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Spodosol–Alfisol intergrades: bisequal soils in NE Michigan, USA

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Abstract

Twenty three well-drained Boralfs, most of which exhibit bisequal soil morphology, were described and sampled in NE lower Michigan, where they occur on landscapes shaped by Greatlakean ice ca 12 ka. Bisequal soils in Michigan are intergrades between Orthods and Udalfs, with a spodic-like upper sequum (A–E–Bs) overlying a sequence of E′–Bt–C horizons. Thus, they frequently occupy a pedogenic "ecotone". The purpose of the study was to characterize these soils, which have been little-studied, and to determine if parent material homogeneity and texture are correlated with various aspects of their morphology.

The soils have formed in coarse-loamy and fine-loamy materials, often with a distinct lithologic discontinuity between the two sequa. The lower material, interpreted as glacial till, is strongly calcareous and slightly coarser-textured, with considerably more dolomitic gravel than the upper material. Water flowing through the material above may "hang" at the discontinuity and deposit illuvial clay; Bt horizons are found at or immediately below the discontinuity. Statistical correlations indicate that bisequal sola and their eluvial horizons are thicker when developed in coarser-textured materials. Finer-textured pedons contain more extractable Fe and Al in the spodic sequum, but have thinner eluvial zones which have not been as completely stripped of metal cations. In the finest-textured pedons, the E′ horizon may be completely lacking.

Keywords: podzolization; eluviation; pedogenesis; factor analysis; discontinuities

1. Introduction

Bisequal soils contain two eluvial–illuvial sequa, typically an E–Bs sequum overlying an E′–Bt sequum (Anonymous, 1987), although by definition the lower sequum may contain a fragipan (i.e., Ex–Bx or Ex–Btx) (Yassoglou and Whiteside, 1960). These

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soils have characteristics of Spodosols in their upper solum, and an Alfisol- or Ultisol-like sequum below, and thus are often found at the interfaces between areas of Spodosols and areas of Alfisols (Stobbe, 1952; Allen and Whiteside, 1954; Beaver, 1966) or Ultisols (Markewich and Pavich, 1991). As a result, they are positioned in an "ecotonal" area, such that their study may shed light on podzolization and the lessivage processes, both of which are active in these soils. In bisequal soils, therefore, lessivage and podzolization may be studied simultaneously.

Most bisequal soils in the Great Lakes area, USA, and in southern Ontario classify as Boralfs in Soil Taxonomy (Soil Survey Staff, 1975). If they contain a glossic (E/Bt) horizon, they key out as Glossic Eutroboralfs or Mollic Paleoboralfs; otherwise these soils are usually Typic Eutroboralfs. If the upper Bs or Bh horizon is strongly-developed and therefore classifies as a spodic horizon, they are Alfic Haplorthods. Using old terminology, they would be intergrades between Podzols and Brown Podzolic soils. Most are in the frigid soil temperature regime (MAST < 8°C with marked seasonality) (Soil Survey Staff, 1994).

Soils with bisequal profiles were initially documented early in the 20th century by Veatch and Millar (1934). Most studies of bisequal soils, however, date from the mid-20th century, with little work in the past 30 years. Characterization studies of a few, select bisequal profiles and their morphological associates were accomplished in the 1940's and 1950's. Often, the purpose of these studies was to place these pedologic anomalies within a developmental and/or morpho-sequence of soils, with more zonal soils as the end members: those dominated by lessivage and clay translocation (the Gray-Brown Podzolic or Red-Yellow Podzolic soils) and those dominated by podzolization (the Podzols) (e.g., Cline, 1949; Frei and Cline, 1949; Gardner and Whiteside, 1952; Stobbe, 1952; Cline, 1953; Allen and Whiteside, 1954; Holt and McMiller, 1956; Markewich and Pavich, 1991).

The purpose of this study was (1) to provide data on bisequal soils, given that a wide range of pedons (23 in all) were examined across a range of parent materials, and thus to (2) determine the effects of parent material, its texture, relative homogeneity (i.e., presence or absence of lithologic discontinuities) and carbonate content, and landform slope, on the morphology of these soils. Soils with this type of profile have not been studied extensively in nearly three decades. By examining the relationships between parent material characteristics and soil morphology, insight into the genesis of these profiles can be ascertained, *sensu* Schaetzl (1992). In soil studies where a large sample size exists, such as this study and a few others (e.g., Litaor et al., 1989; Delgado et al., 1994; Alexander, 1995), statistical analyses of relationships among various morphologic attributes can be performed. The statistical relationships discerned for the 23 pedons studied here were interpreted in light of pedogenic theory.

2. Theory of formation

Bisequal soils usually have horizon E–Bs horizon sequences above and E–Bt sequum, although E–Bt above E–Bh horizon sequences have been described for soils in thermic soil temperature regimes (Daniels et al., 1975). In this study, E–Bs–E′–Bt horizon sequences in soils of frigid soil temperature regimes are the focus. These types of profiles have presumably formed by a combination of two suites of pedogenic processes, both of which follow decalcification: (1) podzolization (DeConinck, 1980; Ugolini and Dahlgren, 1987) and (2) lessivage (clay migration) (Fridland, 1958; Smith and Wilding, 1972). The link between the morphology of bisequal profiles and the two sets of processes was first made by Cline (1949) and Frei and Cline (1949) for soils in New York, and later endorsed by Gardner and Whiteside (1952) for soils in Michigan. The pedogenic theory advanced by these early papers involves a two-step process. First, a sandy or loamy parent material is acidified by weak organic and inorganic acids, depleting most bases from the rooting zone (i.e., decalcification; Franzmeier and Whiteside, 1963). The acidified soil, having abundant vertically infiltrating water, undergoes lessivage (clay translocation) and develops an E–Bt sequum. Horizons thicken with time and their boundaries advance downward into fresh parent material. This first set of processes is typical of *sols lessivé*, Alfisols, Ultisols and many other loamy soils in humid climates (e.g., Cremeens and Mokma, 1986).

Next, as the E horizon becomes sandier, clay-impoverished and increasingly acidic (Cline, 1949 suggested pH < 6.0 but 5.0 to 5.5 may be more accurate), podzolization proper (*sensu* DeConinck, 1980; Buurman and Van Reeuwijk, 1984; Barrett and Schaetzl, 1992) begins. Fe and Al cations are presumably chelated by organic acids, rendering them mobile. As these chelate complexes become translocated downward they produce E and Bs horizons *within* what was previously the E horizon of the sequum formed by lessivage. Thus, the E′ horizon below the Bs is essentially the lower portion of a once much thicker E horizon that overlays the Bt.

In Michigan, the loss of clay from the upper horizons may cause a change in vegetation from predominantly mixed forest to a forest type dominated by conifers. This vegetation change is thought to facilitate the podzolization of the relatively clay-impoverished surficial layers, as the litter produced by the conifers is more acidic than is that from broadleaf trees. Thus, the onset of podzolization may be triggered by the increasing sandiness and acidity of the upper profile and/or a change in vegetation.

3. Study area

The study area is located in recently glaciated terrain in northeastern lower Michigan, USA (Fig. 1), a region that Bailey (1995) placed wholly within the Laurentian Mixed Forest ecoregion. Much of the area today is either in forest or farmed.

The area has been glaciated repeatedly during the Pleistocene, with the most recent activity being the rapid readvance of the Greatlakean ice ca. 11.8–12 ka (Mickelson et al., 1983; Eschman, 1985; Larson et al., 1994). This advance moved from NW to SE across most of the study area, carving out several drumlin fields and other ground moraine landscapes with a distinct NW–SE trend. The sediments deposited by this advance usually have 20–30% carbonates in the fine-earth fraction, due to the dominance of dolomitic and limestone bedrock underlying both the study area and areas immediately to the north. These sediments also often have a sandy loam texture and abundant coarse fragments.

Many (21) of the 23 sampled pedons were located within drumlin fields formed by the Greatlakean ice. Four lines of evidence suggest that subglacial or supraglacial

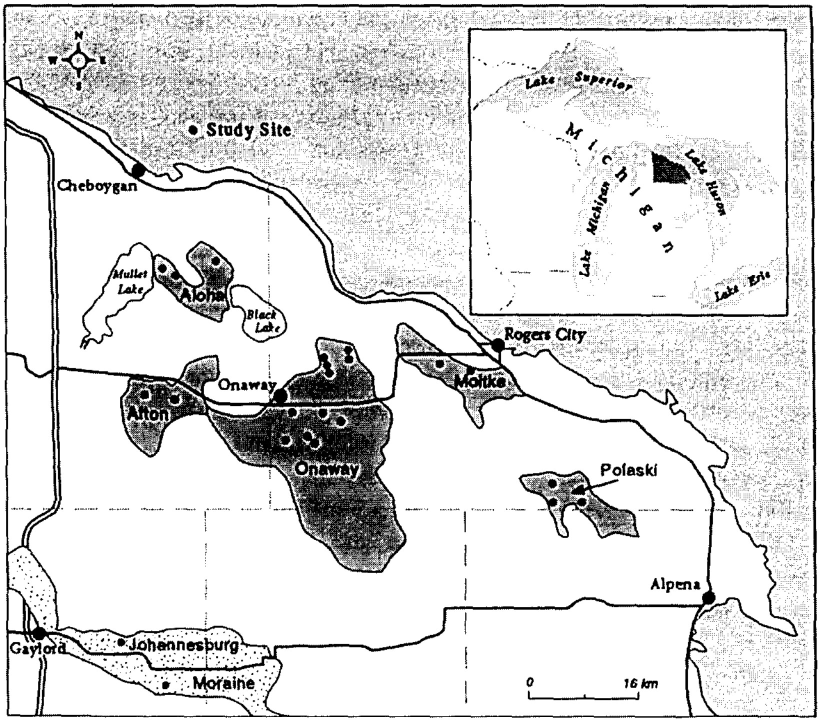

Fig. 1. Study area map showing major cultural features, the Johannesburg moraine and five prominent drumlin fields, as defined by Burgis (1977).

meltwater, in addition to traditional englacial transport and deposition, may have been important in the genesis of these landforms and soils: (1) the ubiquitous presence of sandy zones bedded within the drumlins, (2) many clasts are subrounded or rounded, (3) most of the clasts are of local origin, and (4) eskers are common near and immediately down-ice of some of the drumlin fields (Dardis and McCabe, 1983; Shaw et al., 1989). Eschman (1985) noted that many of the Greatlakean drumlins in Michigan are erosional features, with only a thin veneer of till. In order to insure representativeness, sites were sampled from all five of the major drumlin fields: Onaway, Aloha, Polaski, Moltke and Afton (Fig. 1). In order to obtain a variety of pedons from different parent materials, two sites are located in the Johannesburg moraine, associated with an earlier advance of the Wisconsin ice sheet (ca. 13 ka; Blewett, 1991), this time, however, in a NE-SW direction (Fig. 1).

Soils in this area are predominantly Alfisols, Spodosols, Entisols and Histosols, in the udic or aquic soil moisture regime and the frigid soil temperature regime (Soil Survey Division Staff, 1993; Isard and Schaetzl, 1995). Mean annual precipitation ranges from 700 to 800 mm, with a pronounced summer maximum. Snowfall exceeds 350 cm in the western part of the study area and is slightly less in the east (Eichenlaub et al., 1990). Frozen soil is not uncommon in the winter, especially in the eastern part of the study area where snowpacks are thinner (Isard and Schaetzl, 1995). Because of the cool temperatures and abundant precipitation, soils are leached of carbonates to depths of a few dm, depending upon site conditions (slope, texture, etc.). Translocation of clay, fine silt, sesquioxides, and organic matter are typical pedogenic processes that occur after decalcification. Thus, most Alfisols developed on calcareous parent materials here and throughout the midwest USA have the upper limit of carbonates as the lower limit of the solum.

4. Materials and methods

Twenty-three pedons which met the following criteria, determined from bucket auger reconnaissance, were excavated by backhoe to at least 2 m: (1) bisequal morphology with an E′ (or E′/Bt) horizon below a spodic or spodic-like horizon and above a Bt horizon, (2) well-drained soil drainage class, (3) minimal evidence of erosion, and (4) textures within the coarse-loamy or fine-loamy particle size classes (Soil Survey Division Staff, 1993). Effort was made to find bisequal pedons in a wide variety of parent material textures; the coarsest- and the finest-textured pedons observed with the auger that had bisequal morphology were included in the sample. A variety of slope inclinations were sought, and in the end, the slopes at the sampled pedons ranged from 0 to 27%. Most sites were in abandoned fields; seven sites had never been ploughed.

Description and sampling of genetic horizons followed techniques recommended by the Soil Survey Division Staff (1993). Core samples (9.7 cm dia) were taken in duplicate from all horizons and analyzed for oven-dry bulk density on a coarse fragment-free basis. All horizon-based samples were air-dried and passed through 8, 4, and finally a 2 mm sieve, taking special care not to crush coarse fragments. A wooden pestle was used in the grinding process; some samples that contained many peds cemented by carbonates were wet-sieved to break up the peds while leaving small gravel intact. Particle-size analysis was performed by pipette (Sheldrick, 1984), with double the number of sand-size fractionations than is routinely done (sand splits at 2.0, 1.4, 1.0, 0.71, 0.5, 0.355, 0.25, 0.18, 0.106, and 0.053 mm). Fine clay (< 0.2 μm) fractionation was determined by centrifugation. Organic carbon (OC) was estimated by a modified Walkley–Black procedure (Nelson and Sommers, 1982). Approximate $CaCO_3$ content was determined by weight loss upon exposure to concentrated HCl (Sheldrick, 1984). pH was determined with a glass electrode in 1 : 1 soil : water and soil : KCl mixtures (Soil Survey Laboratory Staff, 1992). Extractions for Fe and Al content were performed using acid ammonium oxalate (Fe_o and Al_o), sodium pyrophosphate (Fe_p and Al_p), and sodium citrate–dithionite (Fe_d and Al_d) (Soil Survey Laboratory Staff, 1992). Extracts were analyzed by Directly Coupled Plasma spectroscopy.

The mineral suite in the clay fraction of selected Bs, E′ and 2C horizons was determined by X-ray diffraction, on a Philips XRG 3100 diffraction unit. Four slide treatments included Mg-saturation followed by glycolation, and K-saturation followed by heating to 550°C. The samples, on glass slides, were scanned with Cu-K_α radiation (35 kV, 20 mA) from 2.375° to 32.375° 2-theta. Results were reported as relative (high, medium, low, absent) amounts of kaolinite, micas, chlorite, vermiculite, smectite and a chlorite–vermiculite intergrade mineral.

Horizon-based soil data (e.g., Fe_o content of E′ horizons and profile-weighted values) were calculated using the formula: $(\Sigma(P \cdot T))/(\Sigma T)$ where P is the value of a given soil property for the horizon in question, and T is horizon thickness. In pedons that had lithologic discontinuities, as determined in the field and verified by lab data, only those horizons formed in what was determined to be the uppermost parent material were included in the profile-weighted values. For most textural data, clay-free values were calculated and used, to minimize the influence of clay translocation. A correlation matrix was assembled for the soil data, using Spearman's rank-order test, which is a non-parametric alternative to the traditional Pearson Product–Moment correlation coefficient (Kraft and Van Eeden, 1968). Although Pearson Product–Moment correlation analysis does not assume dependency or independency among variables, I have grouped the correlation coefficients into "dependent" and "independent" categories, essentially similar to performing rank-order regression and reporting only the r values. "Independent" variables used in the statistical analysis represent soil state factors such as parent material and relief. They are: percent slope; and percent carbonates in the 2C horizon; and profile-weighted amounts of (i) coarse fragments, (ii) 8–2 mm fraction, (iii) clay-free sand, (iv) clay-free silt, (v) clay, (vi) clay-free very coarse [1.4–2.0 mm] sand, (vii) clay-free coarse [500–700 μm] sand, and (vii) clay-free medium [250–355 μm] sand. "Dependent" variables reflect soil properties acquired due to pedogenesis, such as: thickness of the (i) solum, and (ii) E′ horizon, percent clay and fine clay in the E′ and Bt (or 2Bt where appropriate) horizons; ratios of fine to total clay in the E′ and Bt horizons; ratio of clay in the E′ vs. Bt horizons; and amounts (g kg^{-1}) of Fe_o, Al_o, Fe_p, Al_p, Fe_d, and Al_d in the E′ and strongest-developed Bs horizon, and ratios thereof. Only correlations that were significant at $\alpha = 0.01$ (99% confidence interval) will be discussed below. Where appropriate, multiple regression was applied to some soil data, as a way to discern more clearly relationships between solum attributes and parent material. Finally, a factor analysis with varimax rotation, constrained to three factors, was performed on the soils data. This analysis allows for relationships and key aspects of the data set to be identified, and for natural groupings of variables to be sorted out.

5. Results and discussion

5.1. *Typifying pedons and characteristic bisequal morphologies*

Three pedons, of the 23 studied, will be discussed below as examples of the range of textural and morphological characteristics observable in bisequal soils across the study

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Notes to Table 1:

[a] Structure grade: 1 = weak, 2 = moderate, 3 = strong. Structure class: f = fine, m = medium, c = coarse, vc = very coarse. Structure shape: gr = granular, sab = subangular blocky, ab = angular blocky, pl = platy, m = massive.

[b] Consistence: fr = friable, fi = firm, vfi = very firm.

[c] Texture classes: sl = sandy loam, fsl = fine sandy loam, ls = loamy sand, gsl = gravelly sandy loam, cosl = cobbly sandy loam, coscl = cobbly sandy clay loam, vcoscl = very cobbly sandy clay loam, vcofsl = very cobbly fine sandy loam, vcosl = very cobbly sandy loam, sil = silt loam, l = loam.

[d] Boundary distinctness: a = abrupt, c = clear, g = gradual, d = diffuse. Boundary topography: s = smooth, w = wavy, i = irregular, b = broken.

[e] Coarse fragment definitions follow the Soil Survey Division Staff (1993): gr = gravel, co = cobbles.

Table 1

Morphologic data for three representative bisequal soil pedons

Horizon	Depth (cm)	Moist Munsell color	Structure [a]	Moist consistence [b]	Texture [c]	Bdy [d]	Coarse frags [e] (volumetric estimate %)	Effervescence with 10% HCl
Pedon 1: Emmet: Mollic Paleboralf								
Ap	0–27	10YR 3/2	1 f sab	fr	sl	a, s	3 gravel 3 cobble	none
Bs1	27–34	10YR 4/6	2 f sab	fr	fsl	c, b	5 gravel 5 cobble	none
Bs2	34–53	7.5YR 4/6	1 f sab	vfr	ls	c, b	5 gravel 6 cobble	none
E	53–65	10YR 5/4	2 f sab	fr	ls	c, b	5 gravel 3 cobble	none
E/Bt (70%E)	65–72	E: 10YR 5/3 B: 5YR 4/4	1 m sab	fr	ls	a, b	8 gravel 3 cobble	none
2Bt	72–87	5YR 4/4	2 m sab	fr	sl	c, i	10 gravel 3 cobble	none
2C	87–132 +	7.5YR 5/4	2 m pl parting to 2 f ab	fi	gsl	–	12 gravel 9 cobble	strong
Pedon 2: Onaway: Mollic Eutroboralf								
A	0–18	10YR 3/1	1 f gr	fr	fsl	c, w	2 gravel	none
Bs	18–35	10YR 5/6	1 f sab	fr	fsl	c, w	2 gravel	none
E	35–43	10YR 4/2	1 m sab	fr	fsl	c, b	10 gravel	none
Bt	43–72	7.5YR 3/4	3 m sab	fi	coscl	c, w	10 gravel 15 cobble	none
2CB	72–99	10YR 4/3	1 c sab	fi	cosl	g, w	5 gravel 20 cobble	strong
2C	99–123 +	10YR 5/3	3 c ab	vfi	cosl	–	10 gravel 20 cobble	strong
Pedon 3: Omena: Typic Eutroboralf								
Oi	0–1	–	–	–	–	–	0	none
A	1–11	10YR 2/2	3 f&m gr	fr	sil	c, w	2 gravel 2 cobble	none
Bs	11–17	10YR 4/6	2 f sab	fr	sil	c, w	2 gravel 2 cobble	none
E	17–23	10YR 4/4	2 f sab	fr	l	c, w	3 gravel 5 cobble	none
2Bt	23–38	5YR 4/4	2 f sab	fr	vcoscl	c, w	5 gravel 25 cobble	none
2C1	38–85	10YR 5/3	1 m sab	fr	vcofsl	d, s	10 gravel 25 cobble	strong
2C2	85–125 +	10YR 6/3	2 m pl parting to 2 m ab	fr–fi	vcosl	–	10 gravel 20 cobble	strong

area (Table 1). Data from all 23 will, however, be discussed in other parts of the paper. Pedon 1 is a taxadjunct within the Emmet soil series, and classifies as a coarse-loamy, mixed Mollic Paleboralf. It is one of the coarser-textured of the 23 bisequal soils examined. Pedon 2 is mapped within the Onaway series (fine-loamy, mixed Glossic Eutroboralfs), but classifies as a Mollic Eutroboralf. It is finer-textured than many of the bisequal soils encountered. Pedon 3 is in a similar landscape to the two listed above, but has a shallower solum and classifies within the Omena series (coarse-loamy, mixed Typic Eutroboralfs).

All three pedons have typical bisequal morphology for this area (Table 1) and others (Beaver, 1966), with A horizons that overlie Bs or Bhs horizons. Interestingly, an E horizon is often absent between the A and the spodic-like Bs horizons, even when the pedon has not been ploughed. The lack of E horizon could be due to the relative youth of these soils, and/or the fact that the soils are not extremely sandy. Sandier, somewhat excessively-drained soils on similar sites in the study area often have thick, albic E horizons in A–E–Bs horizons sequences, probably because these edaphically drier sites (1) allow for deeper leaching due to lower water-holding capacities, (2) do not favor vigorous organic matter production in the forests, (3) favor coniferous trees and mor-like O horizons, and/or (4) lack the high numbers of soil macrofauna that promote deep A horizons and blur incipient E horizons that may be forming. E′ horizons [2] are observable in all three pedons. In five of the 23 sampled pedons, however, only a glossic horizon (E′/Bt, or less commonly Bt/E′) exists above the Bt, and in two of the three shallow-sola, Omena soils the E′ horizon is lacking. Both the 2Bt and 2C horizons are usually formed in a diamicton that is interpreted to be glacial till, often containing numerous cobbles and gravel [3]. The 2C horizon often has a high bulk density, numerous angular and sub-rounded gravel, and strong, coarse, platy structure that is indicative of dense till. Both the tops and the bases of the Bt or 2Bt horizons often exhibit highly wavy, irregular or broken topography. This may be due to the undulating nature of the lithologic discontinuity that often marks the top of the Bt, or to breakthrough or preferential flow, leading to the formation of deep Bt tongues (Luxmoore et al., 1990). Evidence for the degradation of the Bt and clay loss from it, as reported earlier by Frei and Cline (1949), exists in these soils as white coatings on ped faces, enriched in silt and very fine sand, in the upper Bt (Gorbunov, 1961).

When considered as a whole, the 23 pedons studied exhibit a wide range in textures, ranging from sand to clay loam (Fig. 2). Coarse fragment concentrations of up to 25% can be observed in their upper sequa, whereas estimated coarse fragment concentrations are rarely less than 10% and usually 20–30% or more in the till below. Typically, Emmet soils have sandy loam, fine sandy loam or loamy sand textures (for the < 2 mm fraction) in their upper sequa. The upper sequa of Onaway and Omena soils are finer-textured, with sandy loam textures being rare; silt loam, loam, fine sandy loam and loamy sand textures are more typical of these pedons. E′ horizons in 22 of the 23 pedons

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[2] I use the term E′ for the horizon immediately overlying the Bt, even if an E horizon from a spodic sequum does not exist in the pedon, for the sake of consistency of terminology.

[3] The genetic and depositional origins of the upper parent material are unknown.

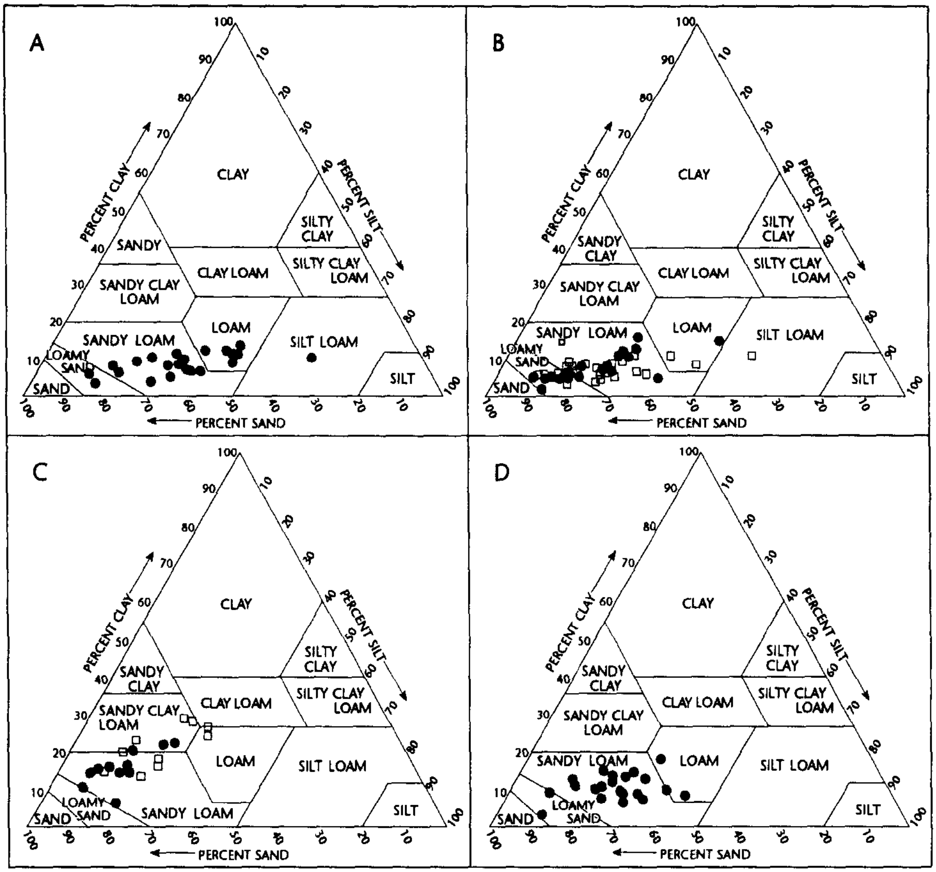


Fig. 2. Ternary diagrams showing the variation in texture for horizon groups of the 23 bisequal pedons studied. (A) A horizons. (B) Bs and Bhs horizons (open squares), and E' horizons (and the E parts of E'/Bt horizons) (filled circles). (C) Bt (open squares) and 2Bt horizons (filled circles). (D) 2C horizons.

studied were either fine sandy loam, loamy fine sand, loamy sand or sand in texture. Bt horizons usually have abundant argillans and strong structure grade. Textures for the fine fraction of Bt horizons are typically sandy loam in Emmet, and sandy loam, sandy clay loam or loam in Omena and Onaway soils. 2Bt horizons are typically slightly sandier than are Bt horizons, which have formed in finer-textured, overlying materials (Fig. 2C). 2C horizons, formed in the lower materials, commonly exhibit sandy loam, loamy sand, or loam textures for the fine fraction (Fig. 2D).

5.2. Parent material considerations

Abundant evidence exists, both from field and laboratory data, to support the hypothesis that these soils are developed in two distinct parent materials, and that the lithologic discontinuity between them is often associated with the Bt horizon — being either within or at the top of the Bt.

Beaver (1966) studied bisequal soils in eastern Wisconsin, in a landscape that was also rapidly overrun by Greatlakean ice. His work, though nearly 30 years old, represents the most recent study of bisequal soils in the midwest USA. Beaver examined a lithosequence of soils on the Greatlakean landscape (though not drumlinized) and concluded that the bisequal Onaway and Emmet profiles had formed in two distinct parent materials, with a stone line often marking the discontinuity. The lower material was assumed to be Greatlakean till, which was often very stony, whereas the genetic origins of upper material were less clear. Finally, Beaver noted that the lithologic discontinuities in bisequal soils often were located within or near the E′ horizon. With minor exceptions, bisequal soils in NE lower Michigan have similar characteristics.

The Bt horizon in these soils is usually developed in a second parent material (i.e., it is a 2Bt horizon). In the field, the top of the Bt (correctly, 2Bt) horizon could often be identified with an auger by a large increase in gravel content, which sometimes drops off again with depth, much like a "stone zone" (Johnson, 1989). This increase is substantiated for almost all pedons; examples are illustrated with depth plots of coarse fragment content and content of the 8–2 mm fraction (Fig. 3A and B). These plots show the large increase in coarser materials below the lithologic discontinuity. The lower material is also sandier, especially in the coarser sand fractions. Fig. 3C shows the summed contents of the medium and coarser sand fractions for all the horizons in four representative pedons, calculated on a clay-free basis to avoid the mathematical impact of clay translocation into and out of some horizons. In most cases, the amount of coarser sands increases with depth. Especially large increases in sand contents occur in the lower parent material. The upper material is often dominated by the finer sand fractions (Fig. 3D) and does occasionally have thin strata of nearly pure fine sand, especially near its contact with the underlying till.

Data on clay-free silt (cfsi), though often showing erratic depth trends, in some pedons provide additional support for the existence of a lithologic discontinuity (Fig. 3D). Cfsi contents are usually larger in the lower parent material, although in some pedons the opposite occurs. In these latter (usually Omena) soils, the loamy "cap" stands in sharp contrast to the sandy, gravelly materials below (Fig. 3D). Thus, the overlying material is best characterized as a fine sand and silt cap with minimal coarse fragments, whereas the lower till has more gravel, coarser sands, and in some pedons, silt.

X-ray diffraction data (not reported here) indicate that major differences in clay mineralogy between the 2C and upper solum horizons do not exist. All samples had high amounts of kaolinite and micas. Rarely was smectite observed. Chlorite and vermiculite were present in intermediate amounts in most horizons. The lack of major mineralogical differences between the upper and lower parent materials may be because the two have similar sedimentologic origins — both may have been deposited from the same Greatlakean ice sheet. Subsequently, weathering and pedogenesis of the clays in the upper horizons have had limited impact, rendering their mineral suites similar to those of the unleached 2C horizons.

The lithologic discontinuity may dramatically affect water flow through these soils, especially since the coarser-textured materials underlie the finer sands above, potentially leading to the formation of hanging water above the discontinuity. In situations where

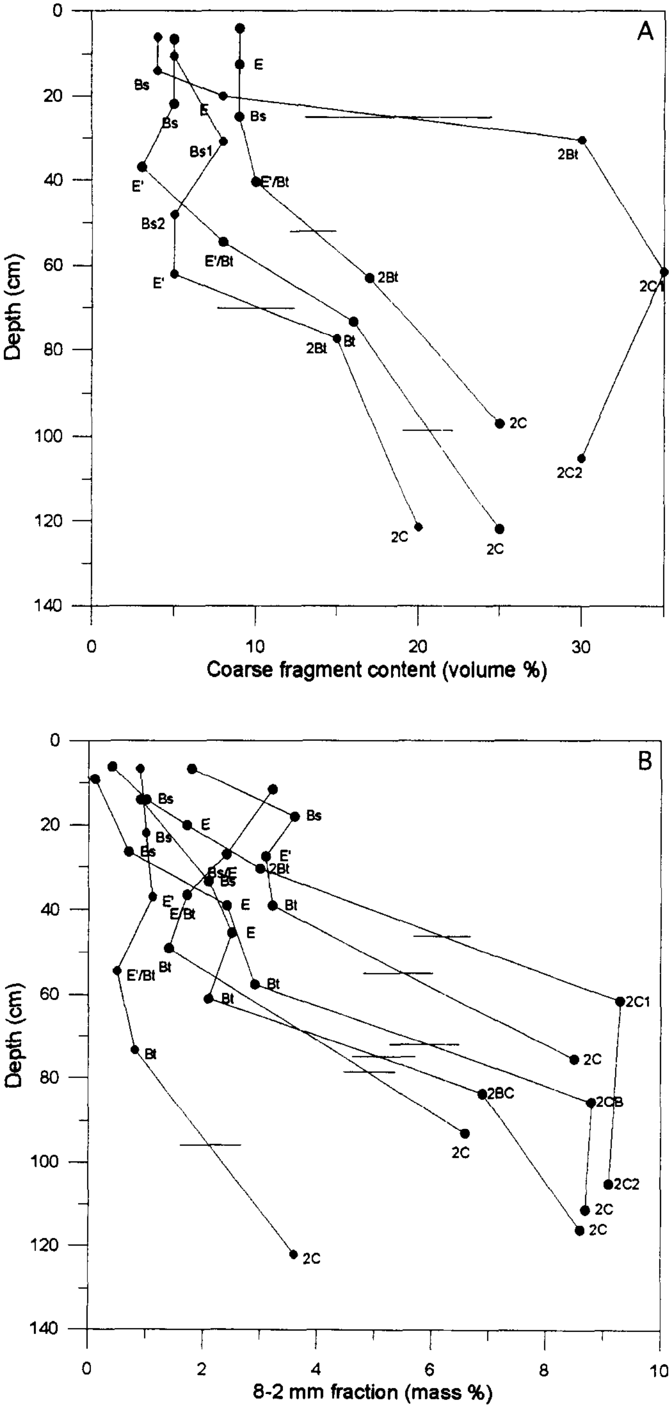


Fig. 3, for caption see p. 35.

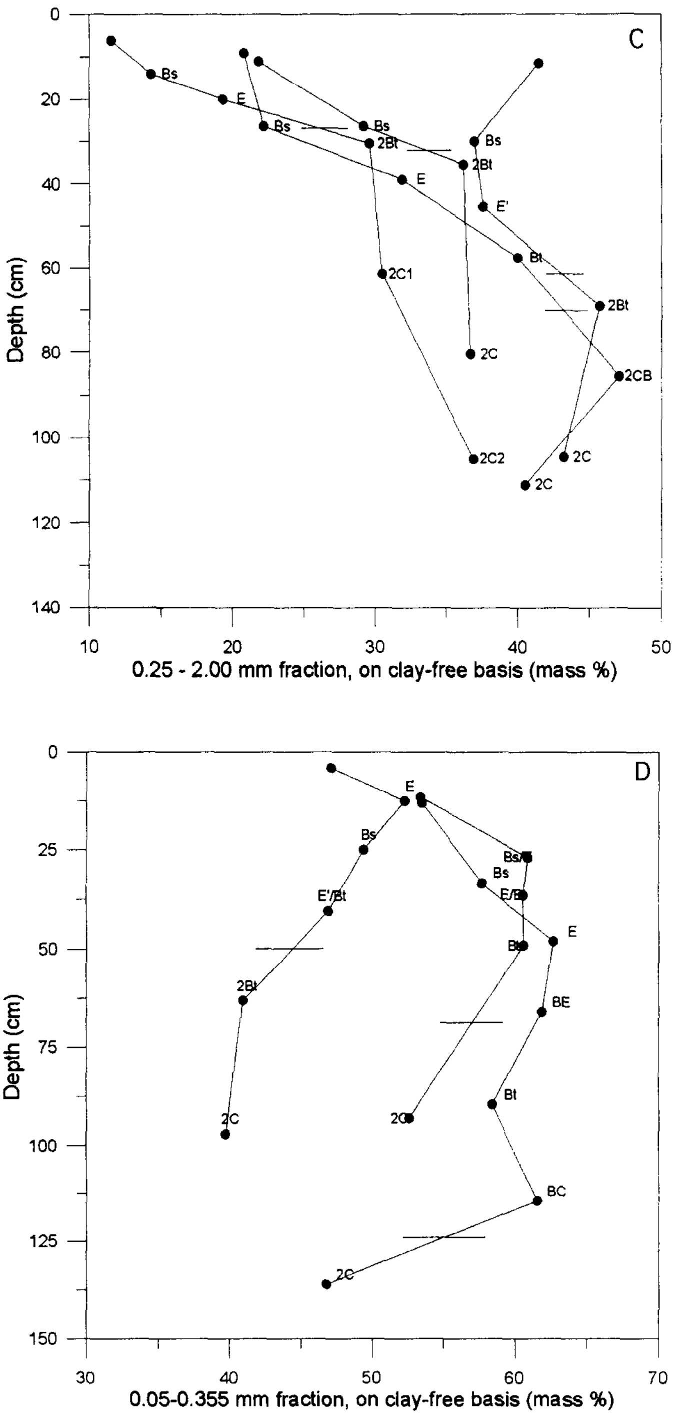


Fig. 3 (continued).

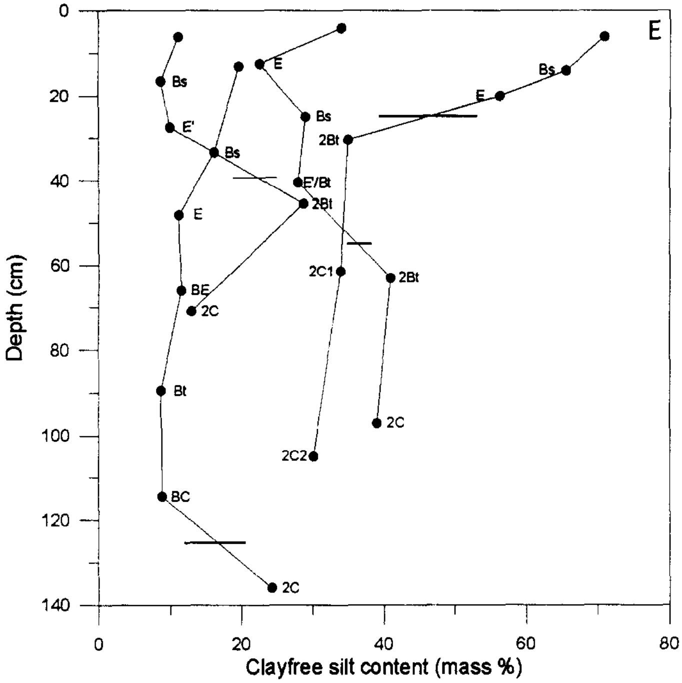
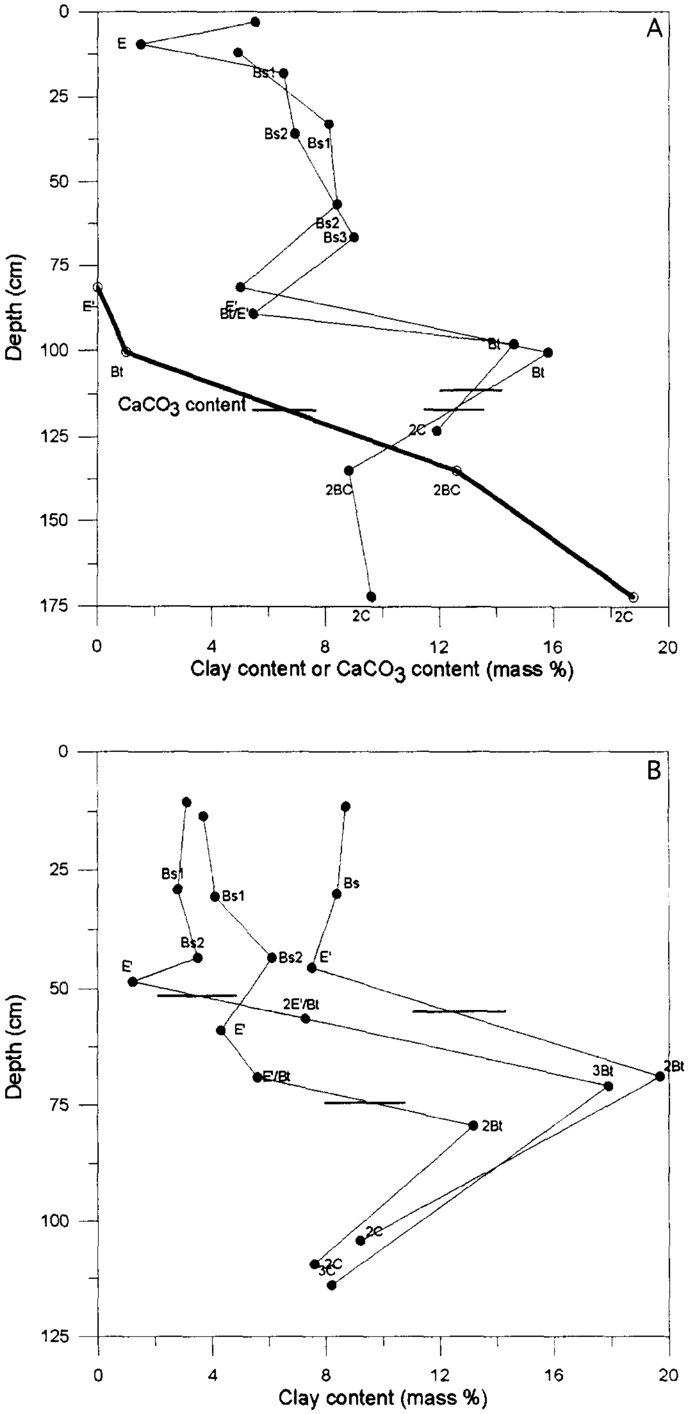


Fig. 3. Depth plots for several Emmet and Onaway pedons. Horizontal lines represent the depths of lithologic discontinuities. (A) Estimated volumetric coarse fragment (> 2 mm) contents for four of the 23 pedons studied. Labels for A and Ap horizons have been omitted to simplify this and the remaining figures. (B) Mass-based contents of the 8–2 mm fraction for six of the 23 pedons studied. (C) Mass-based contents of the 0.25–2.00 mm fraction (coarser sands) for four of the 23 pedons studied, calculated on a clay-free basis. (D) Mass-based contents of the 0.05–0.355 mm fraction (finer sands) for four of the 23 pedons studied, calculated on a clay-free basis. The pedon with the lower values (to the left) is an Onaway pedon whereas the other three are Emmets. (E) Mass-based contents of the silt (2–50 μm) fraction for four of the 23 pedons studied, calculated on a clay-free basis.

gravelly or otherwise coarser-textured materials underlie loamy sediments, illuvial clay has been shown to accumulate, presumably due to marked differences in matric tensions in the two materials (Bartelli and Odell, 1960a,b, Khakural et al., 1993). Wetting fronts may occasionally stop at or near the discontinuity, leading to clay deposition by desiccation. These Bt (Beta) horizons in Illinois exhibit the wavy boundaries typical of those studied here (Bartelli and Odell, 1960a); these morphologies are also indicative of breakthrough or preferential flow. Additionally, the large amount of gravel of predominantly carbonate-lithology in the lower material may further facilitate flocculation of colloids and the formation of a Bt or 2Bt horizon (Fig. 4A).

5.3. Statistical relationships

Of the dependent variables tested, none were significantly associated with percent coarse fragments, percent 8–2 mm fraction, or percent very coarse [1.4–2.0 mm] sand.


A
Depth (cm)
0
25
50
75
100
125
150
175
E
Bs1
Bs2
Bs1
Bs2
Bs3
E'
Bt/E'
E'
Bt
Bt
Bt
Bt
CaCO3 content
2C
2BC
2BC
2C
2C
0
4
8
12
16
20
Clay content or CaCO3 content (mass %)
B
Depth (cm)
0
25
50
75
100
125
Bs1
Bs1
Bs
Bs2
Bs2
E'
E'
E'
2E'/Bt
E'
E'/Bt
3Bt
2Bt
2Bt
2C
2C
3C
0
4
8
12
16
20
Clay content (mass %)

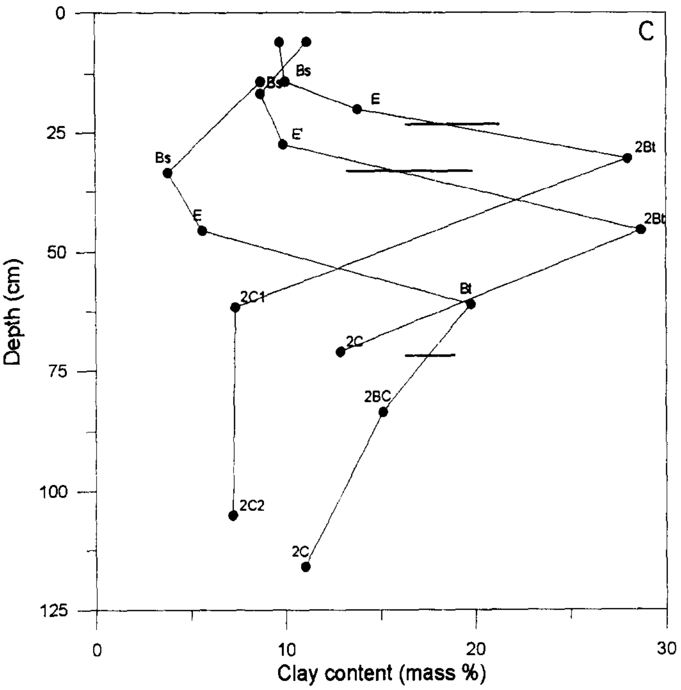


Fig. 4. Depth plots of clay content for several representative pedons. Horizontal lines represent the depths of lithologic discontinuities. (A) Emmet pedons, in which the E′ horizon is significantly more clay-impoverished than are the overlying Bs horizons. $CaCO_3$ content (open circles) for one of the pedons is also shown. (B) Emmet pedons, in which the E′ horizon has only slightly less clay than the overlying Bs horizons. (C) Onaway and Omena pedons, in which the E′ horizon has more clay than the overlying Bs horizons.

This is not surprising, since the range of values for these separates is not large (e.g., Table 2). In other soils, where the amount of gravel is exceedingly high, variation in their content has been shown to dramatically affect morphology (Schaetzl, 1991a,b) and water-holding capacity (Harden, 1988). Similarly, percent slope was not significantly correlated with any of the dependent variables, probably more because slope does not impact the type of sediment that was originally deposited than because it does not impact pedogenic processes. Also, in these sandy soils runoff is minimal, allowing most water to infiltrate and effect translocations, regardless of slope angle.

Cline's (1949) pioneering work on Alfisols and Spodosols in New York showed that the amount of carbonates in the parent material has a dramatic effect on profile morphology, including solum thickness. A statistical analysis of the data from these 23 similar pedons in NE lower Michigan are in general agreement with Cline's findings. Solum depth here also appears to decrease with increasing carbonate content of the parent material, although the data are possibly confounded by lithologic discontinuities, and are not statistically significant, even at $\alpha = 0.05$ (Table 3). A positive correlation between profile-weighted (PW) clay-free silt and carbonate content of the 2C horizons, coupled with equally strong negative correlations between carbonates and the various

Table 2
Chemical and morphological data for three representative bisequal soil pedons

	% of whole soil 8–2 mm	% of < 2 mm fraction									Organic carbon (g kg^{-1})	CaCO$_3$ (%)	pH in H$_2$O	pH in KCl	D$_b$ (g cm^{-3})
		sand 2000–53 μm	silt 53–2 μm	clay < 2 μm	f. clay < 0.2 μm	2–1 mm	1–0.5 mm	0.5–0.25 mm	250–106 μm	106–53 μm					
Pedon 1: Emmet															
Ap	3.0	68.4	28.0	3.7	1.0	2.6	7.4	24.7	24.6	9.3	22.9	nd	5.9	4.8	1.29
Bs1	0.6	66.1	29.8	4.1	0.8	1.2	5.3	23.2	23.1	13.4	8.1	nd	6.0	4.9	1.42
Bs2	3.7	76.9	17.0	6.1	1.1	2.1	10.0	34.7	22.8	7.2	6.0	nd	6.0	4.8	1.30
E	2.9	81.9	13.8	4.3	0.1	1.8	9.5	37.3	26.3	7.0	0.6	nd	6.3	4.6	1.66
E/Bt	2.4	79.8	14.6	5.6	2.3	1.5	7.9	34.0	28.7	7.7	1.0	0.8	6.4	4.8	1.60
2Bt	2.6	66.3	20.5	13.2	6.7	1.2	4.7	24.7	27.5	8.1	2.4	3.1	7.9	6.8	1.54
2C	6.9	69.6	22.8	7.6	1.6	2.7	7.8	27.8	24.7	6.6	0.5	19.9	8.6	7.7	1.78
Pedon 2: Onaway															
A	0.1	57.7	35.6	6.7	5.7	0.2	1.8	17.4	25.7	12.7	17.1	nd	6.7	5.8	1.31
Bs	0.7	61.8	32.3	5.8	1.6	0.5	2.0	18.5	27.3	13.7	3.6	0.3	7.3	6.4	1.49
E	2.4	66.3	27.5	6.3	2.2	1.2	5.1	23.6	26.3	10.1	2.2	1.3	7.4	6.0	1.51
Bt	2.9	56.4	21.8	21.9	8.7	1.6	5.9	23.7	19.6	5.6	5.3	3.7	8.5	7.1	1.41
2CB	8.8	69.3	20.0	10.7	6.7	3.7	8.4	30.0	21.7	5.6	1.5	21.7	8.5	7.5	1.45
2C	8.7	58.4	27.7	13.9	2.9	3.8	7.1	23.9	18.1	5.5	1.1	26.8	8.6	7.6	nd
Pedon 3: Omena															
A	0.4	26.3	64.0	9.7	2.7	0.8	1.9	7.7	8.2	7.7	45.5	nd	6.4	5.6	0.94
Bs	1.0	31.0	59.0	10.0	0.9	0.9	2.1	9.9	11.0	7.2	10.7	nd	6.1	4.6	1.16
E	1.7	37.6	48.6	13.8	2.8	1.1	2.8	12.7	13.6	7.3	6.8	1.0	6.6	5.2	1.33
2Bt	3.0	46.8	25.2	28.0	6.1	1.5	5.1	14.7	20.2	5.2	8.7	4.7	8.1	6.8	1.25
2C1	9.3	61.2	31.4	7.3	1.4	3.3	5.8	19.2	24.9	8.1	1.1	33.2	8.5	7.9	1.63
2C2	9.1	64.9	27.9	7.2	1.1	5.0	7.1	22.0	23.2	7.5	0.8	33.6	8.6	7.9	nd

Table 3

Correlation matrix for various soil properties, as determined by Spearman's rank-order test

	Independent variables					
	CarbsPM	PWclay	PWsilt	PWsand	PWcsand	PWmsand
Solmthk	−0.43	−0.64 **	−0.71 **	0.71 **	0.56 **	0.70 **
ClayBt	0.28	0.58 **	0.75 **	−0.75 **	−0.56 **	−0.56 **
FclayBt	0.01	0.22	0.25	−0.25	−0.08	−0.05
ClayE′	0.41	0.79 **	0.80 **	−0.80 **	−0.45	−0.56 **
FclayE′	0.51	0.70 **	0.63 **	−0.63 **	−0.53 *	−0.46
ClayE′/Bt	0.10	0.44	0.20	−0.20	0.07	−0.05
FclyBt%	−0.23	−0.31	−0.61 **	0.61 **	0.54 **	0.55 **
FclyE′%	0.09	0.22	0.07	−0.07	−0.19	0.04
E′thck	−0.51	−0.51	−0.62 **	0.62 **	0.55 **	0.56 **
$\mathrm{Al_d}$inE′	0.67 **	0.66 **	0.77 **	−0.77 **	−0.61 **	−0.74 **
$\mathrm{Al_o}$inE′	0.50	0.64 **	0.62 **	−0.62 **	−0.39	−0.52
$\mathrm{Al_p}$inE′	0.61 **	0.56 **	0.65 **	−0.65 **	−0.53	−0.67 **
$\mathrm{Fe_d}$inE′	0.58 **	0.79 **	0.85 **	−0.85 **	−0.61 **	−0.71 **
$\mathrm{Fe_o}$inE′	0.51	0.70 **	0.75 **	−0.75 **	−0.55 **	−0.67 **
$\mathrm{Fe_p}$inE′	0.60 **	0.65 **	0.78 **	−0.78 **	−0.64 **	−0.74 **
$\mathrm{Al_d}$inBs	0.18	0.20	0.26	−0.26	−0.36	−0.34
$\mathrm{Al_o}$inBs	0.25	0.23	0.41	−0.41	−0.44	−0.48
$\mathrm{Al_p}$inBs	0.27	0.12	0.33	−0.33	−0.42	−0.41
$\mathrm{Fe_d}$inBs	0.33	0.72 **	0.66 **	−0.66 **	−0.33	−0.53
$\mathrm{Fe_o}$inBs	0.33	0.42	0.72 **	−0.72 **	−0.43	−0.65 **
$\mathrm{Fe_p}$inBs	0.24	0.44	0.53 *	−0.53 *	−0.40	−0.44

** = significant at $\alpha = 0.01$, * = significant at $\alpha = 0.05$.

Variable abbreviations: CarbsPM = carbonates in 2C horizon (%), PWclay = profile-weighted clay (%), PWsilt = profile-weighted clay-free silt (%), PWsand = profile-weighted clay-free sand (%), PWcsand = profile-weighted clay-free coarse [1.4–2.0 mm] sand (%), PWmsand = profile-weighted clay-free coarse [500–700 μm] sand, Solmthk = solum thickness (cm), ClayBt = total clay in Bt or 2Bt horizon (%), Fclay = fine clay in Bt or 2Bt horizon (%), ClayE′ = total clay in E′ horizon (%), FclayE′ = fine clay in Bt or 2Bt horizon (%), ClayE′/Bt = (total clay in E′ horizon/total clay in Bt or 2Bt horizon), FclyBt% = (fine clay in Bt or 2Bt horizon/total clay in same horizon) * 100, FclyE′% = (fine clay in E′ horizon/total clay in same horizon) * 100, E′thck = thickness of E′ horizon (cm), $\mathrm{Al_d}$inE′ = citrate–dithionite extractable Al in E′ horizon, $\mathrm{Al_o}$inE′ = acid ammonium oxalate extractable Al in E′ horizon, $\mathrm{Al_p}$inE′ = sodium pyrophosphate extractable Al in E′ horizon, $\mathrm{Fe_d}$inE′ = citrate–dithionite extractable Fe in E′ horizon, $\mathrm{Fe_o}$inE′ = acid ammonium oxalate extractable Fe in E′ horizon, $\mathrm{Fe_p}$inE′ = sodium pyrophosphate extractable Fe in E′ horizon, $\mathrm{Al_d}$inBs = citrate–dithionite extractable Al in Bs horizon, $\mathrm{Al_o}$inBs = acid ammonium oxalate extractable Al in Bs horizon, $\mathrm{Al_p}$inBs = sodium pyrophosphate extractable Al in Bs horizon, $\mathrm{Fe_d}$inBs = citrate–dithionite extractable Fe in Bs horizon, $\mathrm{Fe_o}$inBs = acid ammonium oxalate extractable Fe in Bs horizon, and $\mathrm{Fe_p}$inBs = sodium pyrophosphate extractable Fe in Bs horizon.

clay-free sand fractions, suggests that much of the carbonate in these soils is found as silt and finer-sized particles.

As was illustrated in Gardner and Whiteside's (1952) lithosequence study, solum thicknesses were greater in the sandier parent materials, possibly because of deeper infiltration of water into the sandier parent materials (Harden, 1988; Schaetzl, 1992). Solum thickness was positively correlated with PW sand content ($r = 0.71$), PW coarse sand ($r = 0.56$) and PW medium sand ($r = 0.70$), and negatively associated with PW silt

($r = -0.71$) and clay ($r = -0.64$) content (Fig. 5, Table 3). Using multiple linear regression with solum thickness as the dependent variable, PW sand and PW medium sand were the two variables with the highest standardized regression coefficients, again suggesting the importance of overall sand content to profile morphology.

Use of E′ horizon thickness in this analysis involves some complicating circumstances. Normally, use of the thickness of an E horizon is a way to include a measure of cumulative translocation or leaching. In bisequal soils, however, it is actually a measure of two processes: lessivage (forming the E horizon initially; stronger lessivage leads to thicker E horizons) and podzolization (destroying the E horizon by forming Bs horizons in its upper part; stronger podzolization leads to thinner E horizons). A second complicating factor involves the lithologic discontinuities, since in many pedons it has ''set'' or ''fixed'' the depth of the base of the E′ horizon. Nonetheless, use of E′ horizon thickness may still provide insight into pedogenesis as long as these considerations are kept in mind, and thus, statistical relationships were determined for E′ horizon thickness (Fig. 5, Table 3). However, in the multiple regression procedure, PW sand had the highest regression coefficient, followed by percent fine clay in the E′ horizon. This sequence suggests that E′ horizons develop best (i.e., are thickest) in the sandiest parent materials, and that the thickest E′ horizons are also the most fine clay-impoverished. Depth plots of clay data suggest that E′ horizons in the sandier pedons (i.e., in the Emmet series, Fig. 4A and B) are not simply remnants of an E due to lessivage, but have indeed continued to lose clay. The E′ horizons consistently have less total clay than do the Bs horizons above, possibly because the latter have accumulated some clay, in addition to chelated compounds, during podzolization. In the Onaway pedons, where E′ horizons are thin and where textures are finer overall, E′ horizons contain more clay than the overlying ''remnants'' of the E — the Bs horizons, again suggesting that E′ horizon development is accelerated in sandier pedons. Finally, E′ horizon thickness is negatively associated with Bt horizon thickness, probably because Bt horizons are thinner in the sandier parent materials, which clearly accentuate E′ horizon development.

Bt horizon development, as indicated by total and fine clay contents and their ratio (FclyBt%, Table 3), is positively associated with PW clay-free silt and PW clay content, and negatively associated with measures of sand content (Table 3). Thicker sola, which tend to be sandier, also tend to have Bt horizons with less clay, in large part because they inherit less clay from the parent material. Interestingly, similar correlations between fine clay content and textural groupings were of a similar direction to those for total clay but were not significant (Table 3). These correlations suggest that overall illuviation of clay per se is directly affected by texture in these loamy soils.

With respect to podzolization processes, extractable Fe and Al contents of E′ and Bs horizons were lowest in the sandier profiles, regardless of the extractant used. This trend was indicated by negative correlations between PW sand contents and contents of Fe

Fig. 5. Scatterplots illustrating the relationships between texture and various profile attributes. (A) Profile-weighted sand content vs. solum thickness and E′ horizon thickness. The best-fit lines are both described by exponential equations with r^2 values > 0.33. (B) Profile-weighted sand content vs. the ratio of $Fe_d(Bs)/Fe_d(E')$. The best-fit line is shown.

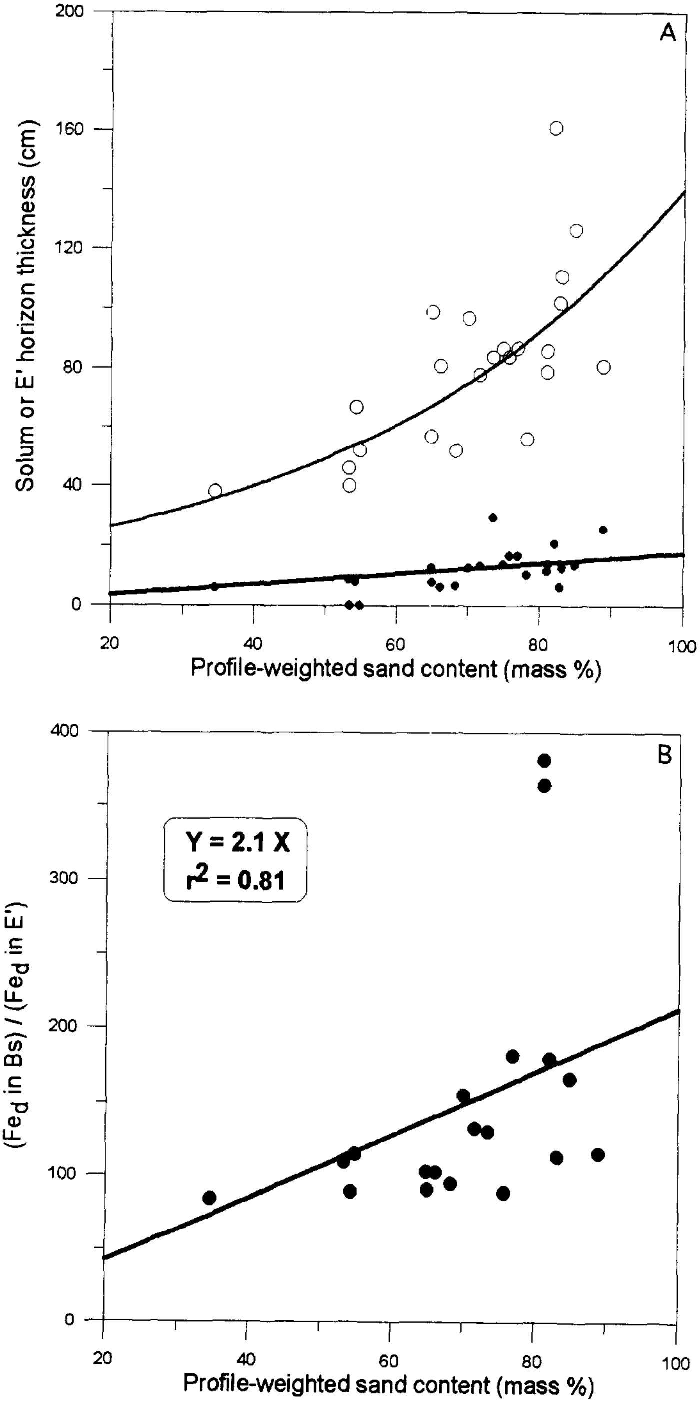

A
Solum or E' horizon thickness (cm)
0
40
80
120
160
200
Profile-weighted sand content (mass %)
20
40
60
80
100
B
Y = 2.1 X
r2 = 0.81
(Fed in Bs) / (Fed in E')
0
100
200
300
400
Profile-weighted sand content (mass %)
20
40
60
80
100

Table 4
Varimax-rotated factor scores and percent of total variance explained by each factor [a]

Soil property (variable)	Factor 1	Factor 2	Factor 3
PW coarse fragments	0.19	0.48	0.43
PW 8–2 mm fraction	0.13	0.08	**0.76**
PW sand	**−0.91**	−0.19	0.17
PW very coarse sand	−0.18	−0.01	**0.46**
PW coarse sand	−0.63	−0.10	**0.55**
PW medium sand	**−0.82**	−0.12	**0.47**
PW silt	**0.91**	0.19	−0.17
PW clay	0.66	0.49	0.31
E′ horizon thickness	−0.63	0.05	0.04
Solum thickness	−0.74	−0.05	0.12
Carbonates in parent material	0.52	0.38	**−0.45**
Bt clay content	0.73	0.07	0.13
Bt fine clay content	0.22	0.11	0.41
E′ clay content	**0.85**	0.45	0.10
Bt fine clay/total clay	−0.47	0.19	0.07
E′ fine clay content	0.71	0.08	0.19
E′ fine clay/total clay	0.11	−0.77	0.08
E′ total clay/Bt total clay	0.47	0.65	0.07
$\mathrm{Fe_d}$ in E′ horizon	**0.90**	0.35	0.08
$\mathrm{Fe_d}$ in Bs horizon	0.68	0.04	0.21
$\mathrm{Fe_d}$ in Bs horizon/$\mathrm{Fe_d}$ in E′ horizon	−0.29	−0.76	0.08
$\mathrm{Fe_p}$ in E′ horizon	**0.81**	0.34	0.02
$\mathrm{Fe_p}$ in Bs horizon	**0.85**	−0.19	0.21
$\mathrm{Fe_p}$ in Bs horizon/$\mathrm{Fe_p}$ in E′ horizon	−0.14	**−0.90**	0.13
$\mathrm{Fe_o}$ in E′ horizon	**0.81**	0.37	0.17
$\mathrm{Fe_o}$ in Bs horizon	0.78	−0.22	0.33
$\mathrm{Fe_o}$ in Bs horizon/$\mathrm{Fe_o}$ in E′ horizon	−0.11	**−0.97**	0.00
$\mathrm{Al_d}$ in E′ horizon	**0.88**	0.33	−0.17
$\mathrm{Al_d}$ in Bs horizon	0.58	−0.32	−0.31
$\mathrm{Al_d}$ in Bs horizon/$\mathrm{Al_d}$ in E′ horizon	−0.07	**−0.97**	−0.11
$\mathrm{Al_p}$ in E′ horizon	**0.81**	0.30	−0.15
$\mathrm{Al_p}$ in Bs horizon	0.62	−0.36	−0.32
$\mathrm{Al_p}$ in Bs horizon/$\mathrm{Al_p}$ in E′ horizon	0.01	**−0.99**	−0.13
$\mathrm{Al_o}$ in E′ horizon	**0.82**	0.32	−0.01
$\mathrm{Al_o}$ in Bs horizon	0.59	−0.50	−0.30
$\mathrm{Al_o}$ in Bs horizon/$\mathrm{Al_o}$ in E′ horizon	−0.06	**−0.96**	−0.13
Slope	−0.36	−0.06	0.22
% of total variance explained	38.0	22.6	7.6

[a] For ease of visualization, scores greater than 0.80 or less than −0.80 on factors 1 and 2 have been bolded, as have scores greater than 0.45 or less than −0.45 on factor 3. See text and Table 3 for complete descriptions of the variables and units used.

and Al (Table 4). The correlations were negative for both E′ and Bs horizons, indicating that the coarser-textured pedons have, in general, less metallic cations available for chelation than do the finer-textured pedons. The correlations are markedly stronger for the E′ horizons, however, suggestive of more rapid cheluviation/podzolization in the sandier pedons, and in general supporting the long-established (positive) relationship between sandy textures and speed of podzolization. In coarser parent materials, both the slower release of metallic cations into solution by weathering *and* the propensity for water to infiltrate to greater depths and translocate them out of the profile, allow for eluvial horizons to form quickly and to be more thoroughly stripped of Fe and Al than in finer-textured materials. Positive correlations between silt and clay contents and extractable Fe and Al also support the process-based conclusion that most of the Fe and Al in these soils comes from the weathering of the finest soil particles. The three pedons with the highest amounts of clay-free silt, the Omena pedons, all had very high amounts of extractable Fe and Al. These relationships imply that much of the extractable Fe and Al and/or the organic compounds vital to podzolization are retained within or adsorbed onto the the silt (and possibly clay) fractions, rendering them nearly immobile. Thus, as has been shown, in finer-textured soils, podzolization is normally retarded (Duchaufour and Souchier, 1978).

The *relative* development in E′ vs. Bs horizons, with respect to podzolization (stronger development implies less extractable Fe and Al for E′ horizons, more Fe and Al for Bs horizons), is slightly higher in the sandier pedons. This trend is illustrated in Fig. 5B, which shows E′/Bs horizon ratios for $\mathrm{Fe_d}$. Thus, the likelihood of E or E′ horizons to form above or below a Bs horizon is greatest in the sandier pedons. This finding implies that bisequal soils, if they do indeed form by podzolization *within* an E horizon which has lost clay, are more likely to be strikingly visible in sandier materials. In loamier materials, E′ horizons may form but are thinner and retain more Fe and Al — probably due to more rapid release of these cations from silt and fine sand particles, and because organics form strong bonds with clays, limiting their availability for chelation.

Factor analysis results support the conclusions discussed above. Generally, factor analysis in pedology is used to interpret the expression of a pedogenic trend or process "bundle" (Delgado et al., 1994). Several soil properties, if grouped together on the same factor, may imply a causal or process linkage among them. Variables that have large loadings on a rotated factor can be thought of as being associated; these associations may be interpreted in light of pedogenic theory and process (Table 4).

The first factor, which explains nearly 40% of the variance in the data, may be interpreted as being associated with sesquioxides and the potential for their release via weathering. This factor loads negatively on sand content, but positively on silt. Weathering of the latter may be responsible for most of the Fe and Al cations released to the soil solution, since silt grains weather faster than do sands and typically contain more Fe-bearing minerals. Other high loadings on factor 1 include Fe and Al contents from various extracts. It is interesting to note that most of the higher loadings are for E′ horizons, possibly indicating that weathering and translocation, if prominent, produces high sesquioxide contents in those horizons. Data from Duchaufour and Souchier (1978) confirm the importance of Fe (and clay) content in determining profile character in soils that have podzolic features. They found that in clayey, high Fe soils, Fe is relatively immobile, whereas in soils with lower clay and Fe contents, more acidic organic matter (fulvic acids) forms, which promotes some Fe and Al translocations. The high loadings of Fe and Al contents on factor 1 illustrate the importance of sesquioxide content (or the potential for their release into solution) on profile developmental pathways — whether, in this case, the bisequal soil has strong spodic or alfic morphology. Thus, factor 1 is best decribed as a "weathering" factor; soils with high amounts of silt may weather faster than sandy soils and thus may release more sesquioxides.

Factor 2 explained nearly 23% of the total variance and is cautiously interpreted as a "podzolization" factor, primarily related to eluviation processes. Bs/E′ ratios for Fe and Al contents for all three extracts load highly negatively onto this factor (Table 4). Though lower in absolute value, loadings were universally negative for extractable Fe and Al for Bs horizons, and positive for E′ horizons. Thus, this factor appears to group together pedons that are experiencing strong podzolization, such that the E′ horizon (below the Bs) has accumulated large amounts of illuvial spodic materials, relative to the Bs above, suggesting that the Bs horizon is building downwards rapidly. In soils undergoing weaker podzolization, the E′ horizon has lower amounts of spodic materials.

The third factor, though not nearly as explanatory as the first two, is interpreted as a textural factor. It loads strongly on coarse fragment content, content of the 8–2 mm fraction, and some of the coarser sand fractions (Table 4). It is negatively loaded onto parent material carbonate content. Data not shown here indicate that carbonate content is significantly negatively associated (using Spearman's rank-order test) with PW total sand, PW very coarse sand, and PW medium sand contents, probably because most of the carbonates are in the silt and clay fractions, and because coarser-textured materials have lower buffering capacities and higher leaching rates. Interestingly, weak negative loadings are found in factor 3 for all the Al extracts, whereas the loadings are all positive for the Fe extracts. The explanation for this pattern is unclear. Factor 3 is therefore a parent material factor, closely related to texture.

6. Conclusions

Soils in ecotonal positions are unique in that they can possibly provide a signal regarding change in pedogenic pathway or process, either due to internal thresholds (Muhs, 1984) or to external forcing, e.g., climate or vegetation change (Johnson and Watson-Stegner, 1987). Bisequal soils are so positioned, and this study provides some insight into their genetic workings. Only with a thorough understanding of the genetic processes and pathways in these soils can their potential for providing such information be realized.

Bisequal soils in NE lower Michigan have many morphological commonalities, especially their A–E–Bs–E′–Bt–2C horizon sequences. Nonetheless, subtlely different morphologies and chemical characteristics do occur, depending primarily upon parent material texture and the presence/absence of lithologic discontinuities. Coarser-textured pedons have thicker sola and the eluvial horizons within them are not only thicker but more thoroughly "podzolized" than are the finer-textured pedons, as indicated by weak positive correlations between Bs/E′ ratios of extractable Fe and Al and profile-weighted sand contents. Finer-textured pedons have significantly more Fe and Al cations, both "free" and chelated, in both eluvial and illuvial horizons, than do the sandier pedons.

Coarse fragment content, though not significantly correlated with profile-based or horizon-based data indicative of podzolization or lessivage, is still important in the genesis of these soils. Increases in gravel content, and sometimes even "stone zones", are present in most of these soils within the Bt horizon, where they mark the location of a lithologic discontinuity. This discontinuity appears to affect the movement of wetting fronts and hence, clay deposition.

The three factors that were isolated from the factor analysis explained 68.2% of the total variance in the data set. Factor 1 appears to represent the ability of the soil to weather and release metallic cations to the soil solution, factor 2 was a podzolization factor, and factor 3 represents textural properties, especially coarser sand and gravel content. By grouping a diverse and large data set, the factor analysis allowed for three key components of bisequal soil genesis to be elucidated: weathering and release of ions, podzolization, and texture, all of which may provide fruitful avenues for further research.

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