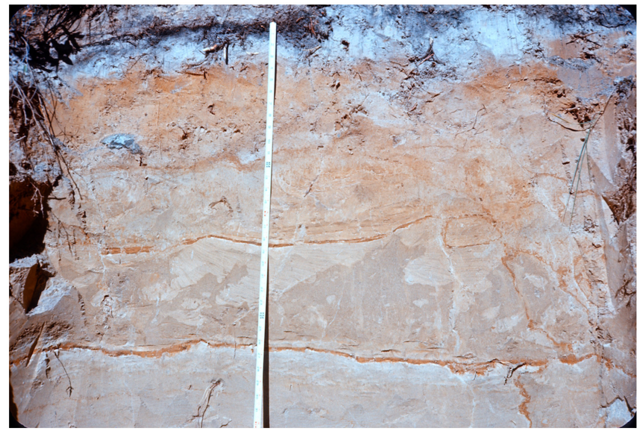
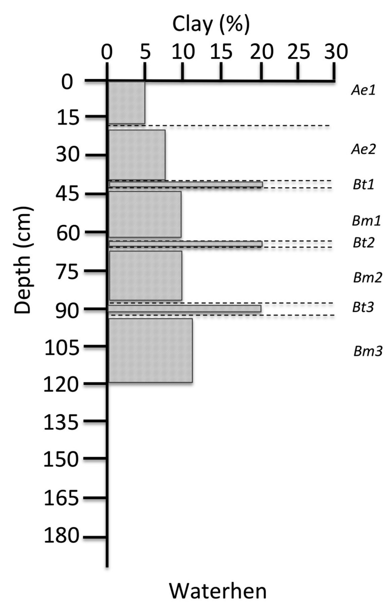


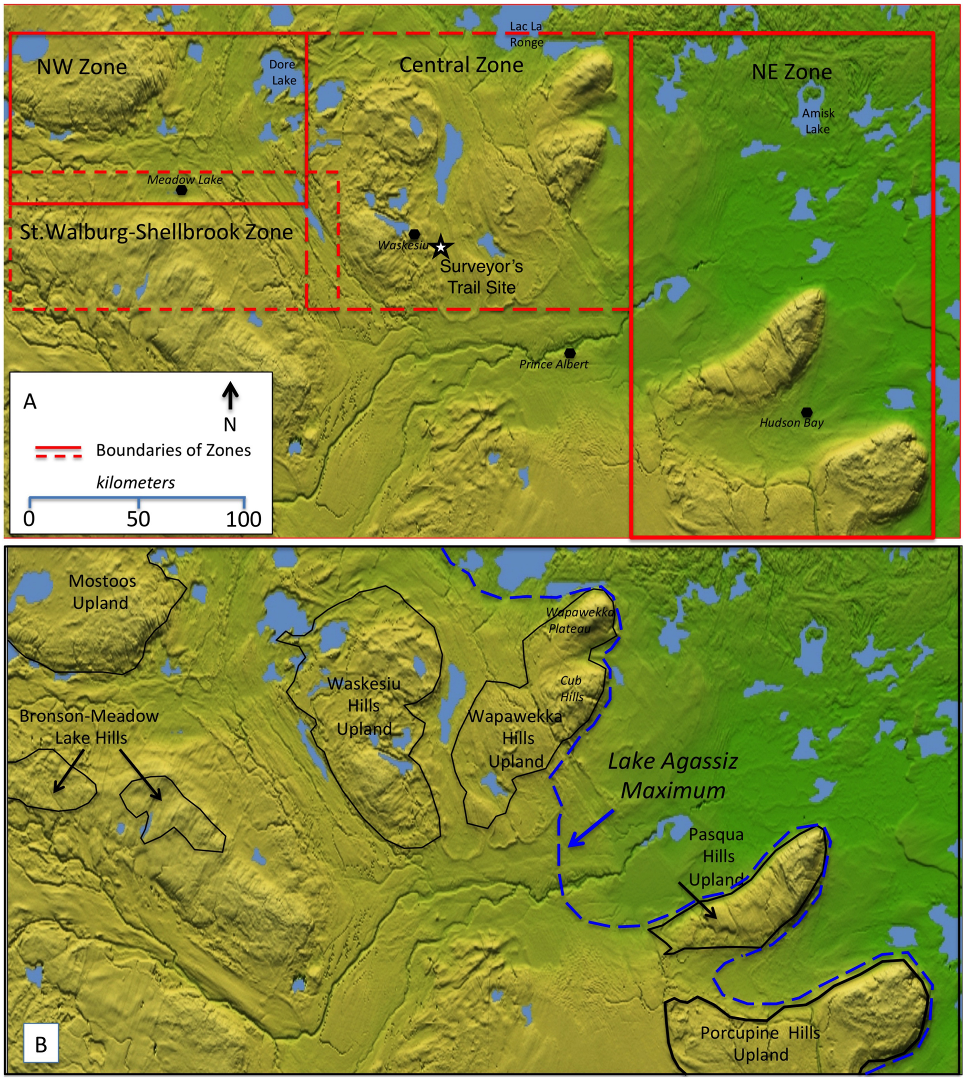
Fig. 7. Clay profile for Waterhen Lake Association profile from the Green Lake/Waterhen River Survey report (SCSR 1996). Horizon labels are from the report.



and approximately 40% of the profiles in this group had texture-contrast horizons, although the origin of these may be pedological. Hence, approximately 50% of the area of Luvisol-dominated associations in Saskatchewan may be texture-contrast profiles with lithological discontinuities and approximately ⅓ of the Luvisol-dominated associations have inherited texture-contrast horizons.

In summary, the majority of Luvisol profiles from the soil survey data set have lithological discontinuities present. Of the 63 profiles, 13 had lithological discontinuities in the A or B horizons identified in the field and a further 28 had shifts in sand fractions indicative of a lithological discontinuity. The percentage of profiles

Fig. 8. Overview map of the regional distribution of Luvisol-dominated associations in the Northern Provincial Forest Reserve of Saskatchewan. Figure 8A shows the boundaries of the four zones represented in Fig. 8B. Figure 8B shows the names of the major uplands in the study area and the maximum extent of Glacial Lake Agassiz. Base map is the hillshade digital elevation model for the 3-arc second (90 m resolution) Shuttle Radar Topography Mission (STRM) imagery (imagery courtesy of NASA-JPL). [Colour online.]



showing lithological discontinuities is similar to that of the study on French soils by Quénard et al. (2011), where 40% to 60% of the profiles they examined had lithological discontinuities. They conclude that for these soils, the change in parent materials is the dominant process responsible for the texture-contrast horizon and that lessivage, if present, had a minor role in horizon formation; we would draw the same conclusion for the Luvisols we examined.

Regional distribution of Luvisol-dominated associations

We can further understand the occurrence of the inherited texture-contrast soils by examining the regional distribution of the Luvisol-dominated associations and their relationship to the regional physiography (Figs. 8, 9).

The physiography of the eastern portion of the region is dominated by streamlined, elongated hills (Wapawekka, Cub, Pasqua, and Porcupine Hills) rising abruptly from the plains (Fig. 8). These hills have steep escarpments on their NW and SE faces and rolling plateaus in the center of the hills. The remaining uplands (Waskesiu Hills, Bronson and Meadow Lake Hills, and Mostoos Upland) have hummocky surface or megascale glacial lineations (Ó Cofaigh et al. 2010). The uplands are separated by broad valleys and river channels.

The shape of the landscape overall was formed by glacial events throughout the Pleistocene epoch, but the composition and form of the surface sediments in which the soils have developed were dominantly formed by the final glaciation (i.e., the Wisconsinan glaciation)

(Ross et al. 2009). In the past 15 years, research on the importance of ice streams (i.e., fast-flowing, highly dynamic elements of ice sheets with velocities up to 12 km·yr^{-1}) (Ó Cofaigh et al. 2010) has enhanced our understanding of the surface-forming processes in the study region (Ross et al. 2009; Ó Cofaigh et al. 2010) and adjacent areas of Alberta (Norris et al. 2018; Evans et al. 2012).

The Laurentide Ice sheet advanced over the study region multiple times during the Pleistocene Epoch. Glacial advances prior to the Wisconsinan glaciation flowed from the NE of the region to the SW. These advances streamlined the isolated hills (e.g., Wapawekka, Porcupine) and incorporated limestone into the tills from limestone bedrock in western Manitoba and northeastern Saskatchewan. This incorporated limestone causes high $CaCO_3$ in tills down-glacier from the source area, and tills in eastern Saskatchewan (including the Pasqua and Porcupine Hills) and the southern portion of the Waskesiu Hills have high $CaCO_3$ contents from this period (see fig. 10 in Ross et al. 2009 for a summary of carbonate contents through the study region). In this period, the till in the NW and N central portions of the study region was deposited from glaciers that did not advance across the limestone region and hence had lower $CaCO_3$ contents.

During deglaciation, conditions at the ice–land interface gave rise to the fast-flowing ice streams; the legacy of several distinct ice streams can be seen in the landscape. The Maskwa ice stream (Evans et al. 2009; called Ice Stream 1 by Ó Cofaigh et al. 2010) flowed from NE to SW across Saskatchewan and streamlined glacial features in the Bronson-Meadow Lake Hills (Fig. 8). Subsequent ice streams were constrained by topography and flowed from Alberta through the valley now occupied by the North Saskatchewan River south of the Bronson-Meadow Lake Hills (Ice Stream 2 Ó Cofaigh et al. 2010), through the Cold Lake Corridor (Evans et al. 2009) between the Mostoos Upland and the Bronson-Meadow Lake Hills (Fig. 8) (Ice Stream 3 Ó Cofaigh et al. 2010), and through the valley now occupied by the Beaver River between the Mostoos Upland and the Waskesiu Hills (Ice stream 4 Ó Cofaigh et al. 2010). These later ice streams cut across the landforms created by the Maskwa Ice Stream. There was also a major ice stream east of the Waskesiu Hills (the Buffalo Corridor of Evans et al. 2009) that flowed to SE Saskatchewan. All of these ice streams deposited low carbonate tills (and other glacial sediments) originating in Alberta and North Central Saskatchewan rather than from the high carbonate (limestone) region in NE Saskatchewan. The major postdeglaciation event affecting the area was the recession of Lake Agassiz (Fig. 8), which left a series of beach remnants throughout the region.

The valleys between the main uplands (Fig. 8) have various glacial sediments present (discussed below), but lowest elevations adjacent to current river channels have large areas of glacio-fluvial and glacio-lacustrine sands with no or low $CaCO_3$ contents (mapped as the Pine association throughout the region), parts of which have been reworked by wind in the postglacial period.

This summary of the deglacial and postglacial history of the region helps us understand the regional distribution of the Luvisol-dominated soil associations that commonly have lithological discontinuities associated with them (Fig. 9).

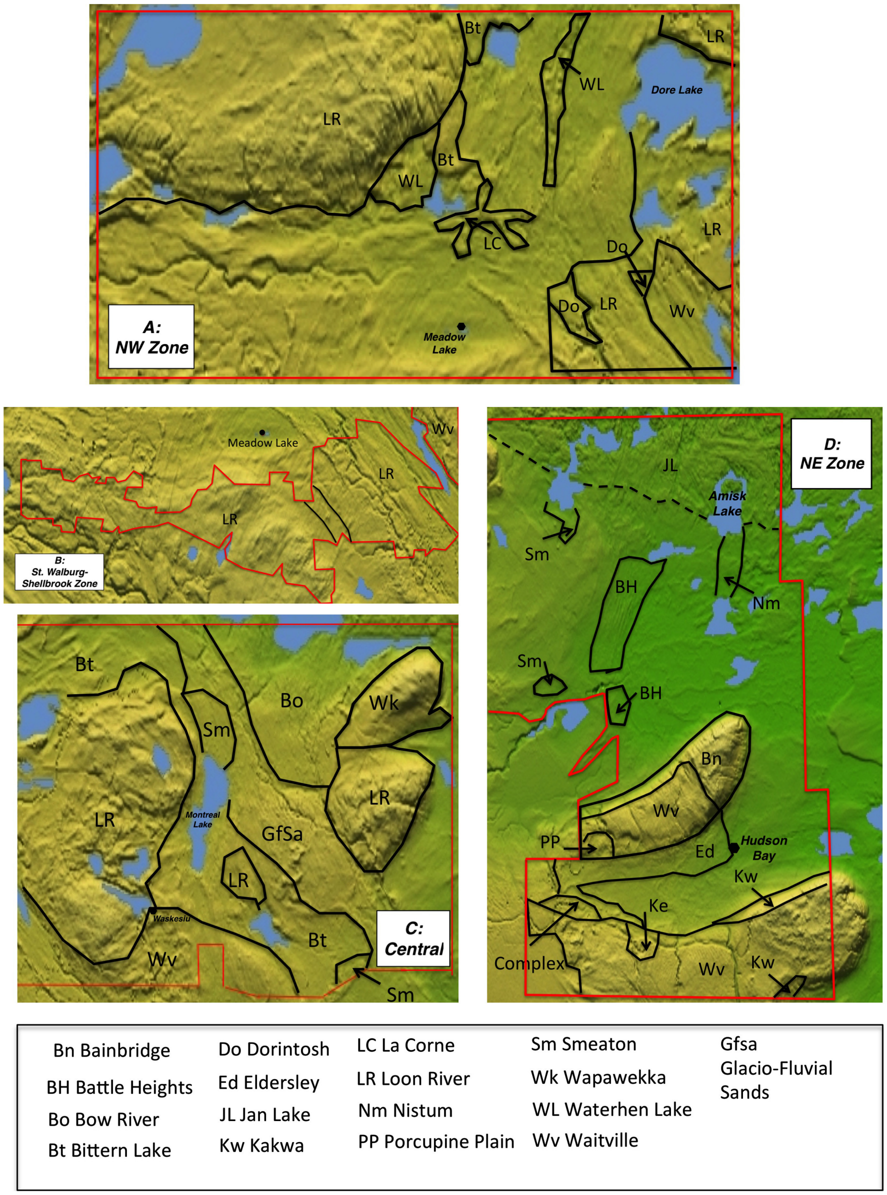
Throughout the region, the major associations developed in till (i.e., Loon River, Waitville and Bainbridge) occur in the major upland areas. These associations are the least likely to have lithological discontinuities present (8/18 profiles) and those that do occur may be due to physical weathering of sand rather than the deposition of different sediments. The distribution of the Loon River and Waitville Associations corresponds generally to the regional distribution of till: tills with the higher $CaCO_3$ content of the Waitville Association occur in the NE zone and in the southern portion of the Central and NW zones, and tills with lower $CaCO_3$ content (Loon River Association) occur in the NW zone, in northern areas of the central zone, and in the St-Walburg-Shellbrook zone (Fig. 9). The Bainbridge association is confined to the Pasqua Hills and contains considerable amounts of bedrock-derived shale. The Bow River association is the exception in the till group as it occurs in the northern part of the lowland between the Wapawekka and the Waskesiu Hills (Fig. 9C). As mentioned above, however, the banded and discontinuous nature of the B horizons in this association suggests that it has a complex genesis.

The major coarse-sediment-over-till associations (Bittern Lake and Wapawekka) have very different regional patterns. As discussed above, the Wapawekka association is a distinct soil/paleosol that occurs only in the Wapawekka plateau (Fig. 9C).

The Bittern Lake association occurs in the lowlands east of the Waskesiu Hills upland and of the Mostoos Upland (Figs. 9A, 9C). Both areas are adjacent to large areas of the sandy Pine Association. Given the proximity of the sandy glacio-fluvial/silty lacustrine sediments and the relatively even thickness of the silty/sandy mantle over landscape features, it seems probable that the upper sandy or well-sorted silt sediments are an aeolian layer deposited during deglaciation. Short-range aeolian transport of sand and silt from lake plains or outwash plains was identified as the source for discontinuous loess deposits in Michigan by Luehmann et al. (2013); a similar phase of eolian transport may have occurred on unvegetated surfaces immediately after deglaciation in central Saskatchewan.

Lithological discontinuities are very common in the modified till associations, which are dominantly associated with the NE zone in the area that was occupied by Glacial Lake Agassiz (Fig. 9D). The Kakwa Association occurs at the base of the escarpment of the

Fig. 9. Regional distribution of Luvisol-dominated associations in the Northern Provincial Forest Reserve of Saskatchewan. (A), Northwestern zone of the study area (see Fig. 8 for locations of zones); (B), St. Walburg-Shellbrook zone; (C), Central zone; and (D), Northeastern zone. Base map is the hillshade digital elevation model for the 3-arc second (90 m resolution) Shuttle Radar Topography Mission (STRM) imagery (imagery courtesy of NASA-JPL). Boundaries of Luvisol-dominated soils redrawn from soil surveys of the Northern Provincial Forest Reserves shown in Fig. 1B. [Colour online.]



Porcupine Hills in the shoreline zone of the glacial lake. Although shown as a solid area on Fig. 9D, the Battle Heights Association is in fact mostly a series of long (20 to 30 km), narrow (1 to 3 km) ridges of eroded till separated by organic soils. The other three associations in this group cover only small areas in the study area.

Lithological discontinuities are also very common (13/16) in the associations with coarser (i.e., sand or gravel) glacio-fluvial sediments (i.e., Bodmin, Flotten, La Corne, Sylvania and Waterhen Lake Associations) but only the La Corne and Waterhen Lake occur at scales that appear on Fig. 9. The La Corne Association occurs in sediments deposited in ice-walled channels or valleys, which have inherently high sediment heterogeneity associated with them; the five-limbed area SE of the Mostoos Upland (Fig. 9A) is the largest extent of this Association in the study region. The banded nature of the Waterhen Lake association was discussed above. It occurs primarily on the SE flank of the Mostoos Upland and along the channel of the Beaver river in the lowland between the Mostoos Hills and the Waskesiu Upland (Fig. 9A).

The silty or clayey glacio-lacustrine sediments occur throughout the study region and were deposited in glacial lakes. These sediments often had till deposited as flows or slides (Kelvington Association) within them or are shallow sediments overlying till (Eldersley Association); hence, discontinuities are expected to be common in these soils (3/6 for the two associations). These two associations, along with the Porcupine Plain and Nistum associations, are associated with Glacial Lake Agassiz in the NE zone of the study area.

The Dorintosh association occurs throughout the study region but only in larger contiguous areas in the NW zone. The silty variants are varved, whereas the clay variants have massive structures. Two (out of 3) profiles had lithological discontinuities and both are silty.

In summary, the Luvisol-dominated associations developed in till have the fewest lithological discontinuities and dominate the upland landscapes throughout the study region. The remaining three groups are associated with lowlands that experienced erosion during the recession of large glacial lakes or through modifications of the land surface by glacio-fluvial or postglacial river systems. These processes have left a modified surface horizon in many locations and hence lithological discontinuities are very common in these landscapes (31/43 profiles).

Implications for horizon nomenclature and soil taxonomy

The analysis of Surveyor's Trail soils showed that the catena at the site formed in a sandy mantle overlying a till and that even though clay skins (which are normally interpreted as illuvial features) were present, it is very unlikely that significant clay illuviation had occurred at the site. The regional analysis of Luvisol-dominated soil associations showed that the majority (41/63) of profiles in Luvisol-dominated soil associations throughout the region had lithological discontinuities, and that the contribution of clay illuviation to the occurrence of textural-contrast horizons cannot be reliably assessed based on particle size differences alone. Nor can we draw upon additional supporting information required by the CSSC for Bt horizon identification (i.e., clay skins and orientated clay in thin sections) in profiles where lithological discontinuities occur as this information is not included in the soil survey reports and nor was it required in the original field descriptions of soils (D. Anderson, personal communication, 2021). Hence, for these soils, the only evidence for clay illuviation is the change in clay content between horizons, and this change (for soils with lithological discontinuities) is more readily explained by inherent differences in sediment.

The linkage between clay illuviation and the definition of the Bt horizon is unambiguous in the CSSC, and hence strict application of the nomenclature rules would bar the use of the Bt label for soils at the Surveyor's Trail site and for an appreciable percentage of Luvisolic profiles in Saskatchewan. These former Bt horizons would need to be relabeled as Btj or Bm horizons and hence the profiles reclassified as Eutric or Dystric Brunisols (depending on the pH of the B horizon). Currently, there are two Brunisol-dominated associations in the study region, the Pine Association developed in sandy glacio-lacustrine/fluvial sands and the Kewanoke Association developed in gravelly glacio-fluvial sands.

We would argue that strict application of the illuvial-only Bt horizons is undesirable for a number of reasons.

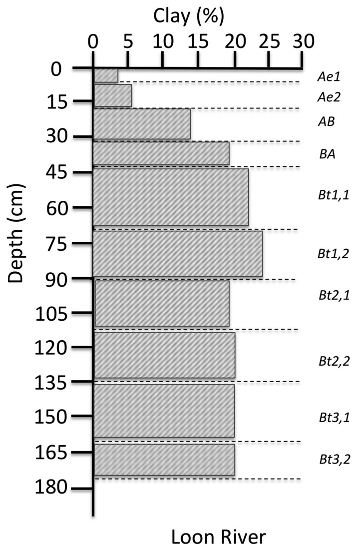
First, to separate illuvial Bt horizons from inherited texture-contrast layers, soil surveyors must either describe and record clay skins or take samples for subsequent micromorphological analysis. As discussed previously, neither approach provides unambiguous evidence for illuviation. Moreover, it has to be noted that the professional (and very experienced) survey staff of the Saskatchewan Institute of Pedology were not required to describe clay skins as part of their field descriptions of soils for the surveys used in this paper (D. Anderson, personal communication, 2021); it seems overly onerous to require field pedologists to add this requirement now.

Second, the presence of a clay layer or band fundamentally changes the water relations of the profile and hence its ability to support plant growth. For example, even the thin clay bands found in Luvisols the Waterhen Lake Association cause them to retain more water than the Brunisolic soils of the Pine Association soils: "the presence of the finer textured bands can effectively store water. This is reflected in the difference in vegetation as compared with that on Pine soils which are virtually the same as Waterhen soil but lack the banding" (Head et al. 1981, p. 36). In all the surveys included in this paper, the Soil Capability for Forestry and for Agriculture is higher for the Luvisolic soils than for the Brunisolic soils. This very practical distinction between the orders would be lost with a strict application of the illuvial-only Bt criterion.

Our suggestion is rather that the CSSC should eliminate the requirement that the Bt horizon be solely associated with clay illuviation. Instead, the t suffix would identify the higher clay content horizon(s) in a set of texture-contrast horizons. The redefined Bt would meet the current criteria for differences in clay content between horizons in the CSSC. The current clay skin and oriented clay criteria could be retained as evidence of clay illuviation (where it occurs) but would not be mandatory for identification of a Bt horizon.

Horizons beneath the uppermost Bt horizon that have clay contents in the same soil texture class as that of the uppermost Bt horizon would also be assigned a t suffix. This does not represent a change insofar as this practice was widespread in the surveys summarized for this report; for example, in the thick sequence of Bt horizons that occurs in the low carbonate tills such as the soils of the Loon River Association (Fig. 10). In this example, the Bt1 horizon begins at a depth of 42 cm, and the two Bt1 horizon samples (Bt1,1 and Bt1,2) show a bulge of clay

Fig. 10. Clay profile for Orthic Gray Luvisol of the Loon River Association. Sample 73I-16 from Wapawekka survey (Head et al. 1981). Horizon labels are from the survey.

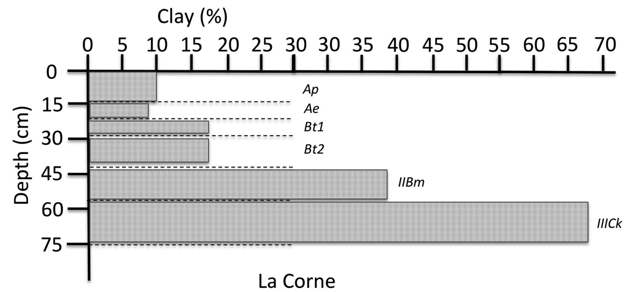


indicative of clay illuviation. The sequence of underlying Bt horizons is at least 85 cm thick and exhibits very consistent clay contents (a range from 18.8% to 20.2%). It seems unlikely that illuvial clay would be so evenly spread through these lower horizons; instead, they were assigned a t label presumably because their clay content was close to that of the upper Bt horizons.

Two additional changes would be required. First, it needs to be recognized that the lower clay content horizon overlying the Bt is not necessarily an eluvial horizon (e.g., the sandy mantle over till in the Bittern Lake Association is not a significant source of clay for the IIBt horizon). This situation is already evident in profiles like the Waterhen Lake profile (Fig. 7), where a series of banded Bt horizons are overlain by Bm horizons, not Ae horizons. The term eluvial should therefore be deleted from the description of the Bt horizon in the CSSC (as in "It <the Bt> forms below an eluvial horizon but may occur at the surface of a soil that has been partially truncated" (SCWG 1998, p. 15)).

Second, a nonilluvial texture-contrast horizon set could readily occur anywhere in a profile. For example, in the complex example from the La Corne association from the Hudson Bay/Swan Lake soil survey (Stonehouse and Ellis 1983) shown in Fig. 11, the two Bt horizons overlie a higher clay IIBm, which in turn overlies a much higher clay III Ck horizon. Three sets of coarse-over-fine texture-contrast layers occur (Ap+Ae/Bt1+Bt2 and Bt1+Bt2/IIBm and IIBm/IIICk), yet only one is evident from the profile labeling. Eliminating the illuvial requirement would allow identification of the increasing amount of clay in each horizon below the Ae (i.e., Ap +Ae/Bt1+Bt2 and Bt1+Bt2/IIBt and IIBt/IIICtk). Therefore,

Fig. 11. Clay profile for Orthic Gray Luvisol of the La Corne Association. No. 63D-3 from the Hudson Bay-Swan Lake map area (Stonehouse and Ellis 1983). Horizon labels are from the survey.



the possibility of a Ct horizon would need to be recognized in the CSSC.

We would also suggest that the Luvisolic Order in the CSSC should be broadened to include nonilluvial Bt horizons. The diagnostic horizon for the Luvisol Order is the Bt, and we would argue that from a management or engineering perspective, the origin of the texture-contrast layers is irrelevant. Clearly, the term Luvisol implies illuviation, and clay illuviation may well occur in varying degrees in most Luvisol profiles; however, the ability of field surveyors (or, for that matter, laboratory-based micromorphologists (McKeague et al. 1980, 1981)) to assess the degree to which a Bt has been formed by illuviation is difficult to standardize and would weaken the observational foundation of horizon designation and subsequent soil classification.

The recognition that processes other than illuviation may contribute to formation of the Bt horizon has already been made by the authors of Soil Taxonomy (Soils Survey Staff 2015). The Concept and Background Information section (Soils Survey Staff 2015, p. 3–44) for the Argillic Horizon (Bt) recognizes that not all of the increase in clay is due to illuviation, and that other processes such as clay weathering, erosional winnowing, and neo-formation of clay may contribute to the clay increase but that "Illuviation of clay, however, is responsible for at least some of the increase". The other major global classification system, the World Reference Base (IUSS Working Group WRB 2015) limits the t designation to horizons with accumulation of silicate clay that has formed in the horizon or has been moved into the horizon by illuviation (or both). It does, however, permit the use of the t designation with C horizons.

The WRB also has a useful protocol (IUSS Working Group WRB 2015, p. 21) for naming sequences of soils where a buried soil is covered by younger deposits. The dominant soil (i.e., overlying or buried) is selected depending on the thickness of the overlying sediment and the nature of the overlying sediment (e.g., Aeolic, Colluvic) is included in the name of the soil. Although not applicable to the great majority of soils discussed in this paper (which inherited the texture-contrast layers from sediment deposition prior to the onset of soil formation), it may be useful to include the buried soil-naming protocol in the revised CSSC.

Conclusion

Both the field study of a Luvisol catena and an analysis of 63 modal profiles from soil surveys in Saskatchewan indicate that lithological discontinuities are common in Saskatchewan Luvisols. It is probable that these discontinuities are the dominant cause of the coarse-over-fine texture-contrast horizons present in these soils. Strict application of the criteria of the CSSC would designate these as Bm (or at best Btj) horizons, and hence the soils would be classified into the Brunisolic Order. We believe that this reclassification is undesirable for both scientific and practical reasons and that instead the diagnostic criteria for the Luvisolic Order should be broadened to include nonilluvial Bt horizons.

This decoupling of the Luvisolic Order from clay illuviation is (curiously enough) consistent with the stated attributes of the CSSC. Although the authors of the CSSC (SCWG 1998) acknowledge the genetic bias of the system, they state (p. 6) that "Classification is not based directly on presumed genesis because soil genesis is incompletely understood, is subject to a wide variety of opinion, and cannot be measured simply". The explicit inclusion of illuvial clay in the definition of the Bt horizon violated this attribute, and the criteria for it should be changed in the 4th edition of the CSSC.

Competing Interest

The authors declare there are no competing interests.

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Contributor's Statement

KF described and analyzed the soils of the Surveyor's Trail site and developed the Introductory section of the paper. DJP completed the remainder of the paper.

Data Availability

Data on the particle size of the 63 pedons are available on request from dan.pennock@usask.ca.

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