Distribution of Soils in Ohio that are Described with Fractured Substratums in Unconsolidated Materials[1]

LAWRENCE A. TORNES, K. EDWIN MILLER, JONATHAN C. GERKEN, AND NEIL E. SMECK, Ohio Department of Natural Resources, Division of Soil and Water Conservation, Fountain Square, Columbus, OH 43224; USDA-Natural Resources Conservation Service, Columbus, OH 43215; and School of Natural Resources, The Ohio State University, Columbus, OH 43210

ABSTRACT. **Soil scientists, who systematically made soil surveys of Ohio, compiled the first comprehensive inventory of fractures in unconsolidated parent materials, or C horizons, of soils. Fractures have been documented in the C horizon of 95 soil series extending across 55 Ohio counties. A variety of terms were used to describe these nearly vertical fractures in otherwise massive materials. By convention, structural units are considered a product of soil-forming processes and the use of structural unit terminology has been limited to the solum consisting of O, A, E, and B master horizons and transitional horizons like AB, BE and BC horizons. Thus, terms used to describe soil structure have not been applied to the C horizon, even though the faces of prismatic structural units in the lower part of the B horizon commonly show continuity with fractures in the C horizon. Fractures have been identified in unconsolidated soil parent materials with textures of loam, silt loam, clay loam, silty clay loam, silty clay and clay. Clay films and carbonate coatings on fracture planes in the C horizon of soils indicate that water moves into and through these fractures. Fractures in the C horizon of soils also affect air movement and plant root extension into C horizons.**

OHIO J SCI 100 (3/4):56–62, 2000

INTRODUCTION

The description and sampling of soil profiles from excavated pits and other exposures during the Ohio Soil Survey Program that was initiated in 1900 have generated a valuable database for Ohio's soil resource. This program has involved the describing, sampling and analysis for complete laboratory characterization of more than 3000 soil profiles at the Soil Characterization and Physical Studies Laboratory in the School of Natural Resources at The Ohio State University. Some soil characterization was also conducted by the USDA-Natural Resources Conservation Service National Soils Laboratory, at Lincoln, NE. The descriptions were essential to properly classify and correlate soils that were mapped in conjunction with the National Cooperative Soil Survey Program (Soil Survey Staff 1999). The color, texture, structure, consistence, clay films, silt coatings, pores, roots, coarse fragments and reaction of each horizon in the soil were recorded in these profile descriptions.

Soil structure refers to the size and shape of the natural aggregates of primary particles (sand, silt, and clay) that result from soil forming processes (Soil Survey Staff 1993). Soil structure forms as a result of organic matter incorporation, biological activity, weathering, and the high frequency of wet-dry and freeze-thaw cycles. Soil structure is one of the best indicators used to distinguish the soil solum (A and B horizons) from underlying, relatively unweathered geologic deposits (C horizons). The formation of soil structure provides plant roots easy access to the soil's reservoir of nutrients and water. Soil structure tends to become less well developed and larger with depth in soils. In upper B horizons, small, well-developed blocky and/or prismatic structural units are dominant with prismatic units commonly parting to blocky subunits. With increasing depth, both the blocky and prismatic units tend to become larger. As the blocky units become less distinct, the prismatic units become more apparent, particularly when viewed in a horizontal plane wherein a polygonal pattern is commonly evident. The prism faces in the lower part of the solum (BC or CB horizons) often merge into spaced polygonal fractures in the C horizon. The origin of polygonal fractures in geologic materials is discussed in another paper in this issue (Brockman and Szabo 2000).

The objective of this paper is to assess the extent of fractured unconsolidated geologic units underlying soils in Ohio by perusal of pedon descriptions and laboratory data obtained during the Ohio Cooperative Soil Survey Program.

METHOD

Soil profile descriptions prepared from soil pits during county soil survey projects and published in county soil survey reports were reviewed to determine whether terminology was used that inferred the presence of fractures in the underlying unconsolidated geologic unit. A soil pit was excavated in a Bennington soil in Crawford County. A sketch was prepared of the pit face showing the prismatic structure in the BC horizon and fractures in the glacial till.

Characterization data for representative pedons sampled during the Ohio Cooperative Soil Survey were used to determine the range in particle size distribution of the geologic materials in which fractures have formed.

RESULTS AND DISCUSSION

Soil Scientists use an assemblage of morphological properties to determine the break between the solum (A, E and B horizons) and the underlying unconsolidated geologic materials (C horizons) (Fig. 1). The C horizon is defined as underlying material that has been

[1]Manuscript received 7 September 1999 and in revised form 11 January 2000 (#99-27).

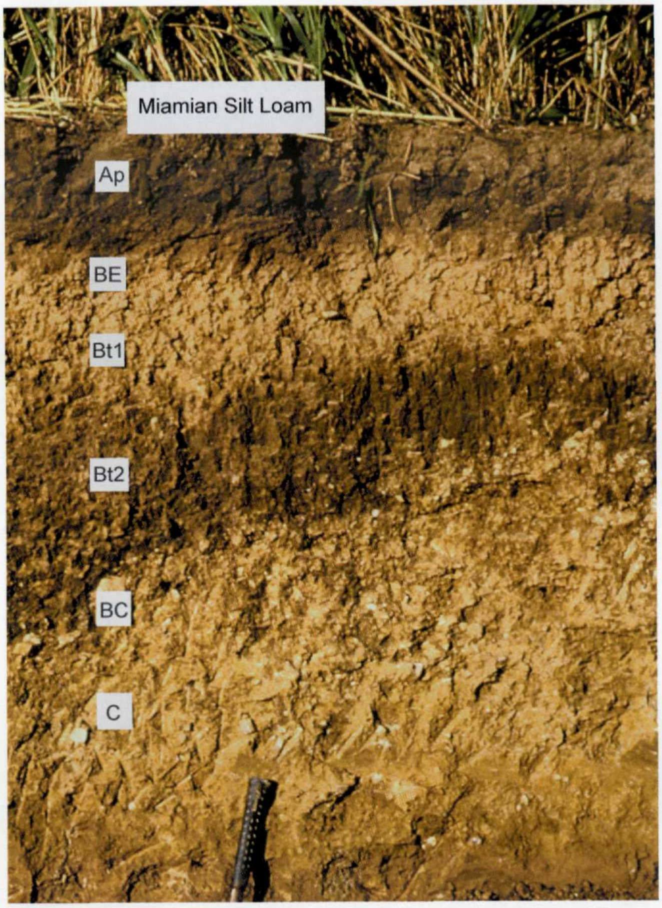

FIGURE 1. Miamian soil profile at the Molly Caren Agricultural Center near London, OH. Soil horizons are distinguished by particular assemblages of morphological properties: color, texture, structure, consistence, and soil reaction.

little affected by soil-forming processes (Soil Survey Staff 1993). Soil sola, however, show evidence of weathering, leaching, and clay eluviation-illuviation, have pedogenic structure, and exhibit colors attributable to oxidation and/or reduction. Plant roots which grow primarily between structural units and in pores are mainly confined to the solum; however, an occasional root extends into the C horizon of friable or loose materials and along fracture planes in dense, unconsolidated materials.

In Ohio, solum depth is closely related to the depth of leaching of carbonates (dissolution of naturally occurring limestone and its removal by water percolating through the soil). Because the lowest portion of the solum is only partially leached of carbonates and exhibits only weak structure, it represents a transition zone between soil and the underlying geologic deposit. As a result, this transition zone is designated as a BC or CB horizon, depending on whether properties of the B or C horizons are dominant.

A wide variety of terms were used by soil scientists to describe the widely spaced polygonal fractures in C horizons. Fractures, fracture planes, partings, cleavage planes, vertical cleavages, and cracks were commonly used in soil descriptions. Terms such as structural breaks, vertical seams, gray seams, light gray vertical streaks, brown coatings on faces of peds, and vertical pressure faces have also been used but less frequently.

Figure 2 is a sketch of a somewhat poorly drained Bennington soil that formed in clay loam glacial till in Crawford County, OH. The vertical fractures that define the coarse prismatic structure in the BC horizon from 61 to 86 cm (24 to 34 in) extend downward into fracture planes in the clay loam glacial till C horizon to 122 cm (48 in). Whereas, the prism interiors in the BC are yellowish brown (10 YR 5/4), the prism faces are dark grayish brown (10 YR 4/2). This color contrast is greater between the light gray (10 YR 7/2) fracture planes and brown (10 YR 4/3) matrix of the glacial till. The gray faces are caused by either an accumulation of secondary carbonates and/or the reduction and removal of free iron in the fracture. For the reduction and removal of free iron to occur, the soil must be saturated for a long enough time for oxygen to be depleted (Vepraskas 1992). The color contrast observed in the BC and C horizons of this Bennington soil profile is not as noticeable in the BC, CB, and C horizons of well drained soils like Miamian and Alexandria, since they have better natural drainage.

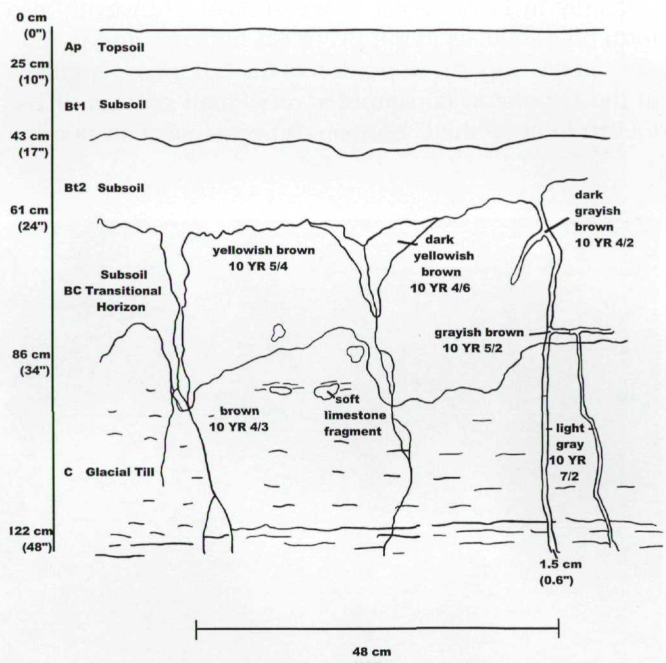

FIGURE 2. Vertical fractures extend from the BC horizon into the C horizon of a Bennington soil formed in clay loam glacial till in Crawford County, OH. The right side of the sketch shows the width of the gray seam along the fracture in the glacial till.

During soil formation in calcareous parent materials, calcium and magnesium carbonates are translocated downward in the soil profile. Most carbonates dissolved in water percolating through the solum are leached completely from the soil into ground water aquifers. However, during this process, some calcite precipitates in the BC and upper C horizons as silt-size grains that form coatings along prism or fracture faces (Schaetzl and others 1996). These calcite coatings, referred to as calcans by soil scientists, precipitate primarily along the fracture faces in the C horizon and contribute to the light gray color of the fracture face. In an investigation of the genesis of Celina and Morley soils derived from till in western Ohio, six pedons, comprising a N-S transect of the till plain along the Indiana border, were studied (Smeck 1966). In this investigation, detailed descriptions of the pedons to at least 75 cm (30 in) below the top of the C horizon were prepared. Whereas all structural units, both blocky and prismatic, in the BC horizons of all six pedons were coated (>40% of area) with argillans, prismatic units in the BC horizons of half of the pedons also exhibited thin (<1 mm) coatings of secondary calcite (calcans). Fractures were observed in the C horizons of all six pedons and all of the fractures were lined with calcans (Fig. 3). The calcans generally became thicker with depth in the C horizon. Calcans in the upper 25 to 100 cm (10 to 40 in) of the C horizon were generally <2 mm thick, whereas calcans were nearly always 2 to 5 mm thick at greater depths. Calcans were found along fractures in all six pedons to the entire depth of sampling [155 to 225 cm (62 to 90 in)] which included the uppermost 83 to 150 cm (33 to 60 in) of the C horizon.

Clay is translocated as a suspension and deposited as coatings (argillans) on the surfaces of peds and in pores primarily in Bt horizons. Some argillans, however, also form on ped faces in the BC or CB horizons and in fractures in the uppermost portion of the C horizon. Argillans in the C horizon constitute a very small portion of the total volume of the C horizon. Whereas most suspended clays are deposited as coatings on ped surfaces in the B horizons due to water movement into the ped interiors as a result of capillary tension, clays in the BC transitional horizon and the C horizon are flocculated due to the high base status associated with the presence of carbonates and are deposited along major channels and fractures where saturated flow occurs (Smeck 1993).

The polygonal pattern formed by fractures in unconsolidated C horizon materials is the same as that formed by very coarse prismatic units present in fragipans (Bx horizons). The only difference is fragipans form as a result of pedogenesis; whereas, C horizons have been minimally impacted by pedogenic processes. Bryant (1989) suggests that the high bulk density and polygonal fracture pattern characteristic of fragipans is a result of the initial desiccation of a wet geologic deposit during the physical ripening process. This is essentially the same process responsible for fracture formation in C horizons.

Perusal of soil profile descriptions in 84 Ohio county published soil survey reports and four unpublished manuscripts indicates that a variety of terms were used to describe the fractures in the C horizon of soils in 55 of the soil surveys (Fig. 4). Although fractures undoubtedly occur in the C horizon of soils in a number of the 33 other Ohio counties, fractures were either not described during fieldwork or were deleted in soil correlation or the

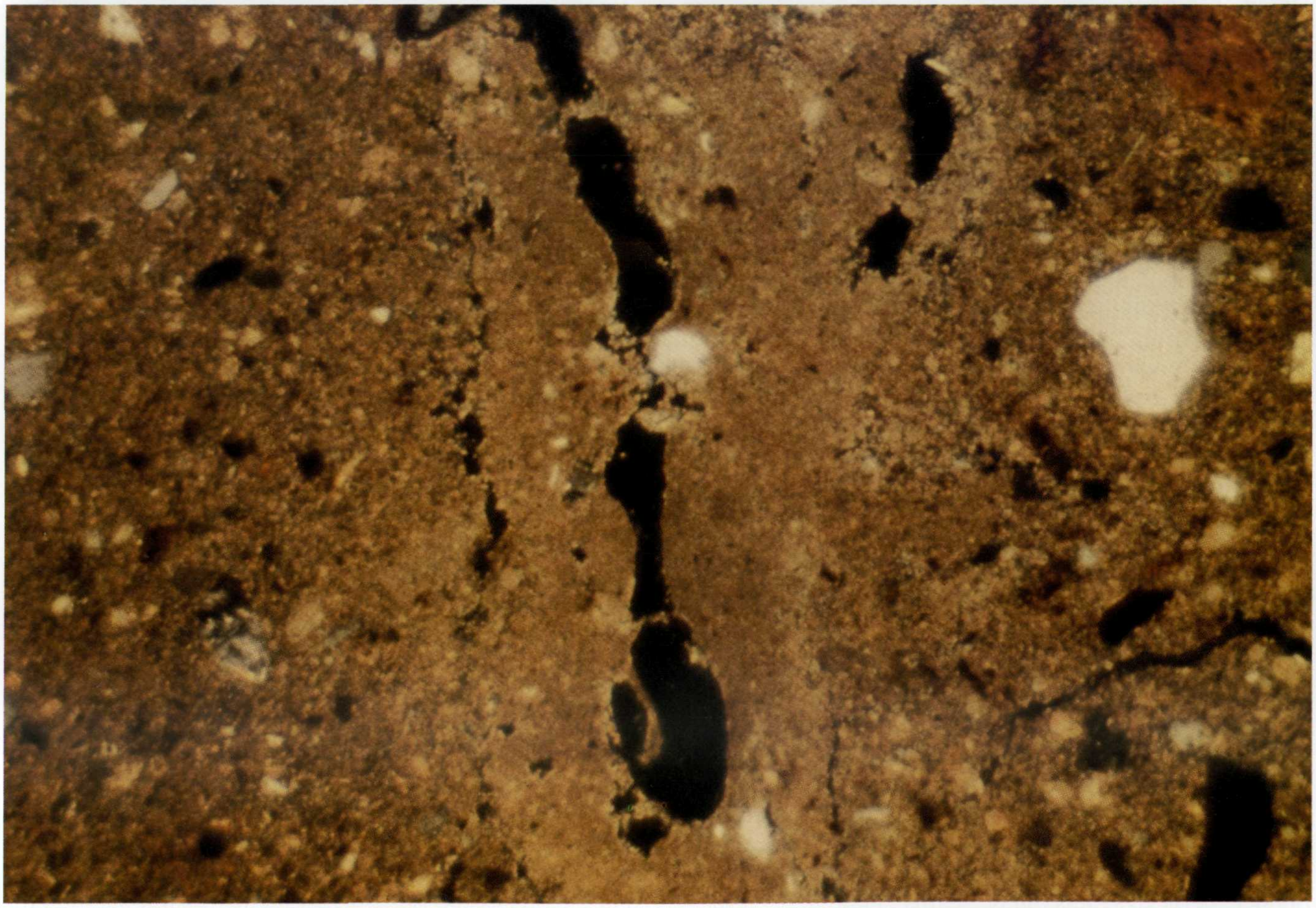

FIGURE 3. Thin section of C horizon of a Morley pedon from Auglaize County showing a fracture in the center of the frame lined with a calcan. Cross-polarized light. Frame width = 3.3 mm.

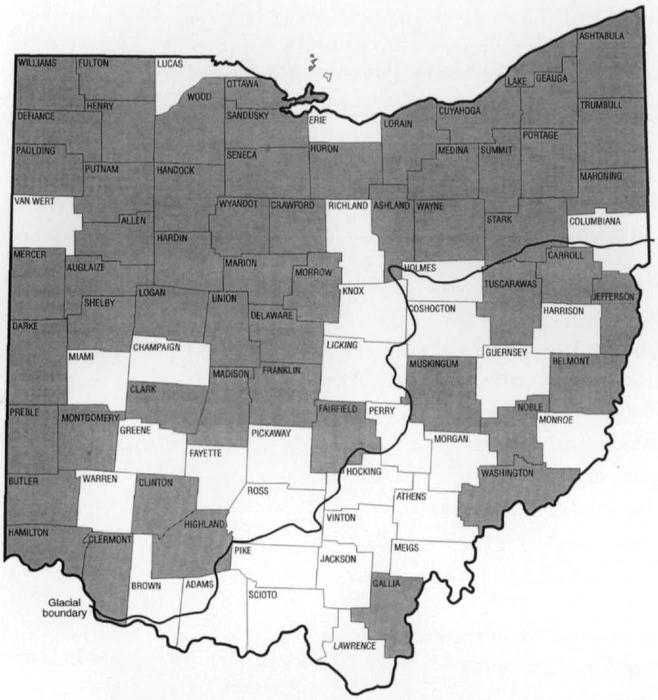

FIGURE 4. Counties in Ohio where fractures have been described in the C horizon of soils by soil scientists.

manuscript editing process. In some cases, soils described during the early years of the Ohio Soil Survey were very rudimentary. Such fractures were not considered to be significant and soil scientists paid little attention to morphological properties of the C horizon. Soil correlators and technical editors oftentimes removed references to fractures from the C horizon because fractures could be construed as soil structure, a result of pedogenesis that is responsible for soil solum formation.

Fractures have been described in the C horizon of 95 of the 483 soil series currently mapped in Ohio (Table 1). This listing was prepared to determine the landscape position and the range of underlying parent materials that exhibit fractures. Soil descriptions with references to fractures in the C horizon are primarily for soils derived from Wisconsinan or Illinoian glacial till or lacustrine materials on till plains and lake plains. Only 8 of the 95 soil series have underlying materials consisting of residuum, colluvium, or alluvium.

As the list of soil series for which pedon descriptions could be found with references to C horizon fractures was being compiled, it became evident that fractures were rare in very sandy or silty materials. The particle size distribution of 45 representative pedons containing fractures was plotted on a textural triangle (Fig. 5). The laboratory sample numbers for these pedons are listed in Table 1. These 45 pedons have underlying parent

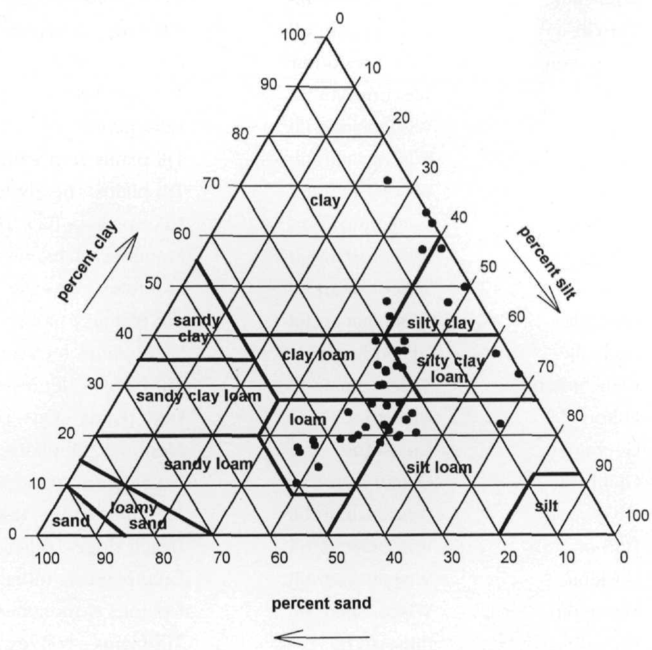

FIGURE 5. Percent sand, silt, and clay in the parent materials of 45 sampled pedons of soil series known to have fractures.

TABLE 1

Parent materials, landscape position, and laboratory sample number of soil series in Ohio exhibiting fractures.

Soil Series	Underlying Parent Material Exhibiting Fractures	Landscape-Landform of Soil Series	Ohio Laboratory Sample Numbers
Alexandria	Wisconsinan till	Moraines - rises, knolls, summits, shoulders, back slopes	PY-17, WN-67
Alvada	Wisconsinan till	Outwash & lake plains - flats, drainageways, depressions	
Ava	Illinoian till	Till plains - ridges, side slopes, shoulders	
Belpre	Shale residuum	Uplands - summits, back slopes, benches	
Bennington	Wisconsinan till	Moraines - swells, knolls, shoulders, back slopes	FR-4, HU-12
Bixler	Lacustrine	Lake plains - knolls, flats, rises, summits, shoulders, back slopes	
Blount	Wisconsinan till	Till plains - knolls, flats, rises, shoulders, back slopes, swells	HD-25, MC-12
Bono	Lacustrine	Lake plains - flats, depressions, drainageways	CR-15
Brookston	Wisconsinan till	Till plains & moraines - depressions	
Broughton	Lacustrine	Lake plains - dissected areas	DF-32

TABLE 1 (*Cont.*)

Parent materials, landscape position, and laboratory sample number of soil series in Ohio exhibiting fractures.

Soil Series	Underlying Parent Material Exhibiting Fractures	Landscape-Landform of Soil Series	Ohio Laboratory Sample Numbers
Canadice	Lacustrine	Lake plains & valley floors - depressions	
Caneadea	Lacustrine	Lake plains - planar positions	
Canfield	Wisconsinan till	Till plains - summits, shoulders, back slopes	
Cardington	Wisconsinan till	Moraines - flats, rises, knolls, summits, shoulders, back slopes	
Celina	Wisconsinan till	Till plains & moraines - flats, rises, footslopes, knolls	MA-5, PB-17
Centerburg	Wisconsinan till	Moraines - summits, shoulders, back slopes	LC-21, LC-22
Condit	Wisconsinan till	Moraines - flats, depressions, drainageways	
Conneaut	Wisconsinan till	Lake plains - nearly level to gently undulating areas	
Corwin	Wisconsinan till	Till plains & moraines - swells	
Coshocton	Mixed residuum	Allegheny Plateau - summits, benches, foot slopes	
Crosby	Wisconsinan till	Till plains & moraines - swells	CK-3, MT-9
Cygnet	Wisconsinan till	Lake plains - rises, knolls, summits, shoulders, back slopes	
Dana	Wisconsinan till	Till plains & moraines - summits, back slopes	
Darien	Wisconsinan till	Till plains - nearly level to moderately steep areas	
Del Rey	Lacustrine	Lake plains - flats, rises, knolls	
Elliott	Wisconsinan till	Moraines - flats, rises, knolls	
Ellsworth	Wisconsinan till	Moraines - dissected areas	
Fincastle	Wisconsinan till	Till plains & moraines - flats, rises, back slopes	PB-10, BR-8
Fitchville	Glacio lacustrine	Lake plains, terraces, outwash plains - plain or convex area	CA-35, WN-61
Frenchtown	Wisconsinan till	Till plains - depressions, flats, benches, drainageways	
Fulton	Lacustrine	Lake plains - flats, rises	
Geeburg	Lacustrine	Moraines, till plains, terraces - planar or convex surfaces	
Glenford	Glacio lacustrine	Lake plains, terraces, outwash plains - level to dissected	WN-45
Glynwood	Wisconsinan till	Moraines - rises, knolls, summits, shoulders, back slopes	
Harbor	Wisconsinan till	Beach ridges, offshore bars, deltas - flats, rises, knolls	
Haskins	Wisconsinan till	Lake plains & moraines - flats, rises, knolls	
Hennepin	Wisconsinan till	Uplands & moraines - side slopes	
Hickory	Illinoian till	Till plains - convex side slopes	
Houcktown	Wisconsinan till	Lake plains & moraines - rises, knolls, summits, shoulders, back slopes	
Hoytville	Wisconsinan till	Lake plains - flats, depressions, drainageways	
Jessup	Mixed residuum	Uplands - shoulders, interfluves	
Kendallville	Wisconsinan till	Moraines, till plains, kames, eskers - summits, shoulders, back slopes	
Kokomo	Wisconsinan till	Till plains - depressions	
Latty	Wisconsinan till	Lake plains - flats, depressions, drainageways	HN-95, LG-25
Lenawee	Lacustrine	Lake plains - flats, depressions, drainageways	
Lewisburg	Wisconsinan till	Till plains & moraines - shoulders, back slopes	
Lowell	Mixed residuum	Uplands - ridgetops, side slopes, foot slopes, benches	
Lybrand	Wisconsinan till	Moraines - shoulders, back slopes	
Mahoning	Wisconsinan till	Till plains - knolls, flats, rises, shoulders, back slopes, swells	
Marengo	Wisconsinan till	Till plains & moraines - depressions, swales	
Markland	Lacustrine	Lake plains - summits, shoulders, back slopes	CL-9, HA-6
McGary	Lacustrine	Lake plains, flood plains - flats, summits, flood plain step	MC-22
Mermill	Wisconsinan till	Lake plains & moraines - flats, depressions, drainageways	
Metamora	Wisconsinan till	Lake plains & moraines - flats, rises, knolls	
Miamian	Wisconsinan till	Till plains & moraines - convex slopes	FY-7, PB-56
Mill	Wisconsinan till	Till plains - flats, depressions, drainageways	
Miner	Wisconsinan till	Lake plains & till plains - depressions, drainageways	
Montgomery	Lacustrine	Lake plains & flood plains - flats, depressions	
Morley	Wisconsinan till	Moraines - rises, knolls, shoulders, back slopes	
Mortimer	Wisconsinan till	Moraines - rises, knolls, shoulders, back slopes	

TABLE 1 (*Cont.*)

Parent materials, landscape position, and laboratory sample number of soil series in Ohio exhibiting fractures.

Soil Series	Underlying Parent Material Exhibiting Fractures	Landscape-Landform of Soil Series	Ohio Laboratory Sample Numbers
Nappanee	Wisconsinan till	Lake plains - flats, rises	HK-22, PT-28
Odell	Wisconsinan till	Moraines & till plains - flats, rises	
Omulga	Lacustrine	Allegheny Plateau - valley fills	
Pacer	Wisconsinan till	Outwash terraces - treads	
Pandora	Wisconsinan till	Moraines - flats, drainageways, depressions	WY-16
Paulding	Lacustrine	Lake plains - flats	UN-21, DF-2
Peoga	Lacustrine/alluvium	Lake plains & stream terraces - flats, treads	
Pewamo	Wisconsinan till	Moraines & lake plains - flats, depressions, drainageways	
Pyrmont	Wisconsinan till	Till plains - flats, rises	
Rawson	Wisconsinan till	Moraines - rises, knolls, summits, shoulders, back slopes	
Ravenna	Wisconsinan till	Till plains - knolls, flats, rises, shoulders, back slopes, swells	CO-59
Remsen	Wisconsinan till	Till plains - knolls, flats, rises, shoulders, back slopes, swells	
Rimer	Wisconsinan till	Lake plains - flats, rises, summits, knolls	HK-35
Rittman	Wisconsinan till	Till plains - summits	CO-31, MD-18
Roselms	Lacustrine	Lake plains - flats, rises	
Rossmoyne	Illinoian till	Till plains - nearly level to steep slopes	
Russell	Wisconsinan till	Moraines & till plains - knolls, ridges	HY-58
Sebring	Lacustrine	Lake plains & stream terraces - depressions, level areas	WN-62
Seward	Lacustrine/Wisconsinan till	Lake plains - rises, knolls, summits, shoulders, back slopes	AL-119
Shawtown	Wisconsinan till	Lake plains & moraines - rises, knolls, summits, shoulders, back slopes	
Shinrock	Lacustrine	Lake plains - knolls, summits, shoulders, back slopes	
St. Clair	Wisconsinan till	Moraines & lake plains - knolls summits, shoulders, back slopes	LG-4, LG-5
Strawn	Wisconsinan till	Till plains & moraines - gently sloping to very steep slopes	
Tiderishi	Wisconsinan till	Lake plains - rises, flats, micro highs	
Tiro	Wisconsinan till	Moraines - flats, rises, knolls, summits, shoulders, back slopes	
Toledo	Lacustrine till	Lake plains - flats, depressions, drainageways	
Treaty	Wisconsinan till	Till plains & moraines - depressions	
Trumbull	Wisconsinan till	Till plains - level & gently sloping slopes, depressions	LR-S4
Upshur	Shale residuum	Uplands - ridgetops, benches, hillsides	
Vandalia	Colluvium	Uplands - foot slopes, colluvial fans	
Vaughnsville	Wisconsinan till	Lake plains - foot slopes	
Venango	Wisconsinan till	Till plains & moraines - convex surfaces	
Wadsworth	Wisconsinan till	Till plains - planar to convex positions	MD-13, AS-23
Westmore	Shale residuum	Uplands - benches, hillsides, ridgetops	
Wooster	Wisconsinan till	Till plains & moraines - convex surfaces	WN-S2, WN-S21

materials that are representative of the range in particle size distribution of the soil series. Fractures seem to occur primarily in materials that have loam, clay loam, silt loam, silty clay loam, silty clay and clay textures. The C horizon contains 10 to 72% clay, 50% or less sand, and 26 to 69% silt. Fractures in geologic deposits have been attributed to shrinkage due to desiccation of an initially slurried material (Bryant 1989). Therefore, it is not surprising that fractures are rare in very sandy or silty deposits because shrinkage due to desiccation will be greater in clay rich material. The clayey materials have smaller polygons. The polygonal pattern is characteristic of desiccation cracks.

It is reasonable to expect that the presence of fractures in the C horizon of soils affect water movement and root growth of deep-rooted plants (McMahon and Christy 2000). These fractures provide a pathway for vertical water movement in these materials (Fausey and others 2000). Unfortunately, there have been few measurements that characterize the flow of water through C horizons of glacial till (Hendry 1982). The occurrence of clay and carbonate coatings on the fracture planes in the C horizon confirms that water moves into and through these fractures. Argillans in the upper part of the C horizon are more indicative of water flow through the fracture than calcans in this zone (McBurnett and Franzmeier 1997). Both argillans and calcans have been observed in fractures in Ohio.

Many of the soils that have fractures in the C horizon have seasonal high-water tables during extended wet periods, especially in the winter and early spring months. Many soil scientists suggest that the water is perched on the dense, unconsolidated C horizon materials and speculate that during periods of saturation, gravitational water moves through the fractures. From an investigation of groundwater fluxes to the bedrock aquifer in northwestern Ohio, Martin-Hayden and others (1999) concluded that a high vertical gradient over large areas of thick glacial till induced significant recharge of the bedrock aquifer. If swelling clay minerals occur in the fractures, expansion of the clays may cause the fractures to close, reducing the water movement along the fractures. Likewise, the dehydration of clay minerals during dry periods may cause fractures to open increasing water movement along the fracture planes.

SUMMARY

Fractures in C horizons have been noted and reported for some soils in more than half of the counties in Ohio. Furthermore, we know that our assessment underestimates the occurrence of fractures. The widespread occurrence of fractures mandates that more effort be devoted to an evaluation of the impact of fractures on water movement through the earth's mantle if we wish to better understand their implications for ground water aquifer recharge and contamination.

LITERATURE CITED

Brockman CS, Szabo JP. 2000. Fractures and their distribution in the tills of Ohio. Ohio J Sci 100(3/4):39-55.

Bryant RB. 1989. Physical processes of fragipan formation. In: Smeck NE, Ciolkosz EJ, editors. Fragipans: their occurrence, classification, and genesis. Soil Sci Soc Am (Spec Publ Nr. 24):141-50.

Fausey NR, Hall GF, Bigham JM, Allred BJ, Christy AD. 2000. Properties of the fractured glacial till at the Madison County, Ohio, field workshop pit site. Ohio J Sci 100(3/4):107-12.

Hendry MJ. 1982. Hydraulic conductivity of a glacial till in Alberta. Ground Water 20:162-9.

Martin-Hayden JM, Andreus ES, Minarovic RJ, Kozak SL. 1999. Carbonate aquifer recharge in western Lucas County, northwest Ohio. Ohio J Sci 99(4):77-83.

McBurnett SL, Franzmeier DF. 1997. Pedogenesis and cementation in calcareous till in Indiana. Soil Sci Soc Am J 61:1098-1104.

McMahon MJ, Christy AD. 2000. Root growth, calcite precipitation, and gas and water movement in fractures and macropores: A review with field observations. Ohio J Sci 100(3/4):88-93.

Schaetzl RJ, Frederick WE, Tornes L. 1996. Secondary carbonates in three fine-loamy alfisols in Michigan. Soil Sci Soc Am J 60:1862-70.

Smeck NE. 1966. Genesis of argillic horizons in Celina and Morley soils of western Ohio. [MSc thesis] Columbus (OH): The Ohio State Univ. 180 p.

Smeck NE. 1993. Evaluation of genetic concepts for Ohio soils. Ohio J Sci 93(4):90-4.

Soil Survey Staff. 1993. Soil Survey Manual. US Department of Agriculture Handbook 18. Washington (DC): US Government Printing Office. 437 p.

Soil Survey Staff. 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 2nd ed. US Department of Agriculture Handbook 436. Washington (DC): US Government Printing Office. 869 p.

Vepraskas MJ. 1992. Redoximorphic features for identifying aquic conditions. North Carolina State Univ Tech Bull 301. 33 p.