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LITHOLOGIC DISCONTINUITIES IN SOME SOILS ON DRUMLINS: THEORY, DETECTION, AND APPLICATION

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This paper discusses the importance of lithologic discontinuities in pedologic and geologic research, reviews the primary methods used to detect them, and examines some soils in northern Michigan that exhibit varying degrees of evidence for lithologic discontinuities. Although many different parameters have been used successfully to detect discontinuities in soils, those involving immobile and inert components offer the best likelihood of success, and these data are best reported on a clay-free basis. Parameters involving acquired (pedogenic) characteristics or the mobile element (plasma) of soils should be avoided.

Six Typic Eutroboralf pedons, formed on drumlins, were the primary focus of this study. Obvious-to-subtle evidence exists for lithologic discontinuities within the lower sola of these soils. Frequently, a weakly expressed stone line exists at or near the discontinuity. In this geologically young landscape, the origin of the discontinuity is presumed to have been glaciosedimentologic rather than pedologic (i.e., formed by bioturbation, surface creep, or eolian additions to near-surface horizons).

Depth functions involving clay-free particle-size data, especially for coarser (coarse sand and fine gravel) fractions, were the most consistent indicators of the discontinuity. Mean particle-size data and heavy versus light minerals were also somewhat useful in discriminating between the two materials. This study may be the first of its kind to use measures of sand grain sphericity (e.g., mean feret diameter, compactness, and shape factor) to identify discontinuities in soils, although the utility of these indices in detecting discontinuities was mixed. The data underscore the need for multiple lines of evidence in the detection of lithologic discontinuities in soils and cautions that they are not all geologic/sedimentologic in origin. (Soil Science 1998;163:570–590)

Key words: Pedogenesis, sedimentation, Michigan, Alfisols, pedogenic theory.

LITHOLOGIC discontinuities represent abrupt changes in the lithology of soil parent material. Buol et al. (1989, p. 65) define them as " . . . detectable changes in the vertical direction of a soil profile that are interpreted . . . to be caused by geologic processes." When they occur within or near the solum, they can impact pedogenesis dramatically. Demonstrating the absence of a discontinuity in a soil, i.e., showing that the solum has formed entirely in one parent material, is paramount to any quantification of soil development (Haseman and Marshall 1945; Evans and Adams 1975; Santos et al. 1986; Chadwick et al. 1990). Knowledge of the presence or absence of lithologic discontinuities and their nature is an essential starting point for any soil genesis study (Chapman and Horn 1968; Raad and Protz 1971; Evans 1978) because establishing that one exists can dramatically affect the pedogenic interpretations drawn from laboratory parameters (Parsons and Balster 1966; Meixner and Singer 1981; Norton and Hall 1985). If two parent materials are recognized where in actuality only one was present originally, the apparent lithologic discontinuity that exists must have been produced pedogenically (Paton et al. 1995). Discontinuities, whether inherited from the parent material or developed during pedogenesis, can provide valuable information on the history of

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the landform, the parent material, and the soil that has developed in it (e.g., Parsons and Balster 1967; Kuzila 1995).

The study of these features and the development of a set of guidelines directed toward their accurate detection have great scientific value (Barshad 1964; Norton and Hall 1985). Nonetheless, lithologic discontinuities have seldom been studied in their own right, probably because (i) the origins and pedogenic impacts of subtle discontinuities are difficult to ascertain, (ii) they are commonplace, as in alluvial soils, or (iii) pedogenesis often blurs or destroys them. Additionally, many sedimentary deposits assumed to be homogenous throughout are often crudely stratified (e.g., till), forcing the investigator to decide to what extent individual strata should be considered new materials (Asamoa and Protz 1972; Cremeens and Mokma 1986; Schaetzl et al. 1996; Liebens and Schaetzl 1997).

Distinct breaks in the lithology of soils can occur in two ways: (i) geologically-sedimentologically and (ii) pedologically (Paton et al. 1995). Although the focus in this paper is on inherited (geologic) discontinuities, the principles put forth are applicable even if the discontinuity is pedogenic. I assume that the discontinuities in the Michigan soils were formed by sedimentologic processes, but I also recognize that the *in situ* (i.e., pedogenic) formation of lithologically distinct layers in soils is commonplace and often conceptually ignored (Johnson 1990; Humphreys 1994; Nooren et al. 1995). In tropical regions, where discontinuities and stone lines exist in soils on old landscapes, their detection and accurate interpretation have enhanced our understanding of soil-geomorphic systems and their evolution (Bishop et al. 1980; Johnson 1993; Paton et al. 1995). Pedologically formed discontinuities are actually commonplace on older landscapes, where the processes of surface wash, creep, eolian transport, and bioturbation have acted in concert for many years to form relatively stone-free biomantles and texture-contrast soils, many of which exhibit stone lines at depth (Johnson 1993, 1994; Schwartz 1996).

This study has two goals: (i) to provide a theoretical discussion of the importance of lithologic discontinuities and review the methods that have been used in their detection and (ii) to apply some standard and some new techniques to determine their utility in detecting obvious-to-subtle lithologic discontinuities in soils developed in glacigenic sediments. I emphasize the use of depth functions as indicators of these discontinuities. This study highlights the importance of lithologic discontinuities within not only a pedogenic but also a glacigenic context and thereby illustrates the utility of discerning shallow discontinuities in glacially derived soils and sediments. Techniques discussed here may assist others in the detection of discontinuities in soils, regardless of their origin.

BACKGROUND

Theory

In theory, a geologically formed lithologic discontinuity (LD) is the physical manifestation of either a break in sedimentation, such as a change from deposition of sands by running water to deposition of silts by wind, or an erosion surface. Therefore, a discontinuity within the near-surface stratigraphic column represents either a temporary interruption in sedimentation or a change in the type of sedimentation system (Kuzila 1995; Soil Science Society of America 1997). Arnold (1968) noted that LDs are more or less horizontal interfaces between two materials, each of which exhibits some amount of internal unity or homogeneity. If the sample size is large enough, it is possible to determine statistically the amount of between-layer variability and within layer homogeneity (Raad and Protz 1971). Pedologically formed discontinuities, such as biomantles, usually involve processes that sort near-surface sediments. Two or more layers may then be formed within the solum, perhaps with the discontinuity near the depth at which the surficially driven sorting process (e.g., splash erosion, ant bioturbation, tree uprooting) diminishes (Johnson 1990).

Detection

Raad and Protz (1971) differentiated between the pedologic profile, the layers of which have been formed by pedogenesis, and the lithologic profile with its sedimentologic layering. Similarly, Follmer (1982) discusses the difference between a lithologic discontinuity, caused by a change in parent materials, and a pedologic discontinuity, caused by pedogenic and horizonation processes operating within a uniform material. According to Follmer, both types are typically expressed by a departure in depth trends (depth functions) between zones of otherwise relative uniformity. Arnold (1968) used the term "abrupt changes" to describe loci within depth functions where LDs might be indicated; Raad and Protz (1971) coined the phrase "disunity of the depth

functions" (p. 24). Pedogenically induced or formed depth functions, however, usually exhibit more gradual changes than do sedimentologically formed discontinuities, and they seldom show abrupt increases or decreases (Smeck et al. 1968).

Depth functions for various pedogenic parameters are often not in agreement (Oertel and Giles 1966; Busacca and Singer 1989). Perhaps this occurs because of the subtlety of the discontinuity or the natural variability within the apparently homogeneous lithologic units, or perhaps it is caused by poor evaluative tools, i.e., the choice of improper or inappropriate parameters. Obviously, the more lines of evidence that point to a discontinuity at a given depth, the more confidence one would have in concluding that a discontinuity exists (Evans 1978; Beshay and Sallam 1995). Numerous closely spaced vertical samples also allow for better detection of lithologic breaks than do horizon-based samples because they may also allow for statistical manipulation of the data (Oertel and Giles 1966; Raad and Protz 1971; Asamoa and Protz 1972). Raukas et al. (1978) list and discuss numerous field and laboratory procedures used in the study of tills, many of which are useful in pedological investigations as well.

Knowing the theoretical underpinnings for the choices of parameters that are most likely to be successful in the identification of LDs is important. Oertel and Giles (1966) observed that the disagreement among three studies on the locations and/or existence of LDs within the same Australian soil was attributable to the use of different criteria for their detection, some of which were inappropriate. Beshay and Sallam (1995) could not reconcile depth function data designed to detect lithologic discontinuities because some of their parameters were developmental (i.e., acquired via pedogenesis) and some were sedimentologic. Table 1 was compiled to assist future researchers in their search for parameters that may be used to detect LDs successfully.

The use of data on a soil fraction that is mobile within the pedologic context (i.e., the soil plasma, generally ions and particles <2 μm or <4 μm; Meixner and Singer 1981; Asadu and Akamigbo 1987) to detect discontinuities can produce erroneous results. This exclusionary list includes soil pH, clay content or mineralogy, organic matter, CEC, and many others (Tables 1, 2). Although depth functions for one or more of these parameters may change abruptly at a LD (e.g., Karathanasis and Macneal 1994; Kuzila 1995), they should not be used as a means of detection. Soil development indices, such as Bilzi and Ciolkosz' (1977) RHD (relative horizon distinctness) index should also not be used. Rather, pedogenic data, or even indexed compilations of acquired pedogenic characteristics, should be used only to *infer the presence* of LDs, not to identify them definitively.

Identification of a lithologic discontinuity is based ideally on data from an immobile and slowly weatherable soil fraction (Langohr et al. 1976). Immobile elements are best because they reflect sedimentology better than do mobile or plasma elements (Washer and Collins 1988). In a profile formed from uniform materials, depth functions of immobile and slowly weatherable parameters should plot along a line drawn vertically from the surface downward (Santos et al. 1986). In most environments that lack permafrost, particles coarser than about 30 μm in diameter can be considered immobile (Karathanasis and Macneal 1994). Caution must be exercised, however, in situations where properties could have formed pedogenically (e.g., concretions) or where they could have been translocated pedogenically by any of the various vectors of pedoturbation (Wood and Johnson 1978; Johnson et al. 1987). Biomantles (Johnson 1990; Humphreys 1994) could easily be mistaken for a second parent material because they commonly overlie a stone line that itself may be mistaken for a second parent material (Johnson 1989). The various bioturbation processes are easily capable of translocating sand, gravel, and even rocks.

The mineralogy of an immobile fraction has been used successfully in the detection of LDs although weathering processes can potentially alter these data and affect the interpretations made from any mineralogical data set (Nikiforoff and Drosdoff 1943). Busacca and Singer (1989) used elemental ratios to point out that textural discontinuities in some profiles are not reflected mineralogically. Because surficial weathering can reduce the amount of larger particles, many researchers have used both immobile and inert mineral particles, such as beryl or zircon, to assess lithologic discontinuities (Table 1).

Calculation of depth functions for immobile and/or inert components is best done on a clay-free basis because this removes the effects of the mobile element, clay, from the stratigraphic data (Rutledge et al. 1975a; Asady and Whiteside 1982; Bigham et al. 1991). Raad and Protz (1971) took this precaution one step further and used clay-free and carbonate-free sand and silt data.

TABLE 1

Some parameters used successfully to detect lithologic discontinuities in soils†

Indicator	References
Presence, absence or change in the content of a mineral	Barnhisel et al. 1971, Raad and Protz 1971, Karathanasis and Macneal 1994, Kuzila 1995
Presence or absence of a detrital fossil	Karathanasis and Macneal 1994
Content of one or more resistant minerals in a silt fraction	Chapman and Horn 1968, Rutledge et al. 1975b
Content of one or more resistant minerals in a sand fraction	Chapman and Horn 1968, Washer and Collins 1988
Elemental composition or abundance in a sand fraction	Arnold 1968
Elemental composition or abundance in a silt fraction	Alexander et al. 1962, Barnhisel et al. 1971, Foss et al. 1978, Norton and Hall 1985, Ransom et al. 1987, Karathanasis and Macneal 1994
Elemental composition of the entire non-clay fraction	Oertel and Giles 1966
Heavy mineral content	Chapman and Horn 1968, Khangarot et al. 1971, Cabrera-Martinez et al. 1989
Clay mineralogy	Follmer 1982, Kizila 1995
Magnetic susceptibility	Singer and Fine 1989, Fine et al.. 1992
Content of coarse fragments	Follmer 1982, Arnold 1968, Raad and Protz 1971, Asamoa and Protz 1972, Meixner and Singer 1981, Schaetzl 1996
Total sand content, content of a sand fraction, or mean sand size	Oertel and Giles 1966, Arnold 1968, Borchardt et al. 1968, Gamble et al. 1969, Caldwell and Pourzad 1974, Meixner and Singer 1981, Follmer 1982, Schaetzl 1992
Total silt content or content of a silt fraction	Oertel and Giles 1966, Caldwell and Pourzad 1974, Price et al. 1975, Meixner and Singer 1981, Follmer 1982
Clayfree sand or a clayfree sand fraction	Washer and Collins 1988, Busacca 1989, Busacca and Singer 1989, Karathanasis and Macneal 1994, Schaetzl 1996
A clayfree and carbonate-free sand fraction	Raad and Protz 1971
Clayfree silt or a clayfree silt fraction	Chapman and Horn 1968, Barnhisel et al. 1971, Asamoa and Protz 1972, Price et al. 1975, Rutledge et al. 1975a, Washer and Colins 1988, Busacca 1989, Busacca and Singer 1989, Karathanasis and Macneal 1994, Schaetzl 1996
A clayfree and carbonate-free silt fraction	Raad and Protz 1971
Any one of a number of fine earth fractions between 20 and 500 μm	Langohr et al. 1976, Santos et al. 1986
Ratio of one sand fraction to another	Fiskell and Carlisle 1963, Oertel and Giles 1966, Washer and Collins 1988, Cabrera-Martinez et al. 1989, Hartgrove et al. 1993, Beshay and Sallam 1995
Ratio of one silt fraction to another (in some cases, clayfree)	Follmer 1982, Kuzila 1995
Ratio of sand/silt or silt/sand (in some cases, clayfree)	Chapman and Horn 1968, Raad and Protz 1971, Smith and Wilding 1972, Asady and Whiteside 1982, Busacca 1989, Busacca and Singer 1989
Ratio of two minerals in a sand fraction	Chapman and Horn 1968, Beshay and Sallam 1995
Ratio of two minerals in a silt fraction	Price et al. 1975, Follmer 1982, Busacca and Singer 1989, Bigham et al. 1991
Ratio of an element to a resistant mineral in the silt+sand fraction	Santos et al. 1986
Ratio of two or more elements in a sand fraction	Smith and Wilding 1972
Ratio of two or more elements in a silt fraction	Smith and Wilding 1972, Foss et al. 1978, Bigham et al. 1991, Karathanasis and Macneal 1994
Formulas involving particle size fractions:	
Uniformity Value	Cremeens and Mokma 1986
Comparative Particle Size Distribution Index	Langohr et al. 1976

†Parameters listed are of the kind that can be displayed as depth functions; qualitative and/or morphological indicators of discontinuities are not addressed in this table. See Raukas et al. (1978) for a list of parameters used to study tills, some of which could have application within pedology.

TABLE 2

Summary of the general utility of various parameters detecting lithologic discontinuities in soils†

Very useful in most instances‡	Useful in some instances†	Rarely useful. Should be used in conjunction with other parameters	Not generally useful
Amount of a clayfree particle size fraction	Amount of a particle-size fraction larger than clay	Clay mineralogy	pH and electrical conductivity
Elemental composition of an immobile and difficult-to-weather particle-size fraction larger than clay	Mineral presence or absence	Magnetic susceptibility	Organic matter content
Content of a resistant mineral in a particle-size fraction larger than clay	Heavy or light mineral content	Paleobotanical or paleontological evidence	Clay content and mineralogy
Presence of a horizontally positioned stone line or zone	Shape (roundness, sphericity, etc.) of a particle-size fraction larger than clay		Morphological indicators such as structure, consistence, color, bulk density, and horizon boundary characteristics
			CEC and base saturation
			Magnetic susceptibility
			Contents of most elements
			Soil "development indices"

†Based on author's experience and a review of the literature.

‡Application of ratios of and between useful parameters is generally encouraged.

Ratios of some of the above parameters, for example, ratios of resistant minerals, are also used widely in the detection of LDs (Santos et al. 1986) (Table 1). Molar ratios of elements and ratios of weatherable to resistant minerals have been used to determine the age or weathering status of soils (Beavers et al. 1963; Busacca and Singer 1989; Bockheim et al. 1996) and often do change abruptly at discontinuities (Foss et al. 1978). However, because they reflect, in part, developmental data, they should not be relied on for detecting LDs. The ratio of two sedimentologic parameters has an advantage over a depth function of one of the same parameters (Foss et al. 1978) in that more data are incorporated, and the magnitude of the between-horizon difference can be increased. Ratios also have a distinct mathematical disadvantage compared with other parameters, however, as extremely small values, when positioned as the denominator, can inflate the ratio and make interpretation difficult. Many ratios of resistant mineral contents encounter this problem because the values are small to begin with and can even be zero (Beshay and Sallam 1995).

Morphological indicators of LDs include horizon variability since horizon boundaries often coincide with depositional discontinuities. Parsons and Balster (1967, p. 257) noted that "... genetically related horizons formed in parent material of uniform texture ordinarily do not thicken and thin independently, but one develops somewhat in proportion to the other." Thus, unusual thickening or thinning of a horizon may be indicative of its connection to a discontinuity. Depth functions of other physical parameters, such as bulk density or porosity, have been used to detect LDs (e.g., Arnold 1968) although their use should probably be avoided, except in cases where strong evidence exists for their application (Table 1). Stone lines within a profile may indicate the presence of an erosional episode or bioturbation (Johnson and Balek 1991) and thus will often lie at or near a discontinuity (Ruhe 1958; Parsons and Balster 1966).

Detection of LDs becomes increasingly more difficult as soils develop (Fine et al. 1992). Translocations, mixing processes, and transformations within the profile may blur and confound the sedimentologic evidence of the discontinuity. Thus, in situations where a LD is suspected but the soil is old, it is imperative that any data on mobile elements, such as pedogenic iron (Singer and Fine 1989) or translocated clay, be removed from the data set and that several methods be used to detect the discontinuity.

The emphasis in this paper is on the detection

of lithologic discontinuities through the examination of pedogenic depth functions. This method has the disadvantage of being potentially highly subjective, though attempts at making it more quantitative and less subjective do exist (e.g., Raad and Protz 1971). Still more quantitative methods involving discriminant analysis have been published (Norton and Hall 1985) although these often require some sort of *a priori* reasoning regarding the possible location and/or existence of discontinuities. Discriminant functions, like depth functions, are best calculated using data from an immobile and slowly weatherable soil fraction.

Application

Discontinuities involving fine-over-coarse layers dramatically affect eluviation-illuviation processes. Bartelli and Odell (1960a) noted that clay is deposited preferentially in a thin layer in finer-textured till where it overlies sand and gravel (Fig. 1). They attributed this deposition to increased hydraulic tensions in the upper, fine-textured material; water cannot enter the lower, coarser-textured sand until it is nearly saturated (Bartelli and Odell 1960 a and b). When water does break through the lithologic/hydraulic contact zone, it often flows rapidly through the lower material and along preferential fingers (Liu et al. 1991; Dekker and Ritsema 1996). Thus, shallow LDs may cause the zone of illuviation to be vertically compressed.

Fig. 1. Soil profile formed in loess overlying calcareous outwash gravels. Marks on the tape are every 10 cm.

Because lithologic discontinuities reflect changing sedimentation systems, their existence is applicable to studies of near-surface sedimentary history. Applications include detecting and distinguishing among various deposits of loess, colluvium, alluvium, till, and lacustrine sediments (Raukas et al. 1978; Bigham et al. 1991; Karathanasis and Golrick 1991). Identification of a paleosol in the upper part of a sedimentary layer implies not only that a discontinuity exists but also that a period of soil formation (a soil-forming interval) has occurred between the depositional events (Ruhe 1956; Foss and Rust 1968; Schaetzl 1986; Ransom et al. 1987; Olson 1989; Tremocoldi et al. 1994). Identification of a stable geomorphic surface buried within the near-surface stratigraphic column has implications for climatic change, landscape stability, and archeology, among many others (Holliday 1988; Cremeens and Hart 1995; Curry and Pavich 1996).

LITHOLOGIC DISCONTINUITIES IN US SOILS

In order to assess the importance of LDs and the frequency with which they are described in US soils, a systematic sample of 1000 soil series was taken from the USDA-SCS published list (USDA-SCS 1990). For each of the 1000 soil series, the official description was retrieved on-line from the USDA-Natural Resources Conservation Service's (NRCS) web site, and the presence or absence of one or more recognized lithologic discontinuities was recorded (Table 3). Based on these data, about one-third (33.5%) of the soil series in the US are interpreted to contain lithologic discontinuities, and nearly 7% have two or more LDs.

LANDFORMS, SOILS, AND SEDIMENTS OF THE STUDY AREAS

Soils in northern lower Michigan 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).

TABLE 3

Frequency of lithologic discontinuities in US soils, based on a sample of 1000 soil series descriptions

Number of lithologic discontinuities	Series described to 60 inches or less	Series described to 60–80 inches	All series (% of sample)
Zero	453	212	66.5
One	204	66	27.0
Two or more	44	21	6.5

Additions of organic matter, leaching of carbonates, and translocations of clay, fine silt, sesquioxides, and organic matter are typical pedogenic processes that occur in this approximate order (Schaetzl 1996).

Most of the area was last glaciated in the Late Pleistocene (Larson et al. 1994). The soils under study are located on shoulder and sideslope positions of drumlins and moraines (Burgis 1977; Schaetzl 1996; Fig. 2). Parent materials for the soils are strongly calcareous as a result of the dominance of shallow dolomitic and limestone bedrock in immediate up-glacier areas. The sediments are often sandy loam in texture and have abundant coarse fragments of all sizes (Schaetzl 1996).

Soils within the Onaway (fine-loamy, mixed Typic Eutroboralfs), Emmet (coarse-loamy, mixed Typic Eutroboralfs), and Omena (coarse-loamy, mixed Typic Eutroboralfs) series were investigated. Typically, these soils exhibit A-E-Bs-E′-Bt-C horizonation. In a previous study (Schaetzl 1996), it was concluded that many of these soils have lithologic discontinuities. The upper material could be a superglacial drape (Hart 1997) or a subaqueously deposited or reworked sediment. The discontinuity between it and the till below usually occurs within or immediately above the Bt (2Bt) horizon, making the horizonation, in actuality, A-E-Bs-E′-2Bt-2C. The E′ horizon is often absent where the upper material is thin, as in the Omena series. Both the 2Bt and 2C horizons are usually formed in a cobbly and gravelly glacial till, whereas the overlying material has fewer coarse fragments and is finer textured (Table 4). A discontinuous stone line usually occurs at the discontinuity. Because the lithologic discontinuity in these soils is relatively subtle (all three series are officially described as having formed in one material), an examination of the parameters that successfully identify the discontinuity was deemed a useful exercise.

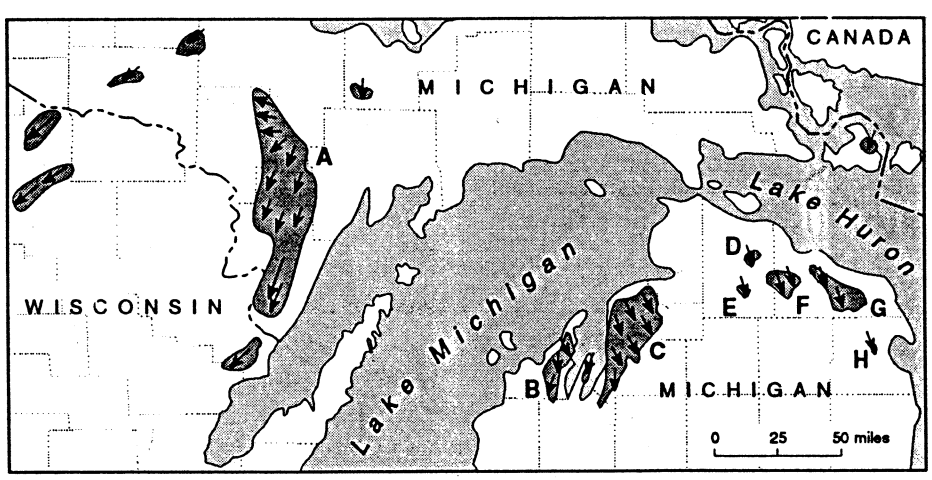

Fig. 2. Locations of the major drumlin fields in northern Michigan and Wisconsin. A: Menominee field; B: Leelanau field; C: Antrim-Charlevoix field; D: Aloha field; E: Afton field; F: Onaway field; G: Moltke-Polaski field.

TABLE 4

Selected morphological data for the six pedons studied

Pedon	Horizonation	Texture	Matrix color (moist)	Structure†
Emmet-1	Ap	sandy loam	10YR 3/3	mod med gr
	Bs1	sandy loam	5YR 3/3	we fi sab
	Bs2	loamy sand	10YR 4/6	we med sab
	E	loamy sand	10YR 5/3	mod med sab
	2Bt	gravelly sandy loam	7.5 YR 4/4	mod med sab
	2C	gravelly sandy loam	7.5YR 5/2	st co pl
Emmet-2	Ap	sandy loam	10YR 3/3	we med gr
	Bs/E	sandy loam	[Bs: 7.5YR 4/6 E: 10YR 5/4]	we fi sab
	E/Bt	sandy loam	[E: 10YR 5/4 Bt: 5YR 4/4]	we med sab
	Bt	sandy loam	5YR 4/4	we med pl
	C	gravelly sandy loam	7.5YR 6/4	st co pl
Omena-1	A	silt loam	10YR 2/2	st fi gr
	Bs	silt loam	10YR 4/6	mod fi sab
	E	loam	10YR 4/4	mod fi sab
	2Bt	very cobbly sandy clay loam	5YR 4/4	mod fi sab
	2C1	very cobbly fine sandy loam	10YR 5/3	w med sab
	2C2	very cobbly sandy loam	10YR 6/3	mod med pl
Omena-2	Ap	loam	10YR 3/3	we fi sab
	Bs	fine sandy loam	7.5YR 4/6	we fi sab
	E	fine sandy loam	10YR 5/4	we fi sab
	2Bt	gravelly sandy clay loam	5YR 3/4	mod med sab
	2C	cobbly sandy loam	10YR 5/2	mod co pl
Onaway-1	Ap	sandy loam	10YR 3/2	mod med gr
	Bs	sandy loam	10YR 5/4	we fi sab
	E	loamy sand	10YR 6/3	we med sab
	Bt	gravelly sandy loam	5YR 4/4	mod med sab
	2BC	cobbly sandy loam	10YR 4/6	mod med sab
	2C	gravelly sandy loam	10YR 5/3	we med pl
Onaway-2	Ap	sandy loam	10YR 3/2	mod fi gr
	Bs	sandy loam	7.5YR 4/6	mod fi sab
	E/Bt	fine sandy loam	[E: 7.5YR 5/2 Bt: 7.5YR 4/4]	mod fi sab
	Bt	sandy loam	7.5YR 4/4	st med sab
	C	cobbly sandy loam	10YR 5/4	st med pl

†Structure grade: we = weak, mod = moderate, st = strong. Structure size: fi = fine, med = medium, co = coarse. Structure shape: gr = granular, sab = subangular blocky, pl = platy. All descriptions follow the Soil Survey Division Staff (1993).

MATERIALS AND METHODS

NE Lower Michigan Drumlin Fields

Twenty-one sites with minimal evidence of erosion were sampled from five major drumlin fields: Onaway, Aloha, Polaski, Moltke, and Afton (Fig. 2). Two additional sites were located in the Johannesburg moraine (ca 13 ka; Blewett 1991). Of the 23 soil pits excavated, most showed field evidence of lithologic discontinuities. Seven of the sites had never been plowed; the remainder were in pasture.

Description and sampling of genetic horizons followed techniques recommended by the Soil Survey Division Staff (1993). Horizon-based samples were air-dried and passed through 8-, 4-, and 2-mm sieves to determine fine earth (<2 mm dia.) and fine gravel (2–8 mm dia.) contents; contents of the entire >2-mm fraction was estimated from pit faces in the field. A wooden pestle was used in the grinding process, such that few coarse fragments were crushed while grinding. Some samples that contained small peds cemented by $CaCO_3$ were wet-sieved to break up the peds while leaving small gravel intact. Particle-size analysis was performed by pipette, without prior sample decalcification (Sheldrick 1984). Sand splits were performed by sieving the

dried, dispersed soil fraction, using sieves of 2.0, 1.4, 1.0, 0.71, 0.5, 0.355, 0.25, 0.18, 0.106, and 0.053 mm. Approximate $CaCO_3$ content was determined by weight loss on exposure to concentrated HCl (Sheldrick 1984).

Three indices, developed to assess the uniformity of soil parent materials, were calculated. For each, the index compares data between the horizon in question and the one immediately above. The Comparative Particle Size Distribution (CPSD) Index of Langohr et al. (1976) was computed on the clay-free particle-size fractions between 2 μm and 2 mm. The CPSD determines the similarity of particle-size fractions of two samples (in this case, two horizons), such that the higher the CPSD, the more similar are the samples. Perfect similarity will result in a CPSD of 100. Additionally, a modified version of the CPSD was calculated, including data on the 2- to 4- mm, 4- to 8-mm, and total (estimated) coarse fragment contents, all expressed in percent. In its original form, perfect similarity will result in CPSD values of 100; in this modified Index, values could potentially exceed 100. The Uniformity Value (UV; Cremeens and Mokma 1986) was also calculated, again by comparing particle-size data with the horizon above. UV is calculated as:

$$UV = \frac{[(\%\text{silt} + \%\text{very fine sand})/(\%\text{ sand} - \%\text{very fine sand})] \text{ in upper horizon}}{[(\%\text{silt} + \%\text{very fine sand})/(\%\text{sand} - \text{very fine sand})] \text{ in lower horizon}}$$

minus 1.0

The closer the UV is to zero, the more likely that the two horizons formed from similar parent materials; Cremeens and Mokma (1986) assumed that UV values > 0.60 indicated nonuniformity. The UV was modified in this study by using clay-free sand and silt data.

Heavy mineral determinations and sand grain shape analyses were performed on samples from a subset of pedons. These pedons ranged from some that definitely did contain LDs to some that were questionable. Heavy mineral contents of the 53- to 250-μm fraction were determined by first isolating the fraction and then separating the heavy minerals from lighter minerals in a solution of sodium polytungstate ($Na_6[H_2W_{12}O_{40}]$) of 2.80 g cm^3, available from Geoliquids Inc., Palatine IL. Mass-based percentages of heavy and light minerals were based on initial sample weights of 8 to 14 g. Grain shape analyses were determined on the coarse sand fraction (500–1000 μm). After isolating this fraction, the grains were cleaned of any sesquioxide coatings by slow shaking in a solution of sodium citrate/sodium hydrosulfite, a method not dissimilar to standard Fe and Al extractions (Sheldrick 1984).

Because the shape and sphericity of sand grains can be diagnostic of their depositional environments (Patro and Sahu 1974), various indices of grain shape were taken. Dry sand grains were scattered randomly on a glass slide and viewed through a Leitz Laborlux 11 polarizing microscope. The microscope image was captured by a Sony CCD-IRIS color video camera and transmitted via cable to a 486–66 personal computer equipped with Mocha™ image analysis software (Jandel Scientific, San Rafael, CA). For each sample, images of 100 individual sand grains were then captured by Mocha as the microscope operator intermittently moved the slide across the microscope stage. Although only two-dimensional images are captured, the large sample size makes it likely that the data adequately reflect the three-dimensional attributes of the grains (Dowdeswell 1982).

Each free-standing sand grain was analyzed automatically, in Mocha, for the following characteristics: perimeter, major and minor axis lengths, feret diameter, shape factor, and compactness. Feret diameter is a measure of circularity, specifically:

$$\text{Feret diameter} = \sqrt{[4^*\text{area}/\pi]}$$

It is the diameter of a fictitious circular object that has the same area as the object being measured. Shape factor is also a measure of circularity:

$$\text{Shape factor} = [(4\pi^*\text{area})/\text{perimeter}^2]$$

A circle has a shape factor of 1.00, whereas the shape factor of a line approaches zero. Finally, compactness, which is similar to shape factor,

$$\text{Compactness} = \text{perimeter}^2/\text{area},$$

can range from 4π for a perfect circle to infinity for a line.

NW Lower Michigan, and NE Wisconsin Drumlin Fields

A less intensive but more areally comprehensive study was conducted in drumlin fields in NW lower Michigan (Antrim-Charlevoix field) and in NE Wisconsin and SW upper Michigan (Menominee field) (Fig. 2). These fields are presumably of similar age, and contain many of the same soil series. Here, auger samples were taken on drumlin crests (38 sites in the Antrim-Charlevoix

field; 31 in Menominee) where surficial erosion was not noticeable. A deep (>1.5 m) sample from the lower material and a shallow (<0.5 m) sample from the upper material were retrieved from all pedons that appeared to have a lithologic discontinuity. Samples from this part of the study were treated similarly to those from NE lower Michigan. Particle-size analysis was performed on all samples. Paired (upper and lower profile) samples from 20 pedons, which, based on bucket auger observations, appeared to have LDs, were also subjected to sand shape analysis as outlined above.

RESULTS AND DISCUSSION

Increases of 10% or more by volume in coarse fragment content at some point in the lower solum are taken as good initial evidence for the presence of a lithologic discontinuity in these soils. The LD usually occurs at between 35 and 160 cm depth, within either the Bt or the BC horizons (Schaetzl 1996). Horizons below the LD also usually contain more coarse sand and less finer sand. In some pedons, the depth to the LD is highly irregular, and where it may exist, it is diffuse and unclear.

Field-based data from the 21 sites suggested strongly that most of these soils contained evidence for LDs. The exact location (depth) of the discontinuity, however, could not always be determined in the field. In this paper, data from six pedons, two each within the Emmet, Onaway, and Omena series, will be presented (Table 4). These pedons were chosen because, with respect to their degree of field evidence for a discontinuity, they range from strong to weak. Thus, they provide a good sample of pedons with which to test the utility of various parameters regarding their ability to detect presumed LDs.

Strong Evidence for a Lithologic Discontinuity: The Omena Pedons

Omena pedons 1 and 2 exhibit strong evidence for shallow LDs (Figs. 3 and 4), especially with respect to the coarse fraction data. At Omena-1, the estimated amount of coarse fragments increases from 4 to 8% above the LD to 30% in the 2Bt horizon immediately below (Fig. 3c). In places, this abrupt increase in coarse fragments resembles a stone line. Lab-based data show similar trends. For example, both pedons show increases in the amount of fine gravel (2–8 mm diameter) below the discontinuity (Figs. 3c and 4c). Amounts of finer sand fractions decrease markedly below the discontinuity, resulting in large increases in mean particle size (Figs. 3 and 4). At Omena-2, the decrease in finer sands below the presumed LD is compensated by an increase in medium and coarse sands, a trend strong enough that it is apparent even if it is not calculated on a clay-free basis (cf., Figs. 4a and 4b). The large increase in finer sands immediately above the LD in Omena-1 (Fig. 3b), coupled with increases in coarser sands immediately below, suggest that the LD may represent some sort of erosional contact. Heavy mineral data were not consistent with textural data in identifying the LD in the Omena pedons (Figs. 3c and 4c), but, again a decrease in heavy mineral content immediately above the LD, sandwiched between higher levels above and below, are supportive of an erosional theory for the discontinuity.

Of the sand grain shape parameters examined, only mean feret diameter (FD) proved to be useful. Subtle differences in FDs occur near the discontinuities in both pedons, and at Omena-1, FD values increase below the discontinuity (Figs. 3e and 4e). In general, however, sand grain shape indices were not extremely useful in identifying the discontinuity in the Omena pedons. Even though there is some indication that the standard deviation of roundness and sphericity data may be more efficacious in environmental differentiation than mean values alone, and may prove to be good differentiator where the mean fails (Patro and Sahu 1974), standard deviation data were not at all useful in differentiating between the different materials (Figs. 3e and 4e).

$CaCO_3$ content increases to high levels in the horizons below the LD (Figs. 3c and 4c). This trend is pedologic and not depositional because it reflects leaching processes. However, the depth of leaching and, hence, solum thickness is often related intimately to the depth to the lithologic discontinuity (Schaetzl 1996), which is why it is reported here. Most of the sands and coarse fragments in these soils have limestone or dolomite lithologies. Thus, two factors may be acting together to lock in the base of the solum near to or exactly at the LD:

1) Infiltrating water may hang at the fine-over-coarse discontinuity (Fig. 1; Bartelli and Odell 1960 a and b; Asamoa and Protz 1972; Busacca and Singer 1989 Khakural et al. 1993), leading to less frequent wetting of the materials below the discontinuity and deposition of illuvial materials immediately above it, and
2) Large contents of coarser materials of predominantly carbonate-lithology in the lower material continue to release bases as they weather, thereby facilitating flocculation of colloids and the formation of a Bt or 2Bt horizon (Schaetzl

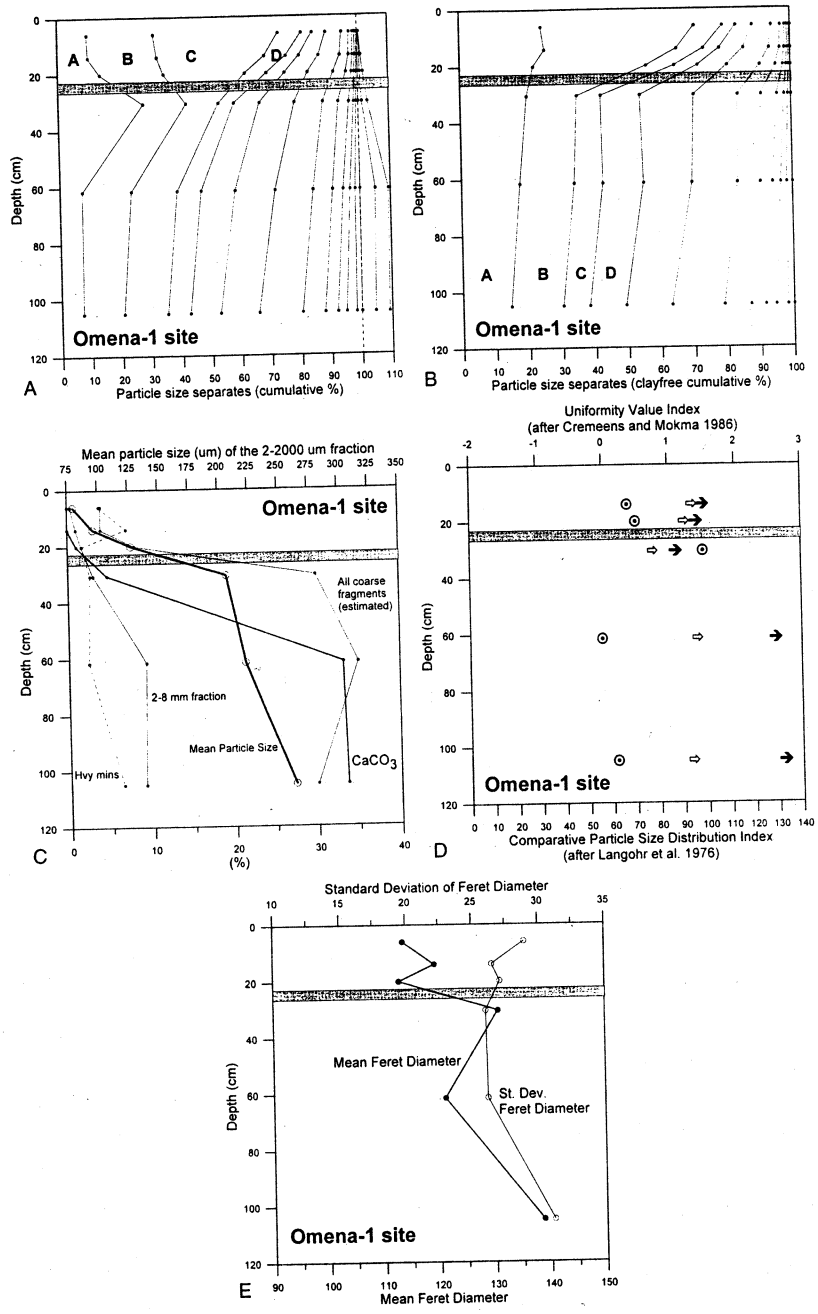

Fig. 3. Three Depth functions for the Omena-1 site. (a) Cumulative percentages of particle size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle-size breaks are provided in the text but begin with clay (labeled A) and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle-size separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Symbols similar to (a) above except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of %, except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000-μm size fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD, including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons; hence, the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e). Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

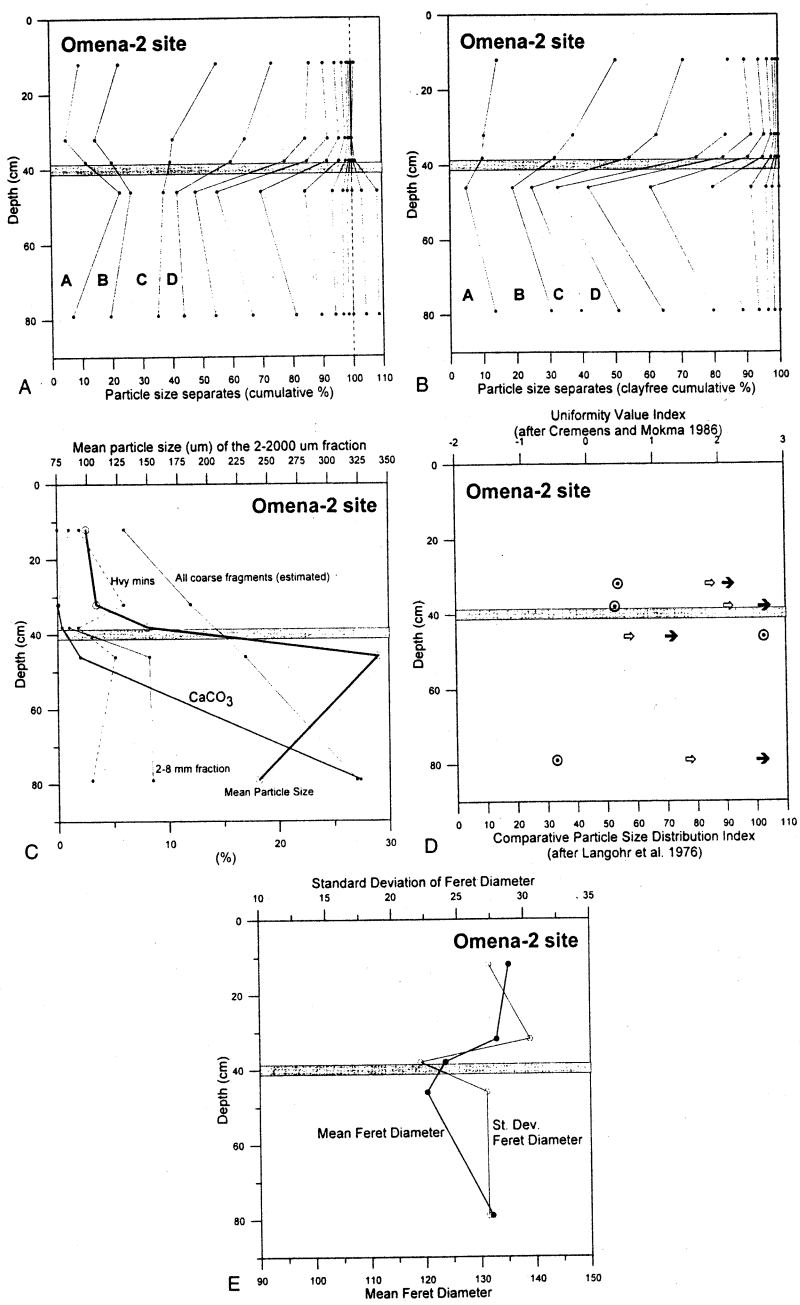

Fig. 4. Depth functions for the Omena-2 site. (a) Cumulative percentages of particle-size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle size breaks are provided in the text, but begin with clay (A), and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle size separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Symbols similar to (a) above except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of %, except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000-μm size fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle-size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons; hence, the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e) Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

1996). Because there are more of these types of clasts below the LD, the amount of time and acidifying water it takes to leach this material may be much greater than for the overlying finer sands, which are more quartz-rich.

Conflicting Evidence for a Lithologic Discontinuity: The Emmet-1 and Onaway-1 Pedons

The Emmet-1 and Onaway-1 pedons exhibit conflicting evidence for the presence of two parent materials. Field evidence, such as coarse fragment content that increases by 7 to 10% below the presumed discontinuity (Figs. 5c and 6c), was convincing. Both pedons exhibit subtle but consistently higher amounts of finer sands above the LD while showing increased coarser sands below (Figs. 5a and 5b and 6a and 6b). These patterns are consistent with those found in the Omena pedons. However, both Emmet-1 and Onaway-1 show slight decreases in mean particle size in the horizon immediately below the LD, and depth function data for some of the clay-free sand fractions maintain a nearly linear pattern as it crosses the presumed LD (Figs. 5 and 6). Content of fine gravel (2–8 mm) does not show the large increases below the LD that were evident in the Omena pedons (cp. Figs. 3 and 4 with Figs. 5 and 6). Consistent with the Omena pedons, heavy mineral amounts show a bimodal depth trend, with higher amounts in horizons above and below the LD and low amounts for horizon(s) near or at the LD (Figs. 5c and 6c). Sand grain FDs declined markedly below the discontinuity at Emmet-1 but showed little change with depth at Onaway-1 (Figs. 5e and 6e). Other indicators of sand grain shape (perimeter, major and minor axis lengths, shape factor, and compactness) were not useful in identifying the LDs in these pedons.

Little Evidence for a Lithologic Discontinuity: The Emmet-2 and Onaway-2 Pedons

Field evidence for a lithologic discontinuity in the Emmet-2 and Onaway-2 pedons was weak. The Emmet-2 pedon exhibited field evidence strong enough that a LD is indicated in Fig. 7. At Onaway-2, however, the evidence for a LD at 57 cm was so weak that it is not shown in Fig. 8.

It appears that neither of these pedons has a discernable discontinuity. The only supporting line of evidence comes from depth functions of coarse fragment content (Figs. 7c and 8c). Fine gravel content and mean particle size both show only gradual or no increase with depth (Figs. 7c and 8c). Depth functions for most clay-free sand fractions are not only linear with depth, but they also lack an increasing or decreasing trend (Figs. 7b and 8b). Depth functions of sand shape indices show little trend with depth (Figs. 7e and 8e).

UTILITY OF SAND GRAIN SHAPE DATA IN DETECTING LITHOLOGIC DISCONTINUITIES

The data for the 20 pedons from the Antrim-Charlevoix and Menominee fields were combined with the soils data from NE lower Michigan (Table 5). For the former, one sample was typically collected from each of the upper and lower materials. Of the six grain shape-related variables studied, only the means of shape factor and compactness were statistically different at $P = 0.01$ (using a Student's t test) between the upper and lower materials. Shape factor values were smaller in the lower material, implying that the grains in the upper material were more spherical; higher grain compactness values in the lower material suggest the same (Table 5). In the depth plots for individual pedons (Figs. 3e through 8e), FD was deemed the most useful shape-related property because it changed dramatically at the LD in some pedons. However, the direction of change was not always the same, increasing with depth in some pedons while decreasing with depth in others. Thus, no generalities can be made about its usefulness as a discriminating variable in these sediments. The decreasing sphericity of the grains with depth, as indicated by higher shape factor and compactness values, does appear to hold for most pedons and agrees with assumptions about the genesis of the upper material. It is likely that grain roundness, rather than sphericity, may be a more discriminating parameter for the detection of lithologic discontinuities in soils developed from two potentially different types of till (Whalley 1978). Roundness data were not determined for these grains.

CONCLUSIONS

Laboratory data often strongly support the lithologic discontinuity field calls. For example, in the Omena pedons, the field evidence for a LD was unmistakable, and the lab data were generally supportive. However, during the course of fieldwork, wherein 21 pedons were sampled, various degrees of confidence in these field calls were encountered. Where there was a subtle indication of a discontinuity, as in Onaway-2, little or no lab data were in support of the call. In other cases (e.g., Emmet-1 and Onaway-1), the lab data could be used either to support or to refute the field call.

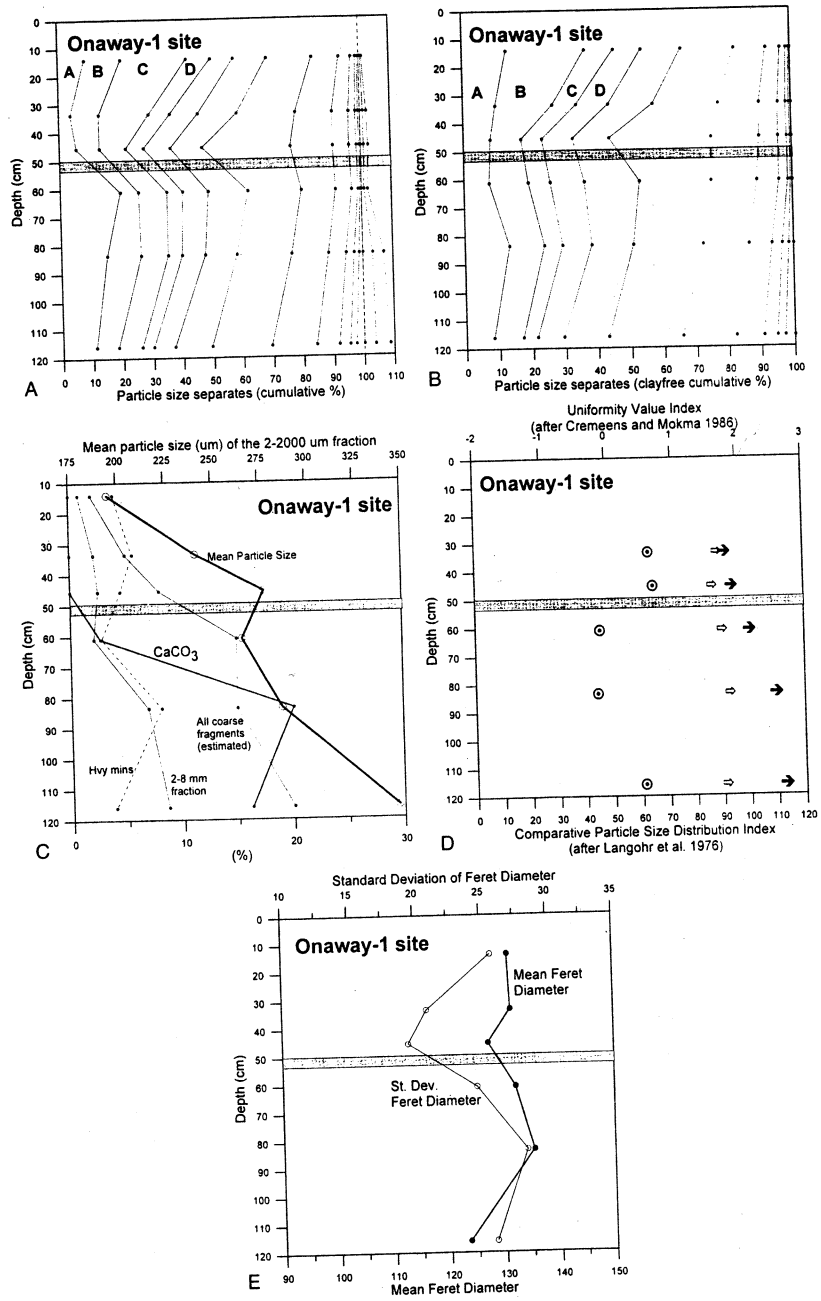

Fig. 5. Depth functions for the Onaway-1 site. (a) Cumulative percentages of particle size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle-size breaks are provided in the text but begin with clay (labeled A), and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle size separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Symbols similar to (a) above except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of %, except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000 micron size fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons; hence the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e) Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

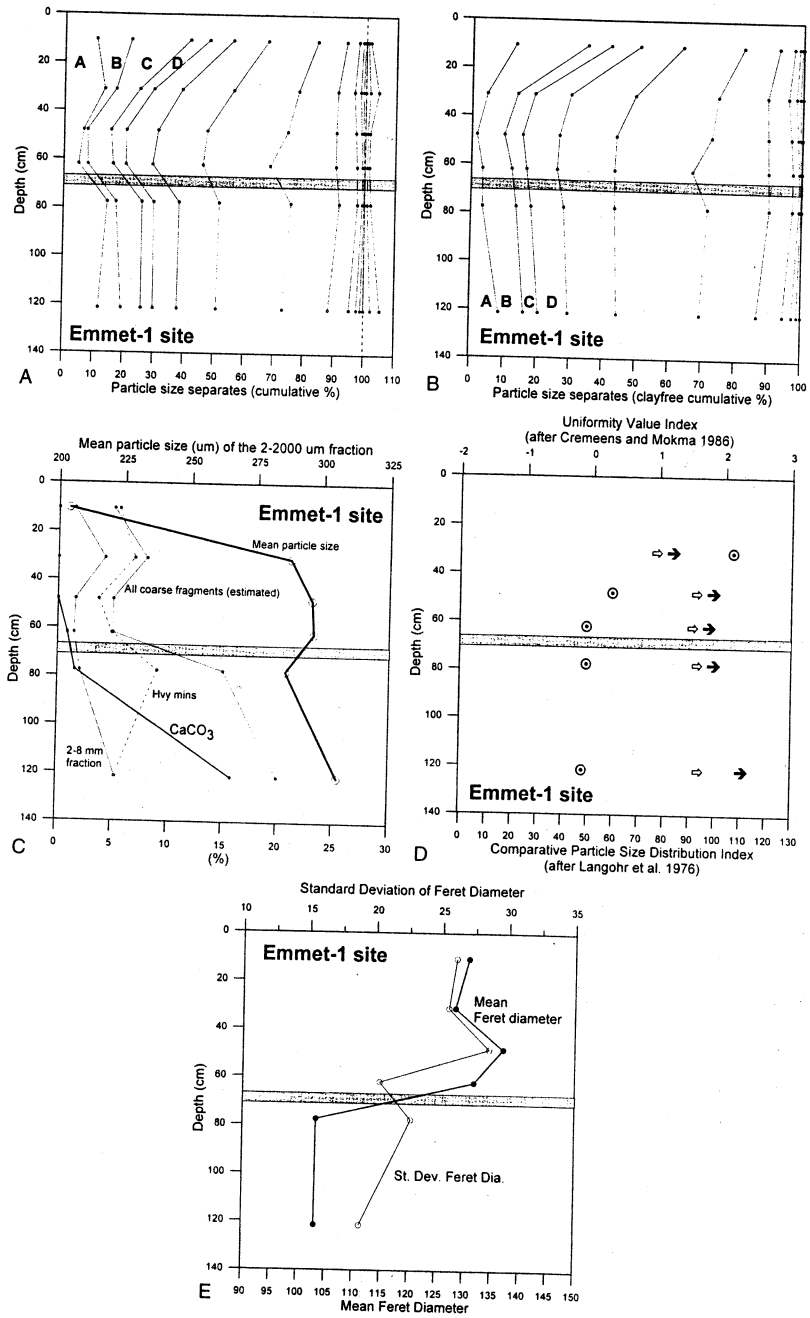

Fig. 6. Depth functions for the Emmet-1 site. (a) Cumulative percentages of particle size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle size breaks are provided in the text but begin with clay (labeled A), and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle size separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Symbols similar to (a) above, except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of % except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000-μm size fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle-size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons, hence the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e) Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

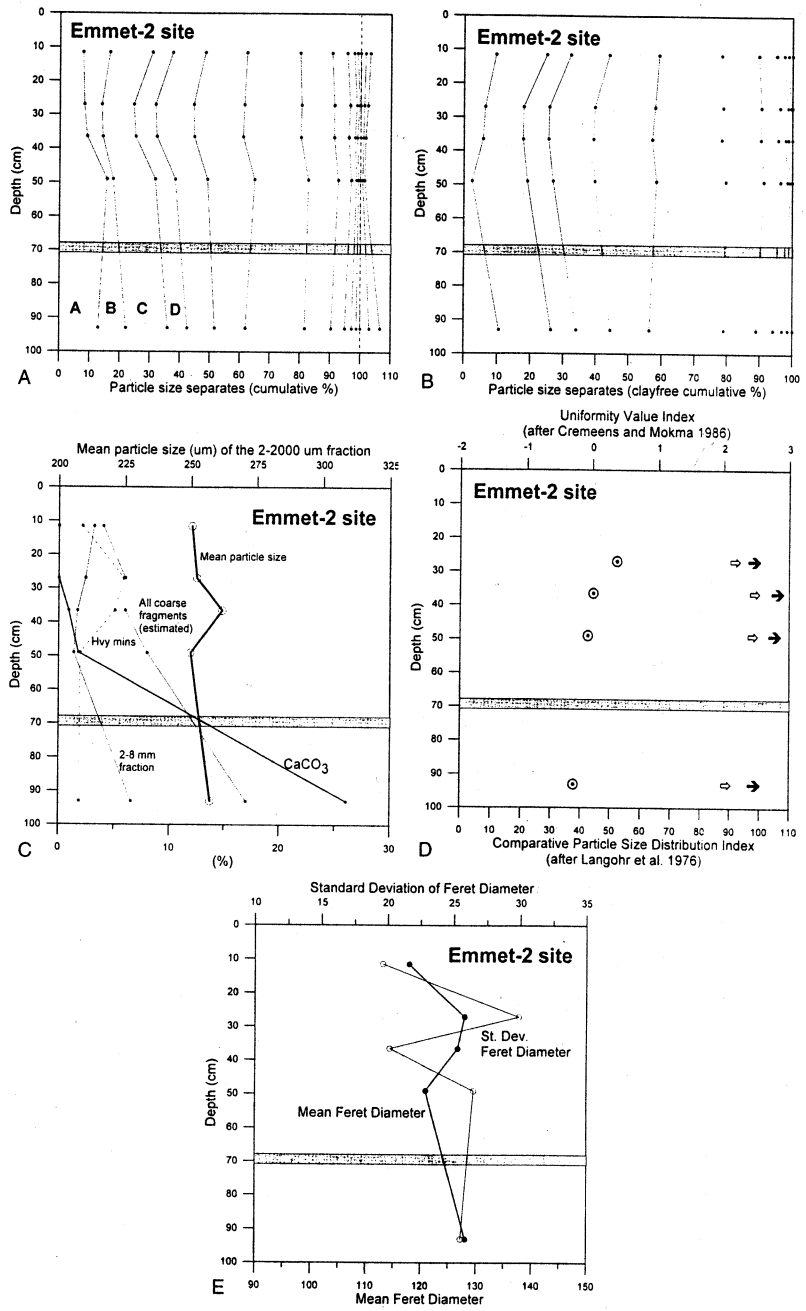

Fig. 7. Depth functions for the Emmet-2 site. (a) Cumulative percentages of particle size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle size breaks are provided in the text but begin with clay (labeled A), and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle size separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Similar symbols to (a) above except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of %, except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000-μm size fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons; hence the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e) Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

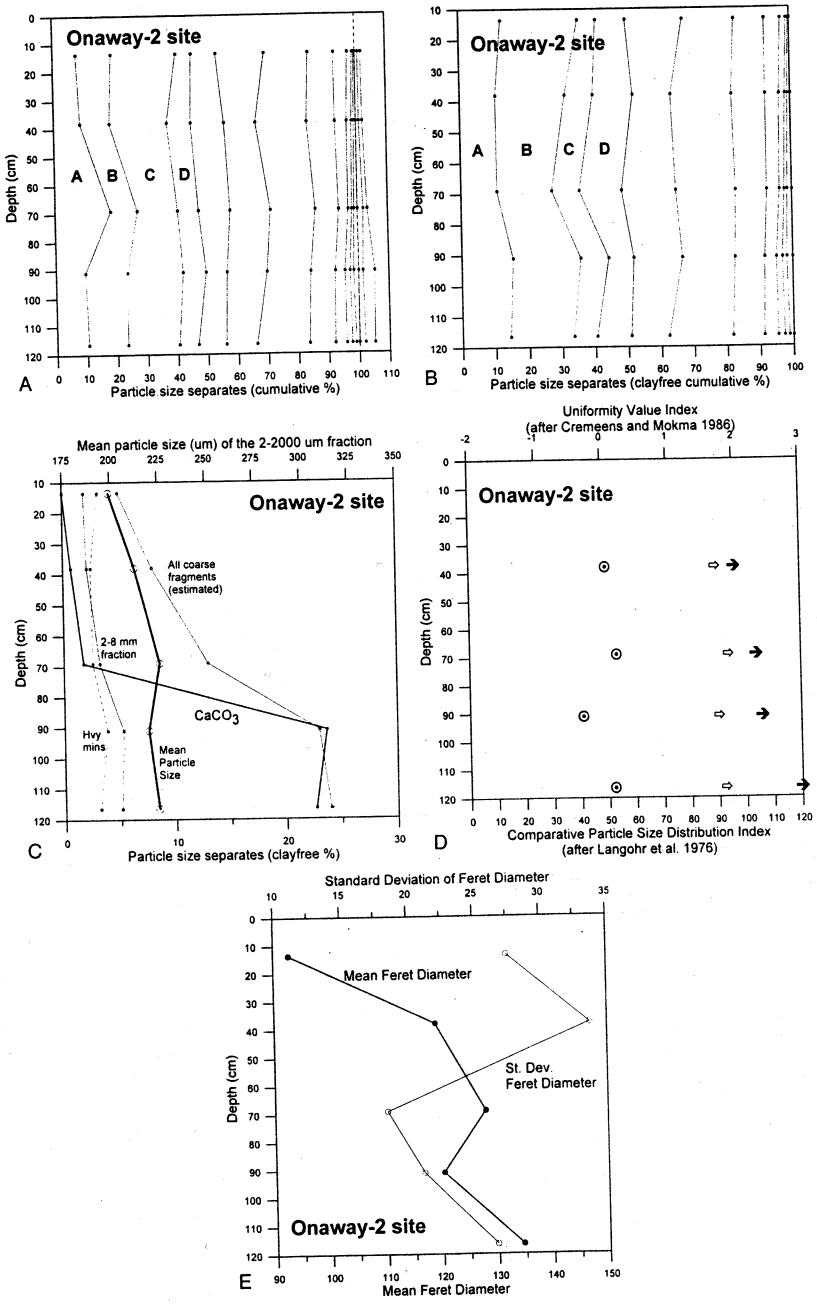

Fig. 8. Depth functions for the Onaway-2 site. (a) Cumulative percentages of particle size separates, from clay (0–2 μm) to very coarse sand (1.4–2.0 mm). To the right of the dotted line are the percentages of very fine (2–4 mm) and fine (4–8 mm) gravel. The particle size breaks are provided in the text, but begin with clay (labeled ") and get coarser to the right (fine silt, 2–8 μm, B; coarse silt, 8–53 μm, C; very fine sand, 53–106 μm, D, etc.). The lithologic discontinuity, as judged in the field, is shown by the broad, stippled band. (b) Clay-free, cumulative percentages of particle size-separates, from silt (2–50 μm) to very coarse sand (1.4–2.0 mm). Symbols similar to (a) above except that no 0–2-μm category exists. (c) Depth functions of various pedologic and sedimentologic data. All are in units of %, except for mean particle size, which is in micrometers. Mean particle size was calculated for the 2–2000 size micron fraction only. (d) Data from three indices designed to show lithologic discontinuities, based on particle-size data (Comparative Particle Size [CPSD] Index: light arrows, CPSD including coarse fragment data: dark arrows, Uniformity Value Index (UV): circles). In each case, the value plotted shows the index value when compared with the horizon immediately above. For the UV, greater deviations, either way from zero, indicate a stronger likelihood that the two horizons are separated by a discontinuity. Higher values for the CPSD Index indicate a lower likelihood of a discontinuity between the two horizons; hence the use of arrows pointing to the right—the farther to the right the value plots, the lower the likelihood of a LD between that horizon and the horizon above. (e) Mean and standard deviation data for feret diameter of coarse sand grains. Axis units are in pixels.

TABLE 5

Data on various aspects of sand grain shape from upper and lower parent materials in the drumlin fields of Michigan

Parameter	Mean and SD, upper material (in pixels)	Mean and SD, lower material (in pixels)	*t* test significance: Difference of means between upper and lower materials‡
Compactness†	16.56 ± 0.39	16.84 ± 0.49	0.006
Feret diameter	127.55 ± 5.99	131.92 ± 9.94	0.358
Perimeter	460.35 ± 22.62	480.62 ± 40.98	0.601
S Factor	0.764 ± 0.017	0.752 ± 0.021	0.005
Major axis length	154.61 ± 7.57	160.79 ± 12.97	0.425
Minor axis length	114.88 ± 5.62	118.86 ± 9.06	0.500

†See text descriptions of the geometric parameters used and the formulae involved in their computation.

‡*t* test data not shown indicated no significant differences in the standard deviations of each variable when comparing lower and upper materials.

In general, data on the immobile and inert fraction were the most useful in identifying lithologic discontinuities in these soils. Heavy mineral and sand grain shape data were useful for some pedons, but they were often not highly discriminating between otherwise contrasting parent materials.

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