Argillic Horizons in Stratified Drift: Luverne End Moraine, Eastern North Dakota

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ABSTRACT

Although pedogenesis and landscape evolution have occurred on the eastern North Dakota till plain since the inception of the Holocene, soils with argillic horizon are recognized on a very limited basis. Argillic soils are not mapped in well-drained positions on the youngest drift prairie landscapes. Roughly half of 47 pedons examined at a precision farming research site in Barnes County, North Dakota show evidence of genetic argillic horizons based on soil structure, hand texturing, and cutan presence. This study applies physical and micromorphological evidence to verify that diagnostic argillic horizons have formed in well-drained settings on this eastern North Dakota landscape. Total clay distributions and fine/total clay ratios show marked increases in genetic argillic horizons compared with surface horizons and parent materials. The argillic horizons average about 28 cm in thickness; only two pedons were thinner than 7.5 cm. Consequently, the increase in total clay and fine clay distributions, and the thickness criteria required to meet diagnostic horizon status as established by *Soil Taxonomy* are satisfied. The upper argillic horizon boundary of seven profiles was 50 cm or more below the surface, possibly indicating relict argillic horizons. Micromorphologic evidence shows the presence of illuvial clay in the three soils sampled for microscopy. Porosity variations caused by the argillic horizons likely affect subsurface flow and may be responsible for variable N levels measured for these soils. These soils formed in well-drained landscape settings, where stratified drift may predispose the soils to illuviation.

Guy Smith (1986) stated that argillic horizons were not "weighted more heavily" in *Soil Taxonomy* than other diagnostic subsurface horizons. However, the definition, recognition, and genesis of horizons featuring accumulated silicate clays have occasionally dominated pedological discourse. Smith (1986) believed the argillic horizon was important not so much for what it was, but for what it does: increase nutrient status, enhance water retention, reduce permeability and "perch" water, as well as reflect geomorphic stability of the landscape. These interpretations, crucial to understanding water and solute movement at the landscape scale, explain why soil stratigraphy has taken on new meaning for environmental and hydrogeological assessments. Many recent studies have attempted to quantify the role argillic horizons, and other restrictive subsurface horizons, exert in soil water flow (McDaniel and Falen, 1994; Perillo et al., 1999; Shaw et al., 2001). We have been investigating the occurrence and distribution of argillic horizons on a precision farming research site in Barnes County, North Dakota for precisely these reasons. An intriguing aspect of this work concerns the fact that soils with argillic horizons have not been mapped on any moraine landscapes in central or eastern North Dakota north of Sargent County, which borders South Dakota. The Forman series (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls), which is mapped in northeastern South Dakota and Sargent County, North Dakota, is thought to form on older till than that in Barnes County (Aandahl 1982).

A large number of moraines are distributed throughout central and eastern North Dakota and individual moraines frequently extend across several counties. Lithology and sediment sizes encountered on the numerous moraines are similar (Clayton et al., 1980). Soil map units recognized on the moraines commonly form in till, water-worked till, sandy sediments, or sediments with a sandy or coarse-loamy mantle above till. Soil parent materials on the moraines and the lower elevation drift prairie have both been exposed to surficial weathering and similar vegetation for similar amounts of time, yet soils with argillic horizons have been recognized on a very limited basis, and only on the drift prairie.

The physical and morphological properties of drift prairie soils were a major focus of extensive field research by North Dakota Agricultural Experiment Station personnel in the late 1950s and early 1960s (McClelland et al., 1959; Mogen et al., 1959). The typical B horizon in well-drained positions was described as a "color B" with high chroma, but a "texture B" having clay films on ped faces that "range from thin and patchy to thin and continuous" was noted as well (McClelland et al., 1959, p. 53). Subsequently, Redmond and Omodt (1967) suggested that the Barnes soil series, an extensive soil of the drift prairie, acquired three developmental forms in eastern North Dakota due to different expressions of the B horizon.

Clearly, illuvial processes were recognized by these early researchers, but Aandahl (1982, p. 10) stated that argillic horizons did not form in the Udic Borolls (currently Hapludolls) because the soils were immature and "formed in recent glacial till." Soils with argillic horizons were "those formed under the influence of trees of the Turtle Mountains, those in shallow depressions with greater leaching by extra water, but shallow enough to permit frequent wetting and drying, and those in older tills; some formed in glacial till are clayey where influenced by sodium" (Aandahl, 1982, p. 10). These environmental settings, and the multiple processes required to form diagnostic argillic horizons in North Dakota

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were examined by Richardson (1989) but no comment was made of illuvial properties for drift prairie soils documented in the 1950s. Richardson stated, "if the wetting and drying process can be accelerated or the amount of water passing through the profile increased, large amounts of illuvial clay should be moved in prairie soils" (Richardson, 1989, p. 95).

Soil Taxonomy (Soil Survey Staff, 1999, p. 29) suggests formation of argillic horizons "requires a few thousands of years." Because pedogenesis has occurred since the advent of the Holocene epoch (approximately 10 000 yr), a sufficient period of time has likely elapsed for development of argillic horizons in the calcareous tills of eastern North Dakota. Because illuvial processes were documented for some drift prairie soils in the 1950s, it is plausible that other geomorphic settings exist in eastern North Dakota where illuviation proceeds at higher rates.

We believe we have identified such a setting on the Luverne end moraine in Barnes County, North Dakota. The objectives of this study are to (i) apply soil morphologic, physical, and micromorphological observations and evidence to verify that genetic argillic horizons identified in the field satisfy the diagnostic criteria for argillic horizons stipulated by *Soil Taxonomy* (Soil Survey Staff, 1999), and (ii) demonstrate that these diagnostic argillic horizons formed in well drained landscape positions.

MATERIALS AND METHODS

Setting

The Luverne end moraine is oriented north-south in eastern Barnes County, North Dakota, and extends well into three other counties (Fig. 1). The moraine averages about 3 km in width throughout the county, but is up to 8 km wide in some areas (Kelly and Block, 1967). The Valley City precision farming site is located near the southern end of "a clearly defined axis, locally called the Alta ridge" (Kelly and Block, 1967, p. 37). The average thickness of the oxidized zone in Luverne drift is 6 to 7 m; a maximum of 13 m was reported for the southern part of the end moraine (Kelly and Block, 1967). The oxidized hillslope sediments are probably <9540 +/− 155 BP years old according to a ^{14}C date taken at the 152-cm depth in a seasonal wetland 20 km southeast of the study site (Malo, 1988).

Kelly and Block (1967) also stated that the Luverne drift slopes to the east and has better integrated drainage than the other six drift units mapped in Barnes County.

The precision farming site is located on low rolling hillslopes situated on the western flank of the Alta Ridge (Fig. 1). Local relief is about 12 m on the 16-ha site. The Barnes County soil survey delineates three map units in the precision farming site, but only two are relevant to this discussion. The Barnes (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) and Buse (fine-loamy, mixed, superactive, frigid Typic Calciudoll) loams, 3 to 6% slopes, comprise about 40% of the precision farming site. Loam textures are described throughout the typifying pedons, but small areas of sands and gravels are listed as inclusions (Opdahl et al., 1990). Clay films are not described for the Barnes profile, and its structure is moderate, medium prismatic. The Lanona-Swenoda fine sandy loams, 2 to 6% slopes, also occupy 40% of the site, but include a lithologic discontinuity between the 50- to 100-cm depth, described as a loamy textured 2Bk horizon. The range in characteristics includes a clay loam for the Lanona (coarse-loamy, mixed, superactive, frigid Calcic Hapludoll) substratum and the possibility of a 2Bw for the Swenoda (coarse-loamy, mixed, superactive, frigid Pachic Hapludoll).

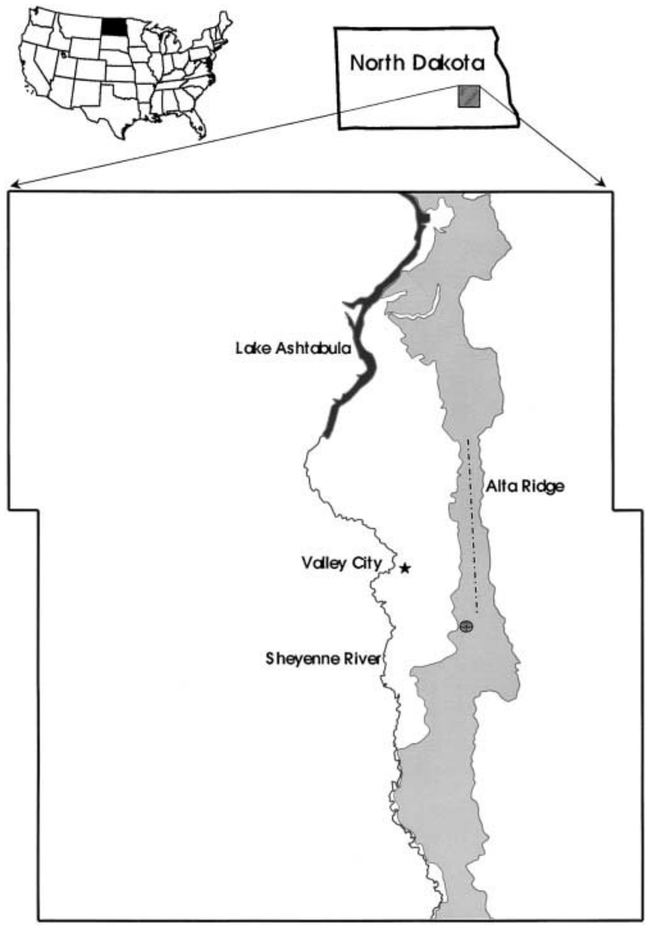

Fig. 1. Location of the Luverne end moraine in Barnes County, North Dakota. Valley City precision farming site is shown by circle.

Field and Laboratory

Surface relief was obtained on the 16-ha site using elevation data collected with a mobile GPS unit with a 33-m grid spacing. Detailed elevations were also obtained at 2-m intervals for intensively studied sites using a surveyors' level. Forty-seven pedons were described from 6 cm diameter cores taken with a hydraulic probe at diverse landscape settings in the grid. Soil color, horizon sequences, hand texture estimates, structure, and reaction to dilute HCl were obtained. Each pedon was closely inspected with a hand lens for pedogenic fabric and presence of clay films. Three pedons representing the range in argillic horizon thickness, depth, and cutan expression across the site were sampled for laboratory and/or micromorphological analyses. Soil particle size was determined by pipette using the methods of Day (1965). Soil organic matter was determined by loss on ignition (Storer, 1984) and results converted to organic C using the 1.72 factor reported by Nelson and Sommers (1982). Images of soil microfabric were taken with an Olympus SZH10 stereo microscope (Olympus America Inc., Melville, NY) at 80 and 140 times magnification at the Bio-imaging and Sensing Facility at North Dakota State University.

RESULTS AND DISCUSSION

Twenty-three of the 47 profiles examined (49%) showed morphological evidence of genetic argillic horizons. Clay films for the majority of the argillic soils were thin and continuous, but six pedons had thick continuous films. Profiles with argillic horizons were found throughout the site (Fig. 2) and are tentatively classified as fine-loamy, mixed, superactive, frigid Calcic Argiudolls. In some of the sandy textured soils, clay fabric bridging sand grains was observed; structural grades in the Bt horizons were generally moderate to strong (Table 1). The thickest clay skins were observed in the deepest argillic horizons, many of which had a sandy clay loam, or sandy clay texture.

Seven of the 47 profiles (15%) had argillic horizons with upper boundaries deeper than 50 cm. Five of these seven pedons had lighter textured A and Bw horizons (fine sandy loams or silt loams) above the argillic horizons, which may reflect truncation and burial of the argillic horizons by younger sediments. The remaining two pedons had argillic horizons in both upper and lower sediments; translocated clay bridged the lithologic discontinuity. Erosional events during the Holocene could have truncated the upper sola leaving the lower more resistant argillic horizons intact as shown by Pedons 32 and 40 (Table 2). Marked changes in total silt, total sand, and sand fractions for the 2Bt horizons of Pedons 36 and 40 may be evidence of past erosional events, but can also reflect sedimentologic attributes of water-worked till. Evidence of stone lines was observed in many pedons but not one buried A horizon was found in pedons with the deep argillic horizons, supporting the premise of landscape erosion and deposition earlier in the Holocene.

Clay content increases sharply with depth for all pedons sampled for particle size (Table 2). Pedologists engaged in hand texturing commonly expect a “clay bulge” when they recognize an argillic horizon in the field. This clay increase reflects the 1.2 ratio of total clay in the argillic horizon to that of an overlying eluvial horizon required by *Soil Taxonomy* (Soil Survey Staff, 1999). The clay increase in Pedon 36 illustrates a relative clay bulge of about 11% from the A to the upper Bt, which continues to increase with depth; clay content doubles in the lower Bt relative to the A horizon (Table 2). The clay increase needed for Pedon 40 to meet diagnostic criteria is a little over 3%, but total clay increased 12% in the Bt, and 22% in the 2Bt; this profile increased in clay sharply with depth (Table 2). Clay films were described to just below 100 cm depth for Pedon 40 in the field, and a reduction in clay was noted from the 101- to 117-cm depth; indicating a distinct clay bulge for this pedon as well (Table 1).

Depth trends of fine clay to total clay ratios for Pedons 32, 36, and 40 illustrate additional evidence that illuvial clay is well expressed for these B horizons (Fig. 3). *Soil Taxonomy* states that in argillic horizons, the ratio of fine clay to total clay “is typically, but not always, highest in the argillic horizons with 2:1 phyllosilicates” (Soil Survey Staff, 1999, p. 31). These argillic horizons formed in stratified drift during Holocene time yet show higher fine clay to total clay ratios than Mogen et al. (1959) reported for the Williams soil series, which formed in older till. The fine clay/total clay ratios also indicate that argillic development shows maximum expression at depths of about 40 cm for Pedons 36 and 40, but nearly twice that for Pedon 32 (Fig. 3). The clay distribution of Pedon 32 could result from an extended period of stable

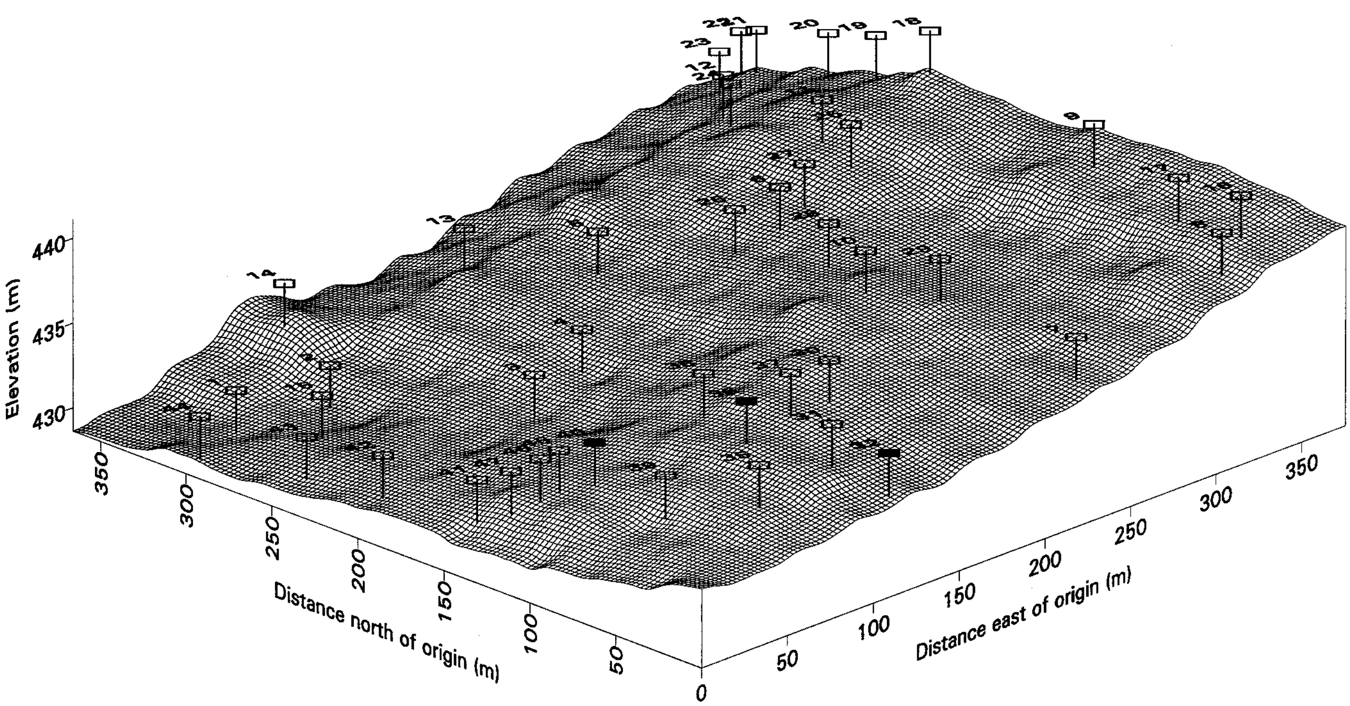

Fig. 2. Landscape and pedon description sites at the Valley City precision farming site: Barnes County, North Dakota. Soil profiles with laboratory or micromorphologic analyses are shown by filled diamonds (32, 36, and 40).

pedogenesis in the early Holocene, which may be plausible based on local paleoecological research. Paleoclimatic reconstructions based on diatom assemblages from sediment cores at Moon Lake (19 km west of the study site) document a transition from spruce forest to deciduous parkland to prairie by 7300 BP (Laird et al., 1996). The fact that seven of the 47 profiles examined had deep argillic horizons (upper Bt boundary >50 cm) may support the concept that the deeper argillic soils formed under forested vegetation sometime before 7300 BP. However, a vegetation reconstruction based on pollen records from a seasonal wetland 20 km southeast of the precision farming site presents conflicting data. Malo (1988, p. 149) stated that a stable interval ended by 4000 BP, when upland vegetation "was dominated by a deciduous forest assemblage composed of elm, maple, oak, and birch." The deeper argillic horizons may have formed during this more recent stable interval.

In some cases the deeper argillic horizons had considerably higher clay contents, possibly indicating longer periods of soil development. Kelly and Block (1967) noted that the Luverne drift slopes to the east, and has better integrated drainage than the other six drift units mapped in Barnes County. Their observations support the premise of longer periods of soil development. Inspection of USGS 7.5 Min. topographic quadrangles shows the eastern slope of the Luverne end moraine is considerably dissected and most streams have extended their headwaters well into the moraine over relatively broad areas. The increase in depth to the water table, which occurs as landscapes mature, has been shown by Ruhe et al. (1967) to foster thicker, more well-expressed argillic horizons in midwestern tills.

To meet diagnostic horizon criteria, argillic horizons must be at least 7.5 cm thick (Soil Survey Staff, 1999). The mean thickness of Bt horizons at the precision farming site was about 28 cm; only two pedons had Bt horizons <10 cm thick.

The pedons with argillic horizons have formed in well-drained landscape positions; surplus water was not necessary for clay translocation in these settings. Detailed elevation data show that Pedon 36 did not form in a position that receives excess water (Fig. 4). The detailed relief transects taken near Pedon 40 are also indicative of a well-drained landscape setting (Fig. 4).

Transitions from cambic (Bw) to argillic horizons (Bt) in this landscape are accompanied by a significant change in pedogenic fabric. Loosely aggregated sands, which characterize the Bw horizon, become increasingly bound within an illuvial matrix with depth (Fig. 5 and 6). Many Bt horizons observed in the field with a hand lens had bleached sand grains randomly distributed on the faces of prisms. Microscopic images frequently showed that pores were coated with illuvial clay, and often, pore openings exhibited a knife edge sharpness to their smoothly flowing lines (Fig. 6). *Soil Taxonomy* (Soil Survey Staff, 1999) states that if peds are present, oriented clay must cover both vertical and horizontal surfaces. Some of the pores are completely coated with illuvial clay (Fig. 7 and 8). Microfabric evident in some of these illustrations bears a close resemblance to the textural fabric of coatings that FitzPatrick (1993; Fig. 12.7) associates with expanding layer clays. The clays in eastern North Dakota (Redmond and Whiteside, 1967) and regionally are largely smectitic. To recognize argillic horizons in stratified parent materials such as those at the precision farming site, *Soil Taxonomy* (Soil Survey Staff, 1999, p. 33) states "clay illuviation must be prominent

Table 1. Pedon descriptions† for three soils at the precision farming site sampled for laboratory analyses (see Fig. 2 for location; some horizons were subdivided for laboratory analyses).

Horizon	Depth cm	Munsell color (dry)	Redoximorphic features	Texture	Structure	Argillans	Effervescence	Concentrations
			Pedon 32: Fine-loamy, mixed, superactive, frigid Calcic Argiudolls					
A	0–20	10YR 2/1		SL	2FGR		NE	
Bw1	20–38	10YR 3/1		SL	1COPR		NE	
Bt1	38–61	10YR 3/2		SL	2COPR	BRF	NE	
Bt2	61–75	10YR 3/2		SCL	2COPR	70%DCLF	NE	
Bt3	75–100	2.5Y 4/3		SCL	2COPR	90%CCLF	NE	
2Btk	100–112	2.5Y 5/2	c, 1, f and d, 2.5Y 5/1 F3M	L	2COPR	90%CCLF	ST	
2C1	112–122	2.5Y 5/2		SICL	MA		ST	15%, f, CAM & T, VPF
3C2	122–150	2.5Y 5/3	c, 1, f, 10YR 4/6 F3M	FS	SGR		NE	
3C2	150–170			COS	SGR		NE	
			Pedon 36: Fine-loamy, mixed, superactive, frigid Calcic Argiudolls					
A	0–13	10YR 3/1		FSL	1FGR		NE	
Abt	13–23	10YR 3/2		FSL	2COPL	50%DCLF	NE	
Bt1	23–29	10YR 3/2		CL	2COPR	70%CCLF	NE	
Bt2	29–38	10YR 3/2.5		CL	2COPR	70%CCLF	NE	
2Bt	38–47	10YR 3/2		SICL	3COPR	70%CCLF	NE	
2Bk	47–98	2.5Y 5/3		SICL	2COPR		VE	
2Bky	98–117	2.5Y 5/3		SIL	1COPR		ST	22%,1, GYX,VPF
			Pedon 40: Fine-loamy, mixed, superactive, frigid Calcic Argiudolls					
A1	0–8	10YR 2.5/1		FSL	1FGR		NE	
A2	8–16	10YR 2/1		FSL	1FGR		NE	
Bw	16–28	10YR 3/2		FSL	2COPR		NE	
Bt	28–39	10YR 4/2		LCL	3COPR	70%CCLF	NE	
2Bt	39–62	2.5Y 5/3		SICL	3COPR	70%CCLF	NE	
2Btk1	62–89	2.5Y 4/2		SICL	3F & MABK	80%CCLF	ST	2%, f, s, FMM
2Btk2	89–101	2.5Y 5/3	c, f, d, 10YR 4/6, F3M	SICL	3MPR	100%CCLF	ST	15%, f & m, s, CAM, VPF
2C	101–117	2.5Y 5/3	f, f, d, 10YR 4/6, F3M	SICL	MA		ST	22% f, s, CAM, VPF

† All codes follow format of the NSSC Field book for describing and sampling soils, Ver. 1.1 (Schoeneberger et al., 1998).

Table 2. Particle-size distribution by depth, USDA textural class, and carbonate clay for Pedons 32, 36, and 40 (B horizons of Pedons 36 and 40 were subdivided to detect particle-size differences).

Horizon	Sampling depth	Texture†	VCOS 2000–1000 μm	COS 1000–500 μm	MS 500–250 μm	FS 250–100 μm	VFS 100–50 μm	Sand 2000–50 μm	Silt 50–2 μm	Clay <2 μm	Fine-C <0.2 μm	FSi 20–2 μm	CoSi 50–20 μm	CO_3-Clay <2 μm
	cm		mg kg^{-1}											
Pedon 32														
A	0–20	Sl	0.4	3.1	10.0	33.8	23.3	70.5	11.1	18.4	7.6	–	–	0.4
Bw	20–38	Sl	0.4	2.1	7.2	29.4	19.8	58.9	23.2	17.9	8.1	17.3	5.9	0.0
Bt1	38–50	Sl	0.3	2.1	6.9	28.9	21.5	59.8	21.3	18.9	9.0	13.1	8.3	0.0
Bt2	61–75	SCl	0.6	2.2	6.7	28.7	20.3	58.5	21.0	20.5	12.4	14.6	6.4	0.5
Pedon 36														
A	0–13	Sl	1.4	3.3	8.9	30.7	17.9	62.1	20.9	16.9	7.8	11.8	9.2	0.0
ABt	13–23	SCl	1.0	2.2	7.1	26.7	15.5	52.6	25.7	21.7	11.3	14.2	11.5	1.2
Bt1	23–29	Cl	0.9	1.1	4.9	20.6	11.9	39.3	32.7	28.0	17.2	23.9	8.7	0.0
Bt2	30–36	Cl	0.6	1.0	3.2	11.8	8.2	24.8	43.8	31.3	22.8	31.9	11.9	0.2
2Bt	40–47	SiCl	0.7	0.8	2.5	8.4	7.2	19.5	46.5	34.0	22.6	37.7	8.8	0.0
2Bk1	54–63	SiCl	3.8	2.1	2.4	4.8	6.5	19.6	51.5	28.8	13.0	37.9	13.7	5.9
Bk2	70–93	SiCl	2.8	1.9	2.8	5.3	6.3	19.2	50.2	30.6	12.0	39.5	10.8	6.8
2Bky	98–106	Sil	3.5	2.1	3.3	5.6	6.5	21.0	52.5	26.5	11.3	41.1	11.4	3.3
Pedon 40														
A1	4–11	Sl	0.5	1.5	6.5	32.6	19.4	60.5	23.4	16.1	8.5	12.8	10.6	0.2
A2	11–15	Sl	0.6	1.4	6.1	32.3	18.7	59.0	23.9	17.1	9.2	13.2	10.7	0.0
Bw1	16–23	Sl	0.2	0.5	4.6	41.8	19.0	66.2	17.7	16.1	10.9	11.4	6.3	0.2
Bw2	23–28	Sl	0.2	0.6	4.8	46.8	17.2	69.6	15.1	15.3	11.6	11.4	3.7	0.3
Bt1	32–37	Cl	0.8	0.9	3.7	26.2	12.7	44.3	28.5	27.2	17.9	20.7	7.8	0.5
2Bt1	39–45	SiCl	0.1	0.5	1.8	9.4	7.3	19.1	43.5	37.4	21.8	33.8	9.6	0.3

† S, sand; Si, silt; Cl, clay; l, loam.

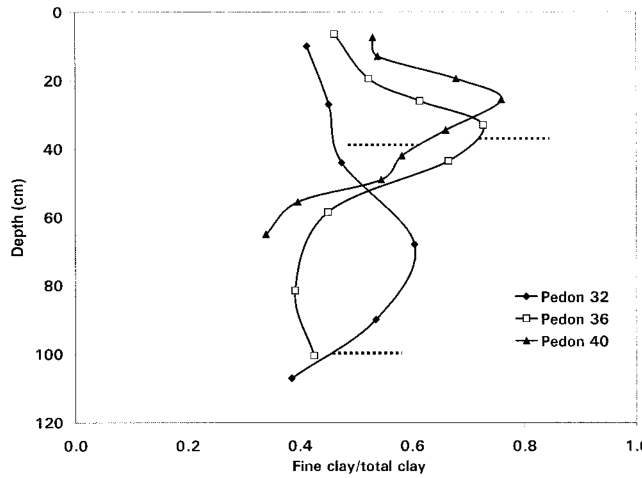

Fig. 3. Ratio of fine clay to total clay in three pedons with genetic argillic horizons; lithologic discontinuities indicated by dashed line for each pedon (see Fig. 2 for location).

enough to obscure fine sand grains on at least 10% of the surfaces of the peds." Images from this study, especially Fig. 8, illustrate that these diagnostic criteria would be easily met.

It appears certain that argillic horizons at the Valley City precision farming site influence porosity and pore-size distribution within the profile. The generation of significant lateral water flow during high rainfall events appears likely. Pionke et al. (1996) point out "it is the nature of these flow domains, and not necessarily the whole soil that exert control" on flow processes. Subsurface solute movement above the argillic horizon could be the reason that N levels were shown to be relatively high in soils with argillic horizons at the precision farming site (Franzen et al., 1998, 2002). The argillic horizons, in essence, present a less permeable layer, which maintains soil nitrate concentrations at higher levels than would be expected following crop removal (D. W. Franzen, unpublished data, 2001). We are currently evaluating a means to quantify the degree of porosity reduction in this landscape by measuring field hydraulic properties with tension infiltrometers and determining soil moisture characteristics in the laboratory.

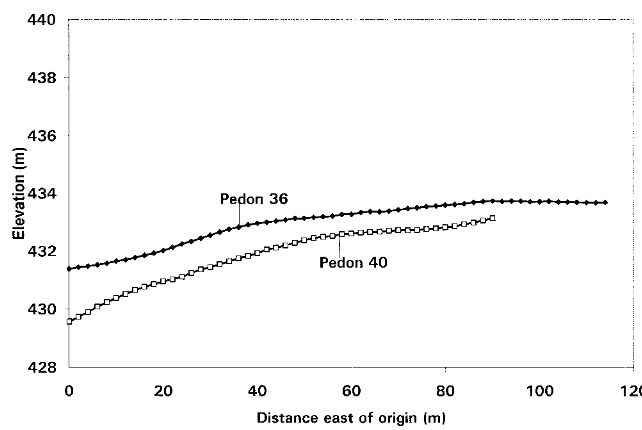

Fig. 4. Well-drained settings typical of argillic horizons at the study site shown by relief on east–west transects near Pedons 36 and 40 (vertical exaggeration ×6).

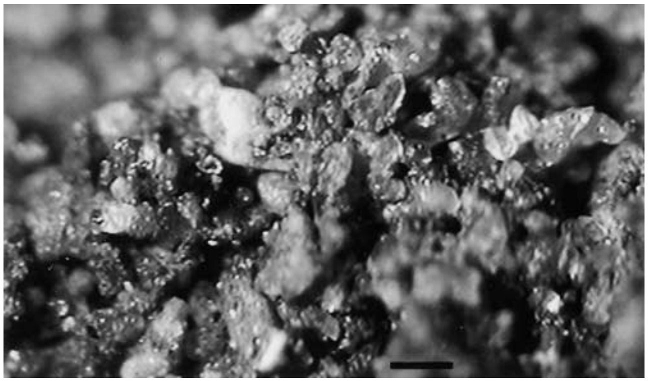

Fig. 5. Fine and very fine sand from the 25- to 28-cm depth in the Bw horizon from Pedon 40 (scale bar = 200 μm).

The sedimentary setting at the precision farming site was described by Holmes et al. (1914) in the initial soil survey of Barnes County. Their work may help explain both variations in the argillic horizons observed in the current study and the potential illuviation of clay. The Carrington loam was the dominant map unit and was described as "free from alkali," hence little chance that Na has accelerated translocation of clay (Holmes et al., 1914, p. 21). A delineation of Carrington silty clay loam was mapped adjacent to the site that allowed a silt loam surface phase. The subsoil was described as being "more clayey and compact," but it lacked stratification and "carried some gravel" (Holmes et al., 1914, p. 17). The compact, clay-rich subsoil may be equivalent to the 2Bt horizons noted in our study, and the lack of stratification suggests that pedogenic rather than sedimentologic factors are responsible for the argillic horizons, such as the 2Bt and 2Btk in Pedon 40 (Table 2). Some of the gravels observed in the early 1900s may have actually been stone lines, such as those observed during fieldwork

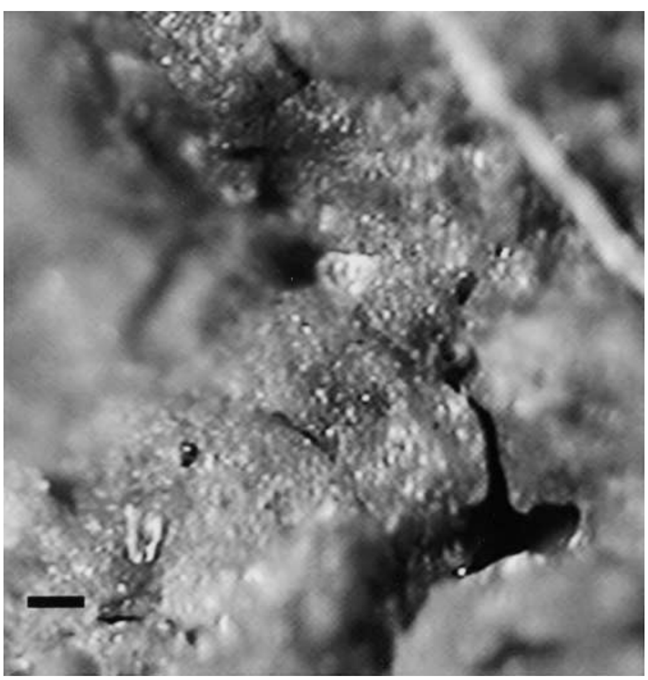

Fig. 6. Bleached sands on continuous clay fabric from the 40- to 43-cm depth in the 2Bt horizon from Pedon 40 (scale bar = 200 μm).

Fig. 7. Continuous thick clay films from the 55- to 58-cm depth (2Bt horizon) in Pedon 40 (scale bar = 200 μm).

for the current study. A fine sandy loam phase of the Carrington series was said to "occur in small patches on the west slope of the Alta Ridge" (Holmes et al., 1914, p. 20), and our observations confirm fine sandy loam surface textures interspersed with loams and silt loams. The efficiency of leaching in this environment, and the possibility of preferential lateral flow are suggested by the early pedologists' reference to "porous sands," "leachy subsoils," and the "warmer, quicker nature" of the Carrington loam (Holmes et al., 1914, p. 21).

Soil map units at the precision farming site were largely fine-loamy till, but numerous profiles with sandy and coarse-loamy textural families were distributed within the till and observed in this study, usually components of the Lanona-Swenoda map unit. This unit, with its 2Bk (or 2Bw horizons), is commonly mapped on the Luverne end moraine and could include significant inclusions of the deeper argillic horizons recognized in this study. These mixed sediments may simply facilitate leaching and the translocation of clay, by virtue of their higher permeability. The development of argillic horizons is a natural progression given these sediments and sets the landscape apart from the drift prairie tills. The Cretaceous marine shales, common components of the

Fig. 8. Fine sand grains enveloped in continuous thick clay films from the 65- to 69-cm depth (2Btk1 horizon) in Pedon 40 (scale bar = 200 μm).

Luverne drift, could also foster development of genetic argillic horizons. If morphologic patterns observed at this site are recognized at additional sites across the Luverne end moraine, then reevaluating soil map unit composition on the moraines of eastern North Dakota may be warranted. Field and laboratory evidence show a significant distribution of soils with argillic horizons at this site. There is no shortage of clay in these landscapes, and evidently, time has not limited the development of these important subsurface horizons.

CONCLUSIONS

1. Nearly half of the 47 profiles examined at the Valley City precision farming site had genetic argillic horizons that meet diagnostic criteria.
2. Laboratory data for total clay content of three representative pedons (32, 36, and 40) show distinct increases in both total clay and in the fine clay to total clay ratios in the illuvial horizons relative to surface horizons.
3. Landscape surfaces where the argillic horizons have formed are in well-drained positions as shown by surface relief maps and line transects.
4. Micromorphologic evidence strongly suggests that the taxonomic criteria for clay films and illuvial features are satisfied for the "argiudolls" in this landscape.
5. Evidence presented on depth distribution of genetic argillic horizons and citations to local paleoclimatic/ecological reconstructions suggest that argillic horizons have formed, not only once during the Holocene, at this eastern North Dakota site, but very probably twice.
6. Stratified sediments common to moraine landscapes may predispose soil parent materials to illuviation.

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REFERENCES

Aandahl, A.R. 1982. Soils of the Great Plains: Land use, crops, and grasses. University of Nebraska Press, Lincoln.

Clayton, L., S.R. Moran, and J.P. Bluemle. 1980. Explanatory text to accompany the geologic map of North Dakota. Rep. Invest. No. 69. ND Geol. Survey, Bismarck.

Day, P.R. 1965. Particle fractionation and particle size analysis. p. 545–567. *In* C.A. Black et al. (ed.) Methods of soil analysis. Part 1. 1st ed. Agron. Monogr. 9. ASA, Madison, WI.

FitzPatrick, E.A. 1993. Soil microscopy and micromorphology. John Wiley and Sons, Chichester, England.

Franzen, D.W., L.J. Cihacek, V.L. Hoffman, and L.J. Swenson. 1998. Topography-based sampling compared to grid sampling in the Northern Great Plains. J. Prod. Agric. 11:364–370.

Franzen, D.W., D.G. Hopkins, M.D. Sweeney, M.K. Ulmer, and A.D. Halvorson. 2002. Evaluation of soil survey scale for zone development of site-specific nitrogen management. Agron. J. 94:381–389.

Holmes, L.C., J.E. Dunn, H.A. Hard, A.C. Anderson, W. Rommel, and A.C. Boucher. 1914. Soil Survey of Barnes County, North Dakota. U.S. Gov. Print. Office, Washington, DC.

Kelly, T.E., and D.A. Block. 1967. Geology and groundwater resources, Barnes County, North Dakota: Part 1-geology. North Dakota Geol. Survey, Bismarck.

Laird, K.R., S.C. Fritz, E.C. Grimm, and P.G. Mueller. 1996. Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains. Limnol. Oceanogr. 41:890–902.

Malo, D.D. 1988. The Holocene sedimentation environment in a seasonal wetland in eastern North Dakota. Soil Sur. Hor. 29:141–152.

McClelland, J.E., C.A. Mogen, W.M. Johnson, F.W. Schroer, and J.S. Allen. 1959. Chernozems and associated soils of eastern North Dakota: some properties and topographic relationships. Soil Sci. Soc. Am. Proc. 23:51–56.

McDaniel, P.A., and A.L Falen. 1994. Temporal and spatial patterns of episaturation in a fragixeralf landscape. Soil Sci. Soc. Am. J. 58:1451–1457.

Mogen, C.A., J.E. McClelland, J.S. Allen, and F.W. Schroer. 1959. Chestnut, chernozem, and associated soils of western North Dakota. Soil Sci. Soc. Am. Proc. 23:56–60.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–579. *In* A. L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.

Opdahl, D.D., W.J. Terry, and N.D. Prochnow. 1990. Soil Survey of Barnes County, North Dakota. U. S. Gov. Print. Office, Washington, DC.

Perillo, C.A., S.C. Gupta, E.A. Nater, and J.F. Montcrief. 1999. Prevalence and initiation of preferential flow paths in a sandy loam with argillic horizon. Geoderma 89:307–331.

Pionke, H.B., R.R. Schnabel, and J.A. Schaffer. 1996. The role of the soil scientist in watershed research. p. 67–73. *In* R.J. Wagenet and J. Bouma (ed.) The role of soil science in interdisciplinary research. SSSA Spec. Pub. 45. SSSA, Madison, WI.

Redmond, C.E., and H.W. Omodt. 1967. Some till-derived Chernozem soils in eastern North Dakota: 1. Morphology, genesis, and classification. Soil Sci. Soc. Am. Proc. 31:89–99.

Redmond, C.E., and E.P. Whiteside. 1967. Some till-derived chernozem soils in eastern North Dakota: II. Mineralogy, micromorphology, and development. Soil Sci. Soc. Am. Proc. 31:100–107.

Richardson, J.L. 1989. Argillic horizon in calcareous North Dakota till: Relationships and conditions of formation. Soil Sur. Hor. 30:92–98.

Ruhe, R.V., R.B. Daniels, and J.G. Cady. 1967. Landscape evolution and soil formation in southwestern Iowa. Tech. Bull 1349. Soil Conservation. Service, USDA. Washington, DC.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 1998. Field book for describing and sampling soils. NRCS, USDA, National Soil Survey Center, Lincoln, NE.

Shaw, J.N, D.D Bosch, L.T. West, C.C. Truman, and D.E. Radcliffe. 2001. Lateral flow in loamy to sandy Kandiudults of the upper coastal plain of Georgia (USA). Geoderma 99:1–25.

Smith, G.D. 1986. The Guy Smith interviews: Rationale for concepts in Soil Taxonomy. Tech. Monogr. 11. Soil Management Support Services, Soil Conservation Service, USDA. Washington, DC.

Soil Survey Staff. 1999. Soil Taxonomy: A basis system of soil classification for making and interpreting soil surveys. 2nd ed. Agric. Handb. No. 436, Soil Conservation Service, USDA, U. S. Gov. Print. Office, Washington, DC.

Storer, D.A. 1984. A simple high sample volume ashing procedure for determining soil organic matter. Commun. Soil Sci. Plant Anal. 15:759–772.